Life Cycle Energy and Cost Analysis of a Net Zero Energy House (NZEH) Using a Solar Combisystem

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ABSTRACT

Life Cycle Energy and Cost Analysis of a Net Zero Energy House (NZEH) Using a Solar Combisystem

Mitchell Leckner

In this thesis, two main house models have been developed for the Montreal, QC climate using the TRNSYS simulation software. The first is the Base Case House model which is a typical 1994 Quebec house construction that is used as a baseline for comparison. The second is the Net Zero Energy House (NZEH) model which is an energy efficient, modified version of the Base Case House containing solar technologies that capture energy (solar collectors) and produce electricity (photovoltaics). The main heating system is also modified from electric baseboard heaters to radiant floors fed by a solar combisystem. Extensive sensitivity analyses are performed on the models in order to determine the best selections for the NZEH in terms of the envelope, energy efficient technologies and solar technologies. Cost and embodied energy analyses are performed on various solar technology combinations (evacuated tube solar collector with PV and flat plate collectors with PV) in order to determine the best mix of these systems when constructing an environmentally friendly and cost effective house.

In terms of annual energy use, the Base Case House requires 25,615 kWh/yr compared to the NZEH which uses 14,061 kWh/yr (before adding any solar collectors or PV modules). The most cost effective combination of solar collectors and PV modules to add to this improved house and make it truly ‘net-zero’ is 4 flat plate solar collectors and 35.8 PV modules. A detailed cost analysis of the NZEH shows that due to the high cost of the solar technologies and the low cost of electricity in Montreal, financial payback is never achieved. However, looking at the house improvements before the solar technologies are added results in a payback of 39.3 years, and the potential to reduce that further, to 6.1 years, with some modifications to the design. In terms of the life cycle energy use, which considers the operating and embodied energy of the houses, the complete NZEH uses 63% less energy than the Base Case House and has an energy payback of 8.4 years.

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List of Abbreviations

ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCH	Base Case House
CCF	Cumulative Cash Flow
CFL	Compact Fluorescent Lights
DHW	Domestic Hot Water
DWHR	Drain Water Heat Recovery
EES	Earth Energy System
EPBT	Energy Payback Time
EPR	Energy Payback Ratio
ERV	Energy Recovery Ventilator
FSC	Fractional Solar Consumption
GSHP	Ground Source Heat Pump
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilating and Air Conditioning
IAM	Incidence Angle Modifier
IEA	International Energy Agency
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
NRCan	Natural Resources Canada
NZEH	Net Zero Energy House
PEX	cross-linked polyethylene
PV	Photovoltaic
RFT	Radiant Floor Tank

RSI	Measure of thermal resistance in SI units ($m^2 \cdot K/W$)
SHGC	Solar Heat Gain Coefficient
SI	International System of Units (from the French Système International d'Unités)
SOP	Standard Offer Program
TESS	Thermal Energy System Specialists (an engineering consulting company)
TRNSYS	Transient Energy System Simulation Tool
TMV	Thermostatic Mixing Valve
XPS	Extruded Polystyrene
ZEH	Zero Energy House

1. INTRODUCTION

1.1 OVERVIEW

The vast majority of scientists working in fields related to the earth's climate agree that rapid global climate change is occurring and is largely due to human activities over the last century. Fossil fuel consumption that releases greenhouse gases into the atmosphere is one of the main causes of this crisis. Since most energy sources these days come from fossil fuels, the use of energy directly contributes to global warming. In Canada, the residential sector accounts for approximately 17% of the country's energy consumption. (Natural Resources Canada 2005). In order to avoid the grave consequences that will likely occur if we continue along this accelerated path of energy over-consumption, things need to change. In the area of residential energy use, the way homes are built, heated, cooled and powered must change. Firstly, homes need to be much more efficient so that they require far less energy than they do currently. Secondly, the remaining home energy consumption needs to be satisfied using non-polluting renewable energy sources. Aspiring towards these goals, the concept of a Zero Energy Home (ZEH) is being developed. The premise behind this is to develop homes that are self powered using technologies such as photovoltaics, passive solar, wind power, geothermal, etc. These self sufficient homes would not require connection to the grid of an electricity provider and are thus perfect for remote locations. Similarly, Net Zero Energy Homes (NZEH) are being developed that are connected to an external electricity provider (or electricity grid), but over the course of the year, the net amount of energy the home is required to buy is zero. This is achieved by using electricity from the grid at peak times when the home's system is not sufficient (such as a cold winter night), but by also selling electricity produced by the home back to the grid when the home produces excess electricity (such as on a sunny spring day).

Having a home that is completely self-sustainable is the ultimate goal; however, due to certain factors like the harsh Canadian climate, the idea of a NZEH is more realistic than a pure ZEH.

The goal of this thesis is to analyze the feasibility, cost effectiveness and environmental impact (from a life cycle energy point of view) of a NZEH in Montreal. For this purpose, two computer simulation models have been developed in TRNSYS, one of a typical Quebec house built in 1994 and one of an energy efficient NZEH equipped with a solar combisystem using solar collectors and a photovoltaic array. These models are compared and analyzed in terms of life cycle cost, operating energy use and embodied energy with the goal of determining the best design options for the NZEH.

This thesis focuses on the use of active solar technologies and simple ways to use these systems to provide, heat, hot water and electricity to the house. Complex HVAC systems (geothermal systems, heat pumps, etc) and detailed passive solar design are not considered in this thesis. In addition, moisture flow analysis and detailed comfort conditions are also beyond the scope of this thesis.

This thesis is intended to be a contribution to the body of research working towards the development of Net Zero Energy Home concepts.

1.2 THE ENERGY & ENVIRONMENT CRISIS

Sustainable Energy Sources and Natural Resources

The term “sustainable development” is becoming a popular catch phrase these days. This is because the general public is finally beginning to realize that over the past century, modern societies have been selfishly abusing the planet’s natural resources without considering the future consequences of these actions. In Canada, and arguably the rest of the developed world, energy resources are being consumed at a rate that cannot be sustained.

The issue of sustainable energy sources is very complex, with problems on several levels. There are the environmental concerns that the burning of fossil fuels is contributing to rapid, unnatural global climate change that is changing the planet and could have a significant impact on the way people live. There are also geopolitical implications due to the fact that a significant percentage of the planet's oil resources are located in the Middle East, an area of continued political instability. This instability results in major price fluctuations and even war. Even though power plants that use oil directly only make up a fraction of the global energy mix, oil is used indirectly in many other types of common power production, namely coal and natural gas. This is because petroleum fuels are needed for excavation and transportation equipment. Finally, the looming question of when the available supply of accessible non-renewable oil resources will run out is one that could have indescribable implications on society as we know it. Not only is oil required for energy and transportation, but pretty much all of the materials and even food that people rely on every day, such as steel, aluminum, wood, fruits, vegetables, etc., are extracted using equipment that runs on petroleum. In addition, petroleum based products are everywhere, from plastics to pharmaceuticals, packaging to computer components and electrical insulation to clothing.

In places such as the province of Quebec, Canada, where the relatively environmentally friendly hydroelectricity supplies close to 95% of the electricity use (Hydro Quebec n.d.), the issues of conservation and sustainability are equally important. Due to the fact that electricity is abundant and inexpensive, Quebec has developed into a society that over consumes and wastes its electricity. In order to act in a responsible and sustainable manner, the citizens of Quebec should also conserve as much as possible since this relatively clean energy can be exported to neighboring areas that currently use the environmentally harmful and politically sensitive sources mentioned above. Therefore, in essence, every watt of wasted clean energy in Quebec indirectly results in the burning of harmful fossil fuels in neighbouring provinces and states. In addition, due to growing energy demands, if Quebecers do not find way to conserve more energy, existing power plants will not be able to satisfy the demand and more facilities will need to be built. This is not only expensive, but new, large hydroelectric dams are actually quite harmful to the environment. For example, the flooding destroys huge ecosystems and natural habitats and drowns enormous amounts of trees which not only negates their carbon sequestration abilities but actually results in huge releases of methane, a highly potent greenhouse gas.

The Kyoto Protocol

The Kyoto Protocol was established in 1997 and as of May 13th 2008 has been signed by 181 countries, 37 of which agreed to reduce their greenhouse gas emissions by a specified amount below their 1990 levels. Canada is one of the 37 signatories and has committed to reducing its emissions by 6% below 1990 levels between 2008 and 2012 (UNFCC n.d). A 6% reduction might not seem like too lofty a goal, however between 1990 and 2006, Canada's greenhouse gas emissions rose by about 22%. This puts Canada in the position of needing to now reduce greenhouse gas emissions by 29.1% to meet the Kyoto requirements (Environment Canada 2008)

The Kyoto Protocol is just a first step in the efforts to stop climate change. It is in fact a mere baby step to help get countries started on the path to reducing greenhouse gases and staving off the dangers of climate change. "In its 2007 Fourth Assessment Report, the IPCC concluded that industrialized countries need to reduce their GHG emissions by 25–40% below 1990 levels by 2020, and by 80–95% below 1990 by 2050, to have a chance of avoiding a 2°C temperature increase", which is considered to be a dangerous level of climate change (The Pembina Institute, 2008). In addition to this, rapidly developing countries that have huge populations and soon to be skyrocketing energy needs, such as China and India, are not included in the list of developed countries that are required to reduce emissions. They have taken part in the Kyoto conferences but are not legally required to reduce or contain their emissions. Hopefully they will realize that the cost to the planet and our future way of life will far outweigh the costs related to controlling climate change as they develop. In fact, a review by Sir Nicholas Stern in 2006 entitled The Economics of Climate Change concluded that "climate change will affect the basic elements of life for people around the world – access to water, food production, health, and the environment. Hundreds of millions of people could suffer hunger, water shortages and coastal flooding as the world warms" and that "the benefits of strong and early action far outweigh the economic costs of not acting". More concretely, the review concluded that acting now might cost around 1% of global GDP annually, but failing to act could cost the world between 5% and 20% of global GDP annually (Stern 2006).

International agreements for greenhouse gas reductions in the post Kyoto timeframe have been happening and more are planned in the future. For example, at the 2008 G8 Leader's Summit in Japan, long term targets were discussed. However, as is often the case regarding the politics of this issue, no concrete or meaningful agreements were reached. The G8 agreed to 'consider' the aspirational goal of reducing greenhouse gas emissions 50% by 2050 (The Pembina Institute, 2008). The problem with this is threefold: 1) The reductions are not required, 2) the target year is so far away that they do not force any immediate action and 3) the baseline year for reduction comparison was not specified and there is a significant difference between the 1990 Kyoto baseline year and the 2006 baseline year that many politicians are trying to use.

The future starts now

Every industry and every individual needs to start acting now in order to reduce our dependence on fossil fuels and avoid considerable and rapid changes to the earth's climate. The preliminary effects are already quite evident in areas such as the Canadian arctic, causing threats to animals and their habitats, as well as to the livelihood and towns of human residents. In the residential building industry, changes must be made to the way homes are designed and built. The potential for improvement is enormous and the motivation is significant. Focusing on conservation and sustainability will not only have a positive impact on people's lives in the present, but it is also our duty as responsible citizens to future generations.

2. LITERATURE REVIEW

2.1 RENEWABLE ENERGY TECHNOLOGIES

The natural world has an abundance of clean, renewable forms of energy. The challenge of this generation is to find cost effective, efficient and environmentally benign ways to harness these sources of energy. The most common, currently available technologies that can be used as sources of energy in homes are discussed in this section. These include solar collectors, photovoltaics, micro wind power, and geothermal technologies.

2.1.1 Solar Collectors

A rough calculation based on the total solar radiation incident on the earth's surface in a year (382,868,040 TWh) and the estimated total world energy consumption in 2005 (135,632 TWh) shows that in a year, the sun provides 2823 times more energy than humans used (Windows to the Universe 2007, EIA 2008). Fortunately, many natural systems do harness that energy, but there is still plenty left over that mankind can capture and use for other purposes such as heating and generating electricity.

There are two popular ways of actively collecting the sun's energy and using it as a heat source for buildings. This is by directly heating the air entering a building, or by heating water that can be used for multiples purposes, such as providing building heat or hot water.

The air entering a building can be heated by installing a special perforated dark metal cladding as the outside layer of the wall. Warm air near the surface is drawn through these perforations and enters the building, commonly known as a solar wall. An added advantage to this technology is that it allows for a significant amount of fresh air to enter the building. In addition, this type of wall absorbs and recaptures warm air that would normally escape through exterior walls, thus effectively increasing the insulation R-Value of the wall (Natural Resources Canada 2000).

Solar water heaters essentially operate by allowing the sun to directly heat a fluid, often mounted on a south facing roof (in the Northern Hemisphere). This heated fluid is then used to heat water in the building using a heat exchanger. In northern climates such as Canada, it is better to heat the water this way rather than directly to avoid the possibility of the water freezing. However, direct water heating does exist. This heated water can then be circulated throughout the building through pipes and radiators to heat the rooms. Another useful application is to use heated water directly for domestic hot water, such as showers, taps, dishwashers, etc. “A typical system will provide 50 to 75 per cent of a family's hot water needs. With water heating accounting for about 20 per cent of home energy use, a solar DHW system is an attractive method of reducing a home's fossil fuel consumption” (Solar Energy Society of Canada Inc. 2003).

2.1.1.1 Solar Water Heaters

According to Natural Resources Canada, a study done a little before 2002 indicated that Canadians had about 12,000 solar water heaters in use, which was less than 1% of the potential market. Due to more recent technology improvements and cost reductions, this number has the potential to grow significantly (Natural Resources Canada 2003).

Solar water heaters can be divided into two broad categories: Active and Passive.

Active Solar Water Heaters

Active solar water heaters, the more common type, are named as such since they require electric pumps and controllers to circulate the fluid between the collector and the storage tank. There are three common types of Active Solar Heaters.

a) Direct-circulation systems. These systems circulate water through the collector itself to be directly heated. They are only suitable for climates that do not generally have below freezing temperatures since the water could freeze.

b) Indirect-circulation systems using anti-freeze. These systems use anti-freeze in the collectors exposed to the outdoor temperature and transfer the heat to water in a conditioned environment. This type of collector is suitable for cold climates.

c) Drainback indirect-circulation systems. These systems use water as the heat transfer fluid exposed to the outdoor temperature and transfer the heat to water in a controlled environment. These systems can be used in some cold climates since when the pump is off and the water is stagnant and susceptible to freezing, the water is drained from the collector to prevent freezing (US Department of Energy, 2006).

Since Montreal has long, cold winters, an indirect-circulation system is clearly the best suited type of solar water heater. There are several different types of these systems. The following two types are the most appropriate for a Montreal residential application:

i) Glazed flat plate collectors: This type of solar collector is essentially a box containing a dark, non-reflective surface that absorbs solar radiation and contains anti-freeze filled pipes attached inside. The heat from the solar radiation is transferred to the fluid through the pipes, and that heat is then transferred to water using a heat exchanger. These systems are appropriate when temperatures in the range of 30-70°C are desired (Natural Resources Canada 2006d).

ii) Vacuum/evacuated tube solar collectors: There are two main variations to this type of collector. The glass-glass version consists of long glass tubes containing smaller diameter glass tubes inside them. The space between these tubes is a vacuum that eliminates the convective and conductive heat losses to the outside air. The smaller central tubes are coated with a substance to allow incoming radiation while resisting its release. The solar energy then causes the liquid in the inner tubes to evaporate and transfers the heat out of the end of the tube through a heat transfer manifold. The glass-metal version is similar except that the inner tubes are metal tubes attached to a heat absorbing fins. The glass-glass evacuated tube solar collectors tend to be slightly less efficient than the glass-metal type but they are more reliable in terms of vacuum seals and are also less expensive (Apricus 2006). In general, evacuated tube collectors are more efficient than glazed flat plate collectors, but can cost twice as much. These collectors are best suited for applications requiring temperatures in the range of 50-90°C (Natural Resources Canada 2006d).

Passive Solar Water Heaters

Passive solar water heaters rely solely on gravity and fluid temperature differences (no pumps or electricity) for the circulation of the fluid. There are two types of passive solar water heaters.

a) Thermosyphon systems. These collectors are installed at an angle so that the hot fluid rises and the cold fluid descends to the bottom of the collector. This results in the required circulation of the fluid. The storage tank is located above the collector since that is where the warm fluid flows. In cold climates, these systems can contain anti-freeze, but the water pipes, often located in unheated attics, need to be properly protected with technologies such as freeze protection piping.

b) Integral-collector (or Batch) storage systems. These systems are quite simple in concept. They are essentially one or more storage tanks in glazed insulated boxes exposed to the sun. This way, the sun directly heats the water in the storage tanks. These systems are not appropriate for cold climates where the water in the piping can freeze (US Department of Energy, 2006).

Advantages of Active vs. Passive Solar Collectors

Although passive solar collectors do not use pumps and thus cost less and do not consume electricity, there are some significant advantages to using active solar collectors for certain applications. One such application is that of a solar combisystem, which happens to be the system used in the NZEH for this thesis. A combisystem requires a pump and a controller so that the hot fluid can be used for either heating the house or the domestic hot water (DHW), which use two separate storage tanks. The pump is necessary since the timing of the flow needs to be controlled as well, and sometimes, if the storage tanks are too hot, the flow of hot fluid needs to be altogether stopped. Another advantage of an active solar collector is that it allows a system to have a controlled, adjustable flow rate. This can be useful to optimize the heat transfer between the sun and the solar collector as well as between the solar collector and the storage tanks.

2.1.1.2 Solar Collector System Sizing

Sizing a solar collector to meet the hot water needs of a house depends on many factors such as the size and insulation level and air tightness of the house, domestic hot water use and available solar radiation. As a general rule, the surface area of a solar collector system that is being used for both domestic hot water and radiant floor heating is usually about 10% to 30% of the heated floor area (US Department of Energy 2003). For space heating, the Solar Energy Alliance (2001) recommends using approximately 1 to 3 evacuated solar tubes per square meter of area that needs to be heated. Since the gross area of a typical evacuated tube is about 0.11 – 0.13 m^2 these guidelines are in agreement with each other.

These systems are always equipped with storage tanks since hot water is also needed at night when there is no sun to heat the collector fluid. The size of the tank is usually about 40 litres per m^2 of collector area (1.5 gal/sq.ft.)(US Department of Energy 2003).

2.1.1.3 Solar Combisystems

The International Energy Agency (IEA) undertook an analysis of solar combisystems in homes called Task 26, from December 1998 to December 2002. Task 26 analyzed, tested, compared and optimized different combisystem designs by simulating them in the TRNSYS environment. Twenty one different systems of varying complexities were simulated and nine of these are documented with detailed results on the IEA website. Many different types of system set-ups were tested with single tanks, double tanks, small tanks immersed in large tanks, tank stratifiers, multiple internal or external heat exchangers and various auxiliary heat sources (gas and biomass burners). The systems were tested in the northern, central and southern European climates to represent the different solar conditions found in Europe. In addition, detached single family houses, grouped single family houses and multifamily homes were analyzed. Although many aspects of these systems were standardized, differences such as those described above end up making the direct comparison of results more difficult. This is especially true if the size of the house or collector areas are different. In order to take this into consideration, the results were normalized using the FSC (fractional solar consumption) method. Of the nine systems with available detailed results, the fractional thermal energy savings ($F_{sav,\ therm}$) at 0.6 FSC ranged from 0.31 to 0.5. This $F_{sav,\ therm}$ is basically the fraction of saved fuel compared to a reference system that does not use solar energy. Therefore, 31% to 50% less fuel is used in those cases. 0.6 FSC is an arbitrarily chosen example since it is plotted between 0.16 and 1.0. FSC is described in more detail in section 5.4.1 (IEA-SHC 2002, Letz 2002).

2.1.2 Photovoltaics (PV)

The potential for photovoltaics is immense. Even though there are many limitations to how much of the sun's energy can actually be captured and put to use, with so much free, clean and fully renewable energy shining down on the earth every day, it is no wonder that this technology is the leading source of electricity generation in new zero energy home projects worldwide.

The main purpose of photovoltaics, also known as solar cells, is to convert sunlight directly into electricity. This is most commonly done using multiple layers of silicon semi-conductors that absorb certain wavelengths of sunlight, and through a chemical process, this allows the transfer of electrons to produce an electric current (US Department of Energy 2005).

One of the main reasons why photovoltaics are still not widely used, given their clear environmental advantages, is due to their prohibitive cost. However, the average price of PVs is now 30 times less expensive compared to the 1970's (Solar Energy Industries Association 2006). In certain applications, such as remote areas needing power, PV technology is now cost efficient. In fact when life cycle cost is considered, photovoltaics are getting closer to becoming cost efficient for more standard applications as well, such as supplying power to residential homes. This is thanks to continued research and development as well as the reduction in manufacturing costs due to increased production. Other large factors that determine the cost effectiveness of PV compared to other sources of electricity are the local cost of conventional electricity, which can vary significantly depending on where you live, as well as government rebates designed to encourage the use of PV technology. In Quebec, for example, electricity is very inexpensive, less than $0.07/kWh (before tax), and there are no rebates for photovoltaics on new homes, so installing PVs can still be prohibitively expensive. However, in Ontario, the government will buy the PV power you produce for $0.42/kWh, which is almost 4 times more than residential consumers pay for it. These differences in pricing and policy will help to make or break the cost effectiveness of a PV project. In Quebec, the best a homeowner can do is sell solar electricity back to Hydro Quebec at the same rate at which they buy it from Hydro Quebec. This is the concept of net metering.

2.1.2.1 Interconnection and Net Metering (Selling Back to the Grid)

Net Metering and interconnection applies to residential power users connected to a public or private power grid but who also have their own electricity producing systems, primarily photovoltaics or wind turbines. This allows the users to effectively store excess electricity that they generate with the utility company. During periods of reduced consumption, perhaps while the user is not home during the day, their system may produce more energy than the house requires. This extra electricity is fed to the utility company who can use it to sell to its other customers. At other times when the user needs more electricity than their system is producing, perhaps at night or on a cloudy day, the user will draw power from the utility company. The meter measures when the home consumes electricity from the grid as well as when it produces an excess and sells it back, and then calculates the net electricity use. Some utility providers will even purchase power from the user if the user creates a net surplus of electricity. This is not required in most places but some companies do this because they buy the electricity at lower rates and sell it to make a profit and boast that they supply environmentally friendly power (U.S. Environmental Protection Agency 2005).

In Canada, there are varying programs depending on the province. As of July 2008, all of the provinces and territories have some form of net metering program in place, aside from the Northwest Territories, Yukon, Nunavut and Newfoundland & Labrador. Of these provinces and territories without a net metering program, most of them are working on putting a program in place in the near future. In the United States of America, the majority of states allow for at least some form of net metering (U.S. Environmental Protection Agency 2005). Net metering is not limited to North America either. There are regulations and incentives that are in place (and likely evolving) across the planet such as in Europe, China and Japan. (Jiménez 2004)

Net-Metering is an essential part of a Net Zero Energy Home. Without this option, achieving net zero energy would require grossly oversized renewable energy systems for part of the year as well as huge battery banks to store the energy on-site. This would add significant cost to the house and would also be a huge waste since many times during the year excess energy that could be produced would not be useable.

2.1.3 Renewable Energy Technologies Not Used in the Model

In addition to the predominantly solar based technologies that are used in the NZEH for this thesis, there are other existing renewable energy technologies that were initially considered. These alternative energy sources are briefly described below, along with the reasons why they were not included in the model.

2.1.3.1 Micro-Wind Power

The technology behind wind power is relatively straight forward and the conversion of wind into work dates back several thousand years. For current micro wind power technology, a wind turbine is set up, usually between 10 m and 40 m high. When wind blows between 3 m/s and 20 m/s, the rotating turbines convert the energy into useful power. Benefits of wind power are of course the fact that it is a clean source of energy and it provides a source of autonomous power. However, with current energy prices in Canada being relatively low, wind power is not always economically beneficial. Large scale wind farms are being competitively built, however micro wind power cost benefits vary greatly depending on the individual situation and location (Canadian Wind Energy Association n.d.).

Although still in its infancy, the industry of large scale wind farms is starting to become more popular around the world. Micro wind power, however, appears to still be a niche market that is most commonly found on farms and isolated, rural properties. Although some companies such as Renewable Devices (www.renewabledevices.com) and Windsave (www.windsave.com) in the UK are developing wind turbines that may be promising for the urban environment, there is currently very little data to verify the effectiveness of these systems.

2.1.3.2 Ground Source Heat Pumps

Ground Source Heat Pumps (GSHP), also known as Earth Energy Systems (EES), are a proven technology that have many benefits. However, these systems have large up front costs, the hardware and piping is quite large and they require excavation and significant underground space. This can act as a deterrent for many homebuyers and in some cases it is just not possible to excavate and use this technology. It can also be very difficult to install these systems if it is not a new home starting on an empty lot. Therefore, this thesis will not include these systems in the analysis in order to see the potential of other technologies in the absence of Earth Energy Systems.

2.2 ZERO ENERGY HOMES

2.2.1 Current state of Zero Energy Homes

Zero Energy Homes are being developed in many countries, on all continents throughout the world. This is especially true if one considers the idea that combining energy efficiency measures with renewable energy technologies has the ultimate goal of producing a self-sustainable, Zero Energy Home. Although there are countless examples of these types of projects, the majority of them are a far cry from being 100% self sustainable or even Net Zero Energy Homes. However, the building industry is in the infancy of what will hopefully become a revolution in home design.

It should be noted that currently in the building industry, the term “Zero Energy Home” is often used quite loosely to describe homes that are very energy efficient, but do not necessary produce as much energy as they consume. This could affect what people think when they hear the term and what kind of home they envision it being in terms of energy savings and environmental impact. It is unclear if the liberal use of this term has any consequences on builders and consumers when making home purchase decisions.

Some recent research on Net Zero Energy Solar Homes was done by Charron (2007), where models in TRNSYS were optimized using genetic algorithms to determine the most cost effective designs. In addition, the International Energy Agency Solar Heating and Cooling Programme approved the new Task 40, 'Towards Net Zero Energy Solar Buildings' in June 2008. This task aims to study and promote realistic designs for net and near net zero energy buildings (IEA-SHC 2008).

Charron (2005) did a review of low and net-zero energy solar homes and some of his findings are discussed in the following five paragraphs.

Japan can be seen as one of the leaders in ZEH development, partly due to a significant PV-Roof market incentive back in 1994 that subsidized 50% of the installation costs. This aided in the development of what is now a thriving PV industry.

In 2000 The US Department of Energy developed the US Zero Net Energy Buildings Outreach and Action Plan. This has resulted in thousands of low energy homes being built across the country, some of which qualify as Net Zero Energy Homes. The initiative also resulted in the Solar Decathlon, held in Washington D.C., which is an international university competition of solar home designs.

Between 1998 and 2001, Cost Efficient Passive Houses as European Standards (CEPHEUS) was a European initiative to create 250 highly efficient homes across Europe. These homes took advantage of passive solar power and efficient design with the added goal of showing that this can be done economically. The energy requirements were low enough that with additional technologies, such as photovoltaics, they would likely be considered Zero Energy Homes. The

International Energy Agency is another organization that has been working on similar initiatives throughout the world.

In Canada, several initiatives have taken or are taking place to further the development of ZEHs. Two of these include: The Advanced House Program and the Net-Zero Energy Home Coalition.

The Advanced House Program was created by Natural Resources Canada (NRCan) in the early nineties. The goal was to develop low energy homes across Canada using various available technologies. None of these ten homes reached Net Zero Energy status, but they did show that significant energy reductions can be achieved, some up to 75% compared to a typical Canadian home. The lowest consumption by one of these homes was 11,607 kWh/yr. compared to 39,000 kWh/yr for an average detached home in 1993. The main technologies used were PV, solar thermal, and of course improved building envelope design to limit losses and leakage. With the ongoing improvements in energy efficient technologies, appliances and design, if some of these homes were built today, they might be much closer to, or even achieve Net Zero Energy status. Formed in 2004, The Net-Zero Energy Home Coalition is a group of not-for-profit, environmental, non-governmental as well as corporate organizations whose ultimate goal is to have all new Canadian homes built by 2030 be NZEHs.

A third initiative in Canada that is still in progress (as of July 2008) is the EQuilibrium healthy housing competition described in the next section.

2.2.1.1 A Sampling of Built and Proposed Zero Energy Homes

The EQuilibrium healthy housing competition, sponsored by the Canadian Mortgage and Housing Corporation (CMHC), is one of the most successful recent initiatives to develop Net Zero Energy Homes. The goal of the competition is to create twelve demonstration Net Zero Energy Homes that have a low environmental impact. The winning projects selected to receive funding have been named. Some of the homes are complete, such as the EcoTerra house, some are in the process of being built and some have not yet begun construction. These projects are located all across Canada with three in Quebec, three in Ontario, one in Manitoba, one in Saskatchewan and four in Alberta. Table 2.1 summarizes the renewable energy technologies used in each project. The projects range in size from the renovation of a small 60 year old post war home to the new construction of a 25 home community. As in all intelligently built NZEHs, these homes are designed with low energy consumption in mind. In addition, many of the homes are designed with passive solar strategies, some of them use hydronic radiant floor heating and most have drain water heat recovery, water saving devices or even greywater reuse. As the name suggests, all of these NZEHs are expected to produce at least as much energy as they consume over the course of the year (Canada Mortgage and Housing Corporation 2008). Currently, measurements are not yet available to show if these homes have been successful in actually being true net zero energy homes, especially since most have not yet been completely built.

As mentioned previously, Zero Energy Homes are being built in other parts of the world as well, such as the USA and Japan. Table 2.2 shows a sampling of existing homes in these countries that were built with the original goal of being or being close to ZEHs or NZEHs and have been well documented in scientific journals or on the internet. Once completed, many of these homes did not actually achieve net zero status. This could have been due to many factors such as an underestimation of the variable loads from lighting and appliances caused by occupant behaviour or possibly weather conditions that required more heating or cooling than expected.

In terms of the technologies used in the homes, all eight used photovoltaics to produce electricity and five of them used hydronic solar collectors as an energy source for combisystems (heating and DHW). The three homes without solar combisystems did also have solar collectors, but they were used for the DHW only. Four of the homes had ground source heat pumps, all of which helped to supplement the heating. Passive solar design was only explicitly mentioned in two cases, but designing to take advantage of the sun is becoming common practice for these types of homes so others likely incorporated this technique as well. Finally, of course all of the houses had tight envelopes and were generally designed with efficiency in mind.

Table 2.1: Renewable Energy Technologies in the EQuilibrium Net Zero Energy Homes

Project	**PV (Rated Power)**	**Solar Thermal**	**Geothermal**	**Wind**
Abondance le Soleil [1] Triplex	●	Evacuated Tubes	●	
EcoTerra [1] Single family detached	3 kW	PV Thermal - Air	●	
Alstonvale Net Zero House [1] Single family detached	7 kW	Evacuated Tubes PVT Air	●	
Avalon Discovery 3 [1],[2] Single family detached	●	Flat Plate		
Echo Haven [1],[3] 25 home community	●	Evacuated Tubes	●	●
***Inspiration* — The Minto EcoHome** [1],[4] Single family detached	●	Flat Plate, Solar Air		
Now House [1] 60 yr old post war home	●			
Riverdale NetZero Project [1],[5] Duplex	5.6 kW	Flat Plate		
The Laebon CHESS Project [1],[6] Bungalow	3.85 kW	Flat Plate	●	
Top of the Annex Town Homes [1],[7] Three freehold condominium townhouses	6.2 kW	Flat Plate	●	
Urban Ecology [1] Two semi-detached homes	●		●	
YIPI! Net Zero Footprint Housing [1] Single family detached	●			

1- Canada Mortgage and Housing Corporation 2008
2- Avalon Central Alberta 2008
3- Echo-Logic Land Corporation 2008
4- Minto Group Inc. 2008
5- Habitat Studio and Workshop Ltd. 2008
6- Laebon Developments Ltd. 2008
7- Rad, F & Fung, A 2008

Although zero energy homes around the world are certainly built to different codes and standards to adapt to their local climates, this usually applies to how much heating and cooling is used and the level of insulation required to make them tight and efficient. In terms of renewable energy technologies and other design strategies, there are also many similarities, regardless of the climate. Photovoltaics are found in essentially all NZEHs since it is the simplest way to produce electricity, although it is still quite costly. Thermal solar collectors are widely used, whether for just DHW or space heating as well, and geothermal heating and cooling is becoming more and

Table 2.2: A sampling of existing net-zero or near-net-zero energy homes

Name, Location, Year, (Reference)	Floor Area (m^2)	Energy Use from Utilities ($kWh/yr{\cdot}m^2$)	Total Energy Use ($kWh/yr{\cdot}m^2$)	% of Energy Demand Produced By the Home	Key Technologies	Extra Initial Cost
Armory Park Del Sol Tucson, AZ, USA, 2003 (NAHB Research Center, Inc. 2004a)	160	10 - 21	55 - 66	68% - 82%	PV: 4.2 kW Array Flat plate solar collector for combisystem Back-up tankless electric water heating 2-speed, 3-ton 18-SEER air conditioning unit Tight envelope	USD$46,000 (14.7% more than without the special features)
Remodeling house project Califon, NJ, USA, 2003 (NAHB Research Center, Inc. 2004b)	139	0	n/a	> 100% (US$235 extra)	PV: 7.2 kW mono-crystalline array Solar pre-heated tank and tankless demand heater for DHW GSHP: 50% of the heating and cooling loads Tight air sealed envelope: estimated 60% reduction in heating and cooling loads Energy efficient lighting and appliances	US$29,000
Haberman House Sendai, Japan, 1996 (Saitoh and Fujino 2001)	260	36	n/a	n/a	PV: 1.5 kW array that produces 1000 kWh/yr 30.4 m^2 solar collector. Underground water storage tank for long term heat storage used for space heating. Heating is supplied by a Fan Coil Unit (FCU) that uses hot water. 15.2 m^2 sky radiator for long term cold storage using an underground water storage tank for space cooling Rainwater collection for toilets and garden use	n/a
Low Energy Building Hokkaido University, Japan 1997 (Yasuhiro, Makoto et al. 2001)	192	17 (electricity only)	37 Electricity only, no data on energy from solar systems	54%	PV: 4.4 kW Passive Solar: Designed for direct solar heat gain. High heat capacity concrete to regulate heat temperature variations Natural Ventilation GSHP: 3 systems for heating and cooling Solar water heater: 8 m^2 for DHW Roof exhaust heat recovery usung a 0.4 kW heat pump Tight building envelope	14% more than a typical japanese house

Table 2.2 (continued): A sampling of existing net-zero or near-net-zero energy homes

Name, Location, Year, (Reference)	Floor Area (m^2)	Electricity Use from Utility ($kWh/yr{\cdot}m^2$)	Total Electricity Use ($kWh/yr{\cdot}m^2$)	% of Electricity Demand Produced By the Home	Key Technologies	Extra Initial Cost
The Hathaway "Solar Patriot" House Washington, DC, USA, 2001 (Norton, Hancock and Reeves 2005)	268	12 (electricity only)	39 Electricity only, no data on energy from solar systems	63% - 70%	PV: 6 kW Solar Water Heater: DHW and Space Heating (forced air system) Ground coupled heat pump for cooling and back-up DHW Tight building envelope Energy efficient lighting and appliances	n/a
Centex Homes Livermore, CA, USA 2002 (US Department of Energy, Building America n.d.)	286	n/a	n/a	104% of electricity from PV 45% of gas heating from solar collector	PV: 3.6 kW Solar water heater: 50% of the DHW Efficient tankless gas water heater: Space heat & DHW Tight building envelope Energy efficient lighting and appliances	US$480/yr net
Cannon Beach Cottage, 2005 Oregon, USA, 2005 (McPhee 2006)	210	n/a	n/a	>100% estimated	PV: 5.9 kW array Solar water heater (feeding a hydronic forced air system)/GSHP combined system: Produces heat for the basement storage tanks used for space heating and 50% DHW Passive Solar: Designed for direct solar heat gain. Thermal mass walls Ventilation heat recovery system Excess heat stored in the basalt rock under the house Passive cooling Tight building envelope Energy efficient lighting and appliances	n/a
Rose House Oregon, USA, 2004 (Kharif 2004)	74	0	~81 Electricity only, no data on energy from solar systems	100% All forms of energy	PV: 3.3 kW array - 300 sq.ft. Solar Heat Pump: Located under the PV array, for space heating, cooling and DHW Energy Recovery ventilator for waste hot air Thermal mass walls Tight building envelope Energy efficient lighting and appliances	Total cost was about US$116,800, which is 22% more than a typical comparable home

more common, found in over half of the homes in this sampling. Passive solar design (taking advantage of the sun through window sizing and positioning and using thermal mass) is also common and used to varying degrees since it is very effective and economical. Finally wind power, another clean energy one might consider using, is not widely used in small scale home energy production since the technology is still more suited to large power plants.

2.3 EMBODIED ENERGY

Embodied energy is the energy that is needed to make a product, from resource extraction, through transportation, transformation, production, delivery, maintenance, demolition and recycling/reuse/disposal. This energy can be a significant part of the energetic and environmental impact of a house and cannot be ignored. Over the years, many studies have been performed that analyze various aspects of the embodied energy in buildings, from individual systems to buildings as a whole. Some of the more recent studies pertinent to this thesis are presented below.

2.3.1 Research on Embodied Energy in Buildings

Yang, Zmeureanu & Rivard (2008) did a literature review concerning embodied energy in six homes located in varying climates across the world (Canada, USA, Sweden & New Zealand). The embodied energy in the construction materials, normalized to house floor area, ranges from 633 kWh/m^2 to 1306 kWh/m^2. This is attributed to different climate conditions, with the house in Montreal having the lowest estimation. For the six homes in the studies, the results show that it takes 7, 7, 15, 18, 19 and 57 years for the operation of the houses to consume as much energy as is embodied in the construction materials. That large difference is attributed to the fact that the smaller number of years is for colder climates like Canada and Sweden, which require significant heating compared to the 57 years for the house located in Auckland NZ, a much milder climate.

Thormark (2002) concluded that the embodied energy in the production of very low energy apartments in Sweden (1954 kWh/m^2) constitutes 46% of their 50 year life cycle energy use. The embodied energy for production can also be calculated as being equivalent to 43 years of operational energy use. Thormark also surveyed results from four other low energy buildings (<70 kWh/m^2) in Scandinavian countries and found similar results. In those four buildings, the embodied energy accounted for 40% of the total 50 year life cycle energy use.

Sartori & Hestnes (2007) analyzed 60 buildings found in the literature (10 of which they considered low energy buildings) with different construction techniques and sizes and in different climates to see how important the embodied energy in the building materials was compared to the life cycle energy use of the buildings. The overall trend showed that even with increases in embodied energy for low energy buildings due to more materials used, the increase is still small compared to the life cycle energy use as a whole.

Verbeek & Hens (2007) concluded that although the there is significant embodied energy in the extra materials required to make low energy buildings (13,890 kWh to 41,670 kWh for the houses they analyzed), the savings in operational energy more than offset the extra embodied energy. They estimated the energy payback time (EPBT) for this type of construction to be typically less than 2 years. "The EPBT is defined as the proportion of the extra embodied energy for energy saving measures to the yearly energy savings they achieve". After the energy is paid back in that short time, for each additional year during the life of the house, the annual energy savings are significant, between 8,330 kWh/yr and 30,555 kWh/yr.

A few conclusions can be drawn from these studies. Some of the studies report that the embodied energy makes up a large percentage of the life cycle energy of low energy houses whereas other studies reported that it is only a small percentage. In very low energy houses it makes sense that the embodied energy would be significant because in these cases the operational energy is very low. These differing conclusions may be due to improvements in building design and materials (better efficiency with less materials), less intensive production methods, the effect of different climates as well as the inherent uncertainly and variability in the calculation of embodied energy. However, more important and less divisive is the issue of whether the incremental increases in embodied energy needed to make low energy buildings is beneficial. The answer to this appears to be a resounding yes. Even if the building material embodied energy is significant compared to the reduced operational energy in a low energy building, the energy payback time appears to be in the range of only a few years. Therefore, after the embodied energy is "paid back" in this short time, compared to standard, less efficient houses, energy use is being reduced from then on.

2.3.2 Embodied Energy in Solar Energy Systems

Embodied energy is a relatively new, complex and sometimes uncertain field of study. Therefore, finding reliable results or sometimes any results at all for specific technologies can be a challenge. Significant study has been done regarding the embodied energy required to produce flat plate solar collectors as well as photovoltaic modules. A summary of some of these studies is presented in sections 6.3.2.3 and 6.3.2.4. However, to the best knowledge of this author, no complete studies have been published regarding the embodied energy of evacuated tube solar collectors.

2.4 THESIS OBJECTIVES

The main objective of this thesis is to analyze the feasibility of building a NZEH with a solar combisystem in Montreal, QC, and performing this analysis using the TRNSYS simulation tool. This is done by comparing the NZEH to a typical house built in Quebec in 1994 as the base case. These comparisons aim to determine the best improvements to the house envelope, the most effective energy efficiency technologies and the appropriate sizing for hydronic solar collectors and photovoltaic modules. Sub-objectives that lead to the main goal are to determine the cost effectiveness of these changes (through a life cycle cost analysis) as well as to estimate the life cycle energy use of the NZEH. Finally, this thesis also aims to look at the different possible combinations of the solar technologies being analyzed that result in net-zero energy use to determine which is the best in terms of life cycle cost and life cycle energy use.

3. MODELING IN TRNSYS

3.1 TRNSYS – OVERVIEW OF THE SIMULATION ENVIRONMENT

TRNSYS (TRaNsient SYstem Simulation program) (Klein et al. 2006a) is the software used in this thesis to develop the model of the home and simulate its energy use performance. This software has its roots in predicting the energy consumption of solar buildings and has become well established over the past 33 years. TRNSYS is a very powerful and versatile tool. The software can be used to model many different types of systems, ranging from something as simple as a domestic hot water system to a more complex multi-story, multi-zone building with all of its functioning and interdependent systems. The software has been developed to allow the user to include various types of components (called "Types") in the system/building being simulated, such as solar panels, fuel cell power or thermal storage systems. If the specific component does not exist in the fairly comprehensive TRNSYS library, the modular architecture of the software allows the user to create a custom component in all common programming languages using the DLL format and add it to the model. In addition, the software can be linked to other software programs, such as Microsoft Excel, Matlab and EES to perform other tasks (Solar Energy Laboratory 2006, p.1.7).

In order to facilitate the modeling of buildings, a secondary program within TRNSYS called TRNBuild, is integrated into the TRNSYS Simulation Studio. TRNBuild allows the user to develop a detailed model of the building which is then placed in the TRNSYS Studio where it can be connected to all of the other components (Types) to simulate the interaction with other systems such as solar collectors or photovoltaics. Although the TRNBuild model contains many details required to model a building (such as the wall and floor construction, internal heat gains, lighting, etc), sometimes additional building components are attached external to TRNBuild, in the TRNSYS Studio. This may be because they are not included in TRNBuild at all or because the user needs to model certain components with more detail, e.g., a photovoltaic system, a DHW tank, seasonal schedules for heating and cooling, etc.

The TRNSYS Studio is quite user friendly and shows all components (Types) as icons which are connected to each other with link-arrows. Take the simple example of a building which is affected by the local climate and contains a hot water tank. The user wants to plot the heating and cooling loads required to maintain the building at 22°C as well as include the effect of heat losses from the tank into the building. The model will show the Weather and hot water tank icons linked to the Building icon and then an arrow leaving the building linking it to the plotter icon.

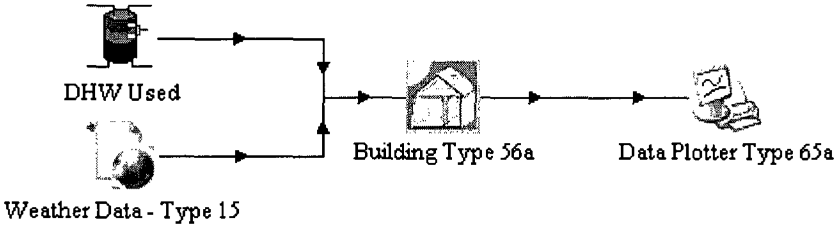


Figure 3.1: Connections between Types in TRNSYS

3.2 COMPONENTS (TYPES) USED

All of the components, represented by icons in the TRNSYS Studio, are called "Types" and have a number associated with them, such as the Multi-Zone Building Model, called Type 56. Types contain parameters, inputs and outputs specific to each Type that are defined or linked in order to specify how the particular Type will behave. For example, in the Weather Data Processor - Type 15, the user will have to define the Ground Reflectance (a parameter) which will impact the Ground Reflected Diffuse Radiation (an output). This radiation value might then be used as an input to the Multi-Zone Building – Type 56. When all of the selected types are fully defined, they are linked together to form the model that will be simulated.

Table 3.1 lists all of the TRNSYS types used in his thesis for the development of the Base Case House (BCH) and/or the Net Zero Energy House (NZEH). A descriptions of each Type is briefly presented after the table.

Table 3.1: All TRNSYS Types used in this model

Name	TRNSYS Type	House Model
Flat Plate Solar Collector	1b	NZEH
Differential Controller with Hysteresis	2d	NZEH
3-Stage Room Thermostat with heating set back and temp deadband	8b	NZEH
Flow Diverter	11f	NZEH
Weather Data Reading and Processing - TMY2	15-2b	BCH/NZEH
Periodic Integrator	55	BCH/NZEH
Multi-Zone Building	56a	BCH/NZEH
Storage Tank; Fixed Inlets, Uniform Losses and Node Heights	60d	BCH
Online Plotter With File	65a	BCH/NZEH
Evacuated Tube Solar Collectors (TESS)	71	NZEH
Heat Exchangers	91	NZEH
Photovoltaic Panels - Crystalline Modules	94a	NZEH
Heating and Cooling Season Schedule (TESS)	515	BCH/NZEH
Hourly Schedule - Weekdays Saturdays and Sundays (TESS)	516	BCH/NZEH
Hourly Schedule - 7 Identical Days (TESS)	517	BCH/NZEH
Cylindrical Tank - Vertical (TESS)	534	NZEH
Mixing Valve (TESS)	649	NZEH
Ground Coupling - Basement Heat Losses (TESS)	701a	BCH/NZEH
Pumps - Variable-Speed (TESS)	742	NZEH
Equation	n/a	BCH/NZEH

3.2.1 The house and its components

Type 56a - Multi-Zone Building (BCH, NZEH)

The Multi-Zone Building is the centerpiece of this model since it is the house being simulated and thus the most important component used. Unlike most other Types which are defined primarily by one window in TRNSYS containing tabs for parameters, inputs and outputs, the Multi-Zone Building model is created with the accompanying program called TRNBuild. TRNBuild allows the user to define many intricate details about the building being simulated, such as:

a) Construction: The walls, floors and windows, containing the details of every layer such as wall board, insulation and wood studs as well as the properties of the materials used for these layers. It is also possible to model active hydronic radiant floors in this Type.

b) Natural air infiltration.

c) Ventilation.

d) Internal gains from items such as occupancy, lighting and other equipment.

e) Space Heating: As defined in the TRNSYS documentation (Solar Energy Laboratory 2006, pp 6.63 – 6.81), the thermal zone is based on one air node per zone which contains the thermal capacity of the air volume and other closely related objects such as furniture. The net heat gain into the air is defined as:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{\inf,i} + \dot{Q}_{v,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cp\lg,i} \tag{3.1}$$

where:

$\dot{Q}_{surf,i}$ = net heat transfer by convection to the zone air from all inside surfaces, W;

$\dot{Q}_{\inf,i}$ = infiltration gains, W;

$\dot{Q}_{v,i}$ = ventilation gains, W;

$\dot{Q}_{g,c,i}$ = internal convective gains, W;

$\dot{Q}_{cp\lg,i}$ = gains due to convective flows from all adjacent zones, W;

In order to calculate the gains in equation 3.1 the surface temperatures are needed. Using transfer function relationships developed by Mitalas and Arsenault, the heat conduction on the inside and outside surfaces are determined (Stephenson & Mitalas 1971, Mitalas & Arseneault n.d., Lechner 1992):

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \tag{3.2}$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{d_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,o}^k \tag{3.3}$$

where:

$T_{s,o}$= outside surface temperature, °C;

$T_{s,i}$= inside surface temperature, °C;

$\dot{q}_{s,i}$= conduction heat flux from the wall at the inside surface;

$\dot{q}_{s,o}$= conduction heat flux from the wall at the outside surface;

Combining equations 3.1, 3.2 and 3.3 with the surface heat flux balance of each wall, the unknown temperatures are calculated. The transfer function method uses temperatures and heat fluxes from past time steps in order to determine those for current time steps. This is to take into consideration the time lag effect from the thermal mass of the walls through which the heat is passing. The superscript k is the time series term, with the current time being k = 0, k = 1 is at the previous time step and so on. The coefficients a, b, c and d are determined by TRNBuild using z-transfer routines.

In TRNBuild, the user can also define various zones in a building, such as the basement, garage, ground and upper floors and the attic. The user can then define which zones are adjacent to each other so that the heat flow is properly simulated.

Additional details that are beyond the scope of this description may also be defined in TRNBuild, such as coupling airflow between zones, the percentage of solar radiation striking surfaces, window shading factors, etc.

Type 60d - Storage Tank; Fixed Inlets, Uniform Losses and Node Heights (BCH)

This vertical storage tank is used to model the hot water tank in the basement with one inlet and one outlet. It models the specific heat losses to the room as well as the energy required to heat the water based on a specific temperature set point, flow rate and tank heat loss coefficient.

Type 60d incorporates its own internal time step based on the critical Euler time step calculated by TRNSYS. This is independent of the overall model simulation time step. The user sets a parameter in Type 60d that defines the fraction of the Euler time step that it uses. This ensures accurate results for the time sensitive calculations in the tank such as the time that the electrical heating element cycles on and off. This is the main reason why Type 60d was chosen over Type 4, another stratified storage tank available in TRNSYS (Solar Energy Laboratory 2006 p. 5-385).

Type 534 (TESS) - Cylindrical Storage Tank with Immersed Heat Exchangers (NZEH)

This vertical storage tank is used to model both the domestic hot water tank as well as the radiant floor water tank for the combisystem. This Type is useful since it can contain multiple heat exchangers, multiple inlets and outlets for the tank fluid, external heating elements and it calculates heat losses. All of these options have parameters controlling how they function to match reality as closely as possible. Type 534 in the NZEH replaced Type 60d in the Base Case House so that the heat exchangers connected to the solar collector could be properly modeled.

Type 1b Flat Plate Solar Collector (NZEH)

This flat plate solar collector represents the bank of flat plate solar collectors on the roof of the house that supplies heated fluid all year to the combisystem (domestic hot water and radiant floor heating). The collector functions based on a quadratic collector test equation which is commonly defined by independent testing agencies. The Incidence Angle Modifier (IAM) is a

2nd order equation in this type. The collector calculates the outlet temperature based on the specified flow rate.

Type 71 (TESS) - Evacuated Tube Solar Collector (NZEH)

This evacuated tube solar collector represents the bank of evacuated tube solar collectors on the roof of the house that supplies heated fluid all year to the combisystem (domestic hot water and radiant floor heating). The collector functions based on a quadratic collector test equation which is commonly defined by independent testing agencies. The transverse and longitudinal Incidence Angle Modifier (IAM) information comes from a linked text file based on additional data from the independent testing agency. The collector calculates the outlet temperature based on the specified flow rate.

Type 94a - Photovoltaic Array (NZEH)

This type can be used to model mono or poly-crystalline PV arrays based on manufacturer specifications. It also includes options for incidence angle modifiers (IAM) and calculations based on the maximum power point.

3.2.2 External influences on the building

Type 15-2b - Weather Data Processor (BCH, NZEH)

The Weather Data Processor is used to supply pertinent weather information to the model for a specific local climate, such as Montreal, QC, Canada. The information can be read from various compatible data formats, namely: Typical Meteorological Year (.TMY), Typical Meteorological Year Version 2 (.TM2), International Weather for Energy Calculations (IWEC), Canadian Weather for Energy Calculations (CWEC), Energy+ (.EPW) or Meteonorm files for TRNSYS (.TM2). This model uses Meteonorm data for Montreal, QC. The file used from TRNSYS is the following: \Trnsys16\Weather\ Meteonorm\North-America\CA-QC-Montreal-716270.tm2

The weather information is essential to run a realistic simulation. The data coming from this component is not limited to just temperature readings. It also has information ranging from solar radiation and angle of incidence to wind velocity and atmospheric pressure.

Type 701a - Basement Conduction (interfaces with Type56) (BCH, NZEH)

The Basement Conduction component is used to model the detailed interaction of heat transfer between the building basement walls and floor with the ground around it. The user specifies information such as soil properties and the size and detail of the temperature grid around the building. The initial ground temperatures in the soil near the building (near-field) and at a distance that is not affected by the building heat (far-field) are calculated using the Kasuda correlation (explained in more detail in section 4.2.2). As the simulation runs, the near field soil temperatures and the building underground wall temperatures from TRNBuild are used in heat transfer calculations to model the heat interactions. Type 701a linked with Type 56 dynamically determines the temperatures on both sides of the basement walls as well as throughout the underground near-field temperature grid at any point in time.

3.2.3 Miscellaneous Physical Components

Type 742 (TESS) – Pump - User Specified Flow Rate - Pressure Drop and Efficiency Mode (NZEH)

This type of pump is used to circulate fluids for the combisystem in the model. One of these pumps circulates fluid from the solar collectors to the heat exchangers in the storage tanks and four others cause the circulation in the heated water loop in the radiant floors. This type allows flows of variable speeds and calculates the relevant power consumption based on the pump efficiency.

Type 11f – Controlled Flow Diverter (NZEH)

This is a valve that has one fluid inlet with two fluid outlets. It directs the flow through the two outlets based on a user defined variable input ratio. In this model this diverter directs the solar collector heat transfer fluid to either the radiant floor tank or the domestic hot water tank heat exchangers.

Type 649 (TESS) - Mixing valve for fluids (NZEH)

This is a valve that combines several inlets into one, and is useful to calculate the resulting fluid temperature and flow. In this model, it is used to mix the water exiting the four radiant floors which is fed back into the storage tank. It is also used as a junction for the heat transfer fluid coming from the heat exchangers in the domestic hot water tank and radiant floor water tank that is sent back to the solar collectors.

Type 91 - Heat Exchanger with Constant Effectiveness (NZEH)

This is used to model the heat exchange between the outgoing warm drain water from the house and the incoming cold city aqueduct water entering the domestic hot water tank.

3.2.4 Schedules

Type 515 - Heating and Cooling Season Scheduler (BCH, NZEH)

This schedule was designed to designate the day of the year where the heating season switches over to the cooling season, and then back again. However, in this thesis, one example of how it is used is in combination with another schedule to designate when windows are left open for cooling or kept closed to keep the heat in the building.

Type 516 - Hourly Forcing Function Scheduler, Weekdays, Saturday and Sundays Separate (BCH, NZEH)

This is a schedule that is used to change a value on an hourly basis and is repeated daily, however it allows different hourly values for weekdays as well as Saturdays and Sundays. In this thesis it is used to define the lighting schedule.

Type 517 - Hourly Forcing Function Scheduler, Identical Days (BCH, NZEH)

This is a schedule that is used to change a value on an hourly basis and is repeated daily. In this thesis it is used alone or in combination with other schedules for the following: Domestic Hot

Water, appliance use, infiltration rates through open windows, window shading and thermostat heating settings.

3.2.5 Calculations and Controllers

Type 2d - ON/OFF Differential Controller (NZEH)

This controller generates a control function which can have a value of 1 or 0. The value is based on the difference between upper temperature and lower temperature inputs. There is also a high limit cut-out that overrides these two if it exceeds a set value and it forces the controller into the OFF position. Hysteresis effects are also modeled with this Type. In this model, Type 2d is used to direct the flow of the fluid from the solar collector to the radiant floor water tank or to the domestic hot water tank.

Type 8b - Three-stage Room Thermostat (NZEH)

This thermostat is used to control various functions, such as flow rates in the radiant floor and the power supplied by the electrical heating elements in the water storage tanks. Based on the input temperatures, the thermostat will specify if it is in stage 1 (high temperature), stage 2 (lower temperature) or the cooling stage. The output is a control function that can indicate which stage is active and if stage 1 remains active when it reaches stage 2 (in the case where each stage results in an independent quantity of heating or fluid flow). In this model, the cooling stage is not used. This Type also incorporates set-back temperatures (for reduced nighttime heating) and hysteresis effects.

Type 55 - Periodic Integrator (BCH, NZEH)

The Periodic Integrator is used to integrate data over a specified time period. It can also calculate various statistical data based on this integration, such as averages, standard deviations, maximums, etc. In this thesis, this Type is primarily used to integrate the demand over time, turning power (kW) into energy (kWh).

Equation (Calculator with no actual Type number) (BCH, NZEH)

The Equation component in TRNSYS is used to do any desired calculations using the output data from a Type. The result is then often used as an input for another Type. For example, in this thesis it is used in one place to convert the heating load from kJ/h into kW.

3.2.6 Output Data

Type 65a - Online Graphical Plotter (BCH, NZEH)

The Online Graphical Plotter is used to plot outputs from any other Type in TRNSYS.

4. CASE STUDY: THE TRNSYS MODEL OF THE BASE CASE HOUSE

4.1 THE BASE CASE HOUSE IN TRNBUILD (TYPE 56)

4.1.1 The Base Case House Overview

The Base Case House (BCH) is modeled as a wood frame house since this is the typical style of house found in Montreal. The general construction details (envelope layers and materials) are based on typical wood frame house construction in Canada (Canada Mortgage and Housing Corporation 1999, Kesik and Lio 1997). The other main characteristics of the BCH in this thesis are based on average data from houses in the province of Quebec constructed in 1994. This information is from John Gusdorf of the Sustainable Buildings and Communities group at Natural Resources Canada (Gusdorf 2005).

This is a two storey house with an unoccupied attic and a basement. Approximately half of the basement is made up of three rooms and the other half is the garage. The driveway slopes down to the underground garage such that the wall with the garage door is exposed to outside air and the other walls abut soil.

The overall plan dimensions of the house are 6.2 m x 13.5 m (83.6 m^2) with a total livable and heated area of 208.4 m^2. This excludes the 83.6 m^2 attic and the 42.4 m^2 garage. The model assumes there are no obstructions from adjacent buildings or vegetation.

In TRNBuild, the house is divided into 5 zones: the unheated garage, the heated basement (Zone A1), the ground floor (Zone B1), the second floor (Zone C1) and the unheated attic.

4.1.2 The Base Case House Construction

4.1.2.1 Walls

Table 4.1 lists each wall type in the house, the layers they are comprised of and their thicknesses and thermal resistances. In TRNSYS, a "wall" refers to walls, floors and roof sections. The WOOD&WOOL layer is the mineral wool insulation layer that is packed in between the wood studs in the walls and floors. The thermal resistance of the envelope complies with the minimum requirements of the Quebec law (Lois et Règlements du Québec 2005).

The properties (density, thermal capacitance and conductivity) of all of the "walls" defined in TRNBuild come from the following sources: ASHRAE 2005, McQuiston, Parker & Spitler 2005 and MatWeb 2008.

Table 4.1: Wall and floor construction in the Base Case House

Wall Type (TRNBuild Name)	Layer	Thickness (mm)	Total U-Value ($W/m^2 \cdot K$)	RSI VALUE ($m^2 \cdot K/W$)	Minimum Thermal Resistance*
BSMNT_FLOOR		266	1.489	0.672	0.350 (Note 1)
	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	13			
	AIR&STUDS_H_40	40			
	CONCRETE	75			
	GRAVEL	125			
GARAGE_FLOOR		200	3.523	0.284	n/a
	CONCRETE	75			
	GRAVEL	125			
GARAGE_DOOR (Note 2)		35	0.474	2.110	n/a
	POLYURETHANE	35			
INT_GAR_WALL		217	0.288	3.472	3.400
	GYPSUM	13			
	WOOD&WOOL	140			
	PLYWOOD_SHEATHING	11			
	AIRSPACE_VERTICAL	40			
	GYPSUM	13			
BSMNT_WALL_LOW		302	0.457	2.188	2.200
	GYPSUM	13			
	WOOD&WOOL	89			
	CONCRETE	200			

* Lois et Règlements du Québec 2005.

Note 1: There is no stated requirement for basement floor RSI values in the Quebec regulation respecting energy conservation in new buildings. The comparative value of 0.35 RSI is from the Gusdorf (2005) building data.

Note 2: The garage door has 26 gauge steel, with a wood-grain finish sandwiching the polyurethane. However, for simplicity in TRNBuild, it is modeled as just the insulation with the appropriate whole-door thermal resistance.

Table 4.1 (cont.): Wall and floor construction in the Base Case House

Wall Type (TRNBuild Name)	Layer	Thickness (mm)	Total U-Value ($W/m^2 \cdot K$)	RSI VALUE ($m^2 \cdot K/W$)	Minimum Thermal Resistance*
BSMNT_WALL_TOP		302	0.457	2.188	2.200
	GYPSUM	13			
	WOOD&WOOL	89			
	CONCRETE	200			
GRNDFLOOR_E		277	0.186	5.376	4.700
	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	16			
	WOOD&WOOL	235			
	GYPSUM	13			
GRNDFLOOR_W		277	1.601	0.625	n/a
	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	16			
	AIRSPACE_HORIZONTAL	235			
	GYPSUM	13			
FRONT_DOOR		34	0.650	1.538	0.700
(Note 3)	POLYURETHANE	32			
OUTWALL		304	0.284	3.521	3.400
	GYPSUM	13			
	WOOD&WOOL	140			
	PLYWOOD_SHEATHING	11			
	AIRSPACE_VERTICAL	40			
	BRICK_WALL	100			
TOP_FLOOR		277			
	HARDWOOD_MAPLE	13	1.601	0.625	n/a
	PLYWOOD_SHEATHING	16			
	AIRSPACE_HORIZONTAL	235			
	GYPSUM	13			
INT_WALL		116	2.204	0.454	n/a
	GYPSUM	13			
	AIRSPACE_VERTICAL	90			
	GYPSUM	13			

* Lois et Règlements du Québec 2005.

Note 3: Although the door has 1 mm of fiberglass on each side of the polyurethane, the thermal insulation of the steel is insignificant and was thus left out of the layers in TRNBuild.

Table 4.1 (cont.): Wall and floor construction in the Base Case House

Wall Type (TRNBuild Name)	Layer	Thickness (mm)	Total U-Value ($W/m^2 \cdot K$)	RSI VALUE ($m^2 \cdot K/W$)	Minimum Thermal Resistance*
TOP_CEILING		289	0.172	5.814	5.300
	GYPSUM	13			
	WOOD&WOOL	260			
	PLYWOOD_SHEATHING	16			
ROOF_N		115	1.939	0.516	n/a
	AIRSPACE	90			
	PLYWOOD_SHEATHING	13			
	SHINGLES_ASPHALT	12			
ROOF_S		115	1.939	0.516	n/a
	AIRSPACE	90			
	PLYWOOD_SHEATHING	13			
	SHINGLES_ASPHALT	12			
ROOF_VERT		153	1.821	0.549	n/a
	PLYWOOD_SHEATHING	13			
	AIRSPACE_VERTICAL	40			
	BRICK_WALL	100			

* Lois et Règlements du Québec 2005.

4.1.2.2 Windows

Window Type:

The windows selected from the TRNBuild library are Luxguard Sunguard Clear Argon, 2.6 6/16/4. This double pane window type most closely matches the R-Value of 0.39 $m^2 \cdot K/W$ (U-value of 2.56 $W/m^2 \cdot K$) from the Gusdorf (2005) house description file. This also exceeds the Quebec regulation (Lois et Règlements du Québec 2005).

The two above ground stories each have 2.325 m^2 of windows per facade and each basement facade has 1 m^2 of window area. This results in a window to floor area ratio of 11.1% for the above ground floors and 7.3% for the basement zone A1. This is within the maximum of 15% based on the Quebec regulation (Lois et Règlements du Québec 2005).

Window Shading:

All of the windows in the house, except for the one in the garage, have internal shading devices. The Reflection Coefficient of 0.6 is representative of translucent roller shades (ASHRAE 2005, p. 31.48). When drawn, these shades reduce the solar radiation, but still allow natural light into the room and thus require less electrical lighting. The shading is on a schedule so that the blinds are down from 9 am to 9 pm between May 1st and October 17th.

4.1.2.3 Convective Heat Transfer Coefficients of Walls and Windows

In TRNBuild the user can specify convective heat transfer coefficients to be used for walls and windows or they can be calculated automatically by TRNBuild, called internal calculations. These TRNBuild internal calculations are based only on the temperatures in the model and a few assumptions and do not consider wind speed. Therefore, the internal TRNBuild calculations cannot be used for the convection coefficients of outdoor surfaces. User defined heat transfer coefficients are used instead.

External Windows and Walls:

The convective heat transfer coefficients for the external surfaces of windows and walls are based on the following equations (ASHRAE 1993):

$$h_n = 9.482 \cdot \frac{\sqrt[3]{|\Delta T|}}{7.238 - |\cos \Sigma|} \tag{4.1}$$

$$h_{c\_glass} = \sqrt{h_n^2 + \left[a V_w^b \right]^2} \tag{4.2}$$

$$h_c = h_n + R_f \left(h_{c\_glass} - h_n \right) \tag{4.3}$$

where:

h_n = Natural component of the convection coefficient, W/m^2·°C;

h_{c_glass} = Window Convection Coefficient, W/m^2·°C;

h_c = Wall Convection Coefficient, W/m^2·°C;

ΔT = Temperature difference between the surface and air, °C;

Σ = Tilted angle of the surface, degree; and

V_w = wind speed over the surface, m/s.

Coefficients a and b and the roughness multiplier R_f are described in Appendix A, Table A-1 and Table A-2.

There is no significant difference between the h_c values anywhere on the house walls (ex. Zone A1 front wall vs. Zone C1 right wall). As shown in Figure 4.1, the differences between the convection coefficients on the basement walls versus the top floor walls are around 3% to 8% and the values are constantly changing so this difference is insignificant. Therefore, for simplicity, the value of h_c that was calculated for A1_F (Zone A1 Front wall), was used as the input for all wall heat transfer coefficients.

Similarly, as shown in Figure 4.2, there is no significant difference between the hc_glass values anywhere on the outside window surfaces. Therefore, for simplicity, the value of hc_glass that was calculated for A1_F (Zone A1 Front window), was used as the input for all window convection coefficients.

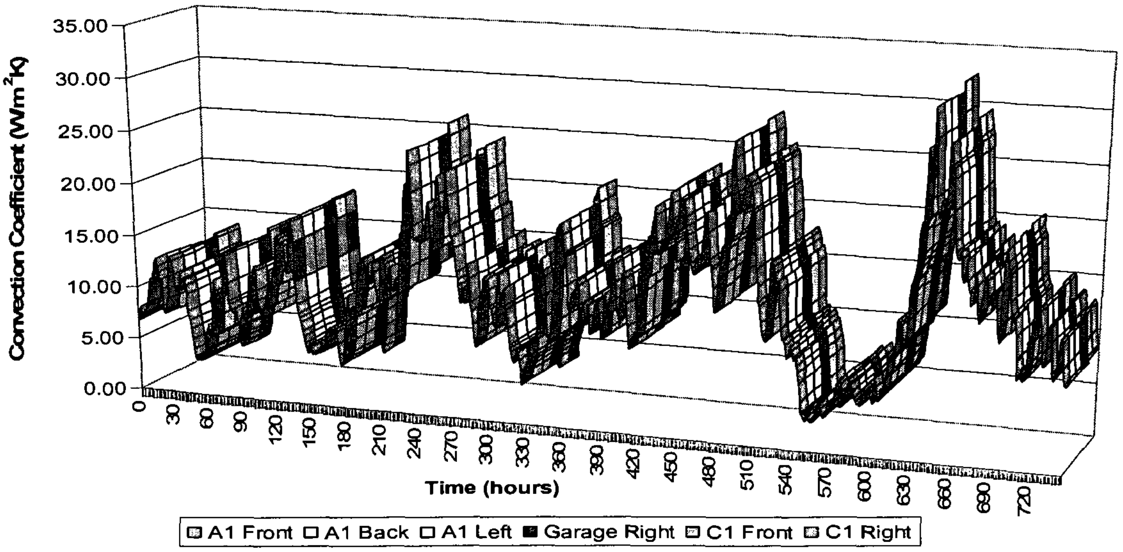


Figure 4.1: Calculated wall convection coefficients for various exterior surfaces

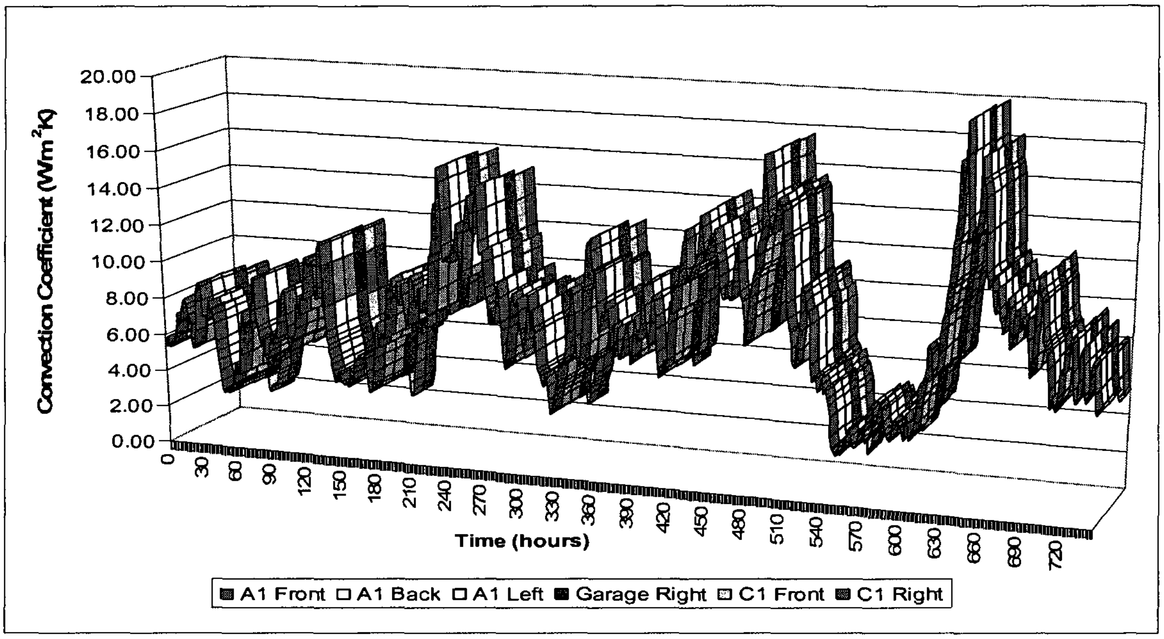


Figure 4.2: Calculated window convection coefficients for various exterior surfaces

The roof h_c value is significantly different than the rest of the house, so it was calculated separately. However, the North roof section h_c was used for both sides of the sloping roof since these values were similar.

The front door and garage door were both given a constant h_c value, 12 $W/m^2 \cdot K$, rather than using the dynamic values calculated since these doors have very little thermal inertia. The constant h value used is the approximate average of the ones calculated for the outside walls

Internal Walls and Windows:

All of the convective heat transfer coefficients for the interior surfaces of external walls and windows as well as both surfaces of the internal walls are calculated internally by TRNBuild, except for the boundary walls which border the ground. Underground boundary walls remain 0 to signify that there is no convection since there is no air; there is only conduction. This conduction is modeled using Type 701a explained in section 4.2.2.

4.1.3 The Base Case House Ventilation and Infiltration

Heat Recovery Ventilators

Heat recovery ventilators (HRV) are used to recover waste heat from the ventilation system in order to reduce heating loads. Since houses require a minimum amount of ventilation to ensure proper air quality, during the winter warm air will be exhausted while the intake will be cold. Capturing some of the heat from the warm exhaust air and transferring it to the incoming air is an excellent energy efficiency measure. HRVs, also known as Energy Recovery Ventilators (ERV) will typically cost in the range of $500-$1700 (Sustainable Sources, 2006)

In the Base Case House (BCH), the mechanical ventilation fresh air change rate is set to a constant 0.35 ACH all year, which is above the minimum recommended 0.3 ACH (Canadian Standards Association 1991). The heat recovery ventilator (HRV) is equipped with a fan and a small heating element that pre-heats the air entering the house if the recovered heat is not sufficient. During the heating season (Oct 17th to May 1st), if the outdoor air temperature is below 21°C, the air is heated to 21°C and then supplied to the zones. When the outdoor air is above 21°C, it is supplied to the zones at the outdoor temperature with no extra heating or cooling. Between May 1st and Oct 17th, when the main house heating system is turned off, the heating element will only heat the air up to 14°C, when the outdoor air falls below that. This is consistent with the fact that during the warmer nights, the windows are left open, but when the temperature falls below 14°C, they are shut. This way, the house is not heated with the windows wide open.

The HRV unit recovers heat from the house exhaust air to preheat the incoming cold ventilation air. When it is cold outside, it cannot heat the incoming outdoor air all the way to the required 21°C, but it will have a significant impact on reducing the energy needed to heat the air. The HRV used in this house is the Venmar AVS Constructo 1.5 (Venmar n.d.) This unit is designed for airflows between 30 L/s and 71 L/s. Based on the specification sheet for this HRV, the apparent sensible effectiveness varies depending on airflow and outside temperature from

70% to 81% as shown in Table 4.2. A conservative value of 70% is used in this model. The power required to heat the incoming ventilation air to 21°C is calculated as:

$$Q_{vent} = Q_{in} - Q_{out} \tag{4.4}$$

where the power required to heat the incoming ventilation air = (the power required to heat outdoor air to 21°C) – (the heat flow rate recovered from the exhausted air by the HRV);

where:

$$Q_{in} = \frac{ACH}{3600} \cdot V_{house} \cdot \rho_{air} \cdot C_p \cdot (T_{vent} - T_{out}); \tag{4.5}$$

$$Q_{out} = \frac{ACH}{3600} \cdot V_{house} \cdot \rho_{air} \cdot C_p \cdot (T_{zones} - T_{exhaust}); \; and \tag{4.6}$$

$$T_{exhaust} = HRV\_eff \cdot T_{out} + (1 - HRV\_eff) \cdot T_{zones} \tag{4.7}$$

This simplifies to:

$$Q_{vent} = \frac{ACH}{3600} \cdot V_{house} \cdot \rho_{air} \cdot C_p \cdot [T_{vent} - T_{out} \cdot (1 - HRV\_eff) - (HRV\_eff \cdot T_{zones})] \tag{4.8}$$

where:

ACH = Air Changes per Hour ventilation rate, 0.35/hr;

V_{house} = Volume of conditioned house, 500 m^3;

ρ_{air} = Air density, 1.2 kg/m^3;

C_p = Specific heat of air, 1.005 kJ/(kg· °C);

T_{vent} = Temperature of ventilation air supplied to the zones, °C; minimum 21°C;

T_{out} = Outside Temperature, °C;

HRV_eff = Effectiveness of the HRV, 0.70; and

T_{zones} = Average return temperature from the three conditioned zones, °C.

Table 4.2: Energy performance of the Venmar AVS Constructo 1.5 (Venmar, n.d.)

Supply Temperature		Net Air Flow	Fan Power (Watts)	Sensible Recovery Efficiency (%)	Apparent Sensible Effectiveness (%)
°C	°F	l/s			
HEATING					
0	+32	31	85	69	81
0	+32	56	124	60	70
0	+32	--	--	--	--
-25	-13	37	114	62	80
-25	-13	--	--	--	--

Air Infiltration

The air infiltration rate for all zones (aside from the attic) is 3.27 ACH @ 50 Pa as an average value for houses built in Quebec in 1994 (Hamlin & Gusdorf 1997, p.13). Following a rule of thumb developed by the Lawrence Berkeley National Laboratory (Sherman 1998) the infiltration rate @ 50 Pa is divided by 20 to give the natural infiltration rate; 3.27/20 = 0.1635 ACH. The attic is set at 2 ACH due to less tight construction in this unconditioned space.

Natural Ventilation

Since no air conditioning is provided, natural ventilation is the source of cooling during the warmer months by opening the windows at night. In this case, from 7 pm to 8 am every day between May 1st and October 17th, the windows are opened and there is an additional 10 ACH of outdoor air flowing through the ground and upper floors. The value of 10 ACH is intended to be a rough estimation of the airflow with open windows around the house since this value may vary widely depending on wind, window size, quantity and location, temperature differences, etc. The value was selected based on experimental results presented by Kreider and Rabl (1994, p. 275) and Siviour (1991). However, since during these months there are some nights that can be quite cool, in reality the house occupants would likely close their windows to avoid cooling the house too much. Therefore, the model is designed to consider that the windows are closed whenever the outdoor temperature is below 14°C.

The extra ventilation from the open windows at night used to cool the home during the warmer months is applicable to the ground floor and the upper floor. In the model, the basement, Zone A1, is not modeled with open windows. In a typical house, the above ground floors will more commonly be the areas where windows will be opened to achieve a good airflow at night.

Coupling Air Flow between zones

Air will naturally flow throughout the home and transfer heat between zones via stairwells. The value of airflow used is calculated based on an even distribution of the mechanical ventilation through the house. With a mechanical ventilation of 0.35 ACH entering the house, half (0.175 ACH) is circulated between the ground and top floor, and half between the ground and basement floor. TRNBuild requires this value in kg/hr. Therefore, for a 500 m^3 house, 500 m^3 x 0.175 ACH = 87.5 m^3/hr = 105 kg/hr (density of air: 1.2 kg/m^3).

Since air will naturally circulate in both directions from zone to zone due to multiple factors, as one of the available options in the TRNBuild model, it is set up to reflect this fact (rather than air flowing primarily or fully in only one direction).

4.1.4 The Base Case House Heating and Cooling

The 100% electric baseboard heating system in the Base Case House is only active during the colder months, from October 17th to May 1st. On the two above ground floors, the thermostat is set to 21°C from 7 am to 11 pm and 18°C from 11 pm to 7 am. The basement thermostat is set to 1°C less than the other two zones. There is no heating in the attic or the garage. These specific dates are selected based on the ambient temperatures in the weather file used in the simulation. In a real home, people will turn on their heat when it is cold, so to reflect reality, the heating system was set to operate during the days that are too cold for this specific weather file.

4.1.5 Heat Gains and Electricity Use in the Base Case House

4.1.5.1 Occupants

This house has a family of two parents and three children. The occupancy schedule is shown in Table 4.3.

Table 4.3: Occupancy schedule in the house

Time	Number of Occupants	
	Weekdays	Weekends
8:00 – 8:30	4	5
8:30 – 15:00	2	5
15:00 – 18:00	4	5
18:00 – 8:00	5	5

The activity level of the occupants, which directly affects how much heat they produce, is designated as moderately active office work (ASHRAE 2005, p. 30.4). The gains in each zone have been multiplied by a fraction to distribute the occupants throughout the house. On average, two occupants are on the top floor, two on the ground floor and one in the basement. Each person contributes radiant heat gains of 43.5 W and 31.5 W of convective heat gains. See *Heat Gains in The House* in Appendix A for further details.

4.1.5.2 Artificial Lighting

The lights used in the Base Case House (BCH) are all incandescent lights. The heat given off by the lights is based on ASHRAE 2005, p. 30.22, table 16 which states that 80% of the heat generated is radiative and 20% is convective. The lighting installed power density in the house is 5 W/m^2 (18 kJ/h) and is set to the schedule shown in Table 4.4. In addition to the heat generated by the lights, the schedule and lighting density are used to calculate the electricity used by the lights. Although artificial lighting varies throughout the year due to different daylight hours, the same daily schedule is used all year. This is because the actual lighting usage is extremely variable, depending on the occupants, so the daily schedule used is intended to be an average for all seasons.

Table 4.4: Lighting schedule in the house

Time	Percentage of Lights On
0:00 – 7:00	0%
7:00 – 9:00	80%
9:00 – 19:00	20%
19:00 –23:00	80%
23:00 – 24:00	50%

Table 4.5 shows the 2004 lighting energy use data for all homes in the survey done for Natural Resources Canada's *Energy Use Data Handbook* (2006). Based on the average survey house area (125 m^2 – not including the basement) and the BCH area (208 m^2 – with the basement), Table 4.5 shows the equivalent lighting energy use (kWh/yr) for the BCH. Using the lighting schedule in Table 4.4, and a lighting intensity of 5 W/m^2, the electricity usage in the BCH is integrated over the year in TRNSYS and results in 2770 kWh/yr. This is not significantly different from 2390 kWh/yr in Table 4.5 since light usage can vary widely in households. This comparison shows that the annual electricity use for lighting, as simulated in the TRNSYS model, is close to the average value from the 2004 survey.

Table 4.5: Average Canadian energy use for lighting

House	Lighting Electricity Use
All Survey Homes	63.80 PJ
Average House	1432.10 kWh/yr·house
Equivalent value for Base Case House	2390.35 kWh/yr·house

4.1.5.3 Appliances

Table 4.6 shows the appliances and associated energy use in the Base Case House (BCH). The heat gains due to the appliances in the house come directly from the energy use values since 100% of this energy use is converted into heat. This results in an average and constant 373.55 W for major appliances (e.g. refrigerator, clothes washer, etc.) and 366.93 W for the other appliances. For the major appliances, 50% of these gains are placed in the basement and 50% on the ground floor. For the other appliances, 20% are in the basement, 40% on the ground floor and 40% on the upper floor.

Table 4.6: Energy consumption appliances in the Base Case House

APPLIANCE	Qty	Energy Use per appliance (kWh/yr)	Total Energy Use (kWh/yr)
Refrigerators [1]	1	778	778
Freezers [1]	1	572	572
Dishwashers [1]*	1	118	118
Electric Ranges (self cleaning) [1]	1	759	759
Clothes washers [1]*	1	72	72
Electric Clothes Dryers [1]	1	973	973
TOTAL Major Appliances			**3272**
Microwave [2]	1	169	169
Toaster oven [3]	1	93	93
Coffee maker [3]	1	97	97
Blender [3]	1	12	12
Cordless/powered Phones [4]	4	28	112
Computers w/ monitor & speakers [2]	2	168	336
External Modem [2]	1	86	86
Printer [2]	1	24	24
Clock Radios [3]	3	19	57
Stereos [3]	2	50	100
DVD/VCR [2]	2	46	92
Televisions [3]	3	412	1236
Cable box or satellite [2]	2	200	400
Small miscellaneous devices	20	20	400
TOTAL Other Appliances			**3214**

* Excluding hot water

Appliance information sources as numbered above:

1- Natural Resources Canada 2006c - (2004 data) Existing Stock

2- Aulenback, et al 2001, *Stand-by Power Requirements for Household Appliances* – Canadian Existing Stock 2001

3- Fung et al. 2000, *Development of Canadian Residential Energy End-use and Emission Model* (1994 data)

4- Rosen, Meier & Zandelin 1999, *National Energy Use of Consumer Electronics in 1999*

It should be noted that there is an appliance schedule in the model, but it is set as constant throughout the day and night. Therefore, the heat gain from them is averaged out over the entire 24 hour day. Since appliance use behaviour is extremely varied from person to person, it was not worth setting a schedule to try to model this behaviour. In addition, the effects of modeling these appliance peaks on the heating and cooling loads are minimal.

For the electricity usage, the total values in Table 4.6 are used. In order to model the (constant) real-time usage of electricity rather than just a yearly total, the total kWh/yr is converted into kW and then integrated over the course of the year in the TRNSYS simulation.

The hot water energy used is not included in the dishwasher or clothes washer values here since the thermal energy is estimated as part of the total domestic hot water calculated separately.

4.1.5.4 Heat Recovery Ventilator (HRV)

The fan power required by the HRV can be estimated from Table 4.2. By graphing the three net air flow values in the table, a non-linear extrapolation was done to determine the approximate power required to run the HRV at 48.5 L/s (0.35 ACH). It takes approximately 122 watts to operate the ventilator, and since this unit operates all the time, it requires 1069 kWh per year.

4.1.6 Thermal Mass from the House Contents

Thermal storage is a means where the thermal properties of certain materials are taken advantage of to either release or absorb heat to achieve the desired indoor climate. If heating is desired, the material (usually concrete, masonry, water tanks or double gypsum) is placed in an area that is exposed to the sun during the day. The material absorbs the heat and due to its thermal heat transfer properties, the heat is slowly released over a long period of time, such as overnight, or even over several days. If cooling is desired, such as in summertime, the thermal mass is shaded so that it can absorb the surrounding heat, thus reducing the room temperature. These methods of heating and cooling are done through various set-ups, from concrete slabs, to large aquarium style water tanks to Trombe Walls which are masonry walls placed several inches inside from external insulating glass walls (US Department of Energy n.d., California Energy Commission n.d).

Although this thesis does not focus on the effects of designing a house to take full advantage of thermal mass, the thermal effects of the contents of the house are modeled into the simulation. When all of the contents of the house (furniture, appliances, etc.) are taken into account in terms of their combined thermal mass, there is a noticeable effect on the temperatures in the house. For every room in the house, the major contents were estimated, using the author's information from a typical home, and broken down into types of materials, and average areas and thicknesses. This information was combined with each material's properties and modeled as internal masses in each zone in TRNBuild. This is summarized in Table 4.7.

Figure 4.3 shows the impact of the thermal mass of the house contents on the temperatures in Zone C1 (the top floor) from mid-March to mid-October. There was very little impact on the temperatures during the heating season since the thermostat ensures a relatively constant temperature, unlike the warmer months where the heating and cooling are due to natural forces. The figure shows a graph of the indoor air temperature difference without the contents compared to with the contents ($T_{without} - T_{with}$). This shows that a house containing objects, furniture, appliances, etc. has a thermal mass effect that reduces the night time drop in temperature by up to 1°C and the day time rise by up to 2°C. Reduced temperature fluctuations from day to night is the expected effect from an additional thermal mass in a house.

Figure 4.4 shows four days (Jan. 15 – Jan. 18) of the differences in heating power in Zone C1 (the top floor) between the cases without and with contents in the BCH ($P_{without} - P_{with}$). The pattern shown is repeated during the entire heating season. The figure demonstrates that the impact of the thermal mass in the house has two distinct effects depending on the time of day, due to the heating set-back temperature. When the set point temperature rises to 21°C from the 18°C night time set back, the heating system in the house with extra thermal mass has to work harder to reach the 21°C air temperature. This is because the thermal mass absorbs some of the heat produced by the heaters. As time passes and the mass heats up, it absorbs less and less heat from the air and thus the difference between the two cases diminishes. Conversely, when the night time

Table 4.7: Summary of the thermal mass from the house contents in each zone

Material	Zone A1 Total (avg.)	Zone B1 Total (avg.)	Zone C1 Total (avg.)	All Zones Total
Wood				
Area (m^2)	6.927	35.653	55.475	98.055
Thickness (m)	0.116	0.017	0.017	0.149
Volume (m^3)	0.803	0.596	0.933	2.332
Paper				
Area	*3.127*		*4.800*	7.927
Thickness	*0.300*		*0.300*	0.600
Volume	0.938		1.440	2.378
Steel				
Area	*0.477*	*0.426*	*0.028*	0.931
Thickness	*0.130*	*0.130*	*0.130*	0.390
Volume	0.062	0.055	0.004	0.121
Foam				
Area	4.200	13.057	*8.043*	25.300
Thickness	0.150	0.119	*0.480*	0.749
Volume	0.630	1.551	3.861	6.041
Textiles				
Area			*108.929*	108.929
Thickness			*0.140*	0.140
Volume			15.250	15.250
Compressed Area			*27.232*	27.232
Plastic				
Area	2.000	3.095	6.648	11.743
Thickness	0.100	0.293	0.077	0.470
Volume	0.200	0.908	0.509	1.617
Ceramic				
Area	*1.085*	2.254	*2.128*	5.467
Thickness	*0.015*	0.057	*0.015*	0.087
Volume	0.016	0.129	0.032	0.177
Marble				
Area		*0.488*	*0.732*	1.220
Thickness		*0.041*	*0.041*	0.082
Volume		0.020	0.030	0.050
Glass				
Area		*0.643*		0.643
Thickness		*0.014*		0.014
Volume		0.009		0.009
Granite				
Area		*1.364*		1.364
Thickness		*0.022*		0.022
Volume		0.030		0.030
Liquidy Food				
Area		1.250		1.250
Thickness		0.400		0.400
Volume		0.500		0.500
Dry Food				
Area		0.500		0.500
Thickness		1.000		1.000
Volume		0.500		0.500
Water				
Area	*0.041*	*0.041*	*0.056*	0.138
Thickness	*0.390*	*0.390*	*0.390*	1.170
Volume	0.016	0.016	0.022	0.054

set back begins, the house with extra thermal mass is now filled with objects storing heat at 21°C, which is 3°C above the required air temperature. Throughout the night, this heat will dissipate into the room and thus reduce the power required compared to the case without any extra thermal mass. As the heat is released from the contents and they cool down throughout the night, the impact on the power is reduced and the difference between the two cases diminishes. Since these two effects on the heating loads tend to counteract each other, the difference in the annual heating load between the two cases is only 115 kWh/yr. The case with the house contents has the higher heating load, most likely because overall it takes a little more energy to heat the contents of the house during the day compared to the amount of useful heat released at night. They do not even out because during the night, the case with less thermal mass is maintaining the air temperature at 18°C whereas in the other case the thermal mass is delaying the onset of the heating systems and actually holding the temperature above the set point slightly longer. So over the whole year, the house with the contents actually contains more energy than the house without contents.

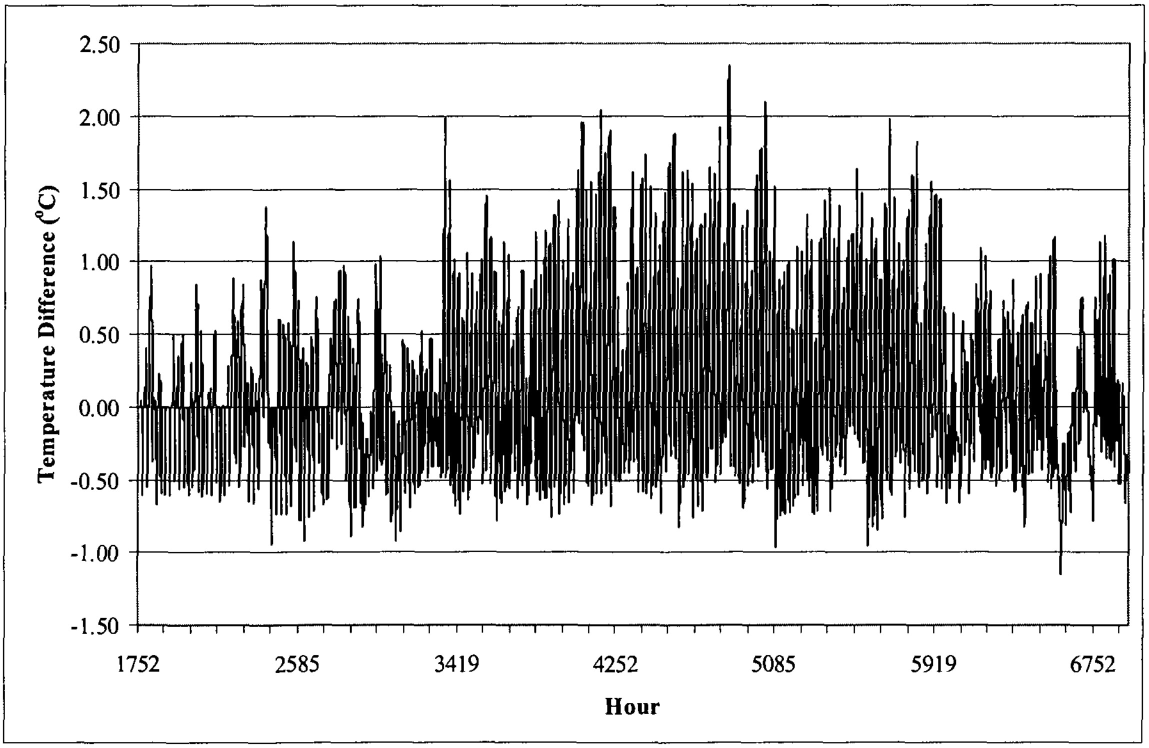


Figure 4.3: Temperature difference in Zone C1 between the cases without and with contents in the Base Case House ($T_{without} - T_{with}$)

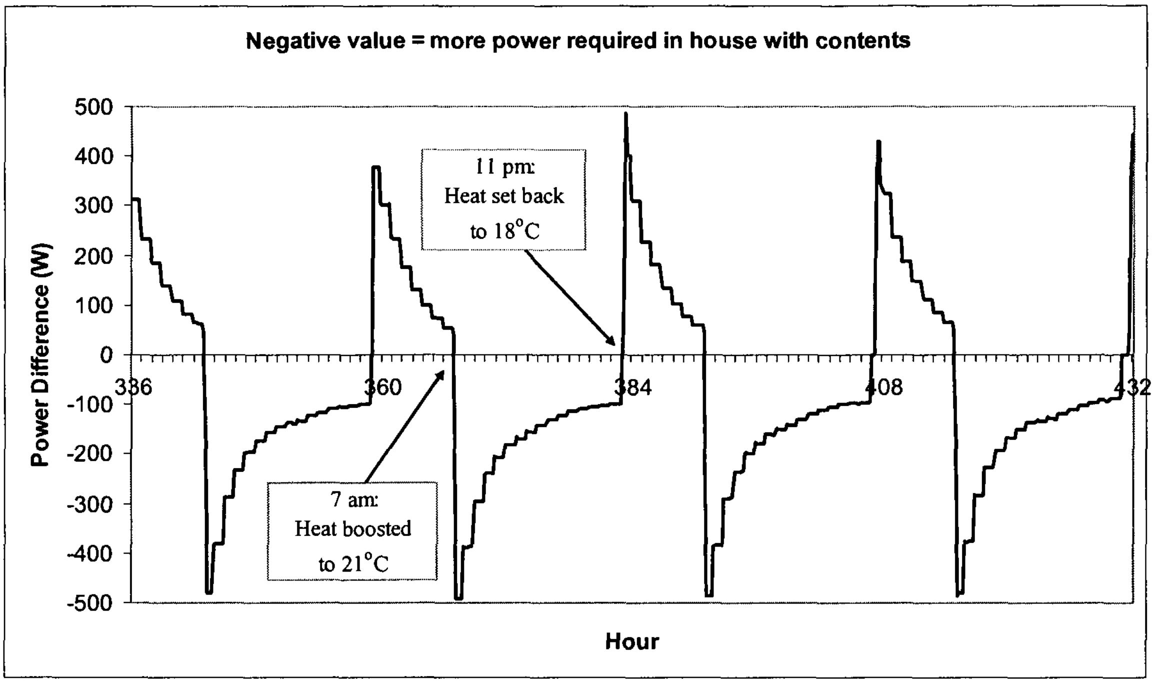


Figure 4.4: Difference in heating power during colder months in Zone C1 between the cases without and with contents in the Base Case House ($P_{without}$ - P_{with})

4.2 COMPONENTS OF THE BASE CASE HOUSE OUTSIDE OF TRNBUILD (TYPE 56)

4.2.1 Domestic Hot Water Use in the Base Case House

The Domestic Hot Water (DHW) in the Base Case House (BCH) was modeled using Type 60d in TRNSYS and linked to the house component (Type 56). Type 60d was used since it is not possible to model the details of DHW consumption directly in Type 56.

4.2.1.1 Type 60d: Storage Tank; Fixed Inlets, Uniform Losses and Node Heights

The tank selected is based on an 80 gallon (303 litre) Maytag HRX 82 DERT tank (Maytag, n.d.) The tank is 1.56 m high and has a loss coefficient of 0.344 W/m^2·K. This coefficient is based on the U-Value from 2.5 in. of polyurethane foam sandwiched between 3 mm of steel. The tank ensures the water is between 55°C and 57°C using one 5500 W electric heating element at the top of the tank.

The DHW tank is located in the basement. This component is connected in a loop with the house model in TRNSYS so that the heat losses from the tank are calculated in consideration of the temperature in the basement. In addition, these heat losses are considered gains in the basement zone (Zone A1) and affect the zone temperature. The heating rate (kW) is calculated based on a water consumption schedule and then integrated over the year to determine electricity consumption due to DHW.

Type 60d has an internal time step that is smaller than the overall simulation time step. This is very useful when large simulation time steps such as 1 hour are used, since in reality, the heating element in a DHW tank turns on and off at intervals much smaller than 1 hour. TRNSYS calculates the critical Euler time step and the user specifies the fraction of the critical time step that should be used. This was set to 1/6 in the model. Due to this internal time step, the results from the DHW tank were nearly identical (0.04% difference) when comparing simulations that were run with 1 hour and 10 minute time steps.

4.2.1.2 DHW Use Schedule

The schedule for DHW usage is presented in Figure 4.5, based on Perlman and Mills (1985) which is reproduced in the 1991 ASHRAE handbook, HVAC Applications, p. 44.9. This estimation of a total consumption of 236 litres/day is validated by another study by DeOreo and Mayers (2000) who measured DHW use per household in 10 Seattle homes to be 247.2 litres/day.

4.2.1.3 Montreal Aqueduct Temperatures

The temperature of the water coming from the municipal aqueduct and feeding into the hot water tank has a direct effect on the energy required to heat the water. The water temperature for a Montreal aqueduct, which varies throughout the year, is calculated from a 5th order polynomial based on actual aqueduct temperature measurements taken in 2000 at 9515 St-Hubert in Montreal (Dumas and Marcoux 2004). The source of this data included temperature information for several other years as well, however the 2000 data was most complete and appeared to be close to an average of all other data. The calculated polynomial was used in TRNSYS to generate temperatures at any point in time throughout the year.

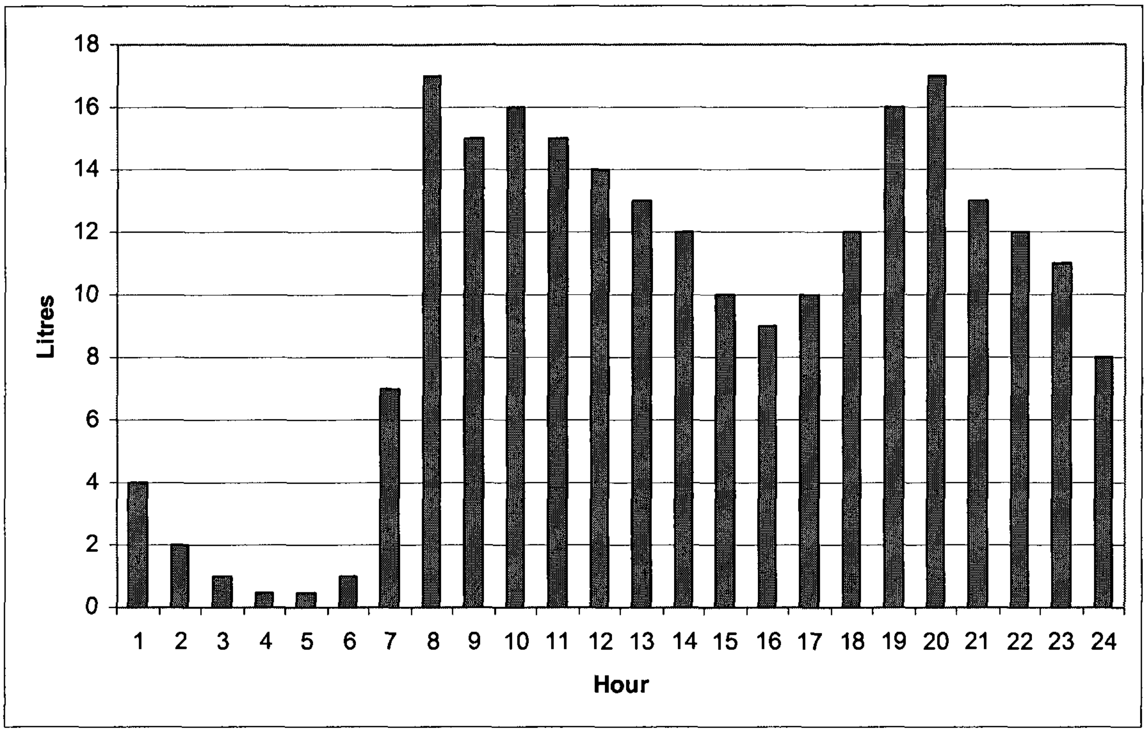


Figure 4.5: Total household DHW use (Perlman and Mills 1985)

The polynomial is the following expression:

$$Temperature = a(DY)^5 - b(DY)^4 - c(DY)^3 - d(DY)^2 - e(DY) + f \qquad (4.9)$$

where,

a = 0.0000000000875974;

b = 0.0000000643792327;

c = 0.0000110242432051;

d = 0.0005639770397329;

e = 0.1016022746462270;

f = 4.6673789001648900; and

DY = Day of the year, with DY = 1 for January 1st.

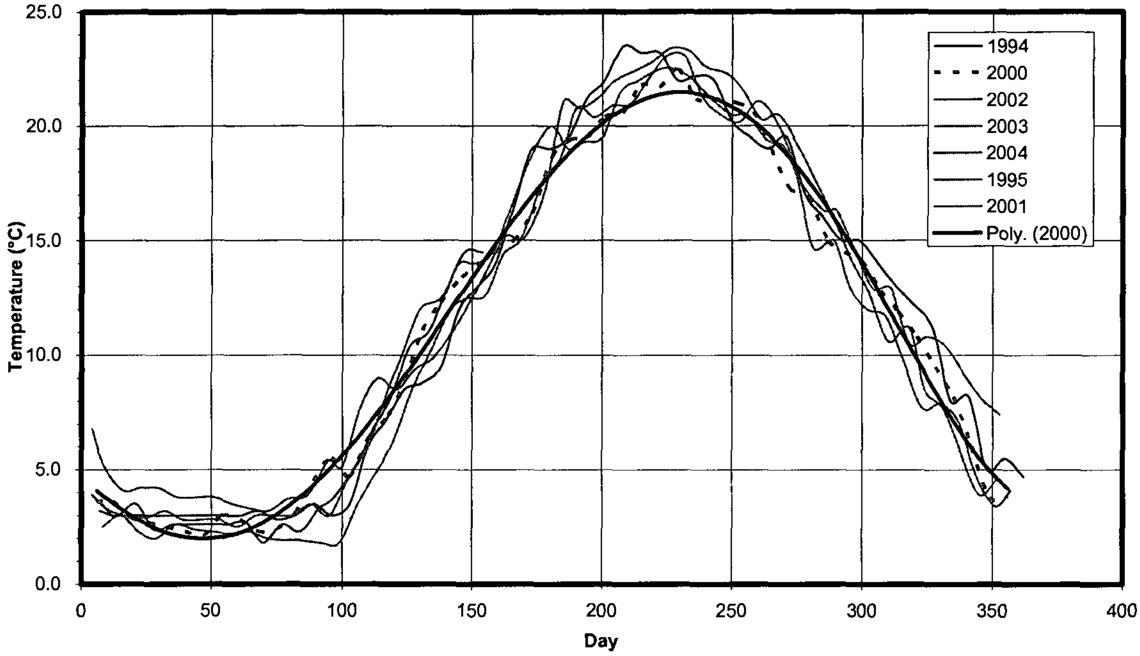


Figure 4.6: Montreal aqueduct temperature data

4.2.1.4 DHW Electricity Demand

The Auxiliary Heating Rate is an output from Type 60d which gives the electricity demand to heat the water based on all of the above information.

4.2.2 Ground Coupling – Type 701a

The "Basement Conduction" component Type 701a is used to model the detailed interaction of heat transfer between the building basement walls and floor with the ground around it.

One of the most important features of this component is the grid used to discretize the near field that surrounds the house. The user defines the size of the area around the house that will have temperatures directly affected by the house and also decides how detailed the spacing of temperature nodes will be. The earth beyond this grid (called the far field) will only be affected by the outdoor air temperature and radiation. The more temperature nodes defined in the grid, the more accurate the calculations will be. However since it increases simulation time, there is a balance between the number of nodes, the time it takes to simulate and the differences in temperature compared to a less detailed grid. The grid size selected is shown in Figure 4.7. In this model, the earth affected by the basement temperature extends 4 m in all directions (N, E, S, W and down) from the house walls and floor. The initial soil surface temperatures are calculated based on the Kasuda correlation (Kasuda and Archenbach 1965):

$$T = T_{mean} - T_{amp} * \exp\left[-depth * \left(\frac{\pi}{365\alpha}\right)^{0.5}\right] * \cos\left\{\frac{2\pi}{365} * \left[t_{now} - t_{shift} - \frac{depth}{2} * \left(\frac{365}{\pi\alpha}\right)^{0.5}\right]\right\} \tag{4.10}$$

where,

T = Temperature, °C;

T_{mean} = Mean surface temperature (average air temperature), °C;

T_{amp} = Amplitude of surface temperature, °C;

Depth = Depth below surface, m;

α = Thermal diffusivity of the ground (soil), m^2/day;

t_{now} = Current day of the year, day; and

t_{shift} = Day of the year corresponding to the minimum surface temperature, day.

The Kasuda correlation sets the surface temperature as a function of the time of the year. "In the near field, the Kasuda correlation is used to set the initial temperature profile in the soil and to obtain a time dependent surface temperature. The temperature of near field soil nodes depends upon conduction effects from neighboring nodes and from the Kasuda calculated surface temperature. In the far field, the Kasuda correlation is used to set the temperature of all nodes. The temperature of these nodes will change, but only as a function of depth and time of year" (Solar Energy Laboratory 2004).

Type 701a uses an input file with temperature values at every node in the near field to begin the simulation. In order to have proper temperature values as inputs, the simulation was run for several complete years and the output file containing the earth node temperatures in the near field was then used as the input for a subsequent run. When the temperatures in the output file (on Dec

31st at 11:59:59) of one simulation matched the input temperatures of that same run (on Jan 1st 365 days earlier), the soil temperatures were then stable. In this model, it only took one year of simulation to achieve temperature stability.

For more detailed information about the parameters in Type 701a, please see Appendix B

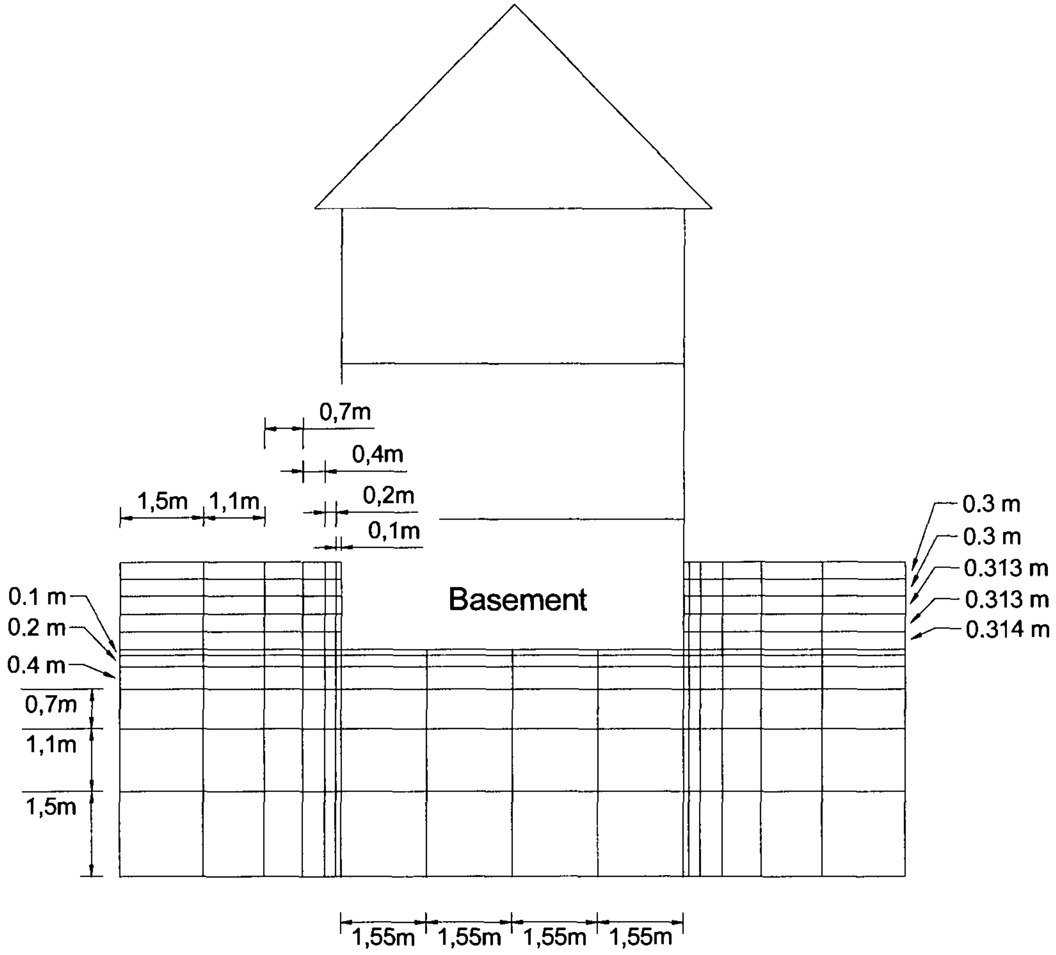


Figure 4.7: The underground grid defined in Type 701a

The Impact of Including Type 701a

The BCH was simulated with and without Type 701a to estimate its impact on the annual heating loads. For comparison purposes, a simpler approach is used with a constant underground temperature, all year long. Two different temperatures were simulated. The results showed that when the underground temperature is a constant 8 °C, the heating loads are greater by 18.3%

compared with the results from Type 701a. With a constant underground temperature of 12 °C, the heating loads are greater by 5.8%. These results are reasonable since with Type 701a, the ground under the house is closer to 15 °C and most of the losses are through the floor which has much less insulation than the walls. Therefore, Type 701a increases the accuracy of the model compared with a constant underground temperature and in this case also results in a reduced heating load.

4.3 SIMULATION RESULTS FROM THE BASE CASE HOUSE

A one year simulation of the Base Case House (BCH) in TRNSYS reveals a great deal of information about the temperatures and energy use of the house. The following two figures summarize the most important results.

Figure 4.8 and Figure 4.9 show the annual energy requirements broken down by end-uses, such as heating, domestic hot water, lighting, etc., for 10 minute and 1 hour simulation time steps, respectively. These figures not only show the total energy in kWh, but also kWh/m^2 since energy use depends very much on the size of the house. The figures show that the results for the 10 minute and 1 hour time steps are very similar. The BCH simulation time for the 10 minute time step was 26 minutes as compared to 6 minutes for the simulation with a 1 hour time step. Heating the house (including the HRV and pre-heated fresh air) is by far the most important energy end-use, at 44% of the total energy use followed by Appliances (26%), DHW (19%), and Lighting (11%). The total annual energy requirement for the BCH using a 10 minute time step is 25,615 kWh (123 kWh/m^2 for this 208 m^2 house – including the heated basement). Similarly, the total annual energy requirement for the BCH using a 1 hour time step is 25,570 kWh, an insignificant difference of 0.18%.

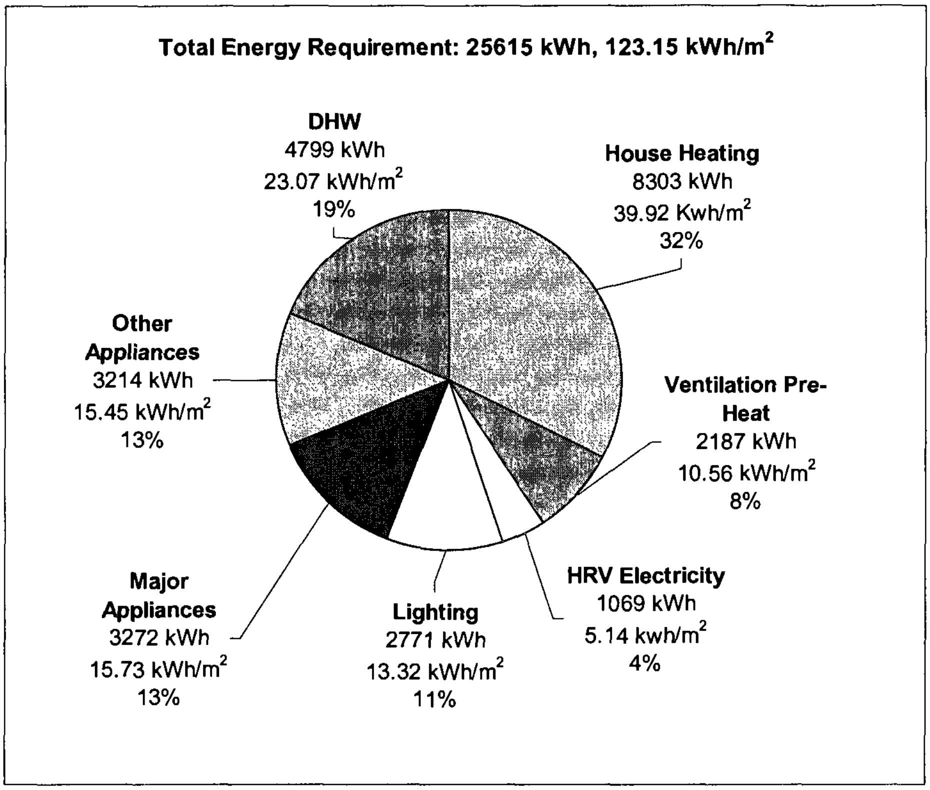


Figure 4.8: Annual energy use for BCH with a simulation time step of 10 min.

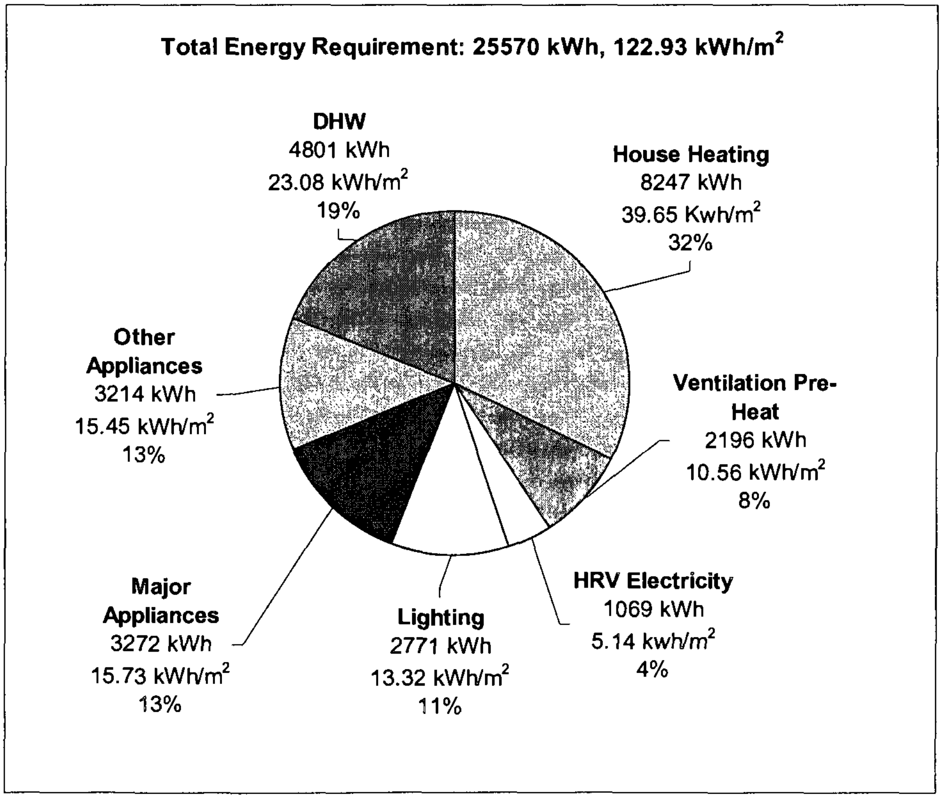


Figure 4.9: Annual energy use for the BCH with a simulation time step of 1 hour

Figure 4.10 shows energy use in the BCH (kWh and kWh/m^2), but on a monthly basis for a 10 minute simulation time step. This demonstrates the seasonal variations in heating compared to the relatively constant use of energy for the Lighting, Appliances and DHW. Although the heating is turned off during the summer, the ventilation and heat recovery ventilator are still active, so there is a little bit of energy use attributed to heating in this figure during those months.

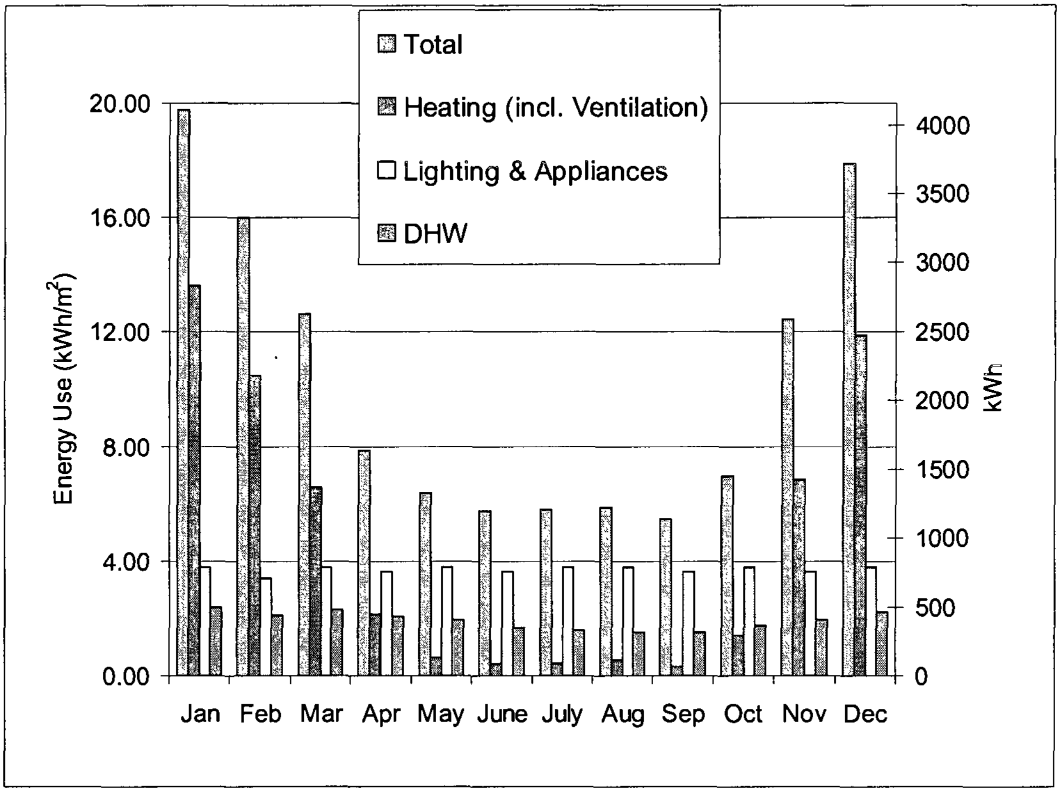


Figure 4.10: Monthly energy use for BCH with a simulation time step of 10 min.

The annual energy consumption of this BCH (based on a house built in 1994) is compared to three other studies in Table 4.8. Zmeureanu et al. (1999) studied actual energy bills from Montreal homes constructed during various years. Hamlin & Gusdorf (1997 pp. 23-28) performed a Canadian Survey that determined space heating for new conventional houses built between 1990 and 1996, with 30 of these 163 houses located in Quebec. Only the results of the Quebec houses are presented here in order to compare homes that are all located in the same climate region. Finally, Natural Resources Canada (2006a) compiled data from a large survey of

Canadian households. Using data from this survey, Table 4.8 shows the total energy use for all Quebec single detached houses (covering any year of construction) as well as all Quebec homes (single detached, double/row houses and apartments) built between 1990 and 2003. Unfortunately these two categories were not combined (i.e. the single detached homes between 1990 and 2003). The two rows stating that the basement is excluded are directly from the survey which states that when calculating the energy intensity (kWh/m^2), basement areas were not included. This artificially inflates the energy intensity values since the total household energy use is being divided by a smaller floor area than actually being heated in many cases. Therefore, a correction factor using a 40 m^2 basement was also included in the table, as seen in the rows which state that a basement area is included. With this basement area included, for the houses with heating areas of 186 - 232 m^2 this estimated number also contains some inaccuracies since 33% of the homes surveyed are apartments with no basements. Therefore the actual average intensity of these Quebec homes is somewhere between those two extremes and likely closer to the value that includes the estimated basement area. Overall, these surveys, all of which are of real homes, validate that the BCH simulation generates reasonable results.

Table 4.8: Comparison of Base Case energy use with other research

Research Source	**Space Heating (kWh/yr·m^2)**	**Total (kWh/yr·m^2)**
Base Case House	55.6	123.2
Zmeureanu et al. - Built 1986 – 1990	-	123.8
Zmeureanu et al. - Built after 1990	-	107.6
Hamlin & Gusdorf 1997	72.7	-
Quebec Single Detached Dwelling – basement area excluded (NRCan)		266.7
Quebec Single Detached Dwelling – estimated basement area included (NRCan)		198.9
Quebec Dwellings 186-232 m^2 heated area – basement area excluded (NRCan)		222.2
Quebec Dwellings 186 - 232 m^2 heated area – estimated basement area included (NRCan)		167.1

5. CASE STUDY: THE TRNSYS MODEL OF THE NZEH

In a NZEH, one of the most important aspects of the design is to make it energy efficient in order to reduce the heating, cooling and electricity loads. This will have a significant impact on the required size of the HVAC and energy conversion systems (PV, solar collectors) in the home. For example, it is estimated that the improved envelope design of an energy efficient R2000 certified home in Canada reduces the energy needs by 30% – 40% at the very least (CHBA 2006). Other, more efficient homes can certainly reduce these loads even more.

The Net Zero Energy House (NZEH) is based on the original Base Case House (BCH) model, but with some significant changes that will be described in detail in the following sections. The reason for these changes is the basis for this thesis; to model a house that is highly efficient – i.e. it has low heating and electric loads - and over the course of the year produces as much energy as it consumes, using clean, renewable solar energy sources. Therefore, improvements in the NZEH model can be divided into three main categories: 1) Changes in the house envelope, 2) Energy efficient equipment and 3) Renewable (solar) energy technologies.

Included in this section are the results of a sensitivity analysis of various variables, performed on the BCH. A 1 hour simulation time step was used for this sensitivity analysis, however, as shown in section 4.3, this would be very similar to results from a 10 minute simulation time step. This analysis is fundamental to the reasoning for many of the design changes to the house that are presented in this chapter.

5.1 DIFFERENCES BETWEEN THE ENVELOPES OF THE BASE CASE HOUSE AND THE NZEH

5.1.1 Insulation

Environmental Considerations

A key component of any wall, roof, ceiling or floor is the insulation. Since one main goal of building a NZEHs is to be environmentally friendly, the energy savings are not the only thing that should be considered when choosing building materials. Although some people have concerns over how green certain types of insulations are, it is generally accepted that the energy saving benefits of most insulations will far outweigh any negative impacts of the type of material used (The Green Guide 2005). However, there are differences between the many types of insulations available. Since this thesis is for a new home, older types of insulations that are known to be less eco-friendly and have potential negative health effects are not considered, such as asbestos. From the current selection of insulation materials, some recommend avoiding sprayed on polyurethane foams since they used to emit CFCs which deplete the ozone layer, and now contain HCFCs that are better but still cause damage. (Austin Energy 2008). Table 5.1 shows a detailed environmental comparison between available insulations materials (Austin Energy 2008, Al-Homoud 2005, Recovery Insulation 2005, Wilson 1995, GreenSpec n.d.).

Insulation in the NZEH

The above ground exterior walls in the BCH have an RSI-value of 3.52 $m^2 \cdot K/W$. A sensitivity analysis of varying wall insulation thickness, and thus varying RSI-value, shows that once the RSI-value reaches about 6.5 $m^2 \cdot K/W$, the benefits to saving heating energy begin to level off (see Figure 5.1). Therefore, the RSI-value used for the NZEH exterior walls, explained in more detail below, is selected as 6.25 $m^2 \cdot K/W$. Table 5.2 shows the effects of varying the insulation thickness for the entire BCH envelope.

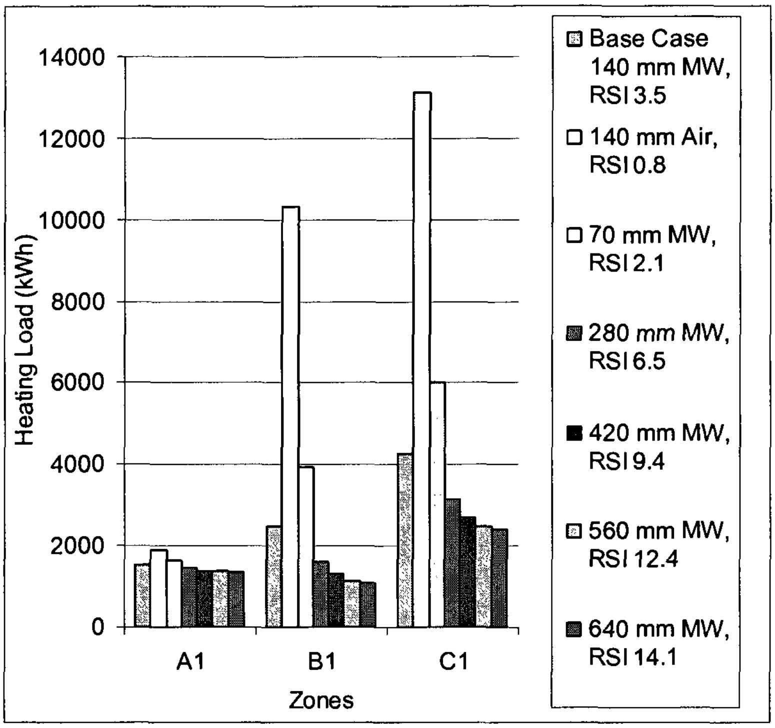
The impact of changes in insulation levels on the heating loads in the BCH were less significant in some other areas tested, such as the below ground walls, so the insulation thickness there was not changed. In terms of the basement floor, there was only a small impact on heating loads when it was insulated in the BCH (-6% in Table 5.2). However, the NZEH has a radiant floor, and without any insulation in the floor below the hot pipes, much of the heat would be sent into the ground resulting in significant losses. For example, by adding 40 mm of XPS insulation in the basement under the concrete slab filled with radiant hot water tubes, the heating load for the NZEH is more than cut in half. Therefore, the basement floor in the NZEH is well insulated. Simulations of the NZEH also revealed that attic insulation is important and it was also increased.

Table 5.1: Environmental assessment of insulation materials

Material	Conductivity (W/m °C)	Made From Recycled Materials	Recyclable	Bio-degradable	Embodied Energy (not incl. transport)	Durability sensitive to moisture	Cost per R-Value	Other Positives	Other Negatives
Insulation derived from organic sources									
Cellulose Batts and Loose Fill	0.034 - 0.040	Yes	Yes	Yes	Low, 21 MJ/kg	Yes	Low $	Non-hazardous fiber	Fire retardant addiives
Flax batts and Rolls	0.037 - 0.042	No	Yes	Yes	Low	No	-	Renewable Resource Non-hazardous fiber	Uses up to 15% plastic binding agents
Hemp Batts	0.043	No	Yes	Yes	Low	No	High $$$	Renewable Resource Non-hazardous fiber	Fire retardant addiives Uses up to 15% polyester matting
Wood Fibreboard	0.04 - 0.08	Sometimes	No	Yes	Low, 16 MJ/kg	When untreated	-		Odors from bitumen treatment
Cork Board	0.04 - .005	Sometimes	Yes	Yes	Low, 4 MJ/kg	No	High $$$	Renewable Resource	Formaldahyde off-gassing in small quantities
Insulation derived from naturally occurring minerals									
Fibreglass Batts and Rolls	0.032 - 0.040	Sometimes	Can be re-used	No	Low, 18 MJ/kg	Yes	Low $	Made from silica, an abundant material	Health risks to workers during manufacturing (resins, dyes and oils)
Mineral (Rock & Slag) Wool Batts and Rolls	0.033 - 0.04	Yes	Yes		Low, 16 MJ/kg	No	Low $	Fireproof	
Foamed Glass	0.042	2/3 recycled glass	Can be re-used	No	High	No	-		Photochemical oxidants, SO2 and NO2 released in manufacturing Bitumen and synthetic adhesives used in installation
Perlite Beads (volcanic glass expanded through heating)	0.040 - 0.060	No	Can be re-used	No, but high natural content	High	No	High $$$	High Fire Resistance	Non- Renewable

Table 5.1 (cont.): Environmental assessment of insulation materials

Material	Conductivity (W/m °C)	Made From Recycled Materials	Recyclable	Bio-degradable	Embodied Energy (not incl. transport)	Durability sensitive to moisture	Cost per R-Value	Other Positives	Other Negatives
Insulation derived from fossilized vegetation									
Expanded Polystyrene Board and Beads (EPS)	0.032 - 0.040	No	Yes	No	High, 75 MJ/kg	No	Low $	No CFCs or HCFC	Petrochemical based Non-renewable Releases toxins when burnt Expanded with smog producing pentane Deteriorates from UV light and releases gases
Extruded Polystyrene Board (XPS)	0.028 - 0.036	Some	No	No	High, 72 MJ/kg	No	High $$$		Petrochemical based Non-renewable Releases toxins when burnt Deteriorates from UV light and releases gases Some still expanded with ozone depleting HCFCs
Polyurethane/Polyisocyanurate Board and Foam	0.019 - 0.028	No	Technically yes, but usually not	No	High, 110 MJ/kg	No	High $$$	Hydrophobic	Petrochemical based Non-renewable Releases toxins when burnt Use of HCFCs



*MW = Mineral Wool

Figure 5.1: Effect of Wall RSI-value on Heating Loads for the BCH

As an improvement over the BCH, based on the environmental analysis in Table 5.1, the insulation used in the NZEH is Roxul Flexibatt® Mineral wool. This material was chosen for the compromise between superior insulating value and environmentally friendly properties. The mineral wool is made from natural and recycled materials and it is recyclable. It is also naturally very fire resistant and does not have any toxic chemical flame retardants. This insulation also repels water and does not degrade over time due to water infiltration, so it maintains its insulating properties. To be environmentally friendly, petroleum based foams and plastics have been avoided, even though they have higher insulating values for the same thickness. This compromise requires a thicker wall to accommodate more insulation to achieve the desired RSI-value. The 2x6 (38 mm x 140 mm) wood studs in the walls have been replaced with 2x10 (38 mm x 235 mm) wood studs. A 140 mm thick section of Roxul Flexibatt® Mineral wool has an RSI value of 3.87 $m^2 \cdot K/W$, therefore the material has a conductivity of 0.0362 W/m·K (Roxul 2007). However, as with the BCH, all of the walls have wooden studs mixed in with the insulation. Therefore, in the NZEH, the effective conductivity of the wood and mineral wool is 0.0416 W/m·K and the RSI-value of the entire wall containing 235 mm of insulaion is 6.25 m^2·K/W.

Table 5.2: The Impact of thermal insulation in the Base Case House

	Insulation Tested	Base Case RSI value (m^2·K/W)	Tested RSI Value (m^2·K/W)	RSI change from Base Case (%)	Change in Total Heating Load (%)
Base Case					
Exterior Walls	140 mm MW	3.52			
Top Ceiling (Zone C1)	260 mm MW	5.81			
Basement Walls	89 mm MW	2.19			
Basement Floor	40 mm AS	0.67			
Changes					
Exterior Walls	140 mm AS		0.75	-79%	207%
	70 mm MW		2.06	-41%	40%
	280 mm MW		6.45	83%	-25%
	420 mm MW		9.35	166%	-35%
	560 mm MW		12.35	251%	-39%
	640 mm MW		14.08	300%	-41%
Top Ceiling (Zone C1)	260 mm AS		0.55	-91%	84%
	130 mm MW		3.09	-47%	11%
	390 mm MW		8.55	47%	-4%
	520 mm MW		11.24	93%	-7%
	730 mm MW		15.63	169%	-9%
Basement Walls	89 mm AS		0.49	-78%	62%
	178 mm MW		4.05	85%	-7%
Basement Floor	No AS		0.47	-30%	7%
	40 mm MW		1.31	96%	-6%

* MW = Mineral Wool, AS = Airspace

The basement floor, which was only insulated with an air space in the BCH, is insulated with 41 mm of extruded polystyrene. This is located below the concrete slab that contains the radiant floor tubing. This results in an RSI-value of 1.9 m^2·K/W for the basement floor. The attic insulation is increased to 420 mm of mineral wool, resulting in an RSI value of 10.42 m^2·K/W for the top ceiling.

Although extruded polystyrene (XPS) insulation board typically comes in increments of 1 inch (25 mm) thicknesses, 41 mm was used. This is because the model was actually simulated using 60 mm of environmentally friendly, natural cork insulation in an attempt to avoid using petrochemical based materials. This has an equivalent RSI value of 41 mm of XPS. However, once all of the analysis and models were complete, the author learned that the cork insulation would cost over \$4,000 compared to \$777 of XPS just to insulate the basement floor. Most homeowners would not be able to justify this price difference. The 41 mm of XPS gives equivalent simulation results. If the more standard 2 in. (50 mm) is used instead, the house loads would be about 95 kWh/yr less (0.8% of the house electricity loads)

5.1.2 Windows

There are four important criteria related to windows when designing an energy efficient house: Window Location & Distribution, Window/Floor area ratio (i.e. window size), Window Pane Type and Window Shading. These window parameters are critical since they directly affect how much solar energy enters the house in addition to the fact that poorly chosen windows can result in significant heat losses through the glazing and leaky seals. The fact that these parameters are interdependent adds to the complexity.

A sensitivity analysis that tested all of the above parameters was performed on the BCH. The different options tested were as follows:

Window Location & Distribution: Five different window distributions for the above ground floors as a whole are considered. The Base Case has 25% of the total window area on each façade: 25-South/25-East/25-West/25-North. The other distributions of total glazing analyzed are: 50/20/20/10, 20/50/20/10, 20/20/50/10 and 70/10/10/10.

Window-to-Floor Area ratio: The results for 11% window-to-floor area ratio of the Base Case are compared with the cases of 20% and 30% window/floor area ratio.

Window Type: The BCH contains *Ordinary Double Pane* windows with an RSI value of 0.39 m^2K/W and SHGC 0.44. Two other windows types are simulated: *Improved Double Pane*, RSI 1.27 m^2K/W & SHGC 0.624, and *Triple Pane,* RSI 1.47 m^2K/W & SHGC 0.407.

Shading: Three shading options are tested: internal, external and no shading. The BCH has internal shading.

The details of the sensitivity analysis of these parameters are discussed below.

5.1.2.1 Window Location & Distribution:

By exploiting the natural and free heat from the sun, the largest reduction of heating energy use occurs when the largest percentage of installed windows face south. This can be seen by comparing Figure 5.2 and Figure 5.3, where Figure 5.3 has 70% south facing windows compared to 25% in Figure 5.2. When the window areas are increased and when better insulating and radiation absorbing window panes are used, the Annual Heating Load reductions due to changes in the window distribution are amplified even further in both magnitude and percent reduction compared to the Base Case.

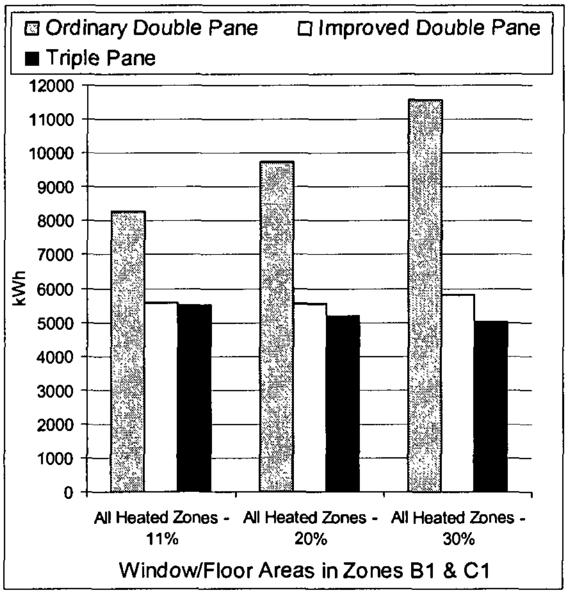


Figure 5.2: Annual Heating Load for 25-S/25-E/25-W/25-N distribution – Comparison between Ordinary Double Pane, Improved Double Pane and Triple Pane Windows

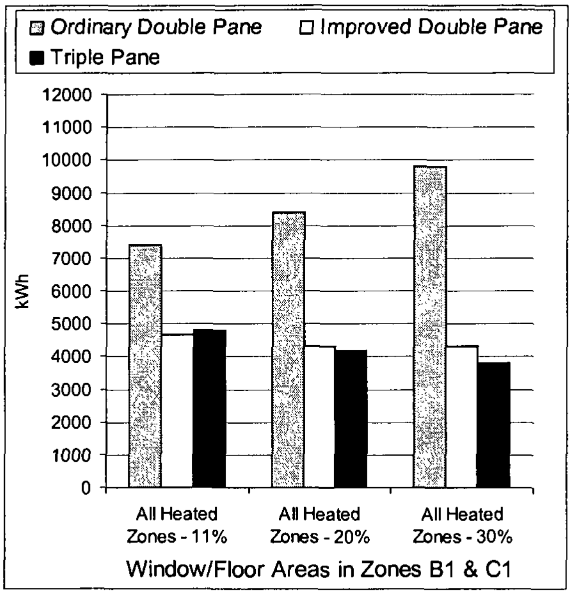


Figure 5.3: Annual Heating Load for 70-S/10-E/10-W/10-N distribution – Comparison between Ordinary Double Pane, Improved Double Pane and Triple Pane Windows

Switching from the 25/25/25/25 window distribution to 70/10/10/10, the reductions in Annual Heating Loads vary over a range of 11%-26% with reductions of 871 kWh/yr to 1509 kWh/yr. However, it is important to note that for the higher reductions, the temperatures in the house were well above acceptable, liveable temperatures. Temperatures often rise between 30°C to 40°C, even during the winter, and in some cases above 50°C. Therefore, some form of cooling would be required to reduce the house temperatures which would likely increase the heating loads by allowing the house to cool faster at night. It would also require significant amounts of electricity to cool the house, thus negating some of the savings from heating load reductions.

5.1.2.2 Window/Floor Area Ratio Change (i.e. change in window size):

A summary of the effects on the house from increasing the Window/Floor area ratio from 11% to 30% is presented in Table 5.3 and is discussed below.

Effect on Total Annual Heating Load

Figure 5.2 and Figure 5.3 show that increasing the window/floor area ratio to allow for more solar radiation does not necessarily result in reduced annual heating loads. For the Ordinary Double Pane windows (Base Case), the total annual heating load is increased by 33% even for the very large 70% south facing window. However, with better quality, more insulating windows, the heating loads are reduced. With the 25% south facing window distribution in Figure 5.2, only the triple pane windows result in heating load savings when the windows/floor area ratio is increased from 11% to 30%. However, for the larger 70% south facing window distribution, both the improved double pane and triple pane windows result in heating load reductions. For the Triple Pane window, the heating load reductions are 9% and 21% when changing the windows/floor area ratio from 11% to 30% for the 25% and 70% south facing window distributions, respectively.

This analysis shows that more window area will not necessarily result in more retained heat from the sun, and thus a reduction in heating loads. Larger areas allow for more solar radiation into the house, but the insulating value (RSI-value) must be high enough to counteract the losses that occur through the larger area of reduced insulation compared to that of the wall it is replacing. This is important even with a high solar heat gain coefficient (SHGC) since large losses often occur at night when the SHGC has no impact. The SHGC is an especially important factor to consider in homes that have cooling systems since the benefits of letting in and trapping heat in the winter can result in unwanted strain on the cooling system in the summer.

Effect on Peak Zone Temperatures

As window-to-floor area ratio increases from 11% to 30%, peak zone temperatures greatly increase in the two above ground zones. This effect is even more apparent when higher performing windows are used. For the three cases of Ordinary Double Pane, Improved Double Pane and Triple Pane windows, peak zones temperatures increased by up to 10.5°C (33%), 16.8°C (46%) and 12.7°C (39%) respectively as window/floor area ratio is increased from 11% to 30% (for the 70/10/10/10 distribution).

Effect on the Number of Hours Above 24°C in the house

Regardless of the window distribution, increasing the window/floor area ratio from 11% to 20% to 30% has a considerable impact on the number of hours throughout the year that the temperature in the house rises above 24°C. The actual changes range from 18% to 52% increases when the window/floor ratios are doubled from 11% to 20% or increased from 20% to 30%. The largest changes from these ~10% window area increases occur between the 11% and 20% window/floor area ratios and with the 70/10/10/10 distribution. Tripling the area of course has an even larger impact, as shown in Table 5.3.

Again, the type of window pane also plays a major role. Since the improved double pane windows let in much more solar radiation than the other two types of windows (due to the higher SHGC), this window type results in the largest number of hours above 24°C, usually about 700-800 more hours per year compared to the Triple Pane windows. Figure 5.4 graphically shows what is described in the above two paragraphs. In Addition (not shown in the figure), the Ordinary Double Pane window has the lowest number of hours above 24 °C in all cases. Compared to the Triple Pane windows, it ranges from about 550 fewer hours in zone C1 for the 11% window/floor area ratio model up to around 1600 fewer hours in zone B1 at 30% window/floor area ratio.

Table 5.3: Examining the impact of increasing the Window/Floor area ratio from 11% to 30% in the BCH (i.e. increasing window size)

	Effect on Total Annual Heating Load			Effect on Peak Zone Temperatures (Top Floor)			Effect on Number of Hours above 24°C (Top Floor)		
Window Type and Distribution	Change (%)	Absolute change (kWh)	Heating Load Range (kWh)	Change (%)	Absolute change (°C)	Temperature Range (°C)	Change (%)	Absolute change (kWh)	No. of Hours Range (# of hours)
Ordinary Double Pane									
25/25/25/25	40	3289	8265 - 11554	-	-	-	68	1020	1491 - 2511
70/10/10/10	33	2404	7394 - 9798	33	10.5	32.1 - 42.6	85	1368	1615 - 2983
Improved Double Pane									
25/25/25/25	4	242	5572 - 5814	-	-	-	59	1634	2788 - 4422
70/10/10/10	-8	-350	4655 - 4305	46	16.8	36.5 - 53.3	68	2079	3077 - 5156
Triple Pane									
25/25/25/25	-9	-471	5502 - 5031	-	-	-	83	1694	2047 - 3741
70/10/10/10	-21	-1010	4810 - 3800	39	12.7	32.4 - 45.1	98	2207	2242 - 4449

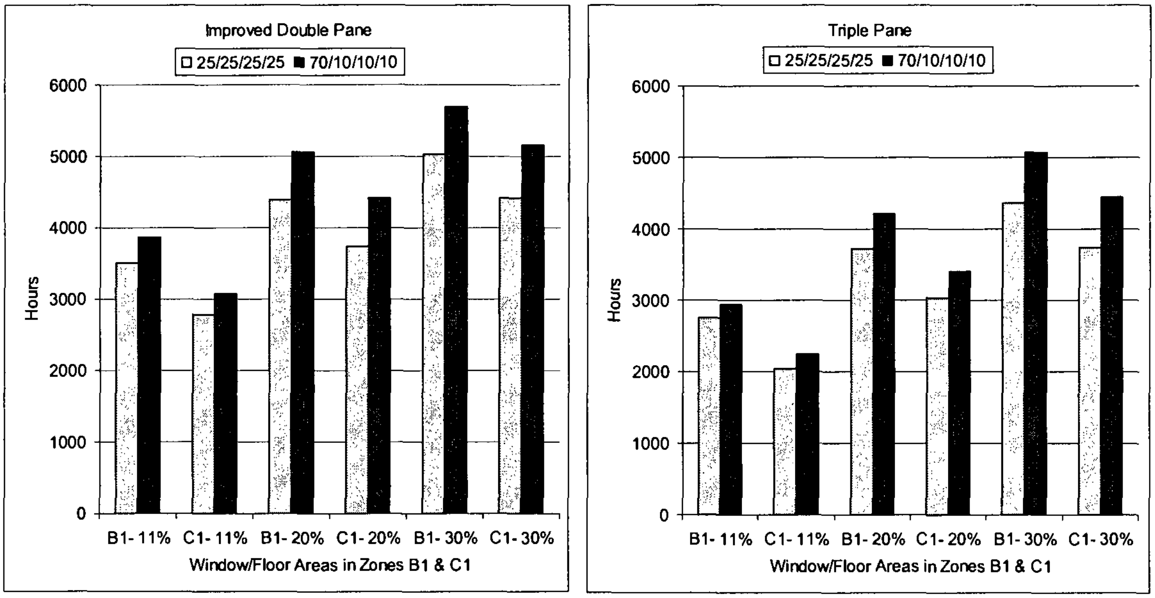


Figure 5.4: The number of hours above 24°C in the house for different window/floor area ratios, different distributions and different window types

These results show that both the RSI-value and the SHGC play important roles in how hot the house gets. However, the SHGC clearly has a more significant warming effect. Even though the Triple Pane windows have a superior RSI-value and can retain more heat 24 hours a day, the larger SHGC of the Improved Double Pane windows, which only has an impact during daylight hours, still results in a much warmer house; sometimes much too warm. In terms of the number of hours above 24 °C, the ability to let in so much sun is actually detrimental in some cases, such as for the case of zone B1 for 30% window/floor area ratio with 70% south window area. In this case, the temperature is above 24°C for 5701 hours which is 65% of the year. This is a problem because far too often the zone temperature is unbearably hot (35-45°C).

5.1.2.3 Window Pane Type:

Due to the complexity of interactions between window pane types, window distributions and window areas, the effects of changing the window pane are best analyzed in concert with changes in other window features. Therefore, it can be seen in the previous two sections how the window pane affects heating loads and temperatures. In general, increasing the insulating ability (RSI-value) as well as the solar heat gain coefficient (SGHC) will reduce heating loads and increase the peak zone temperatures and number of hours above 24°C in the house. However, there is a limit to the benefits of increasing the RSI-value and SHGC of the windows because the house can quickly begin to overheat, even during the winter months. Results are presented in Table 5.3, Figure 5.2, Figure 5.3 and Figure 5.4.

5.1.2.4 Window Shading

Window shades are simple yet important devices used to regulate temperatures in the house. Shading is typically used in the summer, since during the winter it is usually best to take advantage of incoming radiation as much as possible. Therefore, as mentioned in section 4.1.2.2, this house makes use of shading only from May 1st to October 17th between 9 am and 9 pm. Since these dates are the exact opposite of when the heating system is activated in the house, variations in shading do not have any impact on the annual heating load or peak instantaneous heating power. There is, however, a significant impact on temperatures in the home during the warmer months. If the house were equipped with a mechanical cooling system, shading would have a significant impact on those energy loads.

It is obvious that blocking the solar radiation from entering the home will reduce the indoor temperatures, but the point of this section of the simulations is to determine to what degree, literally. Three shading options are tested. The first is the Base Case design which has internal shading devices on all of the windows in the house, except for the one in the garage. The reflection coefficient of these translucent shades is 0.6. The second option tested is an external shading device that does not let in any radiation, such as a shutter on the outside of the window. This is the extreme case and is not common in homes in Quebec, but it is used to show the range of possibilities. More common exterior building shading would be the type that blocks direct radiation, but allows diffuse radiation, such as an overhang. The third shading option tested is that of no shading at all. The main difference between the internal and external shading is that with internal shading, radiation is permitted to enter the room before being reflected away. Through multiple inter-reflections between the inner-window and the shade, some of this radiation is absorbed by the shading, along with the much larger initial amount. Some of this absorbed radiation is then emitted into the room. Since external shading is not located inside the house, all radiation reflected and absorbed (by the shade) never enters the house.

Figure 5.5 shows the effect of shading on the number of hours above 24°C in the house during the year for two different cases. The first set of zones A1, B1 & C1 is for the Base Case with the various shading options. The second set (Case 2) is also using the standard double pane windows but for the case with a 30% window/floor area ratio and a window distribution of 70-S/10-E/10-W/10-N. This shows the two extremes side by side. This figure shows that although the percent increases in number of hours above 24°C are generally higher for the Base Case when shading is reduced, the actual magnitude change in number of hours above 24°C is quite similar for both cases.

Another way to investigate the effect of shading on house temperatures is to compare the actual zone temperatures throughout the year with different shading options. Figure 5.6 shows the temperature in Zone B1 for Case 2 described above during the summer months for the three shading options.

Figure 5.6 shows that not only does the shading result in much lower daytime temperatures, but with more shading, the amplitude of the fluctuation over 24 hours is also significantly reduced. This would result in a more comfortable home to live in. In fact, with the proper use of shading and natural ventilation, a costly, energy hogging cooling system might be avoided. In addition, the type of shading can make a big difference since some types, such as external shutters, can keep out far more radiation than internal blinds.

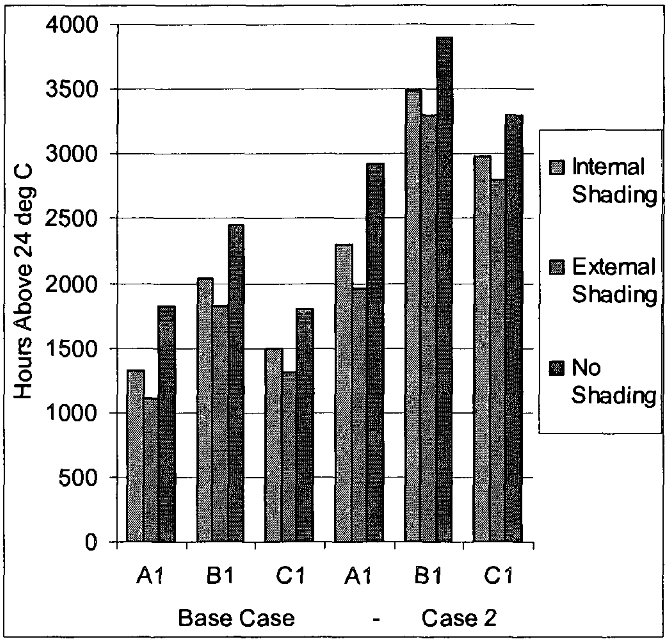


Figure 5.5: The number of hours above 24°C in the house for two different window designs and various shading options

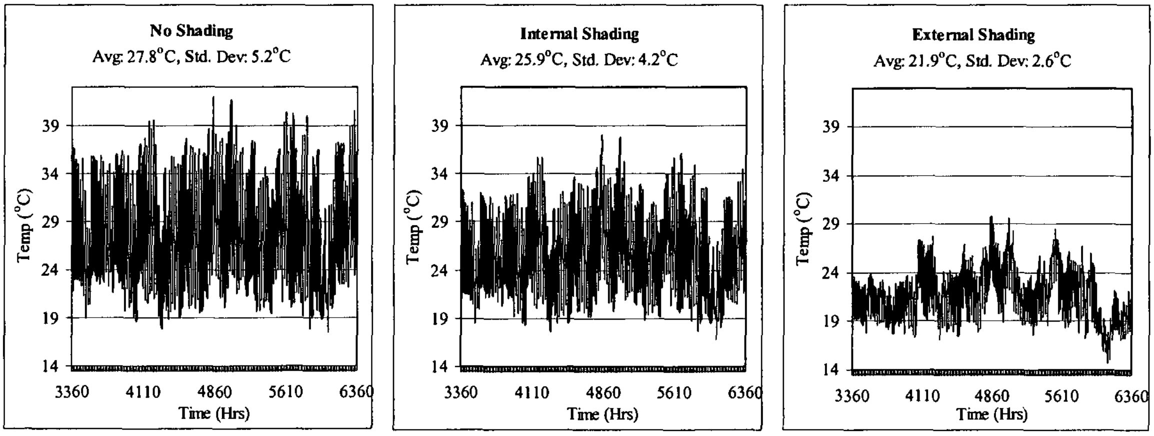


Figure 5.6: Temperature swing in Zone B1 during the summer months for various shading options

5.1.2.5 Window Selection and Design

Based on the above sensitivity analysis, the Window placement (distribution), Window/Floor area ratio, Window Pane Type and Window Shading that are used in the NZEH are as follows (and are summarized in Table 5.5):

***Window Location(Distribution) and Window/Floor Area Ratio*:**

The window/floor area ratio was found to be most efficient around 20%. This results in 16.72 m^2 of window area for each above ground floor. More window area is avoided since it would let in too much heat on hot summer days and would also result in more heat loss during cold winter nights since windows are far less insulating than walls. Using this area, the best distribution tested is to have 70% of the window area on the south wall. The remaining distribution of windows is 20% on the north wall and 5% on both the east and west walls. This is slightly different from the sensitivity analysis distribution of 70% South/10% East/10% West/10% North because from an architectural point of view, it makes more sense to provide more window area on the north wall. It is important that the house is efficient, but it must also be designed in such a way that people would like to live in it. Based on the wall areas, these distributions result in 35% of the south wall being glazed, 10% for the north façade and 5.5% for each of the east and west façades.

***Window Pane Type*:**

Two different wood frame window types have been selected from the Canadian window company Loewen: fixed picture windows and operable casement windows.

A combination of fixed and operable windows is being used since fixed windows have less infiltration and heat loss, but operable windows offer ventilation options in addition to the fact that people like to live in homes where they can open their windows.

Both window types have the same glazing, which is triple pane (HP3 Thermal Edge) and argon filled (these are not the same as the triple pane windows used in the sensitivity analysis for the BCH). For the operable casement windows, the (SI) U-value, SHGC (Solar Heat Gain

Coefficient) and Visible Transmittance are 1.136 W/m^2·K, 0.24 and 0.38 respectively. Similarly, for the fixed picture window, these coefficients are 0.966 W/m^2·K, 0.31 and 0.38.

In TRNBuild, these exact windows are not available, so the closest options were selected from the window library based on the U-value and SHGC. For the casement window, the SI U-value (and RSI value) and SHGC are 1.16 W/m^2·K (0.862 m^2·K/W) and 0.265 respectively. Similarly, for the fixed picture window, these coefficients are 0.97 W/m^2·K (1.03 m^2·K/W) and 0.334.

The placement of the operable and fixed windows is as follows: 50% of the windows on the south facade are operable and all of the windows on the other three facades are operable.

Window Shading:

The internal shading in the NZEH remains unchanged from the design in the BCH. This house uses translucent roller shades only from May 1st to October 17th between 9 am and 9 pm.

5.1.3 Air-tightness and Infiltration

The NZEH is a tighter house and thus has less leakage and infiltration. Whereas the BCH has a natural infiltration rate of 0.1635 ACH (or 3.27 ACH @ 50 Pa), the NZEH is designed to meet R2000 standards and has a natural infiltration rate of 0.061 ACH (or 1.22 ACH @ 50 Pa) (Hamlin & Gusdorf 1997, p.13).

5.2 ENERGY EFFICIENT EQUIPMENT IN THE NZEH

The electrical loads from appliances and lighting can add up very quickly and be a significant energy sink. This is especially true for a house with an energy efficient envelope in terms of the percentage of energy loads per end-use. For example, in the Hathaway Solar Patriot House in Washington, DC, the household appliances and lighting made up 40% of the energy consumption. It was stated that the lighting was all using energy efficient CFL lights so this energy should be quite low. In addition, all of the major appliances (washer, dryer, fridge and oven) were energy efficient models (Norton, Hancock and Reeves 2005).

In order to reduce these loads as much as possible, as many appliances as possible should be Energy Star certified. This is an international certification that ensures that the product is among the most efficient on the market (Natural Resources Canada 2006e)

Lighting should also be Energy Star certified and mostly compact fluorescent lighting (CFL). Some situations do not allow CFL type bulbs, but in those cases the most efficient types of bulbs available should be used. Using CFL bulbs rather than incandescent or halogen bulbs is very beneficial since they use about 75% less energy and last about 10 times longer (Natural Resources Canada 2006b). In the future, the even more efficient Light Emitting Diode (LED) technology might become the preferred technology.

Important ways to reduce DHW energy use, which is also a significant energy sink in a house, are also discussed in the following sections.

5.2.1 Artificial Lighting

The artificial lighting schedule and layout in the NZEH is the same as in the BCH, however, the type of lighting is improved. All of the incandescent lighting is replaced with 75% more energy efficient fluorescent and compact fluorescent lights (CFL). Although the amount of visible light with the fluorescent lighting in the NZEH is approximately the same as with the 5 W/m^2 of incandescent lights in the BCH, the required electric power is only 1.25 W/m^2. In addition, the heat given off by the fluorescent lighting is based on ASHRAE 2005, p. 30.22, table 16. This reference states that 67% of the heat generated is radiative and 33% is convective.

5.2.2 Appliances

Table 5.4 shows the appliances used in the NZEH. All of these appliances are more energy efficient than those in the BCH. The newer appliances in the NZEH are based on actual appliances from EnerGuide and Energy Star listings. Switching from the appliances used in the average Canadian home to the more efficient models saves 1610 kWh (49% reduction) for the major appliances and 1012 kWh (31% reduction) for the other appliances.

As in the BCH, 100% of this energy is converted into convective heat gains and thus 190 W is dissipated from the major appliances and 251 W from the other appliances. The distribution of these heat gains is the same as in the Base Case.

Table 5.4: Energy consumption of the appliances in the NZEH

Appliance	Quantity	kWh/yr per appliance	Total kWh/yr considering quantity of appliances
Refrigerators [1]	1	417	**417**
Freezers [1]	1	354	**354**
Dishwashers [1]*	1	39	**39**
Electric Ranges (self cleaning) [1]	1	397	**397**
Clothes washers [1]*	1	30	**30**
Electric Clothes Dryers [1]	1	425	**425**
TOTAL Major Appliances			**1662**
Microwave [3]	1	118	**118**
Toaster oven [3]	1	65	**65**
Coffee maker [3]	1	68	**68**
Blender [3]	1	8	**8**
Cordless/powered Phones [3]	4	20	**80**
Computers w/ monitor & speakers [2]	2	84	**168**
External Modem [3]	1	60	**60**
Printer [2]	1	14	**14**
Clock Radios [3]	3	13	**39**
Stereos [2]	2	47	**94**
DVD/VCR [2]	2	32	**64**
Televisions [2]	3	288	**864**
Cable box or satellite [3]	2	140	**280**
Other miscellaneous things	20	14	**280**
TOTAL Other Appliances			**2202**

1- Natural Resources Canada – Office of Energy Efficiency 2007, *Appliances - EnerGuide Ratings*

* Excluding hot water since DHW is taken into account elsewhere in the model. According to the California Energy Commission (2007), 80-90% of the energy used by these appliances is from hot water, therefore the value used is 20% of the energy use stated in the referenced source [1].

2- Energy Star 2007, *Home Electronics*. These values are mostly based on the energy use from the Base Case model but reduced by a given percentage taken from the Energy Star website.

3- Based on Energy Star 2007 (looking at various appliances such as TVs, VCRs, etc.), it is assumed these small appliances are 30% more efficient than the standard models used in the Base Case.

5.2.3 Domestic Hot Water Efficiency Schemes

Several schemes are used to reduce the energy demand for heating the domestic hot water and controlling the temperature of the water. These schemes, which are described in the following sections, are 1) a drain water heat recovery (DWHR) device, 2) low flow fixtures and 3) a thermostatic mixing valve (TMV). The impact these schemes have on the energy consumption of the house is summarized in Figure 5.7

5.2.3.1 Drain Water Heat Recovery

A typical house will literally send 80-90% of the energy used to heat water down the drain. Drain Water Heat Recovery (DWHR) systems are used to capture this wasted heat.

Two types of systems exist: storage and non-storage. A storage type system directs the drain pipe containing the hot waste water through a clean water tank. This way, as the hot water flows into the sewage system, some of the heat is recaptured and stored in the water in the tank for later use. The non-storage type systems can only capture and use the waste heat at the same time as when hot water is being used and sent down the drain. This type of system is more common because it is simpler and in the vast majority of cases, hot water being used is immediately sent down the drain, such as during a shower. This type of system typically consists of a copper spiral pipe containing the incoming cold city water which is wrapped around the drain pipe where the hot waste water leaves the house. As the incoming cold water pipe spirals around the hot water drain pipe, it captures the heat and then continues on to the domestic hot water tank or to the showers and taps directly (US DOE 2005, Drain Water Heat-Recovery). There are several different manufacturers of Drain Water Heat Recovery systems and prices can range from $250 to $1200 depending on company as well as the size and length of the pipe.

Since a DWHR device is an effective energy saving device, one is naturally used in the NZEH. The DWHR system in this model is slightly simplified compared to what is more commonly installed in homes in order to avoid an overly complicated modeling set-up for this relatively simple technology. For the system modeled in this thesis, the DWHR system consists of a copper pipe section containing the incoming city water flowing into the DHW storage tank. This pipe is located just upstream of the DHW storage tank and is tightly coiled around the 80 mm drain pipe which contains the drain water from all of the drains in the house. Therefore, as the cold city aqueduct water flows through the coiled pipe into the storage tank, heat from the warm drain water is transferred to the incoming cold water which is pre-heated.

In a real house, both the flow rates and the temperatures of showers and other hot water uses vary, and thus so do temperatures of the water flowing down the drain. For this model, the drain water temperature was assumed to be a constant 41°C, based on a typical shower temperature, the most common hot water use in a house (Zaloum, Lafrance & Gusdorf 2007, p.5). In addition, the effectiveness of the heat exchange can vary based on temperature and flow rate, but an average effectiveness of 0.6 was used based on company specifications (RenewABILITY 2007) and a study performed by Natural Resources Canada (Zaloum, Lafrance & Gusdorf 2007, p.10). The other simplification in this model is the routing of the pre-heated water after it passes through the coiled heat exchanger. The water can take two paths; it can either go into the DHW tank, or it can go directly to the cold water piping in sinks and showers in the bathrooms. The advantage of the latter is that when the shower draws water from the DHW tank, it will need less since the cold water portion will be warm. This alternate routing is not modeled here since the cold water consumption is beyond the scope of this thesis; however, the current set-up, where the pre-heated water goes into the DHW tank gives a good approximation of such a system.

The DWHR system in the NZEH is based on the Power-Pipe™ 60 made by RenewABILITY Energy Inc. This system was one of eight DWHR models tested by Natural Resources Canada and came out on top for its ability to capture the waste heat. Two main things contributed to the better performance of the Power-Pipe™ 60: 1) the rectangular shape of the copper tubing which allowed for more surface area contact between the drain pipe and the incoming water pipe, and 2) the fact that the incoming cold water pipe splits into 4 smaller copper pipes to allow for less pressure loss and more surface area while maintaining high volume (Zaloum, Lafrance & Gusdorf 2007, p.16).

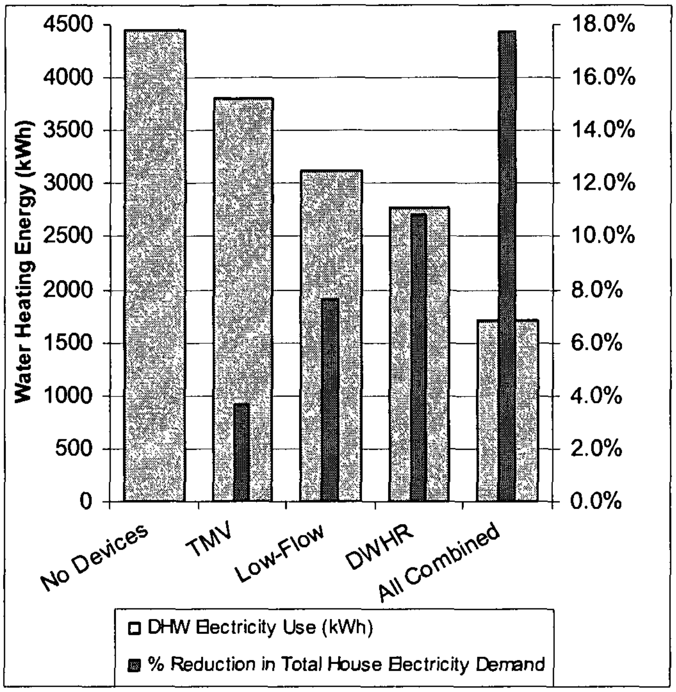


Figure 5.7: Impact of DHW energy saving schemes on the NZEH without active solar technologies

5.2.3.2 Domestic Hot Water Flow Rate Reduction

The DHW entering and leaving the tank is set to the same daily schedule as in the BCH scenario, from research done by Perlman and Mills (1985). However, the flow rate has been reduced by 30% to 165 litres per day to account for the installation of water efficient low-flow fixtures and aerators. This reduction comes from a variety of sources which estimate the conserved quantity of water to be around 40% to 60% (Natural Resources Canada 2008, Toolbase Services n.d.). However, in order to be conservative and to also account for the fact that some people compensate for the reduced flow by using the water longer, a 30% reduction was used.

5.2.3.3 Thermostatic Mixing Valve (TMV)

A thermostatic mixing valve (TMV) is installed downstream of the DHW tank where it mixes the DHW tank hot water with municipal cold water and supplies a stable 49°C to the faucets. This allows the water in the tank to be at least 55°C, and in this case up to 85°C from the solar energy captured by the collector. The water needs to be heated above 55°C to avoid the danger of Legionnaire's disease and to meet code requirements (Reliance Water Controls 2005). The TMV also saves energy because without it, the water coming out of the tap is often either much hotter than 49°C or the temperature is regulated by the user by adding more cold water to the flow rather than reducing hot water flow. This applies to taps that have separate hot and cold knobs. The TMV is modeled in TRNSYS with an Equation.

Table 5.5: Differences between the BCH and the NZEH

Design Parameter	BCH	NZEH
Envelope		
Insulation of basement floor (RSI-value)	0.67 m^2·K/W 40 mm air space	1.9 m^2·K/W 41 mm XPS (below the radiant floor)
Insulation of basement walls (RSI-value)	2.19 m^2·K/W 89 mm mineral wool	2.47 m^2·K/W 89 mm improved mineral wool
Insulation of above ground walls (RSI-value)	3.52 m^2·K/W 140 mm mineral wool	6.25 m^2·K/W 235 mm improved mineral wool
Insulation of attic floor (RSI-value)	5.81 m^2·K/W 260 mm mineral Wool	10.42 m^2·K/W 420 mm improved mineral wool
Window distribution of facades	25%-S/ 25%-E/ 25%-W/ 25%-N	70% South/ 5% East/ 5% West/ 20% North
Window/Floor Area Ratio	11%	20%
Windows: RSI Insulating value SHGC	Double Pane 0.391 m^2·K/W 0.44	All Triple Pane, Argon Filled. -Fixed Picture (50% of south façade): 1.03 m^2·K/W 0.334 -Operable Casement (All other windows): 0.862 m^2·K/W 0.265
Natural Air Infiltration (ACH)	0.1635 ACH 3.27 ACH @ 50 Pa	0.061 ACH 1.22 ACH @ 50 Pa
Energy Efficient Equipment		
Lighting type Average installed power density	Incandescent 5 W/m^2	CFL 1.25 W/m^2
Appliances (Total Annual kWh)	Standard models 6846 kWh/yr	Energy Efficient 3864 kWh/yr
Domestic Hot Water Use	236 litres/day Electric heating element in the tank (5.5 kW)	Low flow faucets: 165 litres/day Thermostatic mixing valve reduces the use of hot water from the tank Solar Collector & Electric Heating (1 kW)
DHW Energy Recovery	N/A	Drain Water Heat Recovery
Renewable Energy Technologies		
Heating System	Electric Baseboard Heaters	Radiant Floor Heating Solar Collector & Electric Heating (2 kW & 4 kW electric elements)
Electricity	Electrical Utility	Photovoltaic Panels

5.3 RENEWABLE (SOLAR) ENERGY TECHNOLOGIES IN THE NZEH

5.3.1 The Solar Combisystem – An Active Solar System for DHW and Space Heating

A combisystem is a heating system that uses one main heating source to supply heat to both a radiant floor as well as the domestic hot water (DHW). With a solar combisystem, the primary heat source comes from a solar collector. This type of system can, however, have individual back-up heating systems, such as electric heating elements or boilers, for either the radiant floor system, the DHW system, or both. Task 26 of the International Energy Agency (IEA) focused on Solar Combisystems. Part of the work in this "Task" simulated many different combinations of storage tanks, heat exchangers, auxiliary heat sources, etc. Nine set-ups shown in subtask C were published with more detail out of approximately 20 different set-ups (IEA-SHC 2002). The two-tank model used in this thesis (one DHW tank and one radiant floor water tank) is roughly based on the Task 26 system #14, but that system is not one of those nine. However, this two-tank set-up was chosen for its simplicity while still being able to perform the desired heating functions.

5.3.1.1 Overview of Radiant Floor Heating

Radiant Floor heating is a technology that has been around since ancient Rome, but is gaining new popularity in modern times due to the comfort that it can provide. There are many benefits and some drawbacks to radiant floor heating. These are described in the following text that was summarized from an article by Alex Wilson (2002).

Energy savings. Since the heat from radiant floors comes from, as the name suggests, radiation at the floor level, rather than convection through the air, the house occupants will be more comfortable at lower air temperatures. When a lower air temperature is needed, less energy is needed. This is because not only is the heat at the floor level where the people are located, rather than up at the ceiling, but with less airflow compared to conventional forced air, there is less of a cooling effect. Increased airflow using conventional systems can also increase or decrease pressure and infiltration in many buildings when the ventilation system is not properly balanced. When using radiant floor heating, reducing this leakage of cold air into the house further reduces heating loads. Finally, taking advantage of free solar energy can be a great source of savings. Concrete-slab radiant floor systems require relatively low hot water temperatures (30°C to 60°C) which make using solar collectors a viable option for these systems.

Comfort. The warm floor gives the added benefit of being able to walk barefoot in comfort. In terms of audible comfort, this type of heating is also good because there is no sound of forced air and fans or gurgling and creaking from baseboard heaters.

Room Layout. Since this radiant heating is hidden beneath the floor, there are no restrictions as to where furniture or appliances can be placed due to risks of access, overheating or fire.

Air Quality. With less forced air there will be less dust circulating in the house. In addition, in conventional houses with baseboard heaters this dust can burn on the hot surfaces and release volatile chemicals or toxic particulates.

Although radiant floor heating can be a great solution to low energy heating, in some situations, it may not be the best choice. Some argue that the cost of a radiant floor heating system far outweighs the benefits when one is installed in a highly insulated, tight house designed to take advantage of passive solar energy. In these types of houses, the annual energy cost required to heat the house might be only around 1% of the cost of the radiant floor system.

The advantage of radiant floor heating, as mentioned above, however, is that this type of system operates at low temperatures. Therefore, since solar collectors often provide low temperature heat, this is an effective use of solar energy. In addition, this energy is free, renewable and pollution free, so in a Net Zero Energy House, it would be wasteful to not take advantage of this energy source.

Various Types of Radiant Floors

There are many different ways to design hydronic radiant floors, such as concrete slab on grade, sub-floor heat transfer plate systems or staple-up tubing on the underside of a floor (Healthy Heating 2006). These and other types of radiant floors differ in the floor layers and materials and how the tubing is attached, but they all contain tubing with warm fluid that transfers the heat through the floor up to the room.

5.3.1.2 The Combisystem Setup and Operation: Modeling with TRNSYS

Figure 5.8 shows a physical schematic of the combisystem but does not include the controllers that are modeled in TRNSYS. These are explained in the following paragraphs. Figure 5.10 shows the section of the TRNSYS model that contains the combisystem and the associated controls (this is not the complete TRNSYS model). The solid lines represent the fluid flow whereas the dotted lines are connections for control functions.

Both the Radiant Floor Tank (RFT) and the DHW tank are 300 litre Vertical Cylinder tanks (Type 534) which allow for stratification in a user defined number of layers; in this case, 4 layers. These layers are defined as nodes, with node 1 being the top node where water exits the tank. Water enters the tank at the bottom into node 4. With the RFT, the water is circulated through the radiant floor and the tank in a closed loop. In the DHW tank, fresh, cold city aqueduct water is pre-heated in the drain water heat recovery coil before it enters the bottom of the tank through node 4. The incoming aqueduct temperature is based on actual measurements taken in Montreal (Dumas and Marcoux 2004).

A solar collector (flat plate Type 1b or evacuated tube Type 71) sends the hot 60% glycol-water mixture at 100 kg/h to either a heat exchanger in the RFT or to one in the DHW tank, with priority given to the RFT. A Differential Controller (Type 2d) and a TRNSYS Equation feed information to the flow diverter (Type 11f) to control the flow of glycol. The hot glycol will only flow to the RFT heat exchanger if it meets all three of the following conditions: 1) the glycol entering the heat exchanger in the tank is hotter than the fluid in the tank surrounding the exiting section of the heat exchanger – this ensures that the solar collectors are always providing heat rather than taking heat from the tank, 2) the temperature of the water in node 1 of the tank is less than 55°C, and 3) it is the heating season (Oct 17th to May 1st). If any of these conditions are not met, then the fluid is directed to the DHW tank. The fluid will only flow through the DHW tank heat exchanger if conditions similar to the first two above are met, except the temperature limit in the DHW tank is for node 3 (where the heat exchanger enters the tank) and is set to a maximum 85°C. This is imposed by a second Differential Controller. When conditions for both tanks are not met, the glycol does not circulate through the solar collector.

The RFT has two electrical heating elements to heat the tank water which are controlled based on the temperatures in the house. Since the control of the radiant floor heating is based on maintaining comfortable living conditions, the 2 kW heating element in node 1 of the RFT is activated when the operative temperature on the top floor of the house drops below 21°C. If the temperature drops below 18°C, the 4 kW heating element in node 2 is also activated. These criteria are set back by 3°C at night. The 1 kW DHW tank heating element is activated when the water in the top of the DHW tank falls below 55°C. The back-up electrical heating elements in the two tanks are modeled using an Equation and the 3-Stage Room Thermostat with heating set back and temperature deadband (Type 8b).

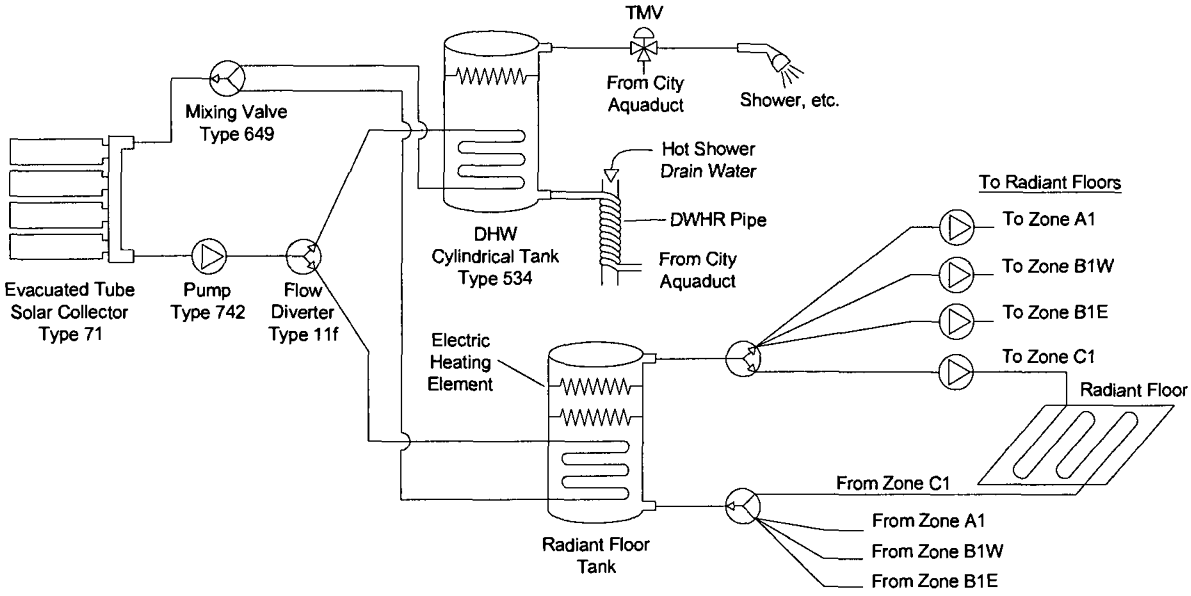


Figure 5.8: Schematic of the combisystem

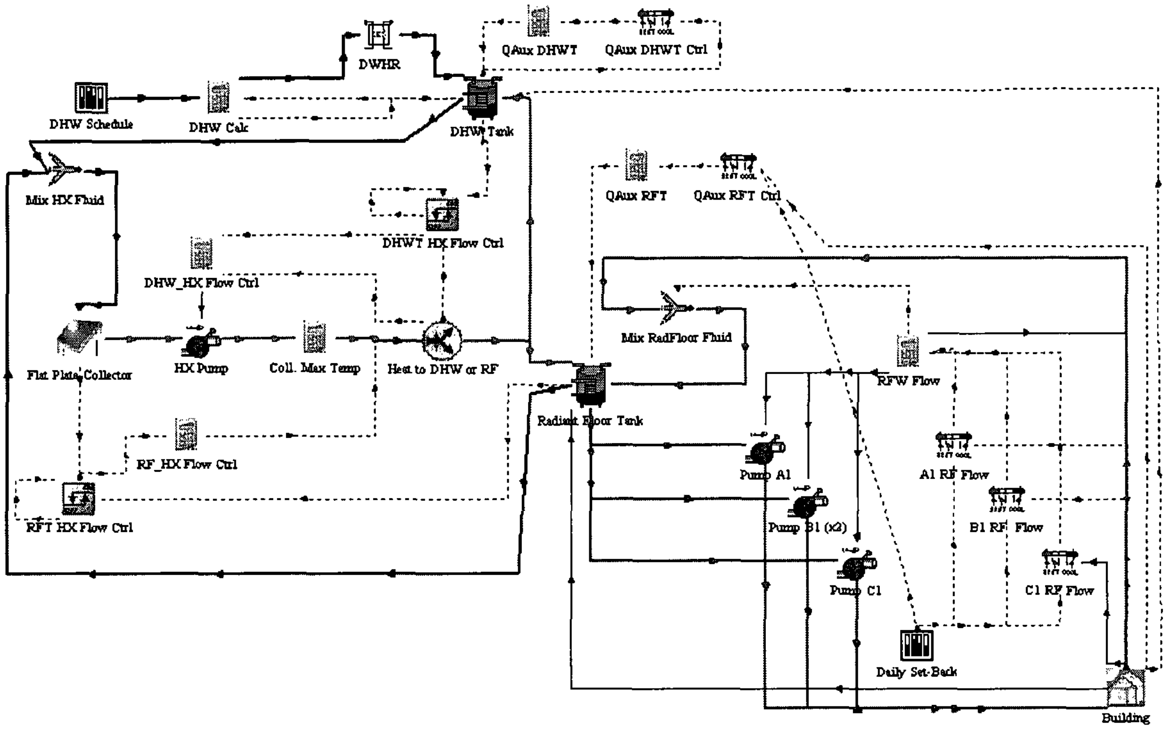


Figure 5.9: The combisystem section of the model in TRNSYS

There are four separate radiant floor heating loops in the house; one in the basement (zone A1), two on the ground floor (zones B1W & B1E) and one on the top floor (zone C1). The water leaving the RFT, which ranges from 25°C to 55°C, is pumped independently through these zones at 300 kg/h, each using a small electric pump (TESS Type 742). The hot water only flows through the radiant floors when the following conditions are met: 1) the operative temperature in the zone is below 21°C and 2) it is the heating season (Oct 17th to May 1st). Since the top floor (Zone C1) is twice as large as the other zones, the flow is doubled in this zone (600 kg/h). In addition, since the basement (Zone A1) is normally less occupied, the temperature setting is 1°C less than the other floors. An Equation and Type 8b, the Three-stage Room Thermostat, are used to control these flows as well as a 3°C temperature set-back from 11 pm to 7 am. The electricity needed to power five pumps for the combisystem is included in the overall house electricity demand. These pumps are modeled after UP 15-10 B5 Grundfos pumps (Grundfos, n.d.). When sizing the pumps and calculating the friction losses from pipe length and fittings, the following references were used: ASHRAE 2005, page 36.7 figure 5, The Engineering ToolBox 2005b and The Engineering ToolBox 2005d.

Table 5.6 shows the Pressure drop that each pump must overcome.

Table 5.6: Pump Pressure Drop

Solar Collector to RFT	Solar Collector to DHW tank	RFT to A1	RFT to B1W/B1E	RFT to C1
135.5 kPa	135.5 kPa	31.8 kPa	63.6 kPa	63.6 kPa

A pre-heat tank located just downstream of the solar collector, before the radiant floor and DHW tanks, was considered in this model for the purposes of comparison. The idea of a pre-heat tank is to capture and store as much of the solar energy as possible by sending the heat from the solar collector into a tank that contains no additional heat source. When there is another source of heat in a tank, such as the electric heating element in the DHW tank and RFT, the water is heated electrically at night. In the morning, when solar energy is available for capture, the tanks are already at elevated temperatures and less heat transfer into the tank takes place. However, with a stratified tank (different temperature layers), the top of the tank is hot, but the bottom, where the heat exchanger from the solar collector enters, is cooler. The result is a much more efficient transfer of heat even without a pre-heat tank. Using these stratified tanks, both cases (with and without a pre-heat tank) were simulated in TRNSYS and the differences were insignificant. Therefore, this model does not make use of a pre-heat tank since it would cost more and require more space but provide no added benefit.

5.3.1.3 Combisystem Component Details: Modeling with TRNSYS

5.3.1.3.1 The Storage Tanks

The tanks are modeled using Type 534 *Cylindrical Storage Tank with Immersed Heat Exchangers* based on a Rheem Solaraide HE solar heat exchanger storage tank (*Solaraide^{TM} HE).* Each tank contains one coiled tube heat exchanger located in the bottom half of the tank, with the heat transfer fluid flowing in at node 3 and out at node 4. Based on the tank specifications, the heat losses from all sides of the tank are considered uniform based on an RSI-value of 3.05 $m^2 \cdot K/W$. Other properties of the storage tanks and heat exchangers are listed in Appendix B, Table B-1.

5.3.1.3.2 The Solar Collectors

Two nearly identical NZEH TRNSYS models are simulated, with the only difference being the type of solar collectors used in the models. This is done to compare two different types of solar collectors: flat plate solar collectors and evacuated tube solar collectors.

Flat Plate Solar Collectors

The flat plate solar collectors are modeled in TRNSYS with the TESS Type 1b *Quadratic Efficiency, 2nd Order Incidence Angle Modifier Solar Collector*. These are modeled based on the Stiebel Eltron SOL 25 solar collector (Stiebel Eltron 2008). Due to financial reasons described in section 6.1.2.4, the NZEH has 4 flat plate solar collectors in series on the roof, totaling a gross area of 10.936 m^2.

The ASHRAE collector test equation used in TRNSYS to define the efficiency of the collector is:

$$\eta = a - b \cdot (T_{in} - T_{amb}) / G - c \cdot (T_{in} - T_{amb})^2 / G \qquad (5.1)$$

where, for this flat plate solar collector,

a, b and c coefficient values are in Table 5.7;

T_{in} = Temperature of fluid entering the collector, °C;

T_{amb} = Ambient Temperature, °C; and

G = Solar radiation striking collector, W/m^2.

Additionally, to account for the fact that the test equation is developed based on a radiation incidence angle normal (90°) to the surface of the collector, there is also an Incidence Angle Modifier (IAM) equation, given by:

$$K_{\alpha\tau} = 1 - d \cdot S - e \cdot S^2;\ and \tag{5.2}$$

$$S = \frac{1}{\cos\theta} - 1,\ 0 \le \theta \le 60 \tag{5.3}$$

where for this flat plate solar collector,

d and e are in Table 5.7; and

θ = the angle of incidence of the radiation striking the collector, degrees.

Test results are from the Solar Rating and Certification Corporation (2008).

Table 5.7: Properties for the Flat Plate and Evacuated Tube Solar Collectors

Solar Collector Property	Flat Plate	Evacuated Tube	Source
a (from the collector test equation)	0.649	0.58	1, 2
b (from the collector test equation)	3.1374 W/m^2·C	1.21 W/m^2·C	1, 2
c (from the collector test equation)	0.0148 W/m^2·C^2	0.0024 W/m^2·C^2	1, 2
d (from the IAM equation)	0.2824	-	1
e (from the IAM equation)	0.0111	-	1
Gross Area per collector	2.734 m^2	2.852 m^2	1, 2
Aperture Area per collector	2.595 m^3	2.150 m^2	1, 2
Fluid Specific Heat*	3.370 kJ/kg.K	3.370 kJ/kg.K	3
Fluid Flow Rate	100 kg/h	100 kg/h	
Collector Slope	45°	45°	
Collector azimuth	0° (south facing)	0° (south facing)	

* 40/60 water/glycol solution. Value taken at about 60 °C average.

1 - Solar Rating and Certification Corporation 2008.

2 - Solartechnik Prüfung Forschung 2008.

3 - The Engineering ToolBox 2005c.

Evacuated Tube Solar Collectors

The evacuated tube solar collectors are modeled in TRNSYS with the TESS Type 71 *Evacuated Tube Solar Collector*. These are modeled based on the Thermomax Solamax 20 – TDS

300 evacuated tube solar collector (Thermomax, n.d.). Due to financial reasons described in section 6.1.2.4, the NZEH has 3 collectors in series on the roof, totaling a gross area of 8.556 m^2.

The efficiency of this collector also uses equation 5.1 but with different coefficients, which are listed in Table 5.7.

Test results are from SPF (Solartechnik Prüfung Forschung 2008). The collector fluid flow rate is a constant 100 kg/h for both types of solar collectors and thus the fluid temperature leaving the collectors is variable.

The Incidence Angle Modifier (IAM) for the evacuated tube solar collector does not use the same equation as the flat plate collector. Type 71, the evacuated tube collector, uses an external file containing IAM data which comes from the specification sheets of tested solar collector, done by Solartechnik Prüfung Forschung (2008) and shown in Figure 5.10. When solar radiation strikes the tubes at an angle other than normal (90°), a correction needs to be performed on the amount that is absorbed. IAM information is needed due to this changing incidence angle and the asymmetry of the longitudinal and transverse sections of the tubes in these collectors (Solar Energy Laboratory 2006, p. 5-342).

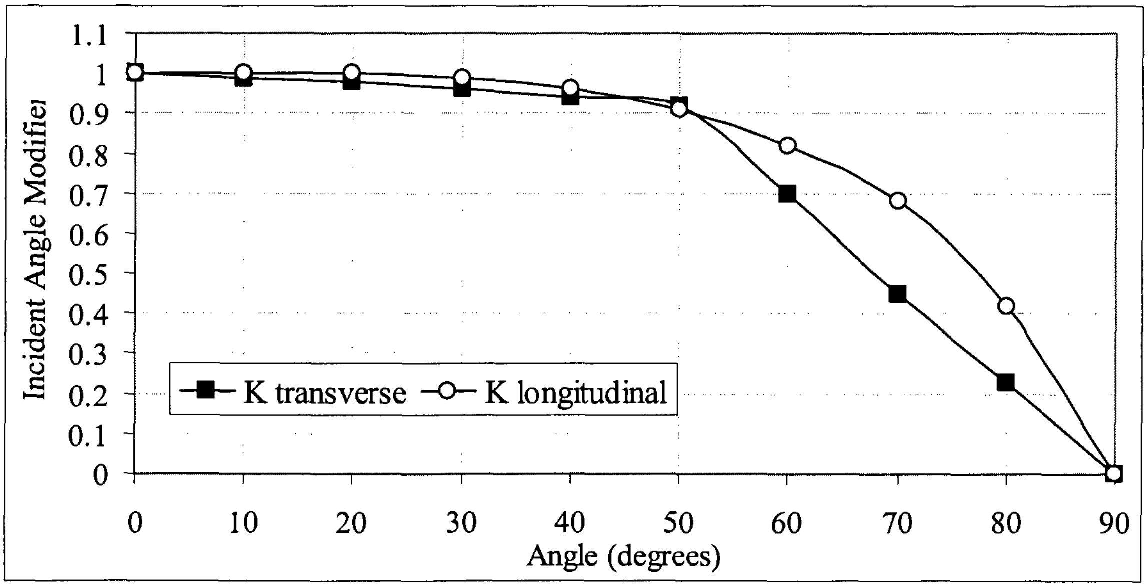


Figure 5.10: The Incident Angle Modifier values for the evacuated tube solar collector

Verification with results from RETScreen

RETScreen is a "Clean Energy Project Analysis Software" developed by Natural Resources Canada. RETScreen helps users estimate the appropriate sizing of solar collector systems in addition to many other clean energy technologies. RETScreen is less detailed compared to TRNSYS and is not a simulation tool, however it is nevertheless a valuable tool to get a good overall idea when designing such a system. Therefore, a comparison was performed to verify if the results from TRNSYS are in the same range as those from RETScreen.

One main reason why results will differ between TRNSYS and RETScreen is because they use different weather (and thus radiation) data. The radiation data used in this TRNSYS model comes from Meteonorm data for Montreal, QC, Canada and is supplied in TMY2 (Typical Meteorological Year) format so it can be easily read using standard TRNSYS weather data readers. This file is supplied with the TRNSYS software. The Meteonorm data provides hourly radiation values for the simulation. Although the Meteonorm data used to run the simulation in TRNSYS does come from hourly values, this hourly data is actually generated from monthly values using a stochastic model. The monthly data is first converted to daily data and then into hourly data which is used in TRNSYS (Meteotest 2007). If the simulation time step in TRNSYS is less than 1 hour, as is the case in much of this thesis where it is 10 minutes, then TRNSYS does another conversion to estimate the value for the given time step increment.

RETScreen, on the other hand, uses monthly average ground based measurements from the RETScreen International Online Weather Database (Natural Resources Canada – CETC Varennes 2005, p. INTRO.42). The differences between the TRNSYS and RETScreen data sets for incident radiation are shown in Table 5.8, Table 5.9 and Table 5.10 for the horizontal, vertical and 45° surface inclinations respectively. These tables show annual differences in incident radiation between TRNSYS and RETScreen of 6.1%, 28.8% and 13.6% for the horizontal, vertical and 45° inclinations respectively.

Table 5.8: Comparison of horizontal incident radiation data from TRNSYS and RETScreen

	Monthly solar radiation - Horizontal kWh/m²/month		**% Difference**
Month	**TRNSYS**	**RETScreen**	**TRNSYS vs RETScreen**
January	49.0	47.4	3.3%
February	72.5	66.9	7.7%
March	119.4	110.4	7.6%
April	137.4	129.3	5.9%
May	176.2	159.3	9.6%
June	186.3	171.6	7.9%
July	186.7	180.1	3.5%
August	150.9	148.2	1.8%
September	120.8	112.5	6.9%
October	78.7	71.6	9.0%
November	36.7	38.4	-4.6%
December	36.4	32.9	9.7%
Annual	**1351.0**	**1268.6**	**6.1%**

Table 5.9: Comparison of vertical incident radiation data from TRNSYS and RETScreen

	Monthly solar radiation - Vertical kWh/m²/month		**% Difference**
Month	**TRNSYS**	**RETScreen**	**TRNSYS vs RETScreen**
January	108.7	100.1	7.9%
February	133.7	112.2	16.1%
March	161.9	121.2	25.1%
April	132.2	86.9	34.3%
May	139.8	84.0	39.9%
June	137.0	80.7	41.1%
July	143.9	87.7	39.1%
August	133.7	89.5	33.1%
September	141.8	93.4	34.1%
October	116.8	83.8	28.2%
November	60.7	56.5	6.9%
December	80.7	66.2	18.0%
Annual	**1490.9**	**1062.1**	**28.8%**

Table 5.10: Comparison of 45° incident radiation data from TRNSYS and RETScreen

	Monthly solar radiation - 45° kWh/m²/month		**% Difference**
Month	**TRNSYS**	**RETScreen**	**TRNSYS vs RETScreen**
January	99.9	93.3	6.6%
February	129.3	111.5	13.8%
March	172.8	144.3	16.5%
April	157.6	134.9	14.4%
May	178.9	147.8	17.4%
June	179.7	151.1	15.9%
July	184.6	162.4	12.0%
August	162.1	147.0	9.3%
September	158.0	130.7	17.3%
October	119.1	100.0	16.0%
November	58.2	61.1	-4.9%
December	73.4	61.6	16.1%
Annual	**1673.6**	**1445.5**	**13.6%**

Another reason for the differences between the results for the energy delivered by the solar hot water system from TRNSYS and RETScreen is due to the different methods used to achieve these results. RETScreen uses the f-Chart method by Duffie and Beckman. Using monthly values of incident solar radiation, ambient temperature and loads, this method allows for the calculation of the monthly amount of energy delivered by hot water systems with storage (Natural Resources Canada – CETC Varennes 2005, p. SWH.29). In addition, the RETScreen model uses a linear version of the collector test equations which calculates the thermal efficiency of the collector. On the other hand, in TRNSYS, while Type 1 and Type 71 (the flat plate and evacuated tube solar collectors) do also use equations from Duffie and Beckman, it is not the f-Chart method. Rather, the internal calculations in TRNSYS use the more detailed, hourly data, such as the weather data described before and can even manipulate this and other data with equations and interpolations to match even smaller user-defined time steps (10 minutes in this model). In addition, TRNSYS uses the quadratic version of the collector test equations rather than the linear version. Combining this with the previously mentioned fact that TRNSYS uses weather data with more accurate time steps, the result is a much more detailed and responsive system (Solar Energy Laboratory 2006, pp. 5-329 to 5-334).

Table 5.11 compares the results of the Solar Fraction from RETScreen and TRNSYS tested for several solar collector areas. The RETScreen model is as similar as possible to the set-up in the TRNSYS model, but there are of course some small differences and less detail in the RETScreen model due to the differences between these tools. This comparison is done for the Thermomax evacuated tube solar collectors dedicated solely for heating the DHW and not the radiant floors since RETScreen does not model combisystems or radiant floor systems. The model tested is the NZEH design without any of the DHW energy saving devices installed, thus it has full flow faucets, no drain water heat recovery (DWHR) and no thermostatic mixing valve (TMV). Although the comparison is not also shown for the flat plate collector, the conclusions regarding the validity of the TRNSYS model from this comparison would the same since the flat plate and evacuated tube NZEH models are identical, aside from a few coefficients that differentiate the two types of solar collectors.

Table 5.11: The Solar Fraction for DHW; RETScreen vs. TRNSYS (Evacuated Tube)

Solar Collector Quantity and Gross Area (m^2)	**Software Tool**	**Total Energy Demand (kWh)**	**Solar Energy Used (kWh) 56/85**	**Solar Fraction (%)**
2 collectors 5.704 m^2	RETScreen	4400	2900	66%
	TRNSYS	5234	4203	80%/
3 collectors 8.556 m^2	RETScreen	4400	3600	81%
	TRNSYS	5859	5278	90%
4 collectors 11.408 m^2	RETScreen	4400	3900	88%
	TRNSYS	6205	5820	93%

The Solar Fraction, as defined by Duffie & Beckman (2006, p. 447) is the solar energy captured and used for heating the domestic hot water (Solar Energy Used) divided by the total energy required to heat water from the city aqueduct to the desired DHW temperature (Total Energy Demand).

$$f = \frac{L - L_A}{L} = \frac{L_S}{L} \tag{5.4}$$

where,

L = Total Energy Demand, kWh;

L_A = Auxiliary Energy Demand (from the heating element in the tank), kWh; and

L_S = Solar Energy Used, kWh.

In Table 5.11, the *Total Energy Demand* for TRNSYS is the net energy removed from the storage tank due to fluid exiting through the outlet and entering the storage tank through the inlet from the city aqueduct. The *Solar Energy Used* is calculated as in equation 5.4; $L_S = L - L_A$. Table 5.11 shows results that are different between RETScreen and TRNSYS, but close enough to show that the model functions properly since differences are expected due to the reasons described above.

The differences in the solar fractions from the two tools can be attributed to a very important difference in the calculations in addition to those presented before. With RETScreen, the Total Energy Demand is calculated based on the assumption that the DHW tank is heated to a constant temperature of 56°C. On the other hand, with the TRNSYS simulation, although the auxiliary heater will not heat above 56°C either, the tank does allow solar energy to heat the water up to 85°C, the limit specified by the tank manufacturer. This results in significantly more energy being stored and eventually extracted from the tank which is evident in Table 5.11.

5.3.1.4 Radiant Floor Construction: Modeling with TRNSYS

Since the heating system for the NZEH uses hydronic radiant floors, it is essentially a system of pipes that contain warm flowing water, embedded in the floors of all the heated zones. The 15 mm ID schedule 40 cross-linked polyethylene (PEX) piping is embedded in a concrete layer since concrete is an excellent thermal mass which allows for a slower and more even heat release. The floors are modified versions of the original Base Case floors and are described in Table 5.12.

Table 5.12: The Modified Floors in the NZEH

Wall Type (TRNBuild Name)	Layer	Thickness (mm)	Total U-Value (W/m^2·K)	RSI Value (m^2·K/W)	QC Bldg Code (RSI)
BSMNT_FLOOR		286	0.526	1.901	0.350
(Note 1)	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	13			
Note 2	CONCRETE with Radiant Floor Pipes	75			
	XPS_INSULATION	60			
	GRAVEL	125			
GRNDFLOOR_E		273	0.251	3.984	4.700
	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	16			
Note 2	CONCRETE with Radiant Floor Pipes	75			
Note 3	NZEH_WOOL&WOOD	140			
	PLYWOOD_SHEATHING	16			
	GYPSUM	13			
GRNDFLOOR_W		273	0.570	1.754	n/a
	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	16			
Note 2	CONCRETE with Radiant Floor Pipes	75			
Note 3	NZEH_WOOL&WOOD	40			
	PLYWOOD_SHEATHING	16			
	AIRSPACE_HORIZONTAL	100			
	GYPSUM	13			
TOP_FLOOR		273	0.570	1.754	n/a
	HARDWOOD_MAPLE	13			
	PLYWOOD_SHEATHING	16			
Note 2	CONCRETE with Radiant Floor Pipes	75			
Note 3	NZEH_WOOL&WOOD	40			
	PLYWOOD_SHEATHING	16			
	AIRSPACE_HORIZONTAL	100			
	GYPSUM	13			

Note 1: There is no stated requirement for basement floor RSI values in the Quebec regulation respecting energy conservation in new buildings. The comparative value of 0.35 RSI is from the Gusdorf (2005) building data.

Note 2: This layer is defined in Type 56 as radiant floor PEX tubing with 1.5 cm of reinforced concrete below and 6 cm of concrete above.

Note 3: The actual construction should be plywood sheathing above the Wool & Wood (mineral wool insulation with wood joists), but Type 56 in TRNBuild forces the user to have a layer of insulation directly below the concrete if the thickness of the concrete below the PEX tubing is less than 6 cm.

In Type 56 (The house model), these radiant floors are simulated using “Active Layers”. The water filled PEX piping that snakes its way through the concrete floor is spaced 0.2 m center to center between each run. The conductivity of the piping is 0.0356 W/m·K.

5.3.2 Photovoltaic Modules

By far, the most common electricity producing technology used in NZEHs is photovoltaics (PV). This evolving technology is quickly becoming more efficient and less costly and will most surely be a key component in most NZEHs. The PV array, usually located on the roof, will supply all of the electricity needed in the house. If on a particular day, more power is produced than is required, the surplus will be sold to the grid to offset days when not enough power is produced.

5.3.2.1 Photovoltaic Selection Process

When selecting the type of photovoltaic technology for a house it is important to consider the efficiency of the modules as well as the embodied energy and cost.

The most widely available solar cell technology applicable to residential power generation uses silicon as the light absorbing semiconductor material. This is divided among monocrystalline silicon, polycrystalline silicon and amorphous silicon. In terms of cost, which is covered in more detail in section 6.1.2.3, mono and polycrystalline modules are not very different and thin film amorphous modules tend to be a bit less expensive. As discussed in more detail in section 6.3.2.4, in general, monocrystalline modules have slightly more embodied energy than polycrystalline modules. Thin film PV modules, which often use amorphous silicon, have far less embodied energy (Hammond & Jones 2006), however they are also far less efficient than the other two types of modules. Typical amorphous silicon modules have efficiencies around 5% to 8% whereas monocrystalline and polycrystalline modules are usually between 11% and 16% with monocrystalline usually being slightly more efficient. The trend appears to be that the more efficient the module, the more embodied energy it contains. The other disadvantage of amorphous silicon is that it tends to experience 10-35% power output degradation over time (Solarbuzz

2007). Efficiency is very important for residential solar applications because there is limited roof area on which the modules need to be placed. With more efficient modules, more electricity can be produced per square meter. Since the NZEH needs to produce almost 11,500 kWh/yr of electricity, which is a significant amount of electricity, efficiency is one of the most important properties to consider for the modules.

Using Natural Resources Canada's RETScreen 4.0, a clean energy project analysis software, different types of solar modules were tested to see how much area is needed to produce 11,500 kWh/yr. All three silicon types were evaluated based on real manufacturer data in the RETScreen product database. This showed that thin film modules are not an option because even the higher efficiency modules (> 6%) that were tested required at least 127 m^2 of area. The entire south facing roof area of the NZEH is less than 69 m^2 and parts of it are required for the solar collectors as well. Further testing with RETScreen led to the selection of the Sanyo HIP-200BA3 modules. These are some of the highest efficiency modules on the market, at 17%, and are made mostly of monocrystalline silicon surrounded by thin film amorphous silicon to provide extra power output. In addition, since an effort is being made to choose eco-friendly products, Sanyo was also selected since based on sustainability initiatives outlined on their website, they appear to be a company making a respectable effort to be environmentally responsible. Using RETScreen, it is estimated that the NZEH requires 47 m^2 (40 units) of these Sanyo solar modules to produce 11,480 kWh/yr.

5.3.2.2 Modeling Photovoltaic Modules in TRNSYS

Crystalline silicon photovoltaic modules are modeled in TRNSYS with Type 94a. The PV system is critical to make this house model an actual Net Zero Energy House. This is because the PVs generate all of the remaining electricity needs in the house after improving the envelope, adding energy efficient equipment and installing solar collectors for a combisystem. Each Sanyo HIP-200BA3 is rated at 200 watts and has an area of 1.18 m^2. Other important parameters used in Type 94a are detailed in Appendix B, Table B-3.

In order to validate the PV electricity generation results from TRNSYS, they were compared to a similar system in RETScreen.

Table 5.13: Estimated PV Energy Production – TRNSYS vs. RETScreen

Array Slope	Azimuth	Annual Energy Production (kWh) 40 Sanyo (HIP-200BA3) PV modules		TRNSYS vs. RETScreen
		TRNSYS	RETScreen	Difference
0	0	9827	10,100	-2.8%
45	0	12570	11480	8.7%
90	0	10786	8,680	19.5%

The 8.7% difference between the results from RETScreen and the TRNSYS simulation at a 45° inclination (which is the angle on the NZEH) is acceptable. Some of the reasons for these differences are explained in section 5.3.1.3.2 where the solar collector results from TRNSYS are compared to RETScreen.

5.4 SIMULATION RESULTS FROM THE NZEH

All of the changes to the house design presented in the previous sections are intended to make the operation of the house more energy efficient. The impact of those changes is presented here and in the following chapters.

As explained in the beginning of this chapter, improvements in the NZEH model can be divided into three main categories: 1) Changes in the house envelope, 2) Energy efficient equipment and 3) Renewable (solar) energy technologies. Some of the results presented below are for the NZEH with no solar collectors. This refers to the design of the house that includes all of the envelope improvements and energy efficient technologies in the NZEH but lacks the solar collectors and PV panels. So although it is referred to at the NZEH (with no solar collectors), it is not yet actually "net-zero". The next step that is also presented in the following results is the NZEH containing the roof mounted solar collectors. This is one step closer to "net-zero", but still lacks the PVs which make it a true net-zero energy house. Results from the true net-zero energy house with the PVs installed are not shown in this section since the only difference is that the correct number of PV modules installed reduces all of the remaining electric grid loads to zero. Most of the results below that refer to the NZEH with solar collectors are presented with four flat plate solar collectors. Although simulations were done for a range of solar collector quantities for both flat plate and evacuated tube technologies, the aforementioned selection is based on the financial analysis presented in chapter 6 which shows how this quantity is the most cost effective choice for this NZEH.

5.4.1 Comparison with the IEA Task 26 Combisystem results

As previously discussed in sections 2.1.1.3 and 5.3.1, Task 26 of the International Energy Agency (IEA) simulated twenty one different combisystems and provided detailed results for nine of them. In order to compare these systems with each other and with other systems not part of Task 26, the IEA developed the Fractional Solar Consumption (FSC) method to help normalize external parameters (e.g. climate, collector size and load). This is described by Letz (2002) as:

$$FSC = \frac{Q_{solar,useable}}{E_{ref}} \tag{5.5}$$

where:

E_{ref} = Yearly reference consumption, kWh; this is the total energy consumption of the combisystem (DHW and radiant floor heating) in the case with no solar collectors; and

$Q_{solar,useable}$ = Useable solar energy, kWh; this is calculated monthly and summed up for the year. Each month, it is either E_{ref} or the area of the collector (m^2) multiplied by the solar radiation incident on the collector plane (kWh/m^2), whichever is smaller. Figure 5.11 graphically shows how to determine the monthly values for $Q_{solar,useable}$ (always the smaller value).

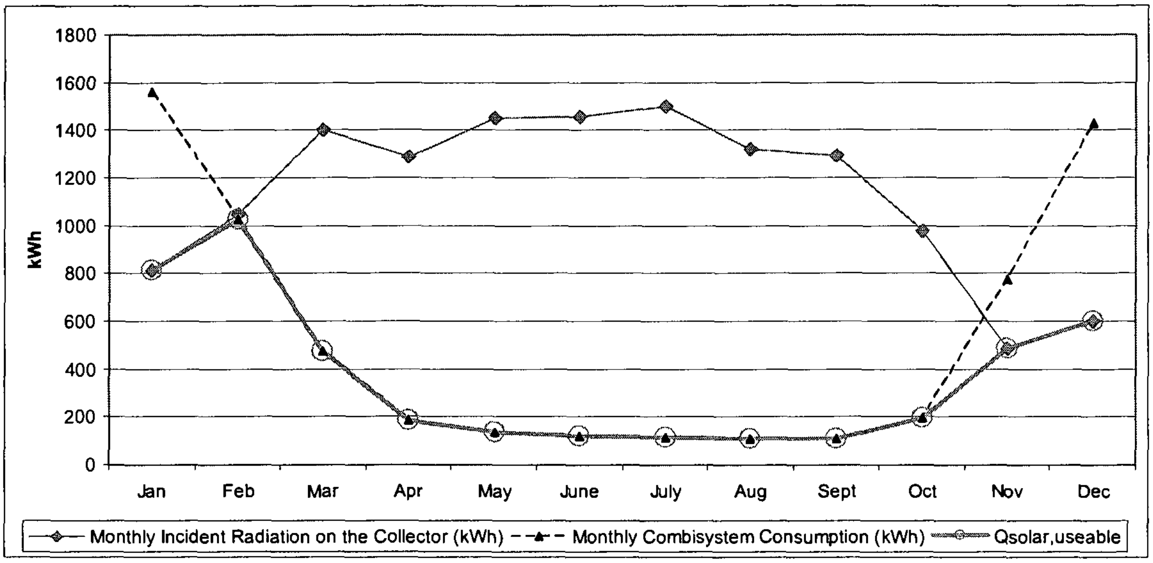


Figure 5.11: Determining $Q_{solar,useable}$

The next step is to determine the fractional thermal energy savings ($F_{sav,\ therm}$) of the collector, and that is plotted against FSC for comparison between solar combisystems. $F_{sav,\ therm}$ is the fraction of saved fuel (or electricity) compared to a reference system that does not use solar energy. (In the context of Task 26, this term contains the word "thermal" energy since the auxiliary heating is supplied by boilers. In this thesis, it refers to the electrical auxiliary energy supplied).

$$F_{sav,therm} = 1 - \frac{E_{aux}}{E_{ref}} \tag{5.6}$$

where in this model,

E_{aux} = the annual electrical energy used by the combisystem, kWh; this is the sum of the electricity consumptions of the auxiliary heating elements in the DHW tank and the radiant floor tank.

Taking the combisystem in this thesis with the case of three Stiebel Eltron SOL25 flat plate solar collectors, the FSC and $F_{sav,\ therm}$ are calculated:

$$FSC = \frac{Q_{solar,useable}}{E_{ref}} = \frac{4364kWh}{6222kWh} = 0.7$$

$$F_{sav,therm} = 1 - \frac{E_{aux}}{E_{ref}} = 1 - \frac{4033kWh}{6222kWh} = 0.35$$

Table 5.14 shows FSC and $F_{sav,therm}$ values for the same solar collector as above, installed on the NZEH for different numbers solar collectors.

Table 5.14: FSC and $F_{sav,therm}$ for the combisystem in the NZEH using the Stiebel Eltron SOL25 flat plate collector

# of Collectors	Aperture Area (m^2)	$Q_{solar,useable}$ (kWh/yr)	E_{ref} (kWh/yr)	FSC	E_{aux} (kWh/yr)	$F_{sav,therm}$
1	2.69	2413	6222	**0.39**	5114	**0.18**
2	5.38	3404	6222	**0.55**	4503	**0.28**
3	8.07	4364	6222	**0.70**	4033	**0.35**
4	10.76	4997	6222	**0.80**	3671	**0.41**
5	13.46	5596	6222	**0.90**	3460	**0.44**

These results cannot be directly compared to any specific IEA task 26 combisystem to see if they match since the combisystem set-up in the NZEH is not the same as any of those plotted below (each line is a different variation of a combisystem modeled in Task 26). None of those systems contain two distinct storage tanks as is the case in the NZEH modeled in this thesis. System #14 of Task 26 was the closest match to the set-up in this thesis since it does contain two distinct storage tanks connected to solar collectors, however no simulation results are available for system #14. Although no direct comparison can be made, the nature of the FSC method allows for general comparisons between different systems, climates and the homes they are in. Therefore, as seen in Figure 5.12, the results from the combisystem set-up in this thesis, shown by the large circles, are comparable to the results obtained from the many systems simulated in Task 26 of the IEA.

5.4.2 Reduced Energy Use in the Net Zero Energy House

Figure 5.13 shows the impact on the annual electricity use when comparing the Base Case House (BCH) to the NZEH with no active solar technologies and then to the NZEH with four flat plate solar collectors. Overall, starting with the 25,615 kWh/yr BCH, total electricity use is reduced by 45% and 56% respectively. For both cases, Figure 5.14 shows the relative impact of

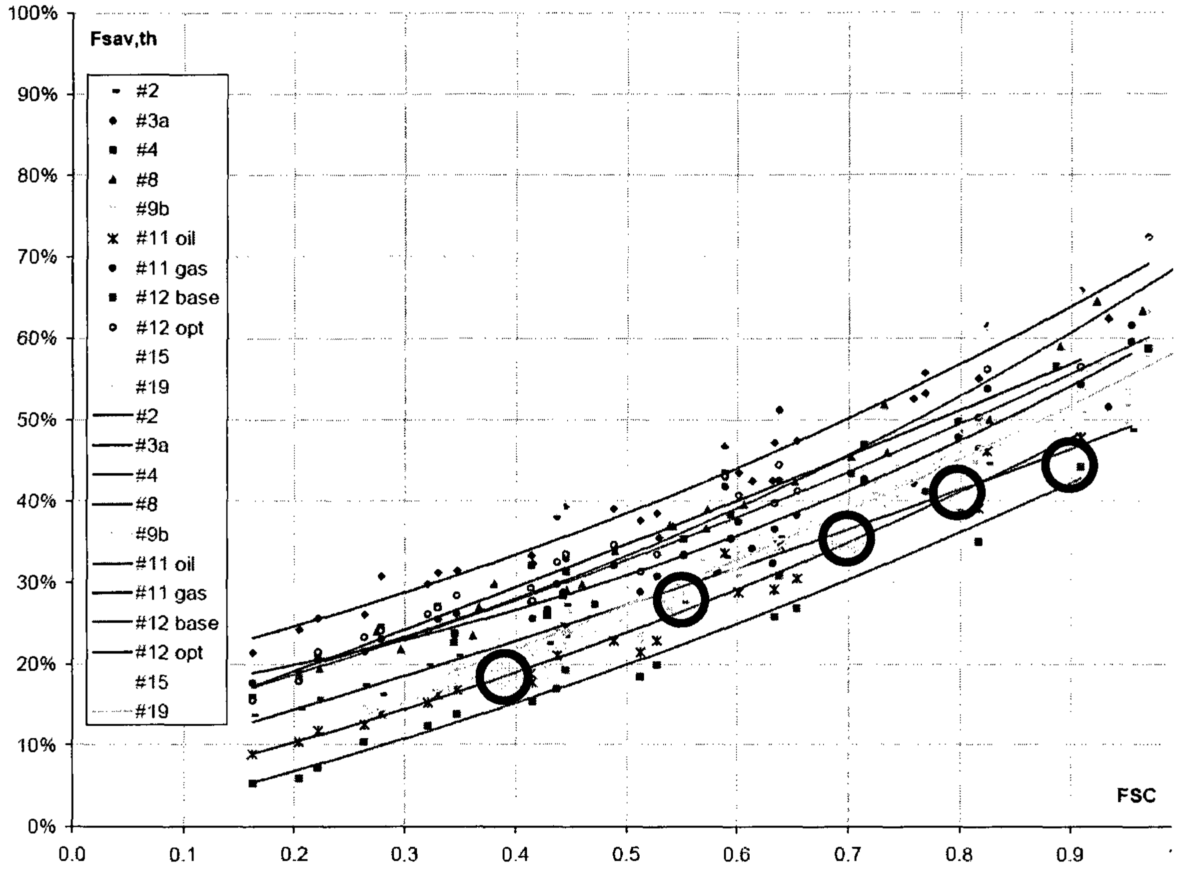


Figure 5.12: Plot of different quantities of Stiebel Eltron flat plate solar collectors used with the NZEH combisystem compared to results from IEA Task 26 (Letz 2002)

each end use on the total electricity use reduction. Looking at both of these figures, it is apparent that the most significant reductions for both NZEH cases occur with the heating loads (44% and 60% reductions in electricity for heating, accounting for 32% and 35% of their respective total house electricity reductions) and the DHW (64% and 92% reductions in electricity for DHW, accounting for 27% and 31% of their respective total house electricity reductions). However, installing energy efficient appliances and lighting also plays a very significant role in reducing electricity use since those changes together, for each model, reduces the electricity loads by 4,700 kWh/yr (51% less than in the BCH). These changes account for 41% of the total electricity reduction in the NZEH without solar collectors and 32% of the total electricity reduction for the NZEH with four flat plate solar collectors.

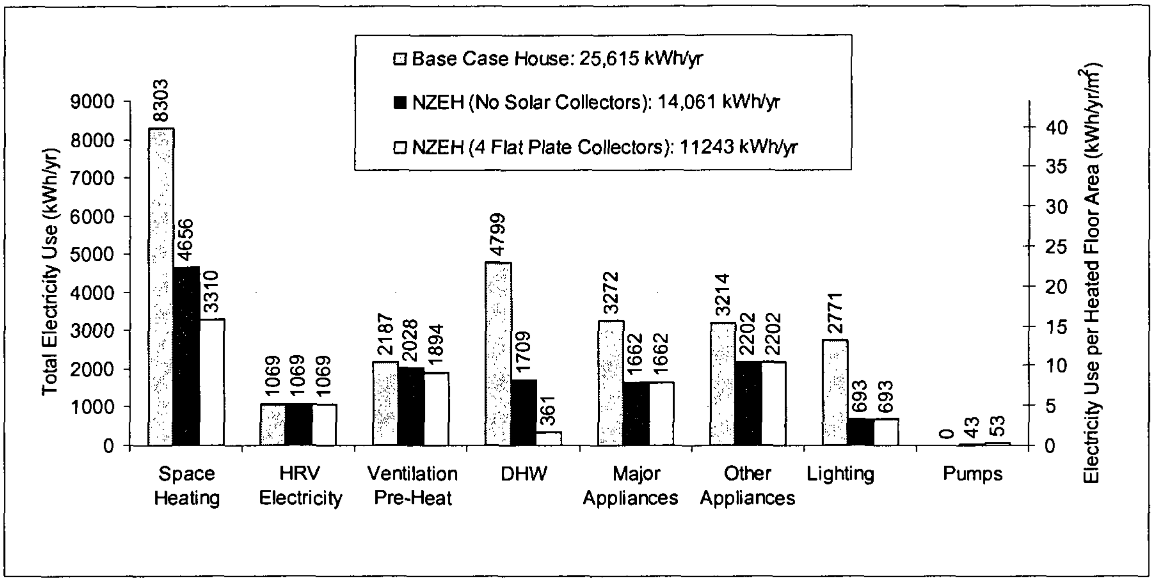


Figure 5.13: BCH vs. NZEH annual end use electricity consumption

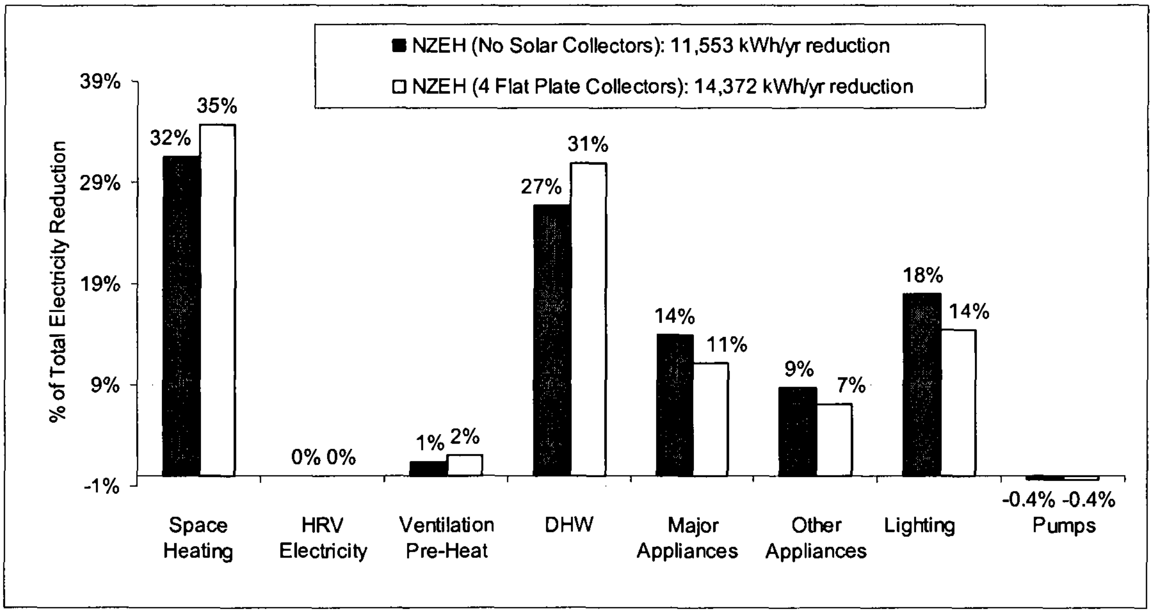


Figure 5.14: End use contribution to the electricity use reduction compared with the BCH

The HRV is the same unit for all three models so the electricity required to run the fan remains unchanged. Since the HRV unit must still heat the incoming cold air to a specified temperature with an electric heating element (after it is pre-heated from the outgoing warm air), that electricity use, labeled 'Ventilation Pre-Heat' in the figure, is also similar for all three cases. The differences can be attributed to the different heating systems in the BCH and the NZEH that result in slightly different zone air temperatures. Finally, the pumps are used for the combisystem and the radiant floors which are not part of the BCH, so in the NZEH model this end use is a small addition to the electricity loads.

Figure 5.15 shows the electricity use for heating and ventilation broken down by month as well as the cumulative electricity use for the year for the BCH, the NZEH with no active solar technologies and the NZEH with four flat plate collectors. Although the heating system is off between May 1st and Oct 17th, the air ventilation system still requires electricity to function. The trends regarding the electricity use reduction discussed with respect to Figure 5.13 are also apparent in this figure. Figure 5.16 is a similar monthly breakdown of electricity use but for the DHW. One new and interesting thing to note from this figure is the fact that for the NZEH with the solar collectors, the DHW requires no electricity during the entire time that the space heating is turned off, from May 1st to Oct 17th. During this time, the solar collectors are dedicated solely to the DHW and are thus capable of providing more than enough energy to heat the water.

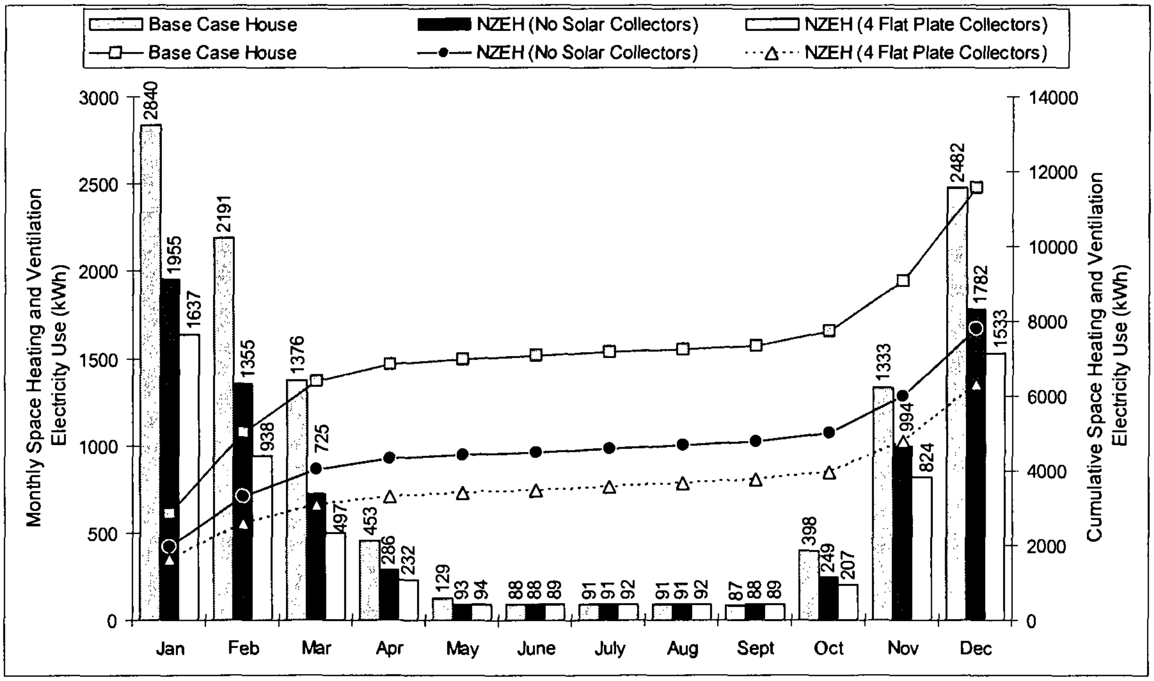


Figure 5.15: BCH vs. NZEH monthly space heating and ventilation electricity consumption

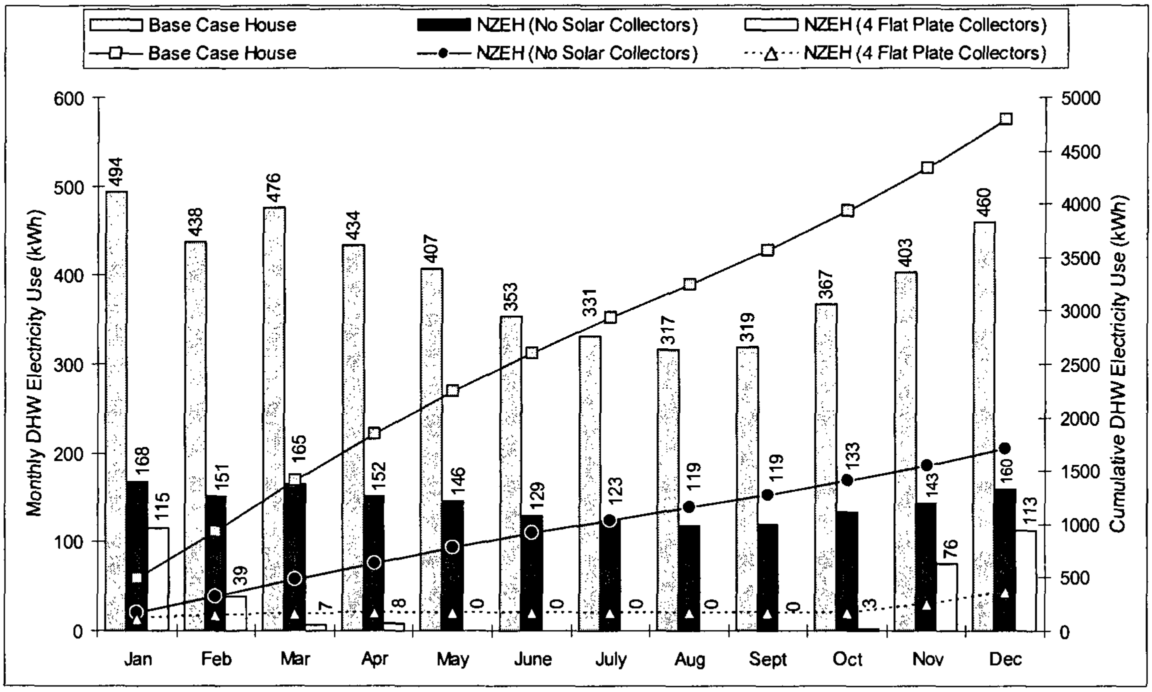


Figure 5.16: BCH vs. NZEH monthly DHW electricity consumption

5.4.3 The Impacts of Solar Collector Type and Quantity on Efficiencies

By simulating the same model with both flat plate and evacuated tube solar collectors (separately), these two technologies can be compared to see which one outperforms the other. It is a known fact that evacuated tube solar collectors are said to be more efficient in a cold climate (Natural Resources Canada 2006d), so the results will demonstrate to what extend that fact holds true. However, it is important to note that these simulations were done for two specific collectors, the Steibel Eltron SOL 25 flat plate solar collector and the Thermomax Solamax 20 – TDS 300 evacuated tube solar collector. Therefore although the results presented here do give a good indication of what to generally expect from these two types of solar collector technologies, the data is specific to those two products and other manufactured collectors will yield different numbers. Without doing an extensive run of simulations with a large sample of collectors by other companies, it is not appropriate to try to quantify how different those results would be. However, the two collectors chosen for this thesis are well established companies that make quality products.

5.4.3.1 Solar Collector Efficiencies

The efficiencies of the flat plate and evacuated tube solar collectors shown in Figure 5.17 are calculated with the following equation:

$$\eta_{collector} = \frac{\sum Q_{collector\_captured}}{\sum Q_{incident\_radiation}} \tag{5.7}$$

where,

$\sum Q_{collector\_captured}$ = The energy captured by the collector based on the flow rate of the glycol and the temperatures flowing in and out of the collector, summed over the entire year, (kWh/yr);

$\sum Q_{incident\_radiation}$ = The total radiation (direct + diffuse) incident on the solar collector, summed over the entire year, (kWh/yr).

Figure 5.17 shows that the evacuated tube solar collector is 11% more efficient than the flat plate solar collector with just one collector and as you add more collectors, the difference narrows to only 5% with six collectors. This is based on the amount of radiation incident on the collector aperture area, which demonstrates the efficiency of the tube technology. The evacuated tubes themselves can collect and retain more energy than the tubing in a flat plate collector. However, a homeowner is likely more interested in how much energy is collected compared to how much space the collector occupies on the roof. This can be better understood by instead using the gross area to calculate the incident solar radiation, even though parts of the gross area, like the frame or manifold, cannot capture useable energy. Since, unlike flat plate collectors, evacuated tube collectors tend to have spaces between tubes as well as large manifolds where the heat is transferred from the tubes to the flowing glycol, the efficiency calculated based on gross area is much less. In fact, the gross area efficiencies of the flat plate and evacuated tube collectors are almost equal and are about 1%-2% less than the flat plate efficiency based on the aperture area.

The energy captured by the solar collector is influenced by the ability to store the captured energy. In this model, if the radiant floor storage tank reaches 55°C and the DHW storage tank reaches 85°C, the flow through the collector is shut off and available solar energy will not be captured and stored. This certainly occurs at times during the summer since the radiant floor loop is bypassed. Therefore, theoretically, if there were unlimited hot water storage available, the efficiencies calculated here could be considerably higher. However, depending on the set-up, a large tank might then be at a much lower temperature and not be able to provide the desired water temperature to the house occupants. The efficiency of a solar collector depends very much on the system it is connected to. Finding the balance between capturing energy and being able to use it effectively to meet specific needs is one of the challenges of designing such a system.

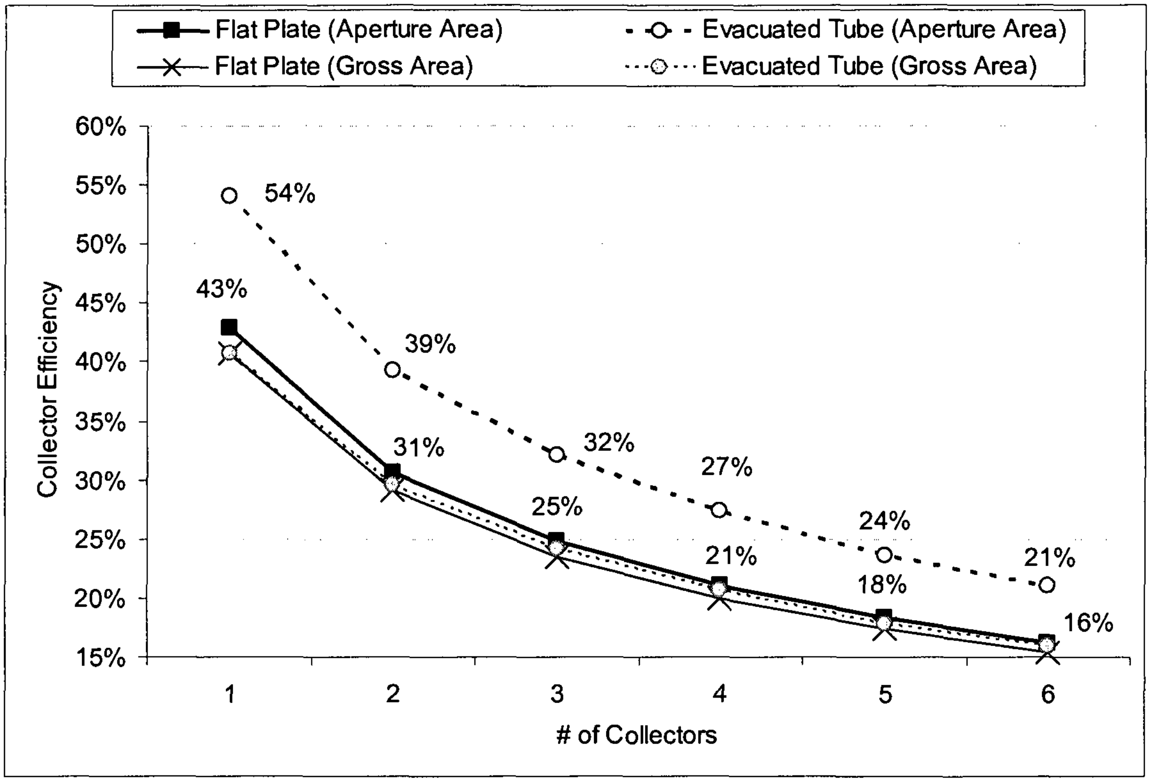


Figure 5.17: Efficiencies of the flat plate and evacuated tube solar collectors (full year)

Looking ahead to the combisystem section, comparing Figure 5.18 with Figure 5.19 gives an indication of how much more efficient the solar collector could be with an unlimited storage volume. This is because Figure 5.18 shows the efficiency of the entire combisystem (explained in section 5.4.3.2) based on a full year of operation, whereas Figure 5.19 shows the same thing but only during the heating season when the system is rarely shut off due to overheated tanks. The differences in these efficiencies are plotted in Figure 5.20. This shows that in situations with more storage and more ways to use the captured energy, the efficiency can be more than 20% better (even still with a limited storage capacity).

5.4.3.2 Combisystem Efficiency

The efficiency of the solar collectors in the previous section shows how well the collectors capture the available solar energy. Taking this one step further, the efficiency of the entire combisystem shows how well the modeled system makes use of all of the energy made available to it, from both the sun and electric sources. This result is expected to be higher since although not all of the solar energy can be used, the electric heating elements located inside the storage tanks transfer essentially 100% of the energy they produce into the water. This efficiency is calculated as all of the energy used by the two tanks divided by all of the solar and electric energy made available to the system and is shown in the following equation:

$$\eta_{combisystem} = \frac{\sum(Q_{RFT\_\sup plied} + Q_{DHW\_\sup plied})}{\sum(Q_{incident\_radiation} + Q_{combi\_electric})} \tag{5.8}$$

where,

$\sum Q_{RFT\_supplied}$ = The energy used by the radiant floor tank based on the flow rate and temperatures of the water at the inlet and outlet of the tank, summed over the desired time period, (kWh);

$\sum Q_{DHW\_supplied}$ = The energy used by the DHW tank based on the flow rate and temperatures of the water at the inlet and outlet of the tank, summed over the desired time period, (kWh);

$\sum Q_{incident\_radiation}$ = The total radiation (direct + diffuse) incident on the solar collector, summed over the desired time period, (kWh);

$\sum Q_{combi\_electtric}$ = The total electricity used by the combisystem from the electric heating elements and the pumps, summed over the desired time period, (kWh).

Theses efficiencies, calculated for both types of solar collectors and based on aperture and gross areas, are shown in Figure 5.18 and Figure 5.19 for the entire year and for only the heating season, respectively. As expected, the efficiencies of the combisystem models are greater than those of the solar collectors alone, and in the case of one flat plate solar collector by up to 27% (70% in Figure 5.18 minus 43% in Figure 5.17). Also as expected, the fewer the number of collectors, the more efficient the system is, because a larger share of the total captured solar energy can be used. However, from an electricity use reduction point of view, this is not necessarily good because more energy needs to be supplied by the 100% efficient electrical auxiliary heating element.

As discussed in the previous section, the ability of the system to store and make use of the available energy greatly affects the efficiency. Therefore it is interesting to compare the efficiency of the combisystem throughout the whole year with that of the same system only for the heating season. It is clear that during the heating season, both the RFT and DHW tanks are storing and using the energy being captured by the solar collectors, whereas during the warmer months that do not require heat, only the 300 litre DHW tank makes use of the abundance of summer solar radiation. The difference between these two cases is shown in Figure 5.20. The difference is smaller (11.7% to 14.5%) with only one solar collector since it captures less energy and thus for both types of collectors, most of it can be used even during the summer. However, as more collectors are added, the difference between the two types grows, and peaks at just under 24% for the evacuated tube solar collector based on the aperture area.

Another conclusion that can be drawn from these efficiency curves is that they demonstrate that the evacuated tube solar collector is noticeably more efficient only when it is calculated based on the aperture area. However, as discussed in the previous section, the area that is of more interest to a homeowner is the space it occupies on the roof. Looking at the efficiencies from this point of view (gross area), all of these figures show that for any number of collectors, there is a negligible difference between the flat plate and evacuated tube solar collectors (at least for those examined in this thesis).

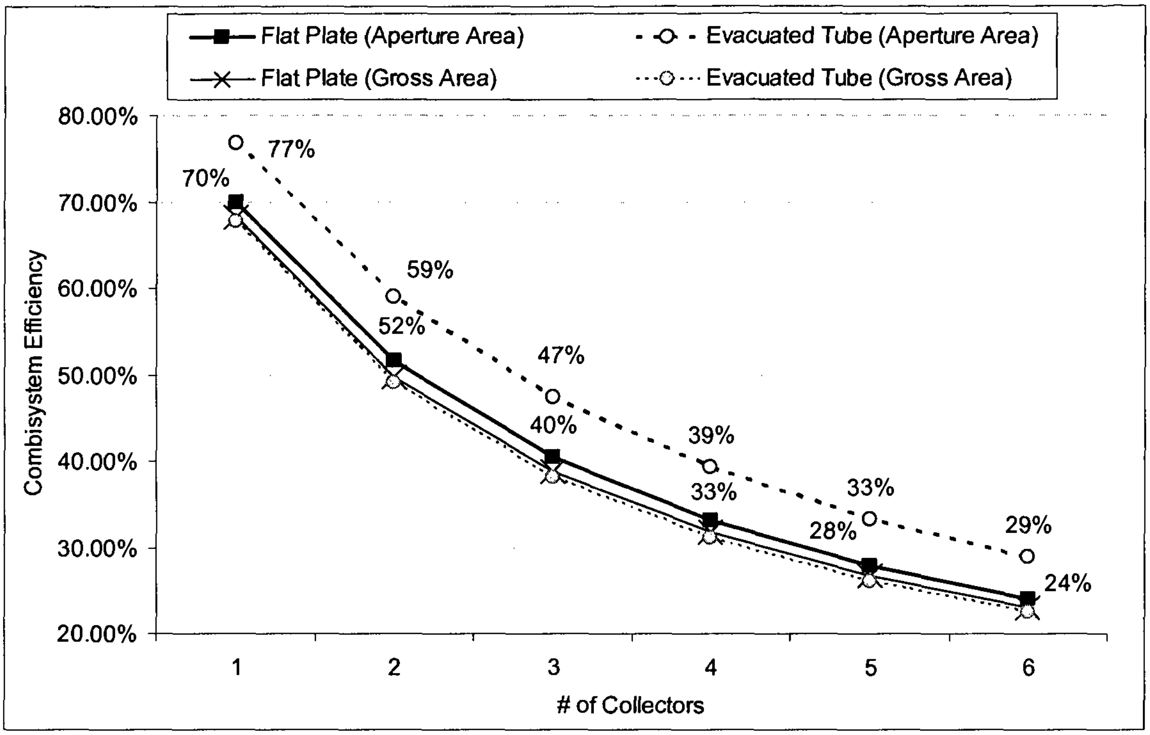


Figure 5.18:The combisystem efficiency for the entire year

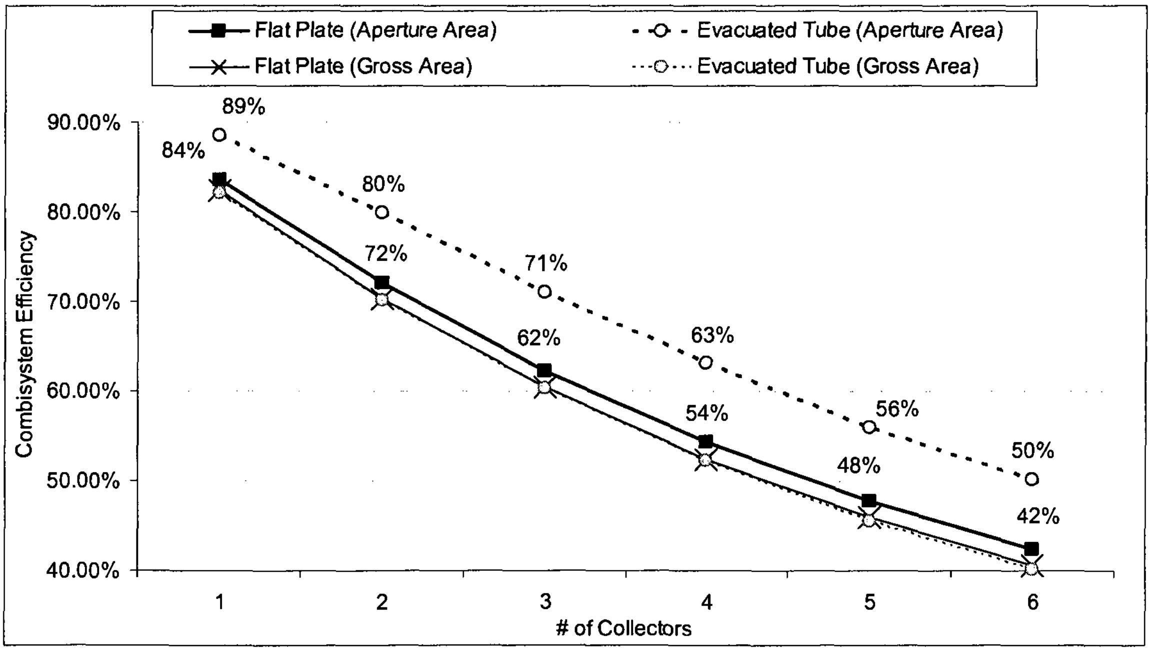


Figure 5.19: The combisystem efficiency for the heating season

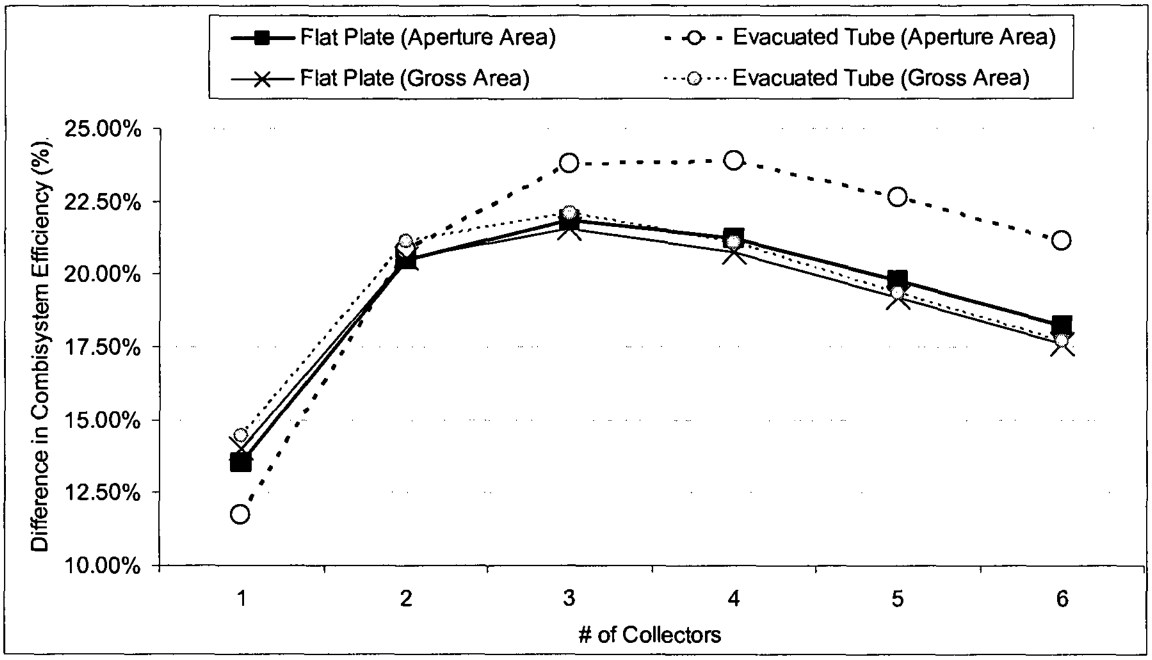


Figure 5.20: The difference between the combisystem efficiency for only the heating season compared to the efficiency for the entire year

5.4.4 The Impacts of Solar Collector Type and Quantity on Reducing Electricity Use

It is obvious that with more solar collectors there is more potential for capturing solar energy. However, it is less obvious how much more energy can be captured as you add more collectors since this is not a linear relationship. As more collectors are added to a system with a fixed demand and storage capacity, the potential for using all of the available energy decreases. This is true for two reasons: 1) Although warm fluid from a solar collector does contain energy, that energy can only be transferred to the storage tank if it is hotter than the temperature in the tank, and 2) The storage tanks have maximum temperature limits, so with a fixed tank volume, there is a limit to the amount of energy that it can store.

The bars in Figure 5.21 show how much the electricity use in the house is reduced when using different quantities as well as different types of solar collectors (flat plate or evacuated tube). To calcuate final house electricity use in each case, these reductions are subtracted from the energy loads in the NZEH without any active solar technologies which is 14,061 kWh/yr. As more solar collectors are added, less electricity is needed for heating and DHW, but the figure shows that the effect of each additional collector in reducing electricity use becomes increasingly smaller. The lines in the figure, based on the gross collector area, portray the same idea of diminishing return, but they show how much electricity is offset per square metre of installed collectors. Comparing the bars in the figure with the lines is interesting. Although the evacuated tube collectors reduce more of the electricity use compared to the same number of plat plate collectors, since the total areas they occupy are different, when plotted per m^2 of space occupied (gross collector areas), the two types of collectors are almost identical. This information, coupled with the cost and embodied energy analysis in chapter 6, helps to determine how many and of which type of solar collector is the best selection for the house.

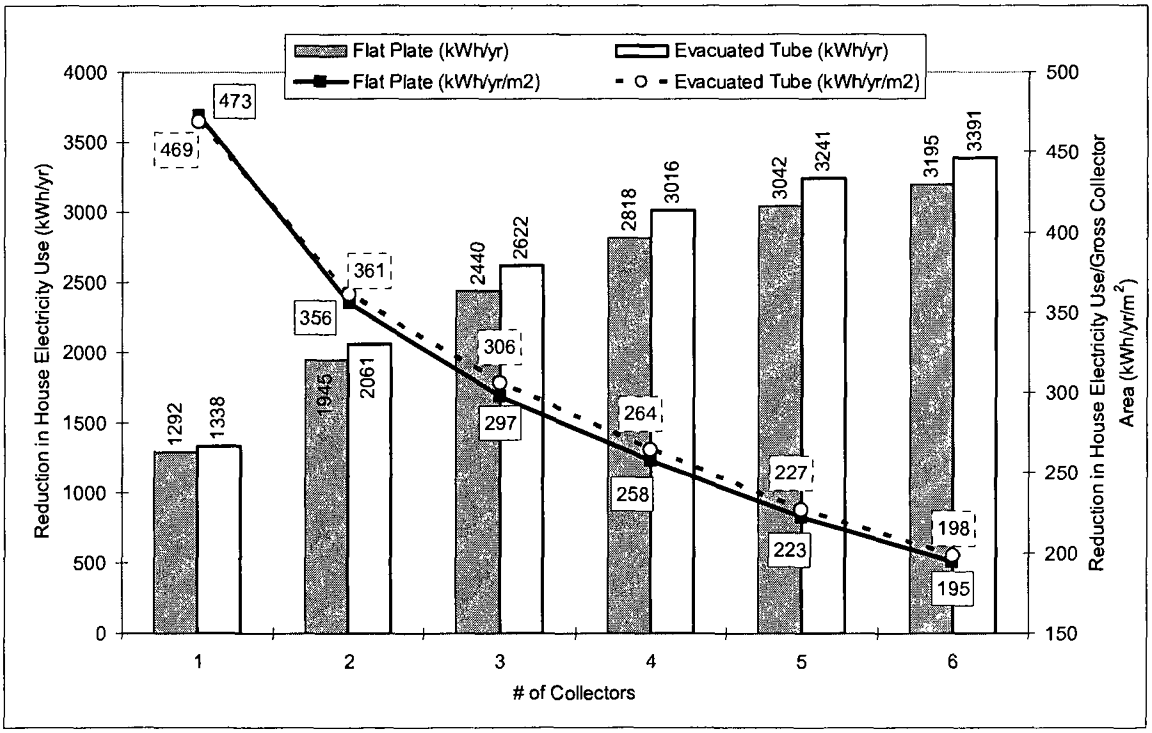


Figure 5.21: Impact of the quantity of solar collectors on the NZEH electricity use. Reductions from the NZEH without any active solar technologies (14,061 kWh/yr)

5.4.5 Achieving Net-Zero Energy Using Photovoltaics

As described in section 5.3.2.2, the NZEH uses Sanyo HIP-200BA3 photovoltaic modules. Unlike the solar collectors, understanding how these PV modules impact the reduction in electricity use in the house is straightforward since the relationship between the number of panels and the electricity they produce is linear. The TRNSYS simulation results for the Montreal climate show that each 200 watt, 1.18 m^2 PV panel produces 314.25 kWh/yr. Therefore, depending on the number of solar collectors installed, making the NZEH truly net-zero in terms of operating energy is done by simply dividing the remaining annual electricity load (kWh/yr) by 314.25 kWh/yr. This gives the number of PV panels required for the NZEH. For the case of 4 flat plate solar collectors (10.94 m^2 gross area) installed on the NZEH, the house needs 11,243 kWh/yr of electricity and thus 35.8 PV panels (42.2 m^2). This can be compared to results from Biaou & Bernier (2007) in which a 156 m^2 house in Montreal requires 6 m^2 of solar collectors and 56.1 m^2 of PV panels to provide close to 14,000 kWh of energy. These results are in the same ballpark, but differences are expected since the houses simulated are designed differently (such as no combisystem), they have different areas and the solar collectors and PV modules are different models which have different efficiencies.

Table 5.15 summarizes the various combinations of solar collectors and PV modules that result in a NZEH, that is, by the end of the year, the house converts and uses as much renewable (solar) energy as it requires to meet the its energy needs. This table, and many more in the following chapters, show the number of PV modules required to make the house exactly net-zero based on the simulation. Therefore the values are actually shown as a certain number of whole modules and a fraction of a module (e.g. 44.7 modules). Although a fraction of a module cannot be purchased, smaller modules that are equivalent to a fraction of a large, 200 watt module can be obtained. For example, 44.7 PV modules can represent forty four 200 W modules and one 140 W module. Therefore, for the purposes of comparison in this thesis, the values in the tables were not rounded up to whole numbers for the modules.

Figure 5.22 shows the progression over one year of how the PV modules produce electricity for the NZEH to offset the electricity it consumes from the grid. This is the example of the NZEH with 4 flat plate solar collectors and thus 35.8 PV modules so that the modules produce exactly as much electricity as the house uses over the course of the year.

Table 5.15: NZEH electricity use and quantity of PV modules required for various quantities of flat plate or evacuated tube solar collectors

	Flat Plate		Evacuated Tube	
No. of Solar Collectors	House Electricity use (kWh/yr)	No. of PV modules required	House Electricity Loads (kWh/yr))	No. of PV modules required
0	14061	44.7	14061	44.7
1	12769	40.6	12723	40.5
2	12116	38.6	12000	38.2
3	11621	37.0	11439	36.4
4	11243	35.8	11045	35.1
5	11019	35.1	10820	34.4
6	10866	34.6	10670	34.0

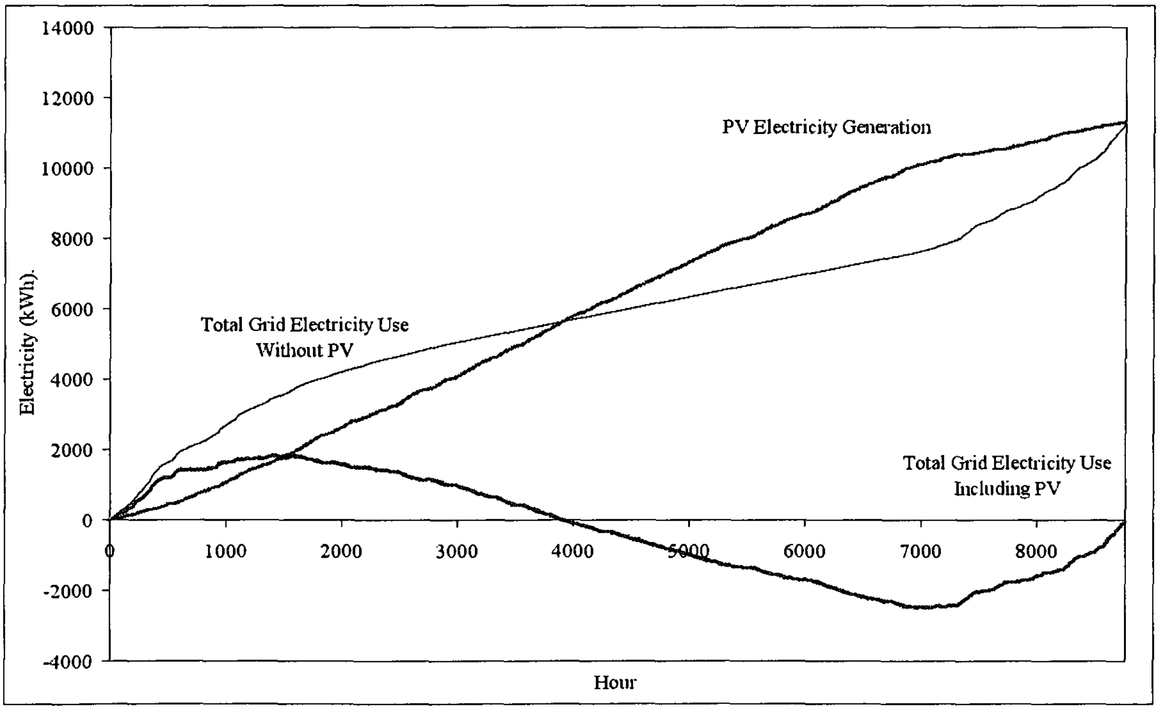


Figure 5.22: The impact of the PV system on grid electricity use in the NZEH equipped with 4 flat plate solar collectors and 35.8 PV modules

6. LIFE CYCLE ANALYSIS

The term Life Cycle Analysis (LCA) or Life Cycle Assessment can sometimes refer to different things, depending on the context. One such use is to describe the environmental impacts of a product, from cradle to grave, i.e. from resource extraction, through transportation, transformation, production, delivery, maintenance, demolition and finally recycling/reuse/disposal. In addition, the impact on the environment can be quantified in several ways, such as natural resource depletion, emissions (to air, water and land) as well as energy use which has a direct impact on the former two. Another form of LCA is Life Cycle Cost Analysis (LCCA) which evidently looks at the economics over the life of the product. In this thesis, the life cycle cost and the life cycle energy use of the Base Case House (BCH) and the Net Zero Energy House (NZEH) are analyzed and the differences between the two house models are compared.

6.1 LIFE CYCLE COST

Determining the cost of materials and systems used in a house is a challenging task. Prices can be significantly different from year to year and depend on location, manufacturers, vendors, market fluctuations, etc. In order to compile the most accurate and realistic prices for a house built in Montreal, QC, every effort was made to get up-to-date pricing from local vendors for the solar technologies. In addition, prices for the building materials and labour come from one of three sources: 1) Quotes from local contractors, 2) prices from local stores, or 3) the most recent 2008 RS Means data, corrected with a location factor for Montreal (RS Means 2008). For consistency, most of the building material prices are from RS Means, however some items were not available. For a complete list of all materials and sources, see Appendix C.

Unless otherwise stated, all costs in this thesis include the 12.875% tax in Quebec.

Evaluating the financial payback time for changes to house components or systems that affect the electricity demand can be done with several methods. The simplest method is the aptly named "simple payback" method. However, this is simply the initial cost of the item divided by the annual cost savings (from reduced electricity use) due to the change and it does not consider the time value of money, the effective interest rate or rising energy prices which can play an important role. The simple payback method is shown in this chapter along with a more realistic and sophisticated analysis method which does consider the above mentioned externalities; this will be referred to as the cumulative cash flow (CCF) method.

Cumulative Cash Flow (CCF)

Four main steps are required to calculate the cumulative cash flow (ASHRAE 2007). They are calculated for every year from n = 0 to n = ∞:

Step 1. Calculate the effective interest rate, a:

$$a = \frac{d - i}{1 + i} \tag{6.1}$$

where,

d = annual discount rate; and

i = annual inflation rate.

Step 2. Calculate the annual cost savings considering escalating energy prices, S:

$$S = E \cdot (1 + e)^{n-1} \cdot R \tag{6.2}$$

where,

E = price of electricity, $/kWh;

e = annual electricity cost escalation rate;

n = year, starting from 0; and

R = annual reduction in electricity use, kWh.

Step 3. Calculate the present worth of the annual money saved considering escalating energy prices, Spw:

$$Spw = \frac{S}{(1 + a)^n} \tag{6.3}$$

Step 4. Calculate the cumulative cash flow, CCF:

$$CCF_n = CCF_{n-1} + Spw_n + repl_n \tag{6.4}$$

where repl = the replacement costs of various system components (e.g. glycol is replaced at 3 year intervals, the pump at 10 year intervals, etc.)

The only exception to these equations, as seen in Table 6.1, is for the values of S and CCF at year 0 since n-1 is not applicable. At year 0 (the beginning of the first year, i.e. zero years have elapsed), S is always equal to zero and CCF is always equal to the initial payment for the technology or house modification being analyzed.

One way to calculate the CCF, which is calculated based on the CCF from previous years, is to tabulate the results as shown in Table 6.1 for the example of five flat plate solar collectors.

Table 6.1: Example of the cumulative cash flow (CCF) method that considers the time value of money, effective interest rates and escalating energy prices

Year	**Annual \$ saved considering escalating energy prices (\$)**	**Present Worth of Annual \$ saved considering escalating energy prices (\$)**	**CCF (Cumulative Cash Flow) (\$)**
n	**S**	**Spw**	**CCF**
	$E(1+e)^{n-1}*R$	**$S/(1+a)^n$**	**$CCF_{n-1}+Spw+repl$**
0	0	0	-12,462
1	229	225	-12,237
2	234	225	-12,012
3	239	225	-12,085
4	244	226	-11,860
5	249	226	-11,634
6	254	226	-11,707
7	259	226	-11,480
8	265	227	-11,254
9	270	227	-11,326
10	276	227	-11,978

For all of the analysis in this thesis, the tables go far beyond 10 years since the payback time is determined by seeing when, if ever, the CCF switches from a negative to a positive value. In this example, that occurs after 54 years for the analysis considering only the initial investment and not taking into account replacements costs. If replacement costs are considered, the CCF never does become positive and thus there is no financial payback time. The analysis including replacement costs is done later on in this chapter so these two cases can be visualized in Figure 6.3 and Figure 6.4 which show the CCF for various quantities of flat plate solar collectors for the initial investment method and the one that includes replacement costs.

CCF Analysis of the solar technologies: Initial Investment Only vs. the Inclusion of Replacements Costs

For the solar technologies, two sets of cost results are presented below. Firstly, the cost analysis is performed by considering only the initial costs at year zero. In this thesis, this is called the "Initial investment only" analysis. This first step in the cost analysis lends itself to calculating specific payback times for all of the technologies. However, this analysis neglects a very important factor: the expected service life of specific components. For example, a payback time of 50.5 years for a flat plate solar collector system does provide meaningful insight into the costs of, and savings achieved from, the system, but it ignores all of the additional costs associated with replacing parts such as tanks after 15 years, the solar collectors after 25 years, etc. When these additional costs are considered, the actual payback time can change significantly and sometimes shows that payback is never achieved since replacement costs can negate the electricity cost savings. Since this is a life cycle analysis, the second set of results does consider these extra and ongoing costs and is noted with the term 'including replacement costs'. For both sets of cost results, however, the basic construction as well as the energy efficient technologies do include the replacement costs, where applicable, such as with the windows and lighting. Again, the two step analysis of 'initial investment only' and then 'including replacement costs' applies only to the solar technologies. All of the other materials that make up the house that are discussed in this thesis do include 'initial + replacement' costs and are designated as such. When these initial and replacement material costs are combined with the operating costs of the house, it completes the cost analysis to become the life cycle cost.

Default Values for the CCF Analysis

Throughout the financial analysis, unless otherwise specified, the following values are used to calculate the CCF:

1) Annual inflation rate, i = 2%. This is the target rate of the Bank of Canada (2008a).

2) Annual discount rate, d = 4%. Also called the "bank rate", the average value from the Bank of Canada between 1998 and 2008 was 4.02% (2008b).

3) Cost of electricity, E = $0.0754/kWh. This is the average 2007 cost of electricity, including tax, for a home in Montreal that uses 1000 kWh/month (Hydro Quebec 2007).

4) Annual electricity cost escalation rate, e = 2.07%. This is the average rate increase between 2002 and 2007 for a home in Montreal that uses 1000 kWh/month (Hydro Quebec 2002, 2007).

6.1.1 Base Case House

6.1.1.1 Base Case House Construction

Table 6.2 shows a breakdown of the costs involved in the construction of the main structure of the Base Case House (BCH). All costs include both materials and the associated labour. These prices do not include the cost of plumbing (aside from the DHW tank), electrical wiring or any furnishings. The total 'initial + replacement' cost for these aspects of the BCH, including the 12.875% tax in Quebec is $232,943. This cost also does not include other factors such as land, excavation, property taxes and other fees that might be related to building a house. This cost, in 2008 Canadian dollars, is the 'initial + replacement' cost over a 40 year period. Therefore, as shown in the more detailed in Appendix C, Table C-1, certain materials need to be replaced during this time, such as the shingles and the windows, and these extra costs are considered. Although the cost of materials that need replacement is expected to increase in the future, for the purposes of this thesis, it is assumed that the increase in cost is equal to inflation. Therefore, when the cost is converted to 2008 dollars, it remains the same as the current cost.

Table 6.2: Total 'initial + replacement' costs (before tax) of the BCH construction

House Assembly/Component	Total 'initial + replacement'Cost ($)
Floor Assemblies	
Footing	1,911
Basement Floor	6,395
B1W Floor	7,253
B1E Floor	8,141
C1 Floor	14,709
Attic Floor	12,739
Roof	11,192
Wall Assemblies	
Basement Exterior Wall	13,596
Basement Interior Walls	1,768
Basement/Garage Interior Wall	2,453
B1 & C1 Exterior Walls	56,024
B1 & C1 Exterior Walls	7,567
Attic Side Walls	6,342
Doors	
Garage Door	2,273
Front Door	1,345
Interior Doors	7,295
Basement interior Garage Door	829
Windows	
A1 Windows	3,546
B1 Windows	16,415
C1 Windows	16,415
Heating - Baseboard Heaters	6,655
DHW - 1 regular 300L tank	1,509
TOTAL*	**206,372**
TOTAL* (incl. tax)	**232,943**

* Basic construction, not including plumbing (aside from the DHW tank), electrical wiring or furnishings.

Sources: RS Means 2008, Rona Renovateur 2008, The Home Depot 2008, Glass Experts 2008.

Detailed cost breakdown in Appendix C, Table C-1.

6.1.2 Net Zero Energy House

6.1.2.1 NZEH Construction

The NZEH design is an improved house based on the basic design of the Base Case House (BCH) which is a typical house built in 1994 in the province of Quebec. Therefore, it is interesting to compare the cost differences between these two designs, which can be evaluated in conjunction with the electricity use differences presented in section 5.4 and the embodied energy differences in section 6.3. Table 6.3 shows a breakdown of the costs of all of these differences (not including the cost of the solar collector and PV systems which are discussed later on in this chapter). Certain differences involve simply adding something new, such as a drain water heat recovery pipe, but in other cases the change in design requires a change in the construction material, such as adding more insulation which requires a different size wall stud. This is why the table shows certain materials that are removed (with the cost subtracted) and others that are added. All costs include both materials and the associated labour but not the cost of plumbing, electrical wiring or any furnishings. The difference in the 'initial + replacement' cost between the BCH and the NZEH including the 12.875% tax in Quebec is $34,287. Therefore, the total 40 year 'initial + replacement' cost of building the NZEH is $267,230. Additional details regarding the costs presented in Table 6.3 can be found in Appendix C, Table C-2.

Payback Time

Since the electricity consumption for the NZEH (without the solar technologies) is 11,554 kWh/yr less than the BCH, the financial payback time for the $34,287 worth of changes, using the CCF method, is just under 40 years. Coincidentally, this perfectly matches the 40 year life cycle of the house, so in the long run the cost of the changes from the BCH to the NZEH (without the solar technologies) do end up paying for themselves through reduced electricity costs. And in reality, after 40 years, many of the replaced components still have some life in them, so after that, the homeowner actually begins to save money compared to the Base Case House. This is of course based on the default cost parameters, but any changes in those, such as more aggressive

Table 6.3: 40 year 'initial + replacement' cost differences (before tax) between the BCH and the NZEH (without solar technologies)

LEGEND:
: New materials added to the NZEH
Ø : Materials removed from the BCH design to make the NZEH

	Material	Total 'initial + replacement' Cost ($)
RADIANT FLOOR COMPONENTS		
	Radiant Floor tubing - All floors	3,134
	Manifolds	2,500
	Thermostats	1,500
	Pumps and controls	4,000
	Regular storage tank (without the heat exchanger which is part of the solar system)	1,509
Ø	Baseboard Heaters (w/ controls), 15 kW	-6,655
INSULATION & WALLS/FLOORS		
	Extruded Polystyrene Floor Insulation, 41 mm	777
Ø	Wood Floor Studs, 2x4 (38 mm x 89 mm) in A1	-82
Ø	Wood Floor Studs, 2x10 (38 mm x 235 mm) in B1 & C1	-1,281
	Wood Floor Studs, 2x3 (38 mm x 64 mm) in B1W & C1	220
	Wood Floor Studs, 2x6 (38 mm x 140 mm) in B1E	213
Ø	Wood Floor Studs, 2x12 (38 mm x 286 mm) in the Attic	-942
	Wood Floor Studs, 3x16 (64 mm x 387 mm) in the Attic	1,352
	Plywood floor, 16 mm in B1 & C1	2,502
	Mineral Wool Floor Insulation, 40 mm in B1W & C1	337
Ø	Mineral Wool Floor Insulation (difference between BCH & NZEH), 95 mm in B1E	-229
	Mineral Wool Floor Insulation (difference between BCH & NZEH), 160 mm in Attic	477
	Concrete floor, 75 mm in B1 & C1	3,491
	Wood Wall Studs, 2x10 (38 mm x 235 mm) in B1 & C1	1,224
Ø	Wood Wall Studs, 2x6 (1.5 x 5.5 = 38 x 140) in B1 & C1	-784
	Mineral Wool Wall Insulation, 229 mm in B1 & C1	2,031
Ø	Mineral Wool Wall Insulation, 140 mm in B1 & C1	-1,217
WINDOWS (Labour separate)		
	Operable Casement, triple pane, argon filled	35,055
	Fixed Picture, triple pane, argon filled	10,722
Ø	Operable Casement, double pane, argon filled	-29,990
	Window Installation Difference between BCH & NZEH	2,920
LIGHTING		
	CFL Lighting	2,292
Ø	Incandescent Lighting	-5,731
DHW DEVICES		
	Thermostatic Mixing Valve	161
	Drain water heat recovery (power-pipe)	870
	TOTAL	**30,376**
	TOTAL (incl. tax)	**34,287**

Sources: Beaulieu 2008, Rona Renovateur 2008, RS Means 2008, The Home Depot 2008, Glass Experts 2008, Canadian Tire 2008, Cash Acme 2008.

Detailed breakdown in Appendix C, Table C-2.

increase in the currently very inexpensive electricity costs could make this even more financially attractive. In addition, section 6.2 discusses which of the individual changes to the house are the most cost effective in terms of dollars spent per reduction in electricity use.

6.1.2.2 Solar Combisystem

The solar combisystem is made up of many components which differ slightly depending if it uses flat plate or evacuated tube solar collectors. The entire costs for the two types of solar collector systems, including installation, are summarized in Table 6.4 and Table 6.5. The individual breakdown of prices are before the addition of tax, but the total cost does include the combined 12.875% federal and provincial taxes. The prices are specifically for a Stiebel Eltron SOL25 flat plate solar collector system and a Thermomax Solamax 20-TDS 300 evacuated tube solar collector system. In addition, for the most part these prices have been obtained from local retailers in order to reflect the real cost of a system being installed in Montreal, QC. All parts of the combisystem downstream of the two hot water storage tanks are not included in these two cost tables (i.e. the radiant floor system and the hot water piping and taps throughout the house).

A more detailed breakdown of the pricing for individual solar collector system components, from multiple sources, can be found in Appendix C, Table C-3, Table C-4 and Table C-5.

Table 6.6 shows the breakdown of the radiant floor component prices that result in the extra cost of installing a radiant floor in the NZEH compared to the baseboard heaters in the BCH. This shows that installing a radiant floor involves many differences compared to a standard wood floor with baseboard heating. In addition to the tubing, manifolds, pumps, controls and the hot water storage tank, this type of radiant floor also requires partial concrete floors, insulation and extra plywood (but smaller wood studs) which all results in a cost increase of $13,472 over the BCH.

Table 6.4: Initial cost of the Stiebel Eltron flat plate solar collectors and associated components

	Cost Before Tax ($)									Cost Including Tax ($)		
No. of Collectors	Collectors	Two Tanks with Heat Exchangers inside	(Minus) Two Regular Tanks	Pump	Controller	Racking	Piping (with insulation and fittings)	Glycol	Installation	Total Collector System Cost	Total Collector System Cost per Gross Collector Area ($/m^2)	$/(kWh of reduced annual electricity demand)
1	948	2,798	1,006	726	199	238	277	144	1,200	6,235	2,280	4.83
2	1,896	2,798	1,006	726	199	386	277	157	1,400	7,713	1,411	3.97
3	2,844	2,798	1,006	726	199	673	277	171	1,600	9,348	1,140	3.83
4	3,792	2,798	1,006	726	199	821	277	185	1,800	10,827	990	3.84
5	4,740	2,798	1,006	726	199	1,108	277	198	2,000	12,462	912	4.10
6	5,688	2,798	1,006	726	199	1,256	277	212	2,200	13,940	850	4.36

Table 6.5: Initial cost of the Thermomax evacuated tube solar collectors and associated components

	Cost Before Tax ($)									Cost Including Tax ($)		
No. of Collectors	Collectors	Two Tanks with Heat Exchangers inside	(Minus) Two Regular Tanks	Pump	Controller	Racking	Piping (with insulation and fittings)	Glycol	Installation	Total Collector System Cost	Total Collector System Cost per Gross Collector Area ($/m^2)	$/(kWh of reduced annual electricity demand)
1	2,474	2,798	1,006	726	199	integrated	277	157	1,200	7,704	2,701	5.76
2	4,948	2,798	1,006	726	199	integrated	277	185	1,400	10,753	1,885	5.22
3	7,422	2,798	1,006	726	199	integrated	277	212	1,600	13,802	1,613	5.26
4	9,896	2,798	1,006	726	199	integrated	277	239	1,800	16,852	1,477	5.59
5	12,370	2,798	1,006	726	199	integrated	277	267	2,000	19,901	1,396	6.14
6	14,844	2,798	1,006	726	199	integrated	277	294	2,200	22,950	1,341	6.77

Table 6.6: Cost to change from baseboard heaters (BCH) to radiant floors (NZEH)

LEGEND:
  : New materials added to the NZEH
Ø : Materials removed from the BCH design to make the NZEH

	Material	Total 'initial + replacement' Cost ($)
Radiant Floors		
	Radiant Floor tubing - All floors	3,134
	Manifolds	2,500
	Thermostats	1,500
	Pumps and controls	4,000
	Regular 300 L storage tank	1,509
Ø	Wood Floor Studs, 2x4 (38 mm x 89 mm) in A1	-82
	XPS Floor Insulation in A1, 41 mm	777
Ø	Wood Floor Studs, 2x10 (38 mm x 235 mm) in B1 & C1	-1,281
	Wood Floor Studs, 2x3 (38 mm x 64 mm) in B1W & C1	220
	Wood Floor Studs, 2x6 (38 mm x 140 mm) in B1E	213
Ø	Mineral Wool Floor insulation (difference between BCH & NZEH), 95 mm in B1E	-229
	Mineral Wool Floor insulation, 40 mm in B1W & C1	337
	Concrete floor, 75 mm in B1 & C1	3,491
	Plywood floor, 16 mm in B1 & C1	2,502
Ø	Baseboard Heaters	-6,655
	TOTAL	**11,935**
	TOTAL (incl. Tax)	**13,472**

Sources: Beaulieu 2008, Rona Renovateur 2008, RS Means 2008, The Home Depot 2008, Sears 2008. Details of these costs can be found in Appendix C, Table C-1 and C-2.

6.1.2.2.1 Flat Plate vs. Evacuated Tube Solar Collectors - Cost

One important question to ask when choosing solar collectors is whether a flat plate or evacuated tube system should be used. In hot climates, it is fairly obvious that flat plate collectors should be used since they are generally simpler and less expensive and evacuated tubes are not necessary since heat loss through the tubes is less of an issue. However, in a cold climate like Montreal, it is not as simple, and in fact, one might argue that it is obvious that evacuated tube collectors should be used since they are more efficient due to significantly less heat being lost to the cold environment through the evacuated tubes. Although it is true that the evacuated tube technology is more efficient, at the present time, they also cost much more. In addition, as shown in the three figures in section 5.4.3.2 and in Figure 5.21, when looking at the gross area of the collectors, thus the total space occupied on the roof, there is almost no benefit to installing evacuated tube compared to flat plate solar collectors (at least those tested here, since some other evacuated tube solar collectors have smaller manifolds and more closely spaced tubes).

Making this comparison between the two specific solar collector brands chosen for this thesis, the results show that flat plate solar collectors are actually the better financial option regardless of how many collectors are installed. In addition, it should be noted that these prices do represent the general trend, as seen in the list of prices in Appendix C, Table C-3. Figure 6.1 demonstrates this point by comparing the flat plate and evacuated tube collectors in terms of cost vs. reduction in house electricity demand from different quantities of collectors. In addition, Table 6.4 and Table 6.5 show the initial cost per kWh of reduced annual electricity demand for the flat plate and evacuated tube solar collectors, respectively.

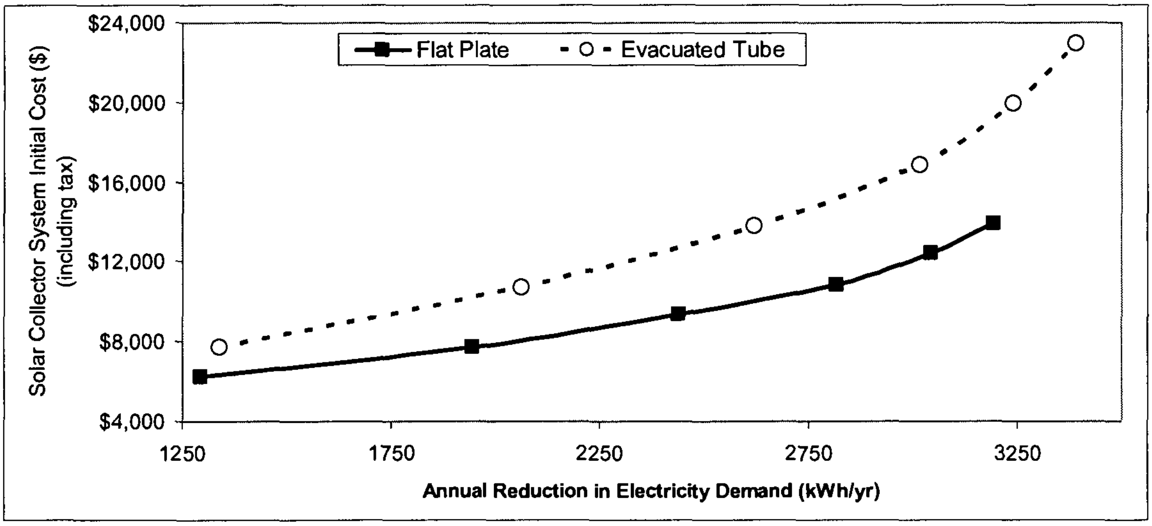


Figure 6.1: Comparing flat plate with evacuated tube solar collectors in terms of the initial cost vs. reductions in electricity demand

Payback Time

Comparing the payback time for various quantities of both flat plate and evacuated tube solar collectors reveals again that flat plate collectors are more cost effective and also shows how many collectors result in the shortest payback time. Figure 6.2 shows the aforementioned initial investment payback times, calculated using both the simple payback method as well as the CCF method on the NZEH before PV modules are included (so it is not yet net-zero). This shows that using the default values related to inflation, interest rates and electricity prices specified above, the two methods result in similar values. However, one must be cautious using the simple payback method for this type of analysis since in this specific case, these similarities are due to the fact that the default values resulted in an almost linear CCF, as seen in Figure 6.3. This is because the energy cost escalation rate (2.07%) is very similar to the effective interest rate (1.96%). When those values are less similar and the CCF lines are no longer linear (such as in Figure 6.12 or Figure 6.16), the CCF payback and the simple payback quickly diverge. It is also important to note that the payback values in Figure 6.2 and Figure 6.3 are based only on the initial investment costs and do not include the recurring replacement costs detailed in Table 6.7. and discussed further down.

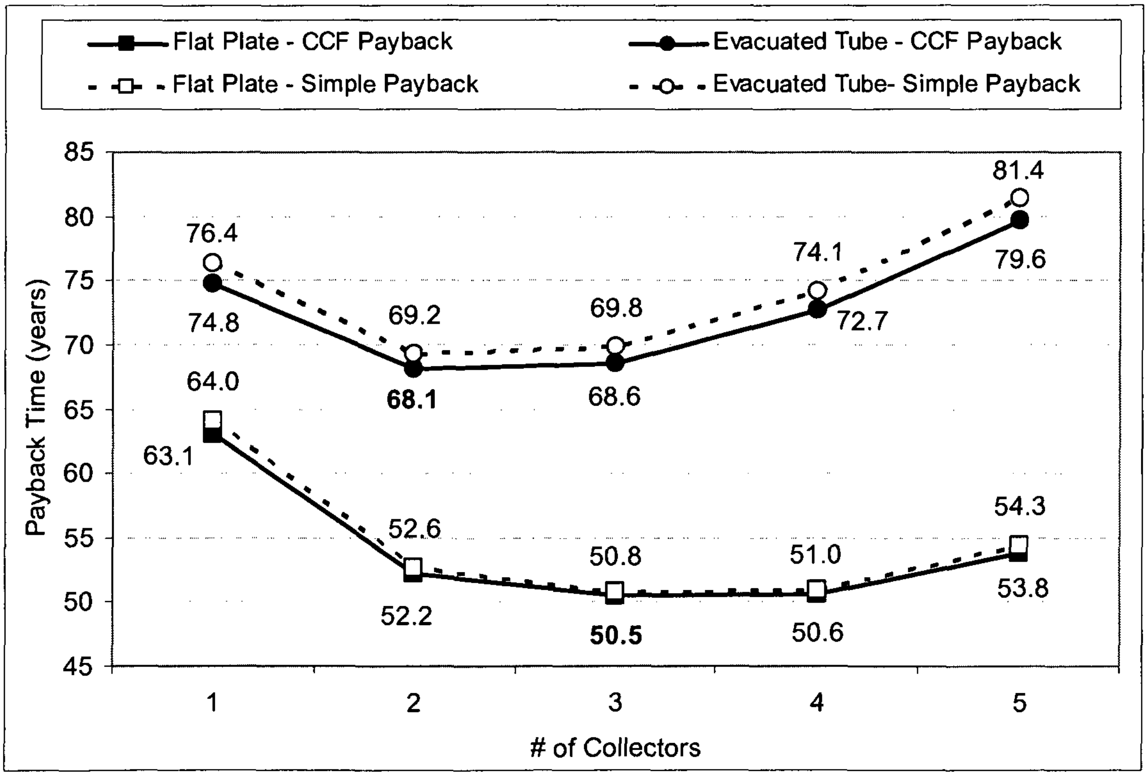


Figure 6.2: Cumulative cash flow payback (initial investment only) and simple payback for varying quantities of flat plate and evacuated tube solar collectors on the NZEH

If flat plate solar collectors are used, the shortest initial investment payback time is 50.5 years using three collectors. For evacuated tubes, two solar collectors are the best financial choice with a payback of 68.1 years. In both cases, these payback times are significantly longer than the expected 25 year life of these products.

Figure 6.3 shows that although two flat plate collectors do have lower initial costs compared to three or four collectors, it takes longer to achieve financial payback with two collectors. However, the financial payback for two collectors does come sooner than systems with one or five collectors. This demonstrates the complexity with the payback of solar collectors and is due to two things. Firstly, as previously shown in Figure 5.21, as more collectors are added to the combisystem, each addition has less of an energetic impact than the previous. So although the cost of the collectors increase linearly, the electricity load reductions curve downward and eventually plateau. The one exception to that is the second reason for the payback complexity. Initially, installing just one solar collector requires not just the collector and racking, but also the

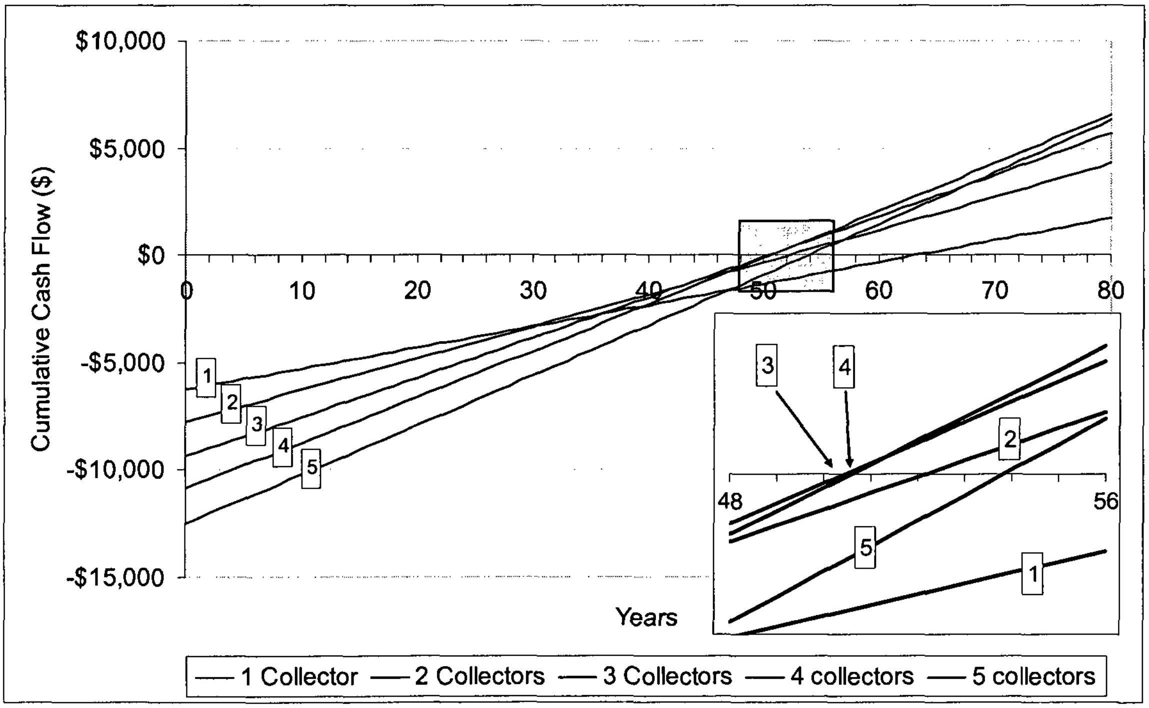


Figure 6.3: Cumulative cash flow (initial investment only) for varying quantities of flat plate solar collectors on the NZEH

controller, pump, piping, storage tank and the glycol. For each additional collector, however, most of those costs are not repeated. For example, the installation of a one flat plate collector system costs $6,235, whereas a two collector system costs $7,713, only $1478 more. Although these complexities do make the full payback time for differing quantities of collectors less obvious, it can be seen in Figure 6.3 that at the 25 year point - the expected life of the collector - none of the lines have yet to cross the break even point. Therefore, the smaller the initial cost, the less the homeowner will be in debt. However, if certain conditions change, such as faster increases in electricity prices, more collectors could become more financially advantageous.

A more complete analysis of the cost of the solar collectors includes the replacement costs shown in Table 6.7. The replacement frequencies are based on the expected service lives of the components. Aside from the solar collectors, the costs to replace the components are assumed to rise in concert with inflation and thus in 2008 dollars, the costs remain the same. The cost of the solar collector is assumed to decrease by 1% per year, after accounting for inflation. This is based on the fact that this is a relatively mature technology that relies on raw materials who's prices will likely rise, and the only likely contributor to a significant decrease in price could be larger production runs resulting in economies of scale.

Table 6.7: Replacement costs and frequencies for the flat plate solar collector system

# of Coll.	Collectors		Two Tanks with Heat Exchangers		Circulation Pump		Controller		Glycol	
	25 yr replacement		15 yr replacement		10 yr replacement		15 yr replacement		3 yr replacement	
	Mat. Cost ($)	Install. ($)	Mat. Cost ($)	Install. ($)	Mat. Cost ($)	Install. ($)	Mat. Cost ($)	Install. ($)	Mat. Cost ($)	Install ($)
0	0	0	0	0	0	0	0	0	0	0
1	832	452	2,023	250	819	60	225	50	162	75
2	1,665	527	2,023	250	819	60	225	50	178	75
3	2,497	602	2,023	250	819	60	225	50	193	75
4	3,329	677	2,023	250	819	60	225	50	208	75
5	4,162	753	2,023	250	819	60	225	50	224	75
6	4,994	828	2,023	250	819	60	225	50	239	75

* Replacement times are primarily based on personal communications (e-mails and phone conversations) with the manufacturers of each product or contractors who work with these types of products.

When these additional costs are considered when calculating the cumulative cash flow of the solar collector system, as shown in Figure 6.4 and Figure 6.5, the payback times are significantly different compared to the 'initial investment only' method. When replacement costs are considered, financial payback is never achieved, regardless of the number of flat plate or evacuated tube solar collectors. The gains made from reduced electricity costs are more than offset by the extra costs to replace the glycol, the pump, the tanks, the controller and eventually the collectors. For example, with a four flat plate solar collector system which has an initial cost of $9,348, after 25 years (the expected end of the life of the collector), the cumulative cash flow is -$11,229. Since the CCF includes the avoided electricity costs, CCF is the extra cost compared to a regular, 100% grid connected electricity system. Replacing the flat plate solar collector after 25 years so that the system lasts 40 years (the life cycle time for the whole house), the CCF then becomes -$17,733. This is at least better than the entire 40 year life cycle cost of the system,

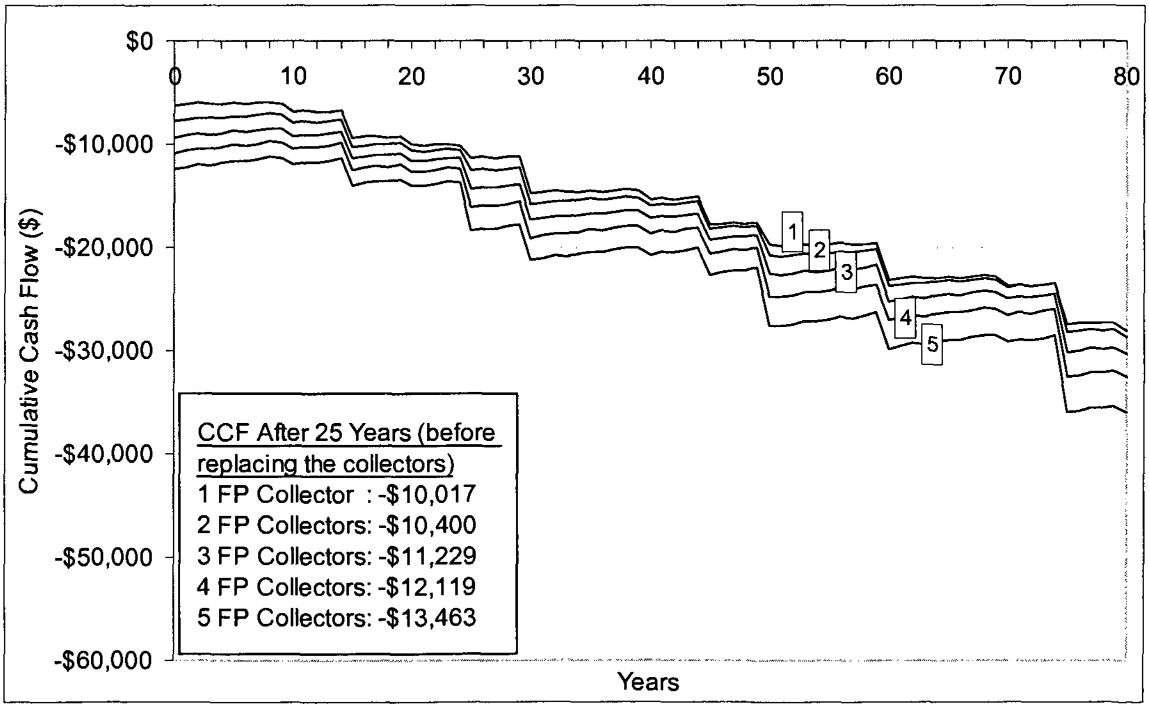


Figure 6.4: Cumulative cash flow for varying quantities of FLAT PLATE solar collectors on the NZEH (including replacement costs)

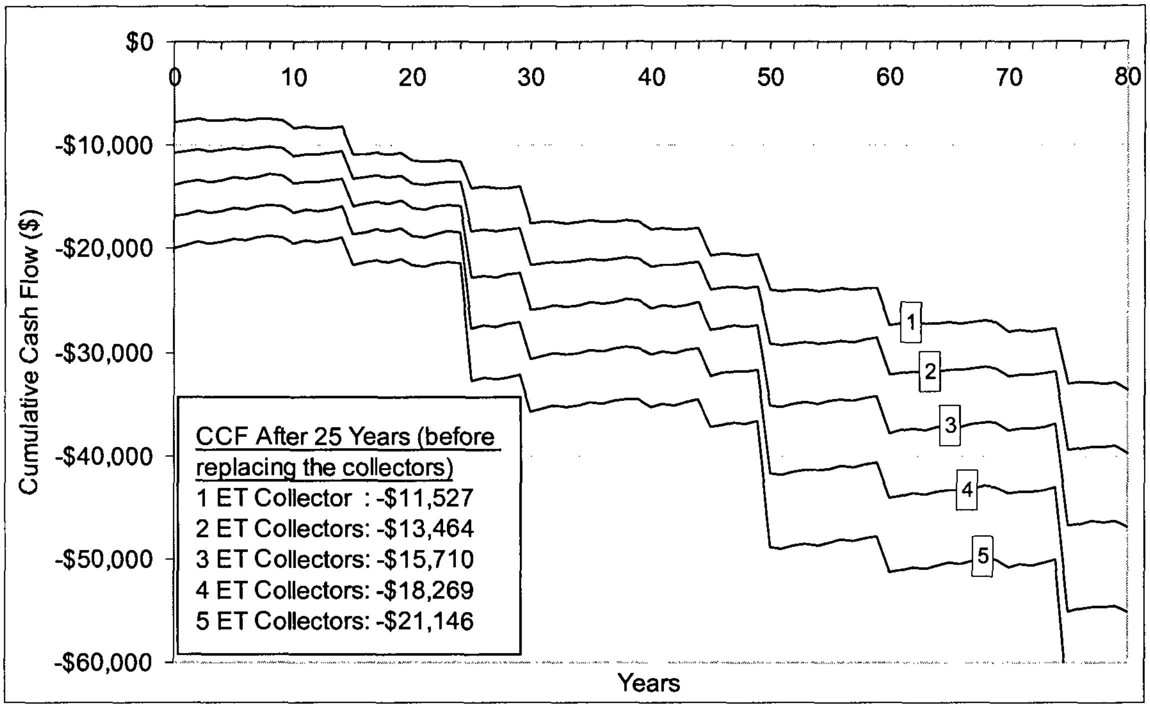


Figure 6.5: Cumulative cash flow for varying quantities of EVACUATED TUBE solar collectors on the NZEH (including replacement costs)

$26,252 (see Table 6.12), since some of the costs are offset by reduced space heating and DHW costs in the house. As these two figures show, these trends are the same for all of the various quantities of both flat plate and evacuated tube solar collectors, with the evacuated tube collectors being substantially more expensive. The 40 year costs including replacements for the various quantities of flat plate and evacuated tube solar collector systems can be found in Table 6.12.

6.1.2.3 Photovoltaic System

The size of the photovoltaic system for the NZEH depends on all of the energy saving features that have been incorporated into the house, as well as the solar collectors. This is because in order for the house to be truly "net-zero", the PV system must produce enough electricity to meet the entire remaining house electricity loads by the end of the year. Since photovoltaic technology is still quite expensive, the goal is to reduce the final amount of electricity demand as much as possible so that the PV system required is as small and as least costly as possible. Based on results from Table 5.15 that show the energy generated by the solar collectors and the remaining energy demand that needs to be supplied by a PV array, Table 6.8 and Table 6.9 show the number of 200 watt Sanyo HIP-200BA3 photovoltaic modules that are required for the NZEH for flat plate and evacuated tube solar collectors, respectively. The tables show the number of PV modules required to be exactly net-zero, so the values are actually shown as a certain number of whole modules and a fraction of a module (e.g. 44.7 modules). Although a fraction of a module cannot be purchased, smaller modules that are equivalent to a fraction of a large, 200 watt module can be obtained. Therefore, for the purposes of comparison, the values in the tables were not rounded up to whole numbers for the modules. Although a 100 watt module is not likely exactly half the price of a 200 watt module, the difference in price is negligible for the large systems in this house. Therefore, a price per watt for PV modules was determined ($6.65/watt) and is multiplied by the number of watts of the required systems. The same logic is applied to the sizing and pricing of the inverters since they can be bought in various sizes. Since inverters are not sized exactly to the wattage of PV system (i.e. a 2 kW inverter is not coupled with a 2 kW PV array), a price per watt for inverters was determined ($0.87/watt) and multiplied by a value 500 watts larger than the PV array size. The cost of racking is similarly based on a price per module ($90/module). The overall labour costs for installation do rise with larger systems, but actually decrease on a per watt basis. In order to determine installation costs, quotes for six systems ranging from 0.7 kW to 5.6 kW (Appendix C, Table C-8) were plotted and fit to a curve to determine an equation for the price per watt ($25.868/W^{0.3822}$ in $/W), as shown in Appendix C, Figure C1. Appendix C also contains Table C-6 which is a detailed breakdown of the pricing for individual PV system components, from multiple sources. Similar to the solar collectors, for the most part the prices used have been obtained from local retailers in order to reflect the real cost of a system being installed in Montreal, QC. All price sources are listed in Appendix C.

Table 6.8: Initial cost of the NZEH PV system based on the number of flat plate solar collectors installed

		Cost Before Tax ($)						Cost Including Tax ($)	
No. of Flat Plate Collectors	No. of PV panels needed	PV Modules	Inverters	Racking	Misc. items (cables, meters, etc.)	Installation	Hydro QC Net Metering Charge	PV System Total	$/W of PV System
0	44.7	59,451	8,213	4,023	500	7,143	400	89,995	10.07
1	40.6	53,998	7,499	3,654	500	6,731	400	82,153	10.12
2	38.6	51,338	7,151	3,474	500	6,524	400	78,321	10.15
3	37.0	49,210	6,873	3,330	500	6,356	400	75,252	10.17
4	35.8	47,614	6,664	3,222	500	6,228	400	72,949	10.19
5	35.1	46,683	6,542	3,159	500	6,152	400	71,604	10.20
6	34.6	46,018	6,455	3,114	500	6,098	400	70,643	10.21

Table 6.9: Initial cost of the NZEH PV system based on the number of evacuated tube solar collectors installed

		Cost Before Tax ($)						Cost Including Tax ($)	
No. of Evacuated Tube Collectors	No. of PV panels needed	PV Modules	Inverters	Racking	Misc. items (cables, meters, etc.)	Installation	Hydro QC Net Metering Charge	PV System Total	$/W of PV System
0	44.7	59,451	8,213	4,023	500	7,143	400	89,995	10.07
1	40.5	53,865	7,482	3,645	500	6,721	400	81,962	10.12
2	38.2	50,806	7,082	3,438	500	6,482	400	77,554	10.15
3	36.4	48,412	6,769	3,276	500	6,292	400	74,101	10.18
4	35.1	46,683	6,542	3,159	500	6,152	400	71,604	10.20
5	34.4	45,752	6,421	3,096	500	6,076	400	70,259	10.21
6	34.0	45,220	6,351	3,060	500	6,032	400	69,490	10.22

Figure 6.6 shows the payback time for incremental sizes of PV systems when considering the initial investment only, and neglecting recurring replacement costs. The number of PV modules shown in this figure, as well as in Figure 6.7, do not match the exact number of modules used in the various NZEH options (e.g. 44.7 or 35.8) since the purpose of this figure is to show a trend over a larger range of PV module quantities (5 to 55). As more PV modules are added, the length of payback time does decrease, but once you reach 35 PV modules (7,000 W), the reduction in payback years begins nearing a plateau. This might seem like an incentive to install the largest PV system that can be fit in the space available, since the payback time does slowly decrease with larger systems, but that ignores two important constraints. Firstly, for most people, the initial investment for a large PV system might be too much since it can be in the area of $100,000. Secondly, and even more importantly, is again the issue of the expected life of the product. With an expected life of about 25 years, the PV system will cease to function more than three times faster than it can pay for itself since even the 11,000 W, 55 PV panel system only has a payback time of 82.1 years. Therefore, from a financial point of view, it is more pertinent to look at the CCF after 25 years. Figure 6.6 shows that the larger the system, the more the homeowner will be in debt after 25 years. In this timeframe, a 5 PV (1000 W) system would result in a negative cash flow of $9,644 compared to $77,262 for the 55 PV (11,000 W) system. From this financial perspective, the homeowner would be best to get the smallest system possible as opposed to the largest as suggested by the complete payback time analysis. This is because when the CCF is plotted for these PV systems, the lines all cross around the 80 year mark, and only then do the larger systems begin to have more advantageous cumulative cash flows.

However, this 'initial investment only' analysis is only one indicator of the financial benefits of the system and does not tell the whole story. A more complete analysis involves the recurring replacement costs of the PV system components which are listed in Table 6.10. The replacement frequencies are based on the expected service life of the components. Due to technological advances and economies of scale, the price of a PV module is expected to decrease by about 5%

annually compared to today's prices (Green 2005, Hoffmann 2006, Payne, Duke & Williams 2001, Van Sark et. al. 2008). Adding the impact of the 2% inflation, that results in about a 7% annual decrease in 2008 dollars. This is only for the first 25 years, after which the technology is expected to be more mature and the price rises with inflation. Since inverters are a mature technology, those prices are expected to rise along with the rate of inflation and thus remain the same in 2008 dollars.

Table 6.10: Replacement costs and frequencies for the PV system

No. of PV Modules	Modules		Inverter	
	25 yr replacement		15 yr replacement	
	Material Cost ($)	Installation ($)	Material Cost ($)	Installation ($)
44.7	10,935	12,095	9,270	100
40.6	9,932	11,397	8,465	100
38.6	9,443	11,046	8,072	100
37.0	9,052	10,761	7,758	100
35.8	8,758	10,544	7,522	100
35.1	8,587	10,416	7,385	100
34.6	8,464	10,325	7,287	100

* Replacement times are primarily based on personal communications (e-mails and phone conversations) with the manufacturers of each product or contractors who work with these types of products.

Figure 6.7 shows the more complete CCF analysis which includes the impact of the replacement costs. Just like in the case of the solar collectors, these results are significantly different compared to the 'initial investment only' method. Due to the many recurring and costly replacements, the PV system is unable to achieve a financial payback. Comparing Figure 6.7 with Figure 6.6 shows the difference in CCF right before the PV modules need to be replaced (after 25 years) for various sizes of systems. This difference is essentially the extra cost of replacing the inverters after 15 years. As time goes on, the difference grows due to more replacements.

In order to be truly net-zero, the NZEH needs 44.7 PV panels if no solar collectors are used. Based on the initial investment only, this results in an CCF payback time of 82.8 years and a CCF of -$64,263 after 25 years (the end of the expected service life of the PV modules). For the same system, the CCF 'including replacement costs' after 25 years (but before spending more money to replace the PV modules) is -$73,033. The CCF 'including replacement costs' for this PV system after 40 years (the house life cycle in this thesis), is -$89,292. This compares to the 40 year life cycle cost of this PV system of $131,766, which does not include the savings from reduced electricity use. The 40 year costs including replacements of various other sizes of PV systems are found in Table 6.12.

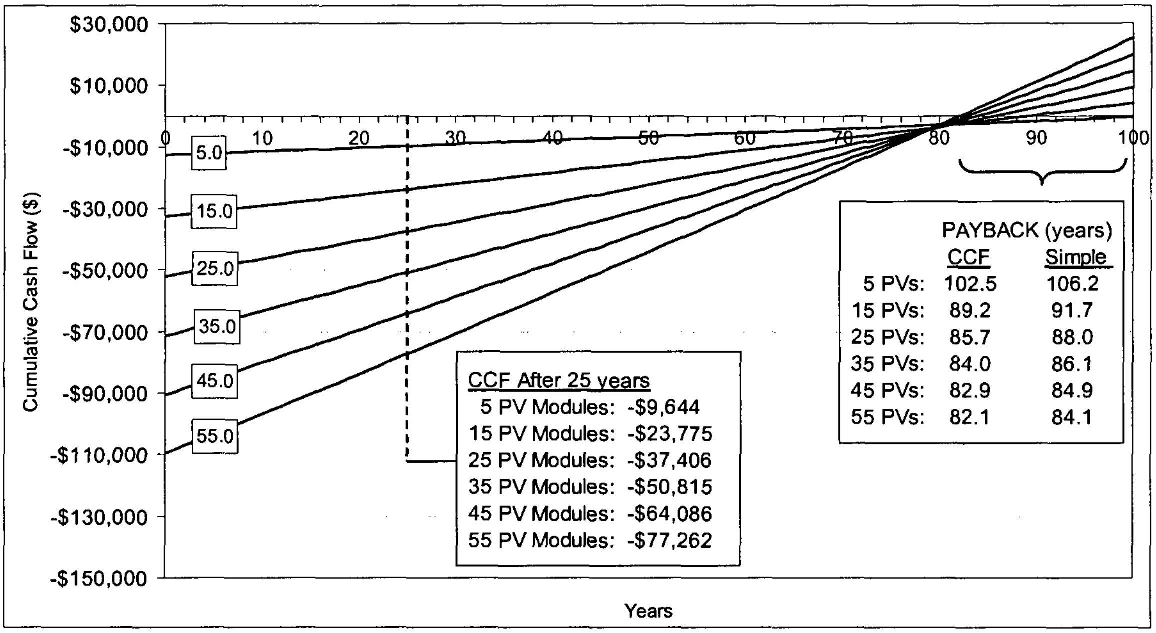


Figure 6.6: CCF and payback times for various PV quantities (initial investment only)

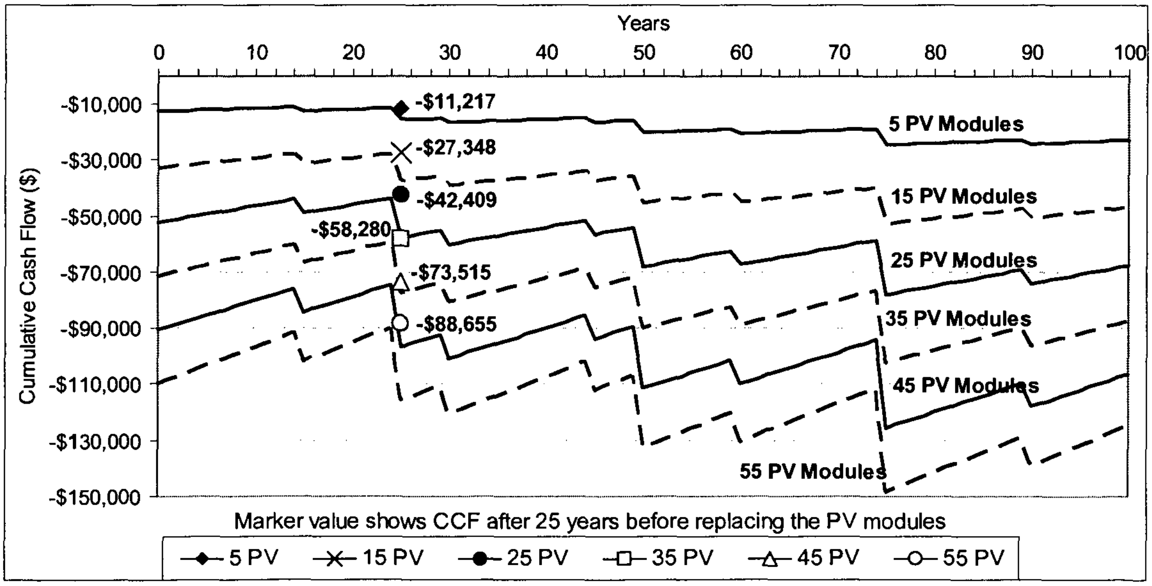


Figure 6.7: CCF for various PV module quantities (including replacement costs)

6.1.2.4 The Combined Solar Energy System (Solar Collectors & PV)

6.1.2.4.1 The Best Combination of Solar Collectors and Photovoltaics

The prices for the individual solar collector and PV systems are presented in sections 6.1.2.2 and 6.1.2.3, however it is even more interesting and useful when this information is combined. Since this is a Net Zero Energy House, the criteria of producing enough energy to be net-zero is not considered to be a flexible option. Therefore, using the total costs of the solar collectors and PV systems, Table 6.11 shows the initial costs and CCF payback time of the possible combinations that meet the goal of being net-zero. Since all of these options result in the same annual electricity cost savings (from a 14,061 kWh electricity use reduction), the 'initial investment only' CCF graph is simply comprised of parallel lines with different initial costs. This is shown in Figure 6.8 with a close-up of the section where the payback occurs (again, this is not the real financial payback time since it does not include the recurring replacement costs). Due to this linearity, the option with the shortest payback time is also the option with the lowest initial cost, and thus from a financial point of view, using this limited method of 'initial investment' analysis, this is the best combination of solar collectors and PV modules. The least expensive initial cost flat plate/PV system (4 collectors and 35.8 PV modules) costs $83,775 which is over $4000 less than the least expensive evacuated tube/PV option (3 collectors and 36.4 PV modules) at a cost of $87,903. The CCF payback time for least expensive option is 77.3 years. Although seemingly better financially than just using PV modules (which have an 82.8 year payback time), this is still three times longer than the 25 year life of the system. The 'initial investment only' CCF at the 25 year mark for this system is -$57,443. Figure 6.9 shows the CCF payback and simple payback times for the various NZEH solar system options using PV modules combined with either flat plate or evacuated tube solar collectors.

The payback times for solar systems are compared between the results provided in this thesis and those from Biaou & Bernier (2007), although the system presented here is much larger and is for heating and DHW compared to just DHW in Biaou & Bernier. They calculated a much shorter payback time of 29 years for a $7,500 solar system composed of 12m^2 of flat plate solar collectors and 5.2 m^2 of PVs to supply a DHW system in Montreal. This large difference is attributed to the significant differences in the reported costs for both the PV and solar collector systems; about 45% and 90% less, respectively, than the data used in this thesis. It is suspected that the costs used by Biaou & Bernier are more simplistic (especially since they are based on a constant price per m^2 for each system which is not the case in this thesis) and possibly did not include all of the extra details included here such as installation, heat exchangers, pumps, racking, piping, glycol and controllers).

Biaou (2004) calculated a 57 year payback for a combined PV and geothermal system for a net zero energy house in Montreal. One difference here is again due to variations in the estimated cost of the PV system. But an even larger reason for the smaller payback time is due to the fact that the Biaou house uses a geothermal heat pump system rather than a solar collector system. The results for this heat pump appear to be much more cost effective than the solar collectors in this thesis since the heat pump costs $17,230 but reduces the electricity load by 10,581 kWh.

Table 6.11: Initial cost for the combined solar technologies on the NZEH

	Flat Plate Collector & PV			**Evacuated Tube Collector & PV**		
# of Collectors	**# of PV panels**	**Initial Cost (incl. tax)**	**Payback time (yrs)**	**# of PV panels**	**Initial Cost (incl. tax)**	**Payback time (yrs)**
0	44.7	$89,995	82.8	44.7	$89,995	82.8
1	40.6	$88,388	81.4	40.5	$89,666	82.5
2	38.6	$86,034	79.3	38.2	$88,308	81.3
3	37.0	$84,601	78.1	**36.4**	**$87,903**	**81.0**
4	**35.8**	**$83,775**	**77.3**	35.1	$88,456	81.5
5	35.1	$84,066	77.6	34.4	$90,159	83.0
6	34.6	$84,583	78.0	34.0	$92,440	85.0

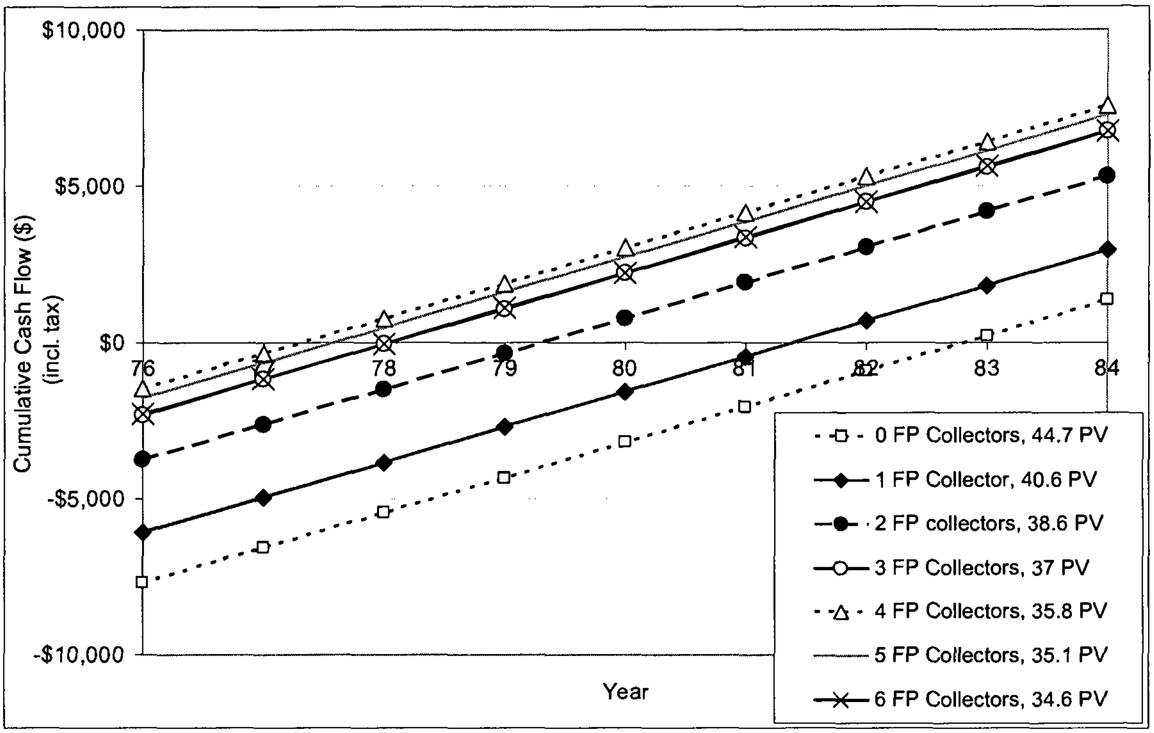


Figure 6.8: Close up - Cumulative cash flow for varying quantities of flat plate solar collectors coupled with a PV system on the NZEH (initial investment only)

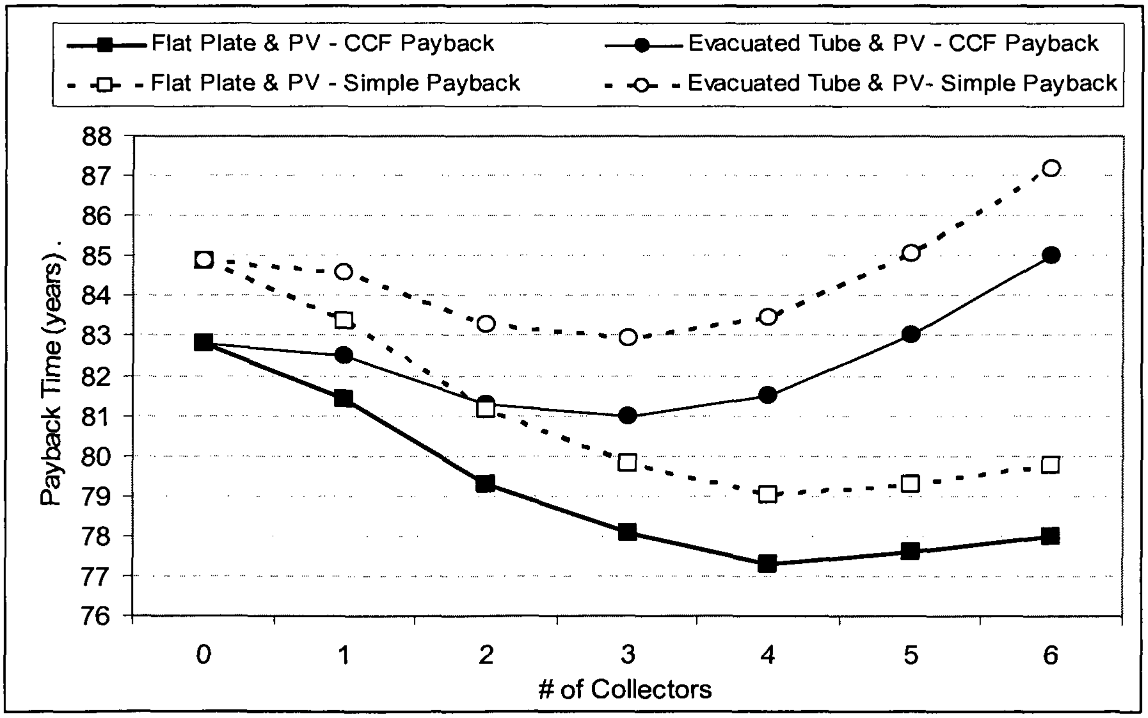


Figure 6.9: Cumulative cash flow payback and simple payback for varying quantities of flat plate and evacuated tube solar collectors coupled with a PV system on the NZEH (initial investment only)

The previous analysis is an interesting first step, but as explained in the previous two sections, it does not paint the full financial picture since it neglects the recurring replacement costs of many of the solar system components which are detailed previously in Table 6.7 and Table 6.10. Figure 6.10 shows the long term trend of the cumulative cash flow for various configurations of solar systems (flat plate solar collectors and PVs) as well as a close up of the initial costs (values in Table 6.11). Figure 6.11 also shows the CCF of the solar system including the replacement costs, but only for the 40 year time frame. The interesting result from these two figures is that although the solar system with 4 flat plate collectors and 35.8 PV modules is the least expensive option initially, and the system comprised of 44.7 PV modules and no solar collectors is initially the most expensive option, as time passes, components are replaced and PV prices mature, the solar system comprising of only PV modules and no solar collectors actually becomes the best choice, financially. The CCF values in the box in Figure 6.11 show that after 40 years, this (44.7 PV) option is only $2,855 better, but as Figure 6.10 shows, as time passes, the difference continues to increase such that after 100 years it grows to $16,670 less. Looking carefully at Figure 6.11, it can be seen that the 'PV only' system, with 44.7 modules, only becomes the best financial choice after 30 years. This happens for two reasons. Firstly, there are more components that need replacement for the solar collector system, and the 15 year tank replacement frequency is what causes the switch at 30 years. Secondly, the assumption that the PV module prices become significantly less expensive every year also plays a very important role. If this assumption about future prices does not hold true, and the cost of PV modules is not driven down as aggressively as expected, or if the cost of solar collectors or even heat exchanger equipped storage tanks happen to reduce more than expected, the best financial option for the solar system could very well remain the option with 4 flat plate solar collectors and 35.8 PV modules.

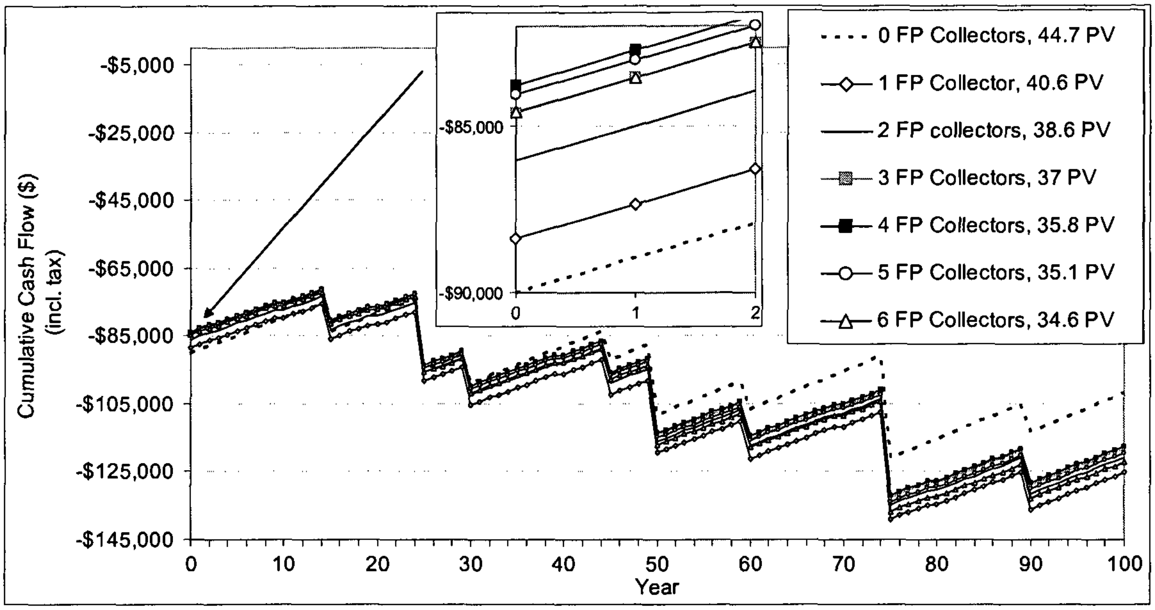
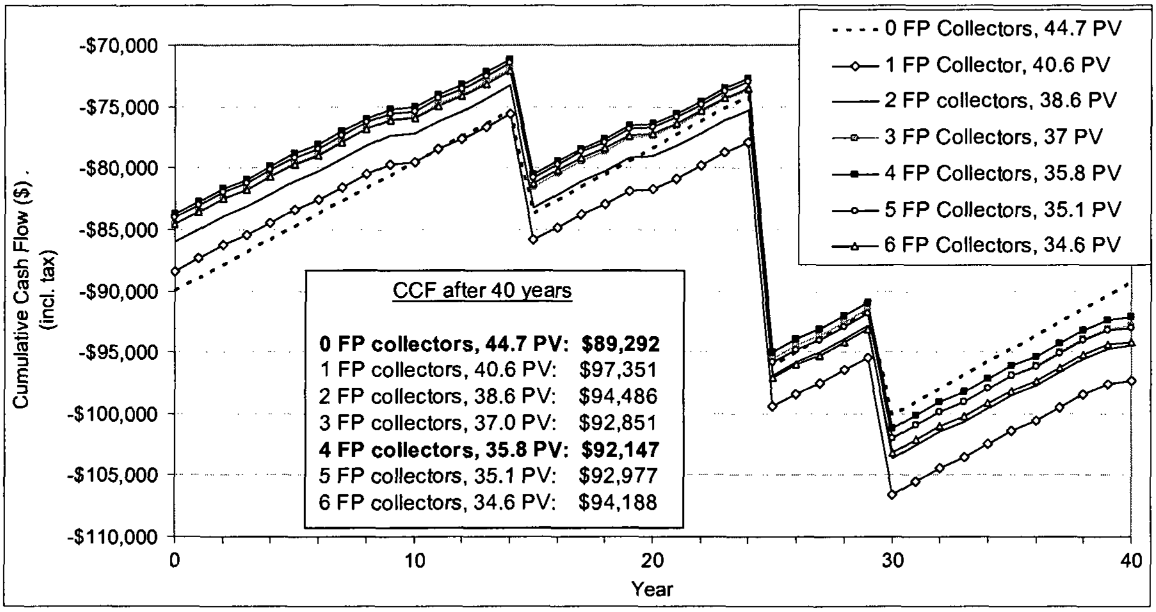


Figure 6.10: Cumulative cash flow for different quantities of flat plate solar collectors coupled with a PV system on the NZEH (including replacement costs)



CCF after 40 years

0 FP collectors, 44.7 PV:	**$89,292**
1 FP collectors, 40.6 PV:	$97,351
2 FP collectors, 38.6 PV:	$94,486
3 FP collectors, 37.0 PV:	$92,851
4 FP collectors, 35.8 PV:	**$92,147**
5 FP collectors, 35.1 PV:	$92,977
6 FP collectors, 34.6 PV:	$94,188

Figure 6.11: Cumulative cash flow during a 40 year life cycle for different quantities of flat plate solar collectors coupled with a PV system on the NZEH (including replacement costs)

Table 6.12 shows the 40 year cost including replacements, of the various solar system options, using flat plate or evacuated tube solar collectors, that would allow the house to become fully 'net-zero'. Since the evacuated tube solar collector system needs replacing just as often as the flat plate solar collector system, the conclusion from the earlier analysis that evacuated tubes are not worth the additional cost still holds true for this more complete analysis.

Table 6.12: 40 year cost including replacements for the combined solar technologies installed on the NZEH

No. of Coll.	40 Year Cost Including Replacements							
	Flat Plate & PV System				Evacuated Tube & PV System			
	Flat Plate System ($)	No. of PV Modules	PV System ($)	Total System Cost ($)	Evacuated Tube System ($)	No. of PV Modules	PV System ($)	Total System Cost ($)
0	**0**	**44.7**	**131,766**	**131,766**	**0**	**44.7**	**131,766**	**131,766**
1	18,335	40.6	120,612	138,947	21,345	40.5	120,339	141,684
2	20,922	38.6	115,155	136,077	27,043	38.2	114,062	141,105
3	23,665	37.0	110,781	134,446	32,741	36.4	109,139	141,880
4	26,252	35.8	107,495	133,747	38,439	35.1	105,577	144,015
5	28,995	35.1	105,577	134,572	44,137	34.4	103,656	147,793
6	31,582	34.6	104,205	135,787	49,835	34.0	102,558	152,393

Finally, Table 6.13 shows the 40 year life cycle cost of the BCH as well as the two best options for the NZEH discussed above. The table also shows the difference between the initial investment only method compared to when the replacement costs for the solar systems are considered (replacement costs of basic construction components such as windows, lighting, shingles etc. are included in all cases). Included in the table is the cost of 40 years of electricity for the BCH which is avoided in the NZEH designs. This gives a true 40 year life cycle cost comparison between the BCH and the NZEH options. This shows that the NZEH with 44.7 PV modules costs $47,607 more than the BCH when replacement costs are considered. Although there is a cost premium for achieving the goal of net-zero energy, section 6.2 below shows that costs can be reduced by avoiding some of the expensive changes to the windows that have a proportionally small impact on electricity use. This would reduce the cost of the windows by $16,276, but would also increase the electricity use and thus add some extra costs for more PV modules. However, these extra costs are less than the savings from avoiding the expensive window change. In addition, the radiant floors cost $13,472 but are not necessarily required to heat the house if the solar system with only PV modules is used. This could also reduce the cost significantly, but would also eliminate the benefits of having a radiant floor heating system. These cases are discussed in more detail in section 6.2.

Table 6.13: Summary of the 40 year life cycle costs for the BCH and NZEH

	40 year life cycle cost					
	Initial Investment Only ($)*			Including Replacement Costs ($)		
	BCH	NZEH with 44.7 PV modules	NZEH with 4 flat plate collectors & 35.8 PV	BCH	NZEH with 44.7 PV modules	NZEH with 4 flat plate collectors & 35.8 PV
♦Basic Construction	232,943	232,943	232,943	232,943	232,943	232,943
Energy Efficiency Modifications	0	34,287	34,287	0	34,287	34,287
Grid Electricity over 40 years	118,446	0	0	118,446	0	0
Solar Collector System	0	0	10,827	0	0	26,252
PV System	0	89,995	72,949	0	131,766	107,495
TOTAL Life Cycle Cost	351,389	357,225	351,006	351,389	398,996	400,977

* This includes replacement costs for the basic construction. The initial investment only refers to the solar systems.

♦ Basic construction, not including plumbing (aside from any plumbing related directly to the combisystem and specified in the text), electrical wiring or furnishings

6.1.2.4.2 Variations of the Default Values for the CCF analysis

As described in the introduction to this chapter, when calculating the CCF for all of the analysis in the previous sections, the following default values are used:

1) Annual inflation rate, i = 2%, 2) Annual discount rate, d = 4%, 3) Cost of electricity, E = \$0.0754/kWh, and 4) Annual electricity cost escalation rate, e = 2.07%. Based on current and historical information, these values were determined to be realistic assumptions. However, it is impossible to know for certain what the price of electricity, inflation, discount rates or energy cost escalation rates will actually be will be in the future. Since these parameters can have a significant impact on the financial feasibility of the solar technologies in the NZEH, variations of

these values have been tested on the most cost effective solar collector/PV combination. In addition, this section shows the impact of these variations for both the 'initial investment only' method as well as the more complete method that includes replacement costs. Since the less complete 'initial investment' method concludes that the most cost effective combination is with 4 flat plate solar collectors and 35.8 PV modules, this solar system configuration is the one analyzed for that method. For the more complete analysis involving replacement costs, the best solar system configuration after 40 years is the one with 0 flat plate solar collectors and 44.7 PV modules, so this is the configuration analyzed for that method.

One key difference between the two different payback results achieved from these two methods is that for the initial 'investment only' method, when the payback time exceeds the life of the system, it essentially means that it will never break even financially. In fact, a payback under 25 years (the life of the solar collectors and PV modules) does not even necessarily mean that the system will break even since it also does not consider the costs of replacing some other components (tanks, inverters, etc) before the collectors or PVs cease to function. However, the method that does include replacement costs takes all of this into consideration and continually replaces components at the end of their service lives. Therefore, a payback time from this more robust method is the actual time it will take to break even. This again shows how important it is to consider the cost of replacing components since it has a very significant impact on the conclusions.

In the following analysis, when one variable is tested, all others remain as their default values. Also, for simplicity, the 4 flat plate solar collector and 35.8 PV module solar system is referred to as the 4/35.8 system and the 0 solar collector and 44.7 PV module solar system is referred to as the 0/44.7 system.

Electricity Cost Escalation Rates

Figure 6.12 and Figure 6.13 show the impact on the CCF when the electricity cost escalation rate varies between no increase (0%) and 11%. Since the homeowner avoids paying for electricity with the solar collectors and PVs, the faster the cost of electricity increases, the more quickly they will recoup their initial investment. At an initial rate of $0.0754/kWh, the price of electricity would need to increase by 11% per year for the solar system to break even, financially, in 25 years for the 'initial investment only' method (for 4/35.8 system). Figure 6.13 shows that the 25 year payback is achieved with a 13% annual electricity rate increase for the analysis that includes the replacement costs, and a 7.3% annual electricity rate increase for a payback of 40 years (for the 0/44.7 system). With replacement costs, anything under 3% would take a very long time to achieve a financial payback and a little over 2% or less will never result in a payback (such as the expected 2.07% being used as the default in the main analysis).

Figure 6.13 also includes the replacement cost method results from the best solar system option that does include solar collectors (the 4/35.8 system). This is to show that although the CCF and payback times are not identical to the case with 44.7 PV modules and no solar collectors, the results and patterns are very similar. This applies not only to the electricity cost escalation rates, but to all of the variations of the default values presented in this section.

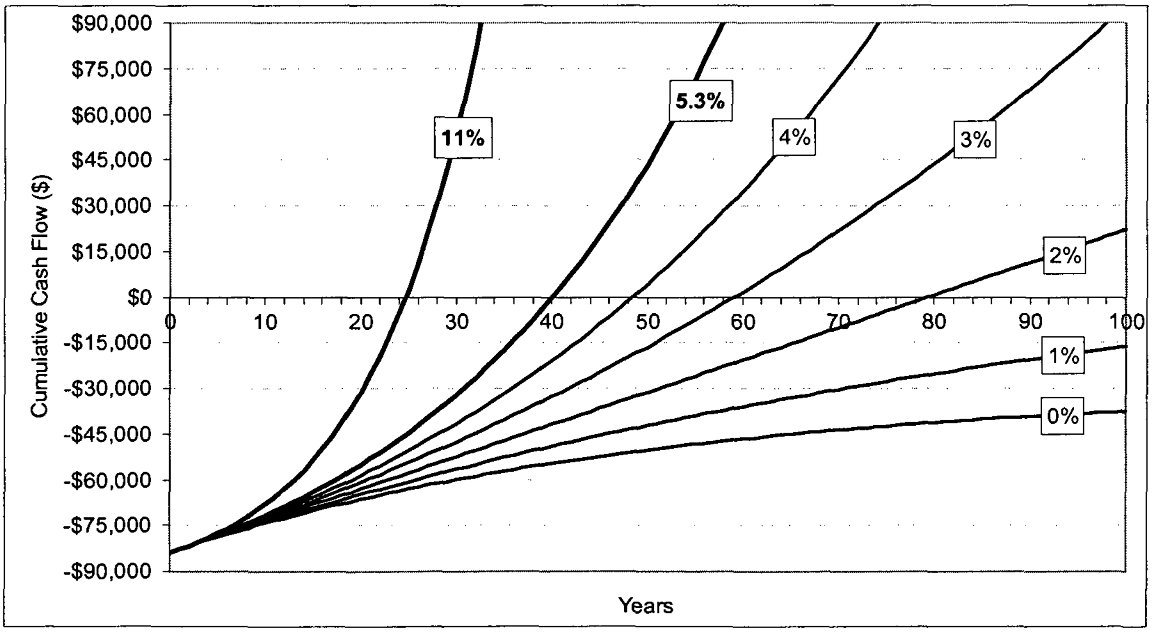


Figure 6.12: Cumulative cash flow (initial investment only) for the 4 solar collector & 35.8 PV system on the NZEH for various electricity escalation rates, starting with the current electricity price of $0.0754/kWh

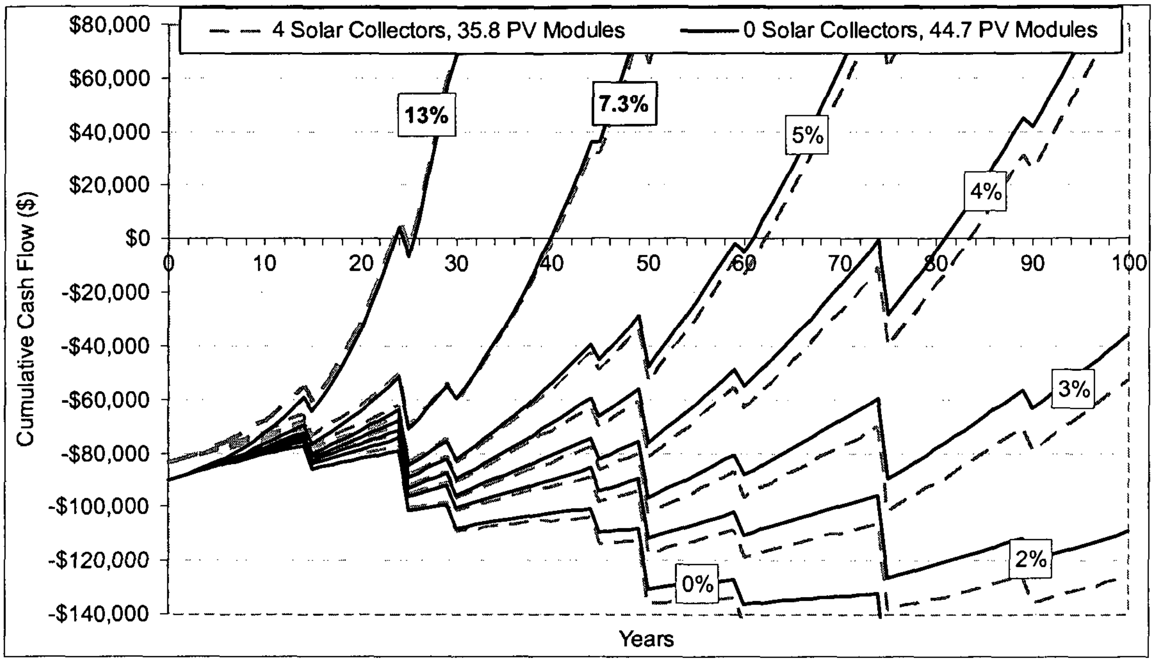


Figure 6.13: Cumulative cash flow for two solar system options on the NZEH for various electricity escalation rates, starting with the current electricity price of $0.0754/kWh (including replacement costs)

Electricity Prices

For the 'initial investment only' method, Figure 6.14 shows the impact on the CCF of the 4/35.8 system when the current price of electricity is between $0.0754/kWh and $0.30/kWh. This shows that the price of electricity needs to be at least $0.24/kWh for the 4/35.8 solar system to be able to pay itself off in its 25 year expected life. At $0.30/kWh, the payback time is 20 years. When replacement costs are considered, as in Figure 6.15, the price of electricity needs to be $0.32/kWh for a 25 year payback for the 0/44.7 system. Looking at the figure, it shows that the payback actually arrives around 22 years, but then due to the replacement of the PV modules after 25 years, it drops down again into the negative cash flow region and finally breaks even once and for all at 27 years. Looking at how much above and below the break even point the line goes, this averages to about 25 years. A rate of $0.24/kWh results in a payback time just under the life cycle time for the house of 40 years.

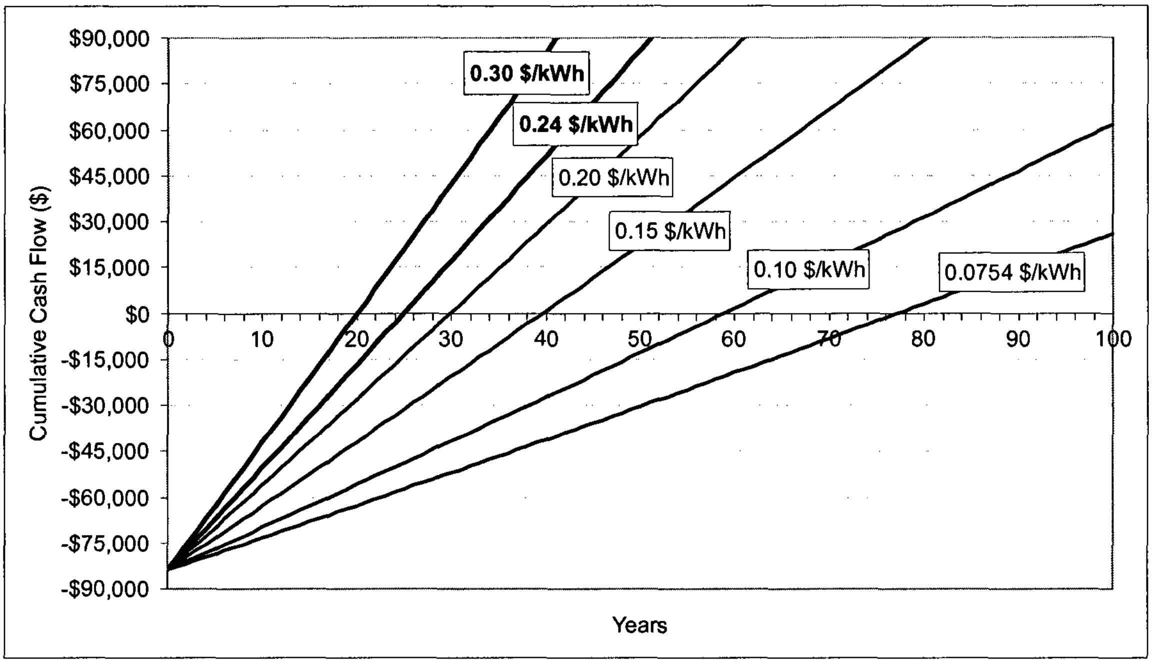


Figure 6.14: Cumulative cash flow for the 4 solar collector & 35.8 PV system on the NZEH for various electricity prices (initial investment only)

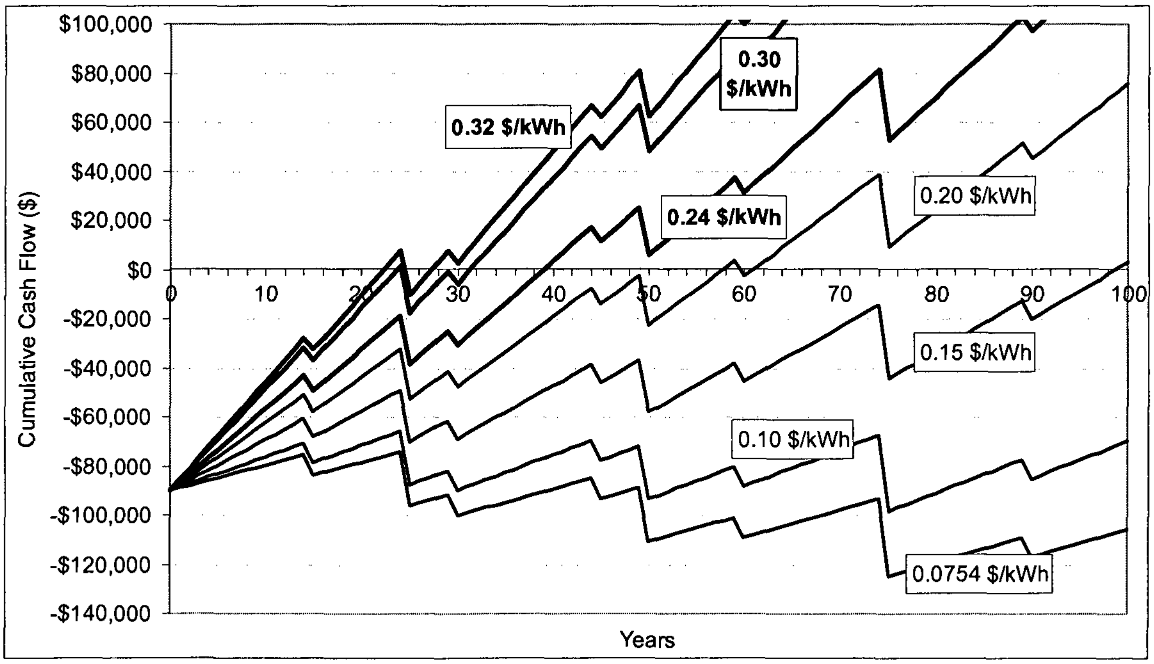


Figure 6.15: Cumulative cash flow for the 44.7 PV system on the NZEH for various electricity prices (including replacement costs)

Although $0.24/kWh is significantly more than the current $0.0754/kWh in Montreal, QC, it is not totally unreasonable in other cities in North America. New York City, for example, has its electricity priced at $0.2513/kWh. In Canada, the most expensive city on the list from Hydro Quebec's 2007 "Comparison of Electricity Prices in Major North American Cities" is Charlottetown, PEI with a price $0.1418/kWh. At this rate it would unfortunately take over a century to achieve financial payback when replacements are included and just over 40 years without including replacement costs.

Effective Interest Rate (Inflation and Discount Rates)

The effective interest rate is a function of inflation and the discount rate as shown in Equation 6.1. Figure 6.16 and Figure 6.17 show the impact on the CCF when the effective interest rate varies between 0% and 5.88%. These rates come from varying the discount rate between 2% and 8% while keeping inflation fixed at 2%. This is done since in Canada the discount rate does tend to vary much more than inflation which is kept relatively stable by the Bank of Canada. The figure shows that as the discount rate increases more and more above inflation, and thus the effective interest rate increases, the payback time becomes longer and longer. This is because as the discount rate increases, the money initially spent to purchase the solar system becomes

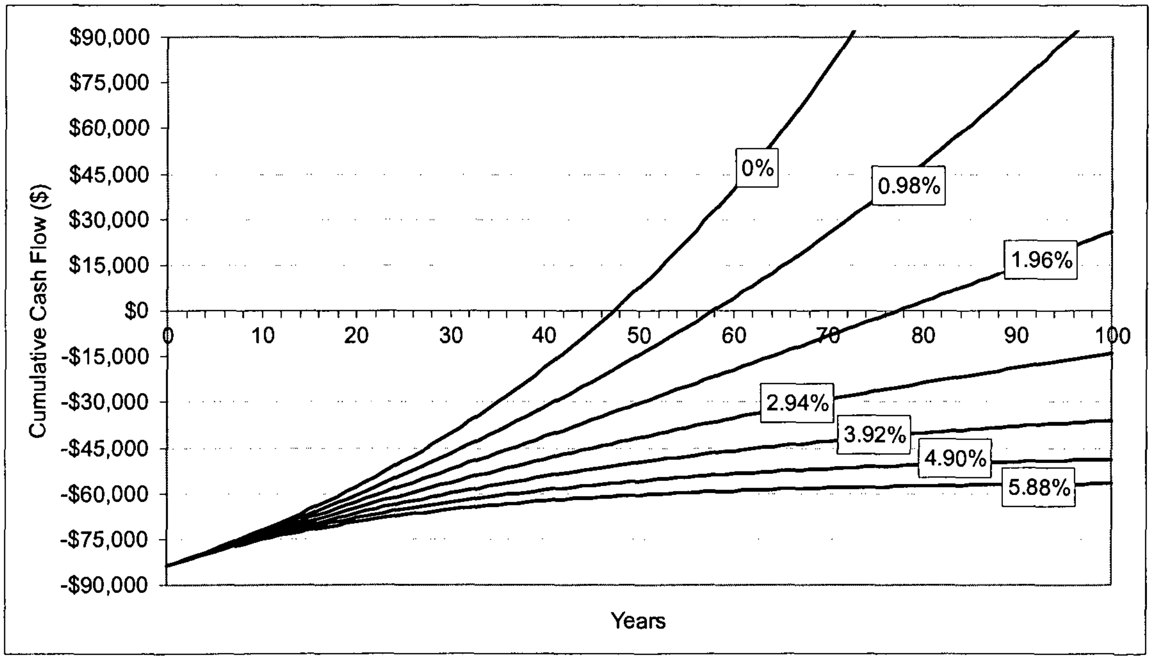


Figure 6.16: Cumulative cash flow for the 4 solar collector & 35.8 PV system on the NZEH for various effective interest rates (initial investment only)

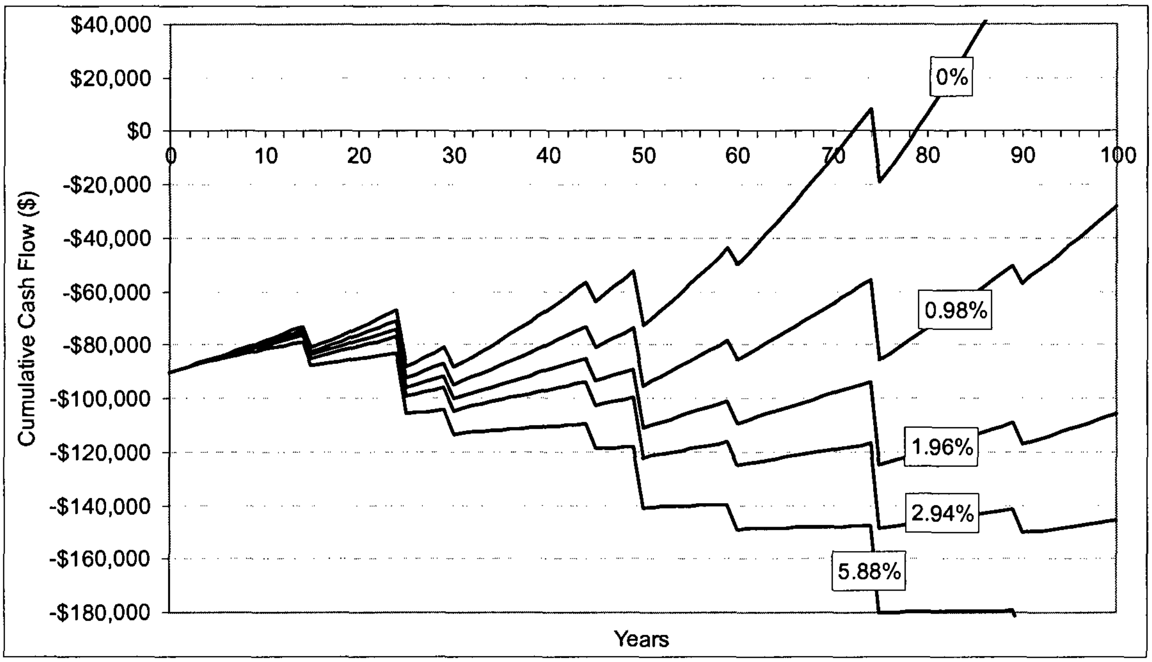


Figure 6.17: Cumulative cash flow for the 44.7 PV system on the NZEH for various effective interest rates (including replacement costs)

theoretically more and more valuable since it is assumed that it could be invested with a higher rate of return. Even if the discount rate equals inflation (effective interest rate = 0%), and thus the return on invested money in terms of present day dollars is zero, the payback for the 4/35.8 system based on the initial investment only is still 48 years, twice as long as the expected life of the system. When accounting for replacement costs, the payback takes about 78 years (for the 0/44.7 system).

6.1.2.4.3 The Impact of Incentives and Rebates on Payback Time

Across Canada, there are a variety of government and power company funded incentives and rebates for renewable energy and specifically solar powered energy generation. Unfortunately, in Quebec, none of the available federal, provincial or power company sponsored programs for renewable energy apply to newly constructed homes. There are a few grants or subsidies that do apply, however, to home renovations/retrofits. Since policy and programs are always changing and incentives for new construction could very possibly be introduced in Quebec in the future, some of the available programs from other provinces are examined here.

The Standard Offer Program (SOP)

One of the most interesting government programs is Ontario's Standard Offer Program (SOP). This program allows a homeowner with a PV system to sell all of the electricity they produce to their electricity provider through the grid at a price of $0.42/kWh. At the same time, all of the electricity the homeowner uses in the house is still supplied by and purchased from their electricity provider at the current rate, around $0.12/kWh (incl. tax) in Ontario. It is as if the PV system on the house is a separate electrical generation system that simply feeds the electrical grid. This is different from typical net metering programs which allow the homeowner to use the PV electricity produced directly, to buy more electricity from the electricity provider when needed and to send any extra PV electricity produced into the grid to turn the homeowner's meter backwards (which is essentially selling it for the same price at which it is purchased) (Ontario Power Authority 2008). The downside to net metering is that this usually only allows the house to be net-zero, even if they produce more than they use. However, the electricity still feeds the grid, so the environmental benefit is not negated. On the surface, the SOP seems like an incredible incentive in a province where electricity prices are around $0.12/kWh (incl. tax), and even better if it were available in Quebec with electricity at $0.0754/kWh (Hydro Quebec 2007). However, although homeowners are allowed to stop using the program at any time, if they do sign on, it is for a 20 year contract, with no increase in the $0.42/kWh.

As Figure 6.18 and Figure 6.19 demonstrate, the SOP program, if applied to the NZEH in Montreal, is slightly beneficial during those 20 years, but because the price that the homeowner pays for electricity continues to rise while the rate the homeowner sells it for remains stable, the benefit is less impressive than one might originally imagine. Based on both the 'initial investment only' method (Figure 6.18) and when considering replacement costs (Figure 6.19), after 20 years, an SOP program user will recover an extra $5,748 from their initial investment of $83,775 compared to no incentive program. However, for the 'initial investment only' method, the homeowner will still be $57,018 away from breaking even (for the 4/35.8 system) and $72,608 away from breaking even when considering the replacement costs (for the 0/44.7 system).

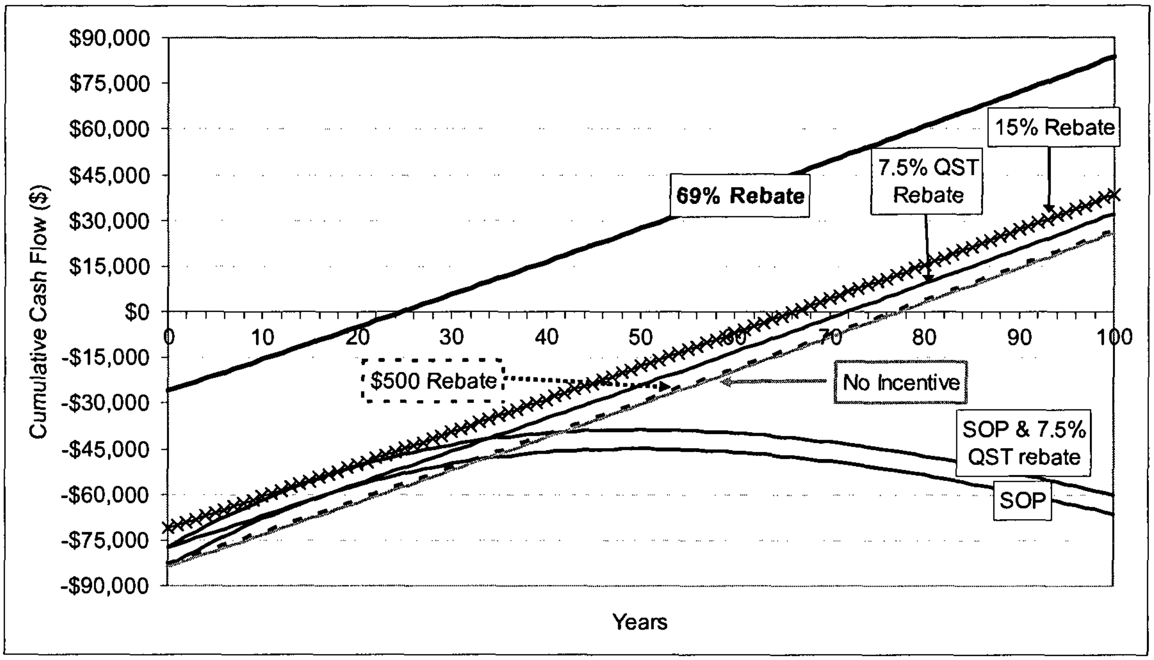


Figure 6.18: Cumulative cash flow for the 4 solar collector & 35.8 PV system in the NZEH with various financial incentives (initial investment only)

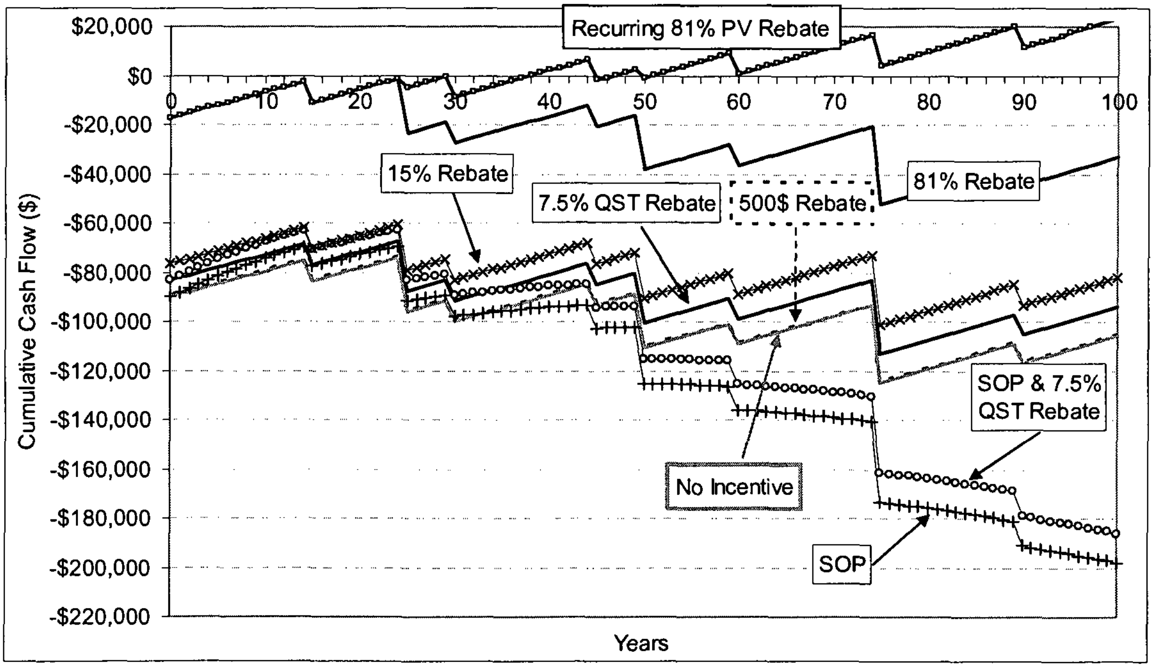


Figure 6.19: Cumulative cash flow for the 44.7 PV system in the NZEH with various financial incentives (including replacement costs)

Both figures also show that if the $0.42/kWh rate were to continue beyond the 20 years, it would start to be less beneficial than the regular net metering with no incentive at all after 34 years and as time went on, and electricity prices rose above $0.42/kWh, the homeowner would actually start to lose more and more money. Of course by this time the homeowner would cancel the SOP contract unless the new contract reflected the increase in electricity prices.

Overall, this program is of some benefit, but far less than one might think when the idea of selling electricity for almost 6 times what it costs to buy is first contemplated.

Provincial Sales Tax Rebates

Another possible incentive, which is available in the provinces of Ontario, British Columbia and Prince Edward Island, is a rebate on the provincial sales tax for both the solar collectors and PV systems. As seen in Figure 6.18, this would allow the homeowner to recover an extra $6,283 from the initial investment in the 4/35.8 system but still results in a long payback time of 72 years for the 'initial investment only' method. When considering replacement costs and applying the rebate to the full initial amount but only to the PV modules for the replacements (since inverters have other purposes and might not qualify for a rebate), the homeowner will recover $8,476 in rebates during the first 40 years (for the 0/44.7 system, as seen in Figure 6.19). However, this is not enough to change the downward direction of the CCF and thus a break even point is never achieved, even long after the 40 years.

Combining this 7.5% rebate with the SOP (using Quebec rates and taxes), after 20 years the homeowner would recover an extra $12,031 from the initial investment compared to no incentive program (for the 4/35.8 system). But again, the homeowner will still be $50,735 away from breaking even. For the 0/44.7 system including replacement costs, the homeowner recoups $12,498 compared to no incentive but is still $65,858 away from recovering the investment.

15% Solar Water Heating Rebate

Nova Scotia has a program from Conserve Nova Scotia called the 'Solar Water Heating Rebate'. This is a 15% rebate on the installed cost of the solar water heating system, up to a maximum of $20,000. The impact of this incentive is obviously similar to, but slightly better than the 7.5% tax rebate. With twice the rebate, monetary recovery is essentially double. The initial investment recovery for the 4/35.8 system is $12,566 and results in a payback time of 67 years for the 'initial investment only' method. When considering replacement costs and applying the rebate to the full initial amount but only to the PV modules for the replacements, the homeowner will recover $16,593 in rebates during the first 40 years (for the 0/44.7 system, as seen in Figure 6.19). However, this is still not enough to change the downward direction of the CCF and thus a break even point is never achieved, even long after the 40 years.

$500 Federal Rebate

The federal government also offers a $500 rebate on solar energy retrofits (Natural Resources Canada 2008). If this were applicable to a new home, in this case this NZEH, this grant would do very little to help a homeowner recoup the initial investment. The $500 reduction in the initial cost of the systems would reduce the payback time from 77.3 to 76.9 years for the 4/35.8 system using the initial investment method. The impact when considering the replacement costs is evidently also minimal. This is shown in both Figure 6.18 and Figure 6.19 but it is hard to actually see the lines since they are so close to the cases with no incentives.

Rebate Needed for 25 Year Payback

Finally, the last incentive tested is not an actual incentive available, but rather the amount that would be required to achieve a payback of 25 years, the service life of the solar collectors and PV modules. For the 'initial investment only' analysis of the 4/35.8 system, this requires a 69% rebate on the initial cost of the entire $83,775 solar system. Considering the 0/44.7 system and taking into account replacement costs, the incentive would need to be an 81% rebate on the initial $89,995 cost of the system. Since at this point the PV modules need to be replaced, Figure 6.19 shows that to keep a positive cash flow, the incentive must be applied to the replacement system as well. If the rebate applies only to the newly replaced PV modules and not the inverter replacements, then the CCF will dip into the negative for a while but eventually become positive again after about 38 years.

6.2 THE COST VS. ENERGY USE REDUCTION IN THE NZEH

Previously, in section 6.1.2.1, it was shown that the payback time for all of the differences between the BCH and the NZEH (before including the solar technologies) is just under 40 years and costs $34,287 (initial + replacement costs). However, what is even more interesting is to look at each individual change and see their payback times as well as which of those are the most effective in reducing the electricity use. In order to do this, simulations of many variations of the model were run to determine both the individual and cumulative impact of each of the changes made to the house. These results show the reduction in electricity use in the house if only the change in question is made, such as only improving the insulation, as well as the impact on electricity use when each change is cumulatively added, step by step. The order selected for this step by step process of cumulative changes follows the logical process of constructing an energy efficient house. First construct the structure and envelope, then determine the energy saving devices used in the house and then size the solar technologies used to reduce the house electricity loads to zero.

Each figure in this section appears to be duplicated, but there is one key difference in these paired figures. The first shows the most cost efficient case (over the 40 year life cycle) which is the case that uses a solar system with only PV modules and no solar collectors. The second figure shows the most cost efficient version that does contain solar collectors as well. This is done to show the case that was determined to be the best solar system choice from a life cycle cost point of view but also show the case with solar collectors, which after 40 years is only slightly more expensive ($1,981 more).

Figure 6.20 and Figure 6.21 show many details related to the individual and cumulative impacts on the electricity use in the house when improving the house. Firstly, the *Real*

Cumulative Reduction is the reduction in electricity use as a result of cumulatively combining one change after another. For example, changing the BCH from electric baseboards to a radiant floor system results in an electricity reduction of 597 kWh/yr. Then, taking that new model one step further by improving the insulation in the walls and attic, the house uses 3,390 kWh/yr less than the original BCH. The next step of changing the windows from double pane to triple pane (+Better Windows) cumulatively reduces it by 4,814 kWh/yr. This process continues with each change until it becomes the completed NZEH with a cumulative reduction of 25,615 kWh/yr.

The *Independent Electricity Reductions* and the *Real Incremental Electricity Reductions* are very similar with one key difference. The *Real Incremental* values relate directly to the *Real Cumulative Reductions* described above. These are the real incremental differences in electricity reductions from one modification to the next, and added together they equal the final value for the *Real Cumulative Reduction.* For the example above, the *Real Incremental Electricity Reduction* for the +Better Windows step is 1,424 kWh/yr. This is the incremental change from the case with radiant floors and more insulation to the next step with the better windows (3,390 + 1,424 = 4,814 kWh/yr).

The *Independent Electricity Reductions* on the other hand, are also the reductions for each incremental change, however these values are independent of all of the other changes. Whereas the *Real* values are impacted by all of the changes made previous to the one in question, the *Independent* values were simulated completely on their own (in the BCH with radiant floors), with no other house modifications in place. For example, for the +Better Windows step, the model was simulated with triple pane windows, but without any of the increased insulation. Showing the independent impact of each modification compared to the real incremental impact reveals how much the previous changes influence the potential of any given additional change. For the case of the +Better Windows, the difference is small (1,424 kWh/yr vs. 1,427 kWh/yr), but for other cases, such as the 4 flat plate solar collectors, the difference is considerable (4,394 kWh/yr vs. 2,819 kWh/yr). This shows that the same technology or change can have a very different impact depending on what other changes it is combined with. In this case, the solar collector has a smaller impact on the NZEH when all other changes are made, because tested on its own it was simulated in the BCH that uses much more hot water. When the DHW tank is emptied of its hot water much more often and the radiant floor hot water tank is used more often to heat a poorly insulated house, the solar collector can potentially collect much more energy since it has more opportunities to use it and store it. However, although this gets more use out of the solar collectors, that does not mean it is better to have an inefficient house. For example, although 1,575 more kWh/yr are collected and used by the solar collector when, among other things, the insulation is not improved, the insulation improvements alone reduce the electricity use by 2,793 kWh/yr. This is 1,218 kWh/yr better, and that does not even include the other 7,479 kWh/yr in reductions from all of the other changes that were made before adding the solar collectors.

As explained above, the *Independent Electricity Reductions* are basically the difference between the BCH (with radiant floors) and the same model including the change in question. However, the *Independent Electricity Reductions* could have just as easily been done by comparing the 'final NZEH' with the 'final NZEH minus the change in question'. These two methods do give different results, but are both equally valid. The method shown in this thesis – adding to the BCH – was chosen to allow insight into the effects of taking a regular house and making just one improvement. The other method (not shown here) that works backwards from the completed NZEH is useful to see the cost and energy impacts of individually avoiding any of the many modifications made to achieve the complete NZEH design. One example of this is shown later in this chapter regarding the + *More Better Windows* step (going from a small area of triple pane windows to a large area of triple pane windows).

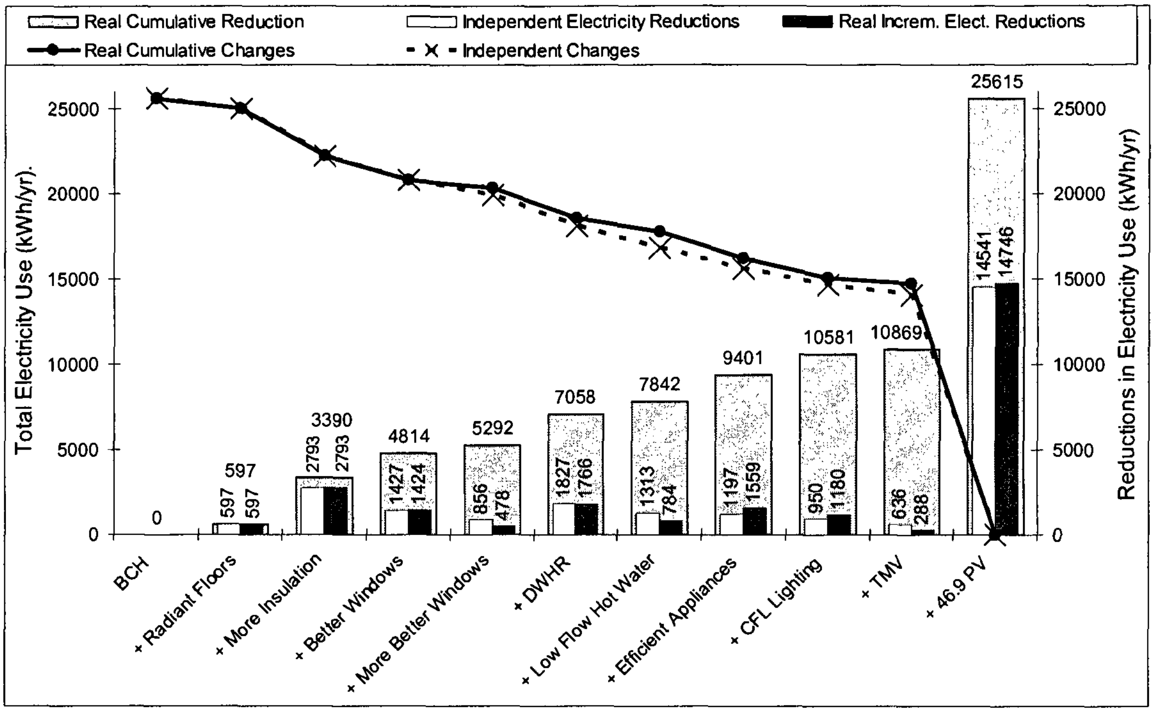


Figure 6.20: The incremental impact on electricity use reductions from changes made to the BCH for it to become the NZEH (Case with PVs only and no solar collectors)

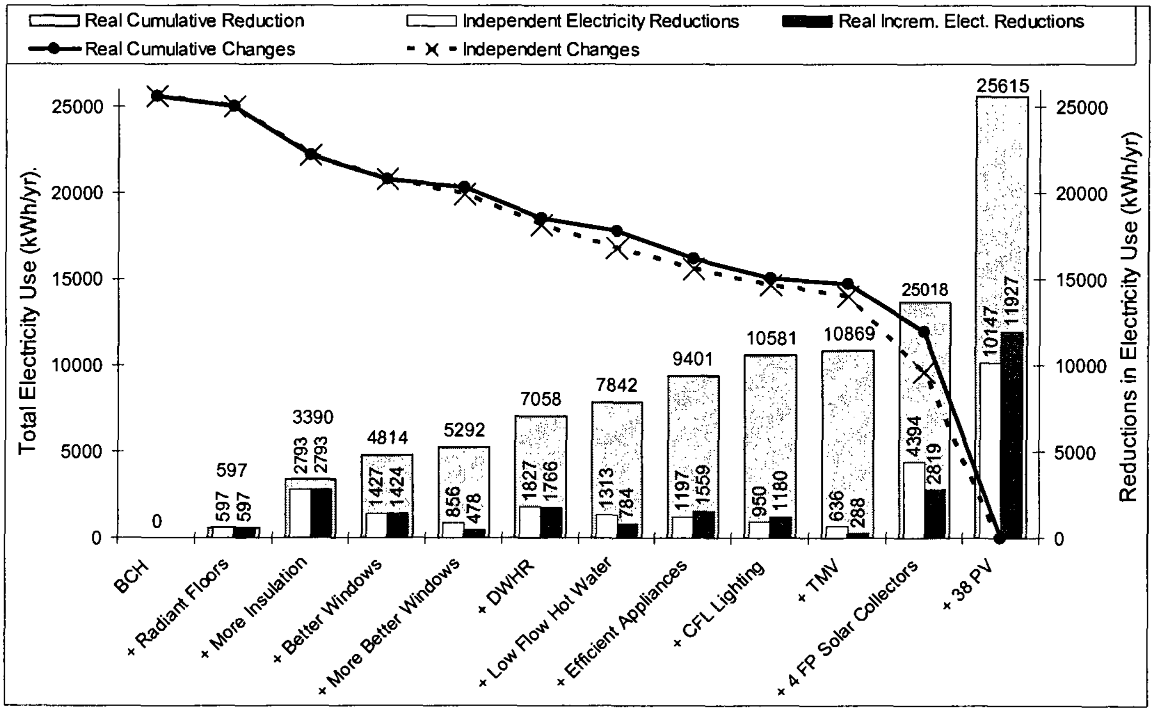


Figure 6.21: The incremental impact on electricity use reductions from changes made to the BCH for it to become the NZEH (Case with 4 flat plate solar collectors and PVs)

One important detail for all of the figures that relate to the *Independent Electricity Reductions* is that the results are of individual changes in the BCH with radiant floors. This was necessary, as opposed to using the BCH with baseboard heaters, for two reasons: Firstly, in the NZEH, all of these changes have an impact when the radiant floor heating system is in place, so it makes more sense to test them individually with the same type of heating system. Secondly, the solar collectors cannot be tested without the radiant floors since they provide hot water for both DHW and space heating.

Figure 6.20 and Figure 6.21 also have two lines plotted that show the cumulative effect of the electricity reductions from each change made to the house. The terms *Real* and *Independent* are the same as described above with the *Independent* line being the sum of all of the *Independent Electricity Reductions*. The last step of adding 46.9 PV modules in Figure 6.20 (or 38 PV modules in Figure 6.21) actually applies to the *Real* case since the sum of the independent changes results in only needing 46.3 PV modules (or 32.3 PV modules in Figure 6.21), which is not what is really needed when all of the changes are combined to make the NZEH. Since the lines are so close together, this demonstrates that aside from the solar collector step, compared to the total house electricity loads, most changes have a similar impact whether they are made in combination with the others or independently. This would be reassuring to a homeowner or builder who might decide to make some, but not all of these changes, since they will still likely have the intended impact on electricity reductions.

One noteworthy point is the fact that the number of PV modules in these two figures is not the same as the quantity mentioned throughout the rest of this thesis that are required to make the home truly ‘net zero’. As opposed to the often mentioned 44.7 PV module system, Figure 6.20 shows 46.9, and in the usual case of 4 flat plate solar collectors and 35.8 PV modules, Figure 6.21 shows 38 PV modules. The former quantities (44.7 and 35.8) are the correct numbers of modules for the simulated NZEH models described throughout this thesis. The reason for these differences relates to the electrical heating elements and heating set points used specifically in the simulations for the incremental and individual data presented in this section. In the complete NZEH, the power and set points for the heating elements are configured to heat the house to the desired temperatures. However, when the same configuration is used in the house for simulations with reduced insulation and lacking other energy efficiency measures, the simulations result in house temperatures that are too cold. In order to maintain temperatures similar to those in the finished NZEH, some small modifications are made to the heating element configurations for this specific investigation. These changes result in the need for slightly more electricity overall. These slight differences cause the results for the incremental reductions in electricity use to be a little bit different than the main NZEH model and thus the payback times are also slightly different as well. For example, the financial payback time for the changes to the house just before adding the solar technologies is 41.7 years in Figure 6.24, but the actual payback based on the main simulations of the NZEH is 39.3 years. In general, the results from this incremental analysis based on the BCH result in financial payback times a few years longer than the expected results using the main NZEH model. Although there are some minor differences between this incremental analysis and the main simulations in this thesis, this was unavoidable, it is more important to achieve results for a house with the proper zone temperatures and the conclusions drawn from this analysis are no less valid.

As incremental changes are tested in this model, several variations of window installations are described. *More and Better Windows* refers to the complete window change between the BCH and the NZEH where the smaller area of double pane windows is changed to a larger area of triple pane windows. *Better Windows* refers to changing to triple pane windows but keeping the same area as in the BCH. *More Windows* refers to keeping double pane windows but adding more to cover the area used in the NZEH. And finally, *More Better Windows* (not to be confused with *More AND Better Windows*) is the step of going from triple pane windows coving the smaller BCH area to installing more triple pane windows to achieve the NZEH window area. Table 6.14 shows how the prices for some of these window combinations are calculated. It also shows the calculation for the extra cost of more wall and attic insulation. To get the cost of the *More Better Windows* step ($16,276), the cost of the *Better Windows* ($4,840) is subtracted from that of the *More and Better Windows* ($21,116).

Table 6.14: Incremental cost differences for various cases of improved insulation and windows (From the Base Case House with radiant floors to the specified change)

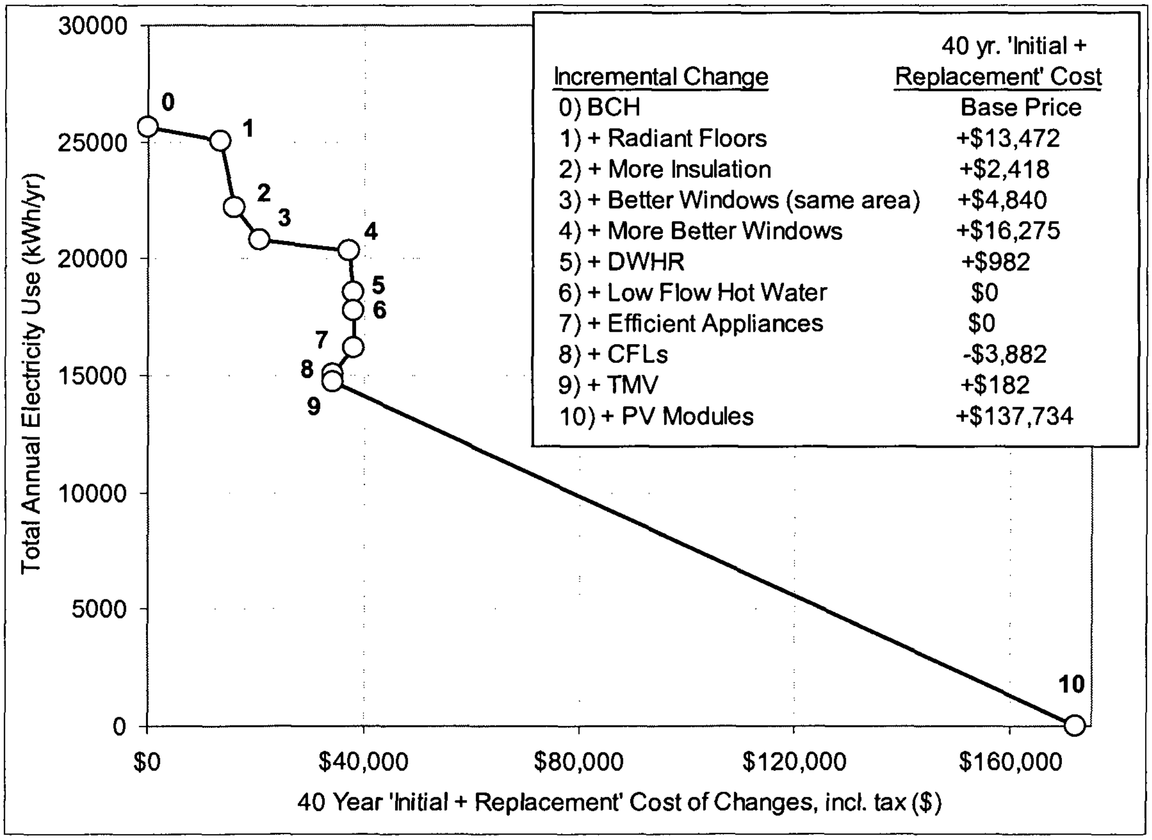
LEGEND:
: New materials added to the NZEH
Ø : Materials removed from the BCH design to make the NZEH

	Material	**Total 'initial + replacement' Cost ($)**
Wall and Attic Insulation Modifications		
Ø	Wood Floor Studs, 2x12 (38 mm x 286 mm) in the Attic	-942
	Wood Floor Studs, 3x16 (64 mm x 387 mm) in the Attic	1,352
	Mineral Wool Floor insulation (difference between BCH & NZEH), 160 mm in Attic	477
	Wood Wall Studs, 2x10 (38 mm x 235 mm) in B1 & C1	1,224
Ø	Wood Wall Studs, 2x6 (1.5 x 5.5 = 38 x 140) in B1 & C1	-784
	Mineral Wool Wall insulation, 229 mm in B1 & C1	2,031
Ø	Mineral Wool Wall insulation, 140 mm in B1 & C1	-1,217
	TOTAL	**2,142**
	TOTAL (incl. Tax)	**2,418**
Window Type and Quantity Modifications (*More and Better Windows*)		
	Operable Casement, triple pane, argon filled	35,055
	Fixed Picture, triple pane, argon filled	10,722
Ø	Operable Casement, double pane, argon filled	-29,990
	Window Installation Difference between BCH & NZEH	2,920
	TOTAL	**18,707**
	TOTAL (incl. Tax)	**21,116**
Window Type Modifications. Double Pane to Triple Pane with BCH window area (*Better Windows*)		
	Operable Casement, triple pane, argon filled	33,613
Ø	Operable Casement, double pane, argon filled	-29,325
	TOTAL	**4,288**
	TOTAL (incl. Tax)	**4,840**
Window Quantity modifications. NZEH window area with double pane (*More Windows*)		
	Operable Casement, double pane, argon filled	30,368
	Fixed Picture, double pane, argon filled	8,772
Ø	Operable Casement, double pane, argon filled	-29,990
	Window Installation Difference between BCH & NZEH	2,920
	TOTAL	**12,070**
	TOTAL (incl. Tax)	**13,624**

Sources: Rona Renovateur 2008, RS Means 2008, The Home Depot 2008, Glass Experts 2008
Details of these prices can be found in Appendix C, Table C-1 and Table C-2

Figure 6.22 and Figure 6.23 allow for a visualization of the annual house electricity reduction vs. the 40 year 'initial + replacement' cost for each incremental change made to the house. The most cost effective changes are the lines that are the most vertical. In addition, the longer a line descends vertically, the more that particular change reduces electricity use in the house. This shows that the increased insulation is one of the most cost effective changes since it is costs relatively little for the large electricity use reduction. Other excellent changes that both cost very little and reduce the electricity use significantly are: the DWHR pipe, the efficient appliances (since chosen properly, they do not necessarily cost more than regular appliances) and the CFL lighting. The CFLs are actually a special case since, as the figure shows, the cost line goes backwards. This means that they actually cost less than standard incandescent lights. This is because all of these costs are life cycle costs. Since CFL lighting lasts about 8 times longer than regular incandescent lights, although the initial cost of the bulbs are more, they need to be replaced far less often over the course of 40 years. Therefore, not only do they reduce the electricity use in the house by 1,180 kWh/yr, but they save the homeowner $3,882 over 40 years in material costs alone.

On the other end of the spectrum, Figure 6.23 shows that change no. 4, adding more triple pane windows, has relatively little impact on the house electricity loads (-478 kWh/yr) compared to their high cost ($16,275). In hindsight, this change is probably not worth implementing when designing an efficient, but cost conscious house. The other relatively flat line is the addition of the radiant floors. Deciding whether or not to keep this in the NZEH is more complicated. If solar collectors are being installed as part of the solar system then radiant floors are necessary since the majority of the hot water from the bank of solar collectors is used to heat water for the radiant floors. However, if the slightly less expensive (over a 40 year life cycle) 'PV only' system is used as the solar system, then technically the electricity can also be used to power baseboard heaters rather than electrical heating elements in the radiant floor hot water tank. Considering that the change from baseboard heaters to radiant floors costs and additional $13,472 over 40 years, this could be seen as a compelling argument. However, removing the radiant floors also eliminates the benefit of more stable room temperatures due to the thermal mass from the concrete floors as well as the fact that many people find that radiant floors provide a much more comfortable living space. Therefore, from a purely financial point of view, all PVs and baseboard heaters might be optimal, but this could very possibly sacrifice occupant comfort which might be worth the extra cost. In addition, although this may be the most cost effective solution, using PVs to power baseboard heaters may not be the best choice from a thermodynamic point of view. Other options not covered in this thesis, such as using heat pumps or geothermal energy are likely more efficient due to their COP values. But if the goal is to encourage homeowners by providing cost effective solutions, baseboard heaters are certainly an option to consider.



Incremental Change	40 yr. 'Initial + Replacement' Cost
0) BCH	Base Price
1) + Radiant Floors	+$13,472
2) + More Insulation	+$2,418
3) + Better Windows (same area)	+$4,840
4) + More Better Windows	+$16,275
5) + DWHR	+$982
6) + Low Flow Hot Water	$0
7) + Efficient Appliances	$0
8) + CFLs	-$3,882
9) + TMV	+$182
10) + PV Modules	+$137,734

Figure 6.22: Annual house electricity use vs. cumulative 40 year 'initial + replacement' cost for changes made to the BCH to become the NZEH (PV only and no solar collectors)

Finally, the solar collectors and the PV modules are still quite expensive, as seen by the more gently sloped lines, but they are both critical technologies required to design the NZEH. Figure 6.23 shows that the slope of the lines from the solar collector and PV systems are almost identical and thus the cost per resulting reduction in electricity use is very similar for these two technologies. Although it is true that initially PV modules are typically the more expensive technology, even on a dollar per kWh reduced basis, this is not necessarily the case in a complete life cycle cost analysis. This is explained in the previous cost section and is mostly due to the expected future reduction in PV prices as well as more frequent replacement costs associated with some solar collector system components.

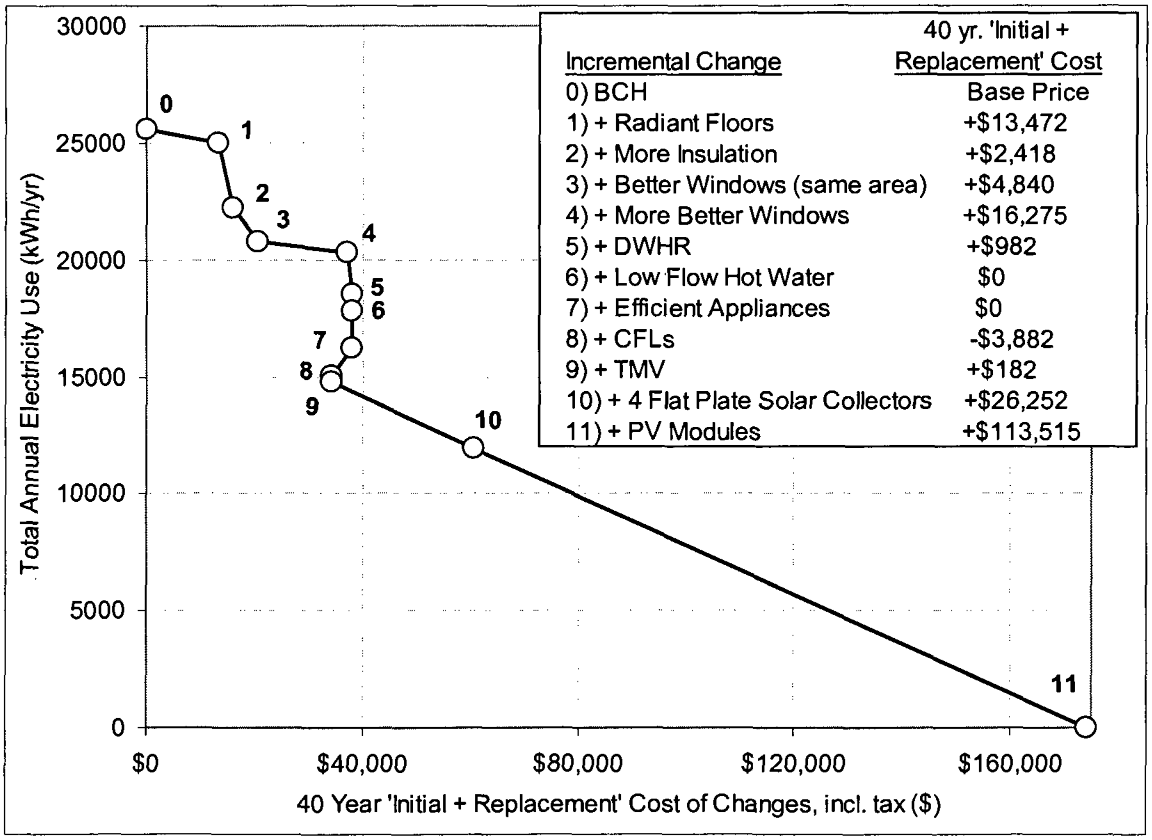


Figure 6.23: Annual house electricity use vs. cumulative 40 year 'initial + replacement' cost for changes made to the BCH to become the NZEH (4 flat plate solar collectors and PVs)

Figure 6.24 and Figure 6.25 show the CCF payback for all of the changes discussed above. It is important to note that these payback times are based on the 40 year 'initial + replacement' costs and do not include the cost of any replacements after the 40 years. This means that if the payback time is longer than 40 years, it serves only as a comparison tool but is not likely the actual time to achieve financial payback. Since most of these items will need replacement parts after the 40 years, which will drive the cumulative cash flow down, the items with payback times much longer than 40 years will not ever result in a financial payback. In addition it is assumed that since the life cycle of the house is 40 years, other major replacements will also be required. These figures also show which changes are the most cost effective and will end up paying for themselves.

What is also interesting in this figure is the *Real Cumulative Payback* since it progressively shows what the CCF payback time is, as each house modification is added, starting from the BCH. In the end, the final NZEH design with all of the solar technologies installed has a payback time of 83.8 years (the slightly modified version of the NZEH used for the incremental analysis shows 86.7 years in Figure 6.24). Although this does exceed the 40 year life cycle of the house, there are some positive things to note from these figures. Many of the changes made to the house do have much shorter individual payback times, such as the insulation, the three DHW related changes, the CFL lighting and the appliances. Even the change from double pane to triple pane windows nearly pays for itself in the 40 year house life cycle since they have a payback of 44.9 years. And of course it is important to note that the assumptions of the service life of each product are of course estimates and might actually last a bit longer than expected, resulting in better payback periods. Finally, these figures do show that overall, it is at least cost efficient to implement all of the changes to the house envelope and energy efficiency devices before adding the solar technologies because at the point just before the solar systems are added, the cumulative payback is 41.7 years (and as mentioned previously, this payback is actually 39.3 years using the main, unmodified NZEH model).

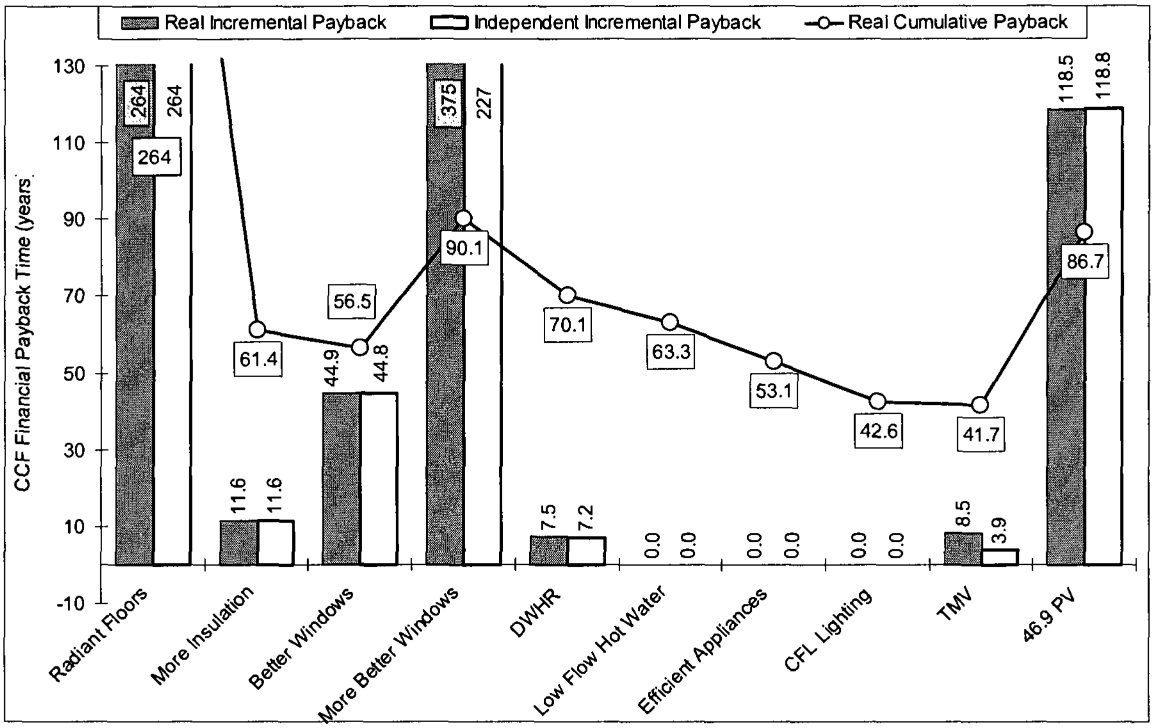


Figure 6.24: CCF payback times for each change to the BCH as it becomes the NZEH (PVs only and no solar collectors based on 40 year 'initial + replacement' costs)

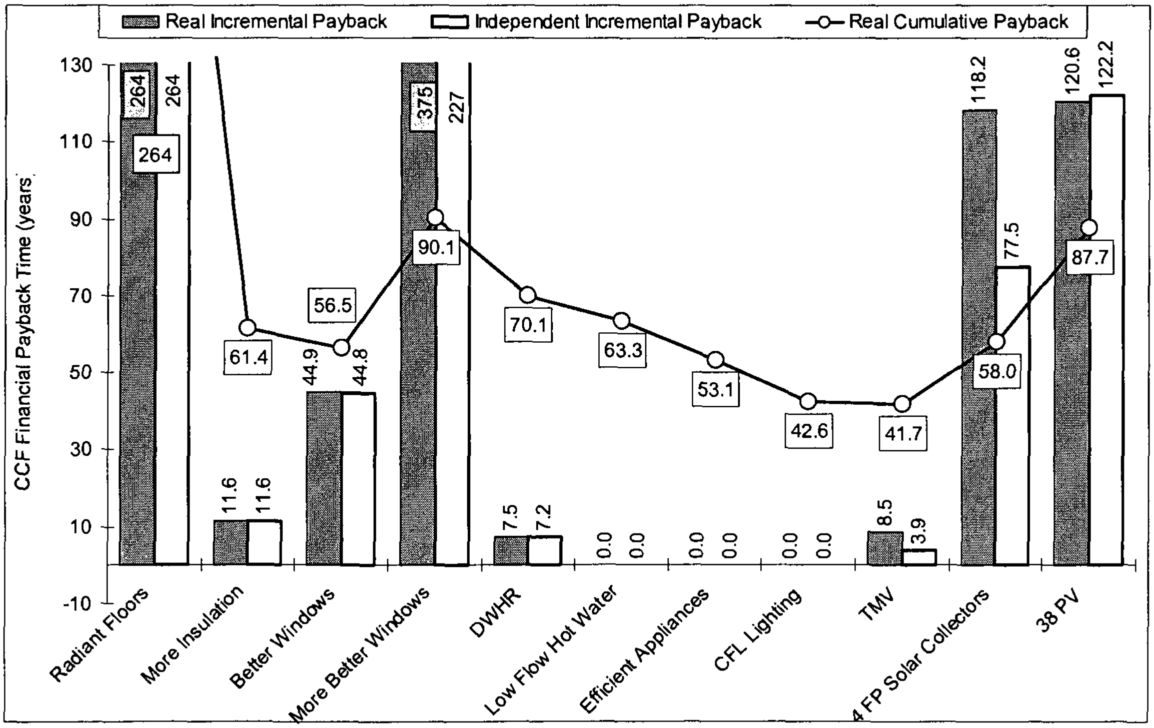


Figure 6.25: CCF payback times for each change to the BCH as it becomes the NZEH (4 flat plate solar collectors and PVs based on 40 year 'initial + replacement' costs)

Additionally, as suggested earlier in this section, it is not very cost effective to add the 'More Better Windows' (increased area of triple pane windows), but rather it is better to just change the existing, smaller area of double pane windows to triple pane windows. When the NZEH is simulated with the smaller area of triple pane windows, it requires 907 kWh/yr more electricity for the 'all PV' model and 541 kWh/yr for the NZEH with 4 solar collectors and PVs. Therefore, more PV modules (which also have a cost) are needed to make up the for the added electricity use, however more importantly, this reduces the cost of the windows by $16,275. The 'all PV' NZEH needs 2.9 more PV modules (costing an additional $7,864 over 40 years) and thus the net reduction in the life cycle cost of the house is $8,411. The NZEH with four solar collectors and PVs needs 1.7 more PV modules (costing an additional $4,654 over 40 years) and the net reduction in life cycle cost is $11,621. This results in total life cycle costs for the NZEH designs of $390,585 and $389,356 respectively and can be compared to the original NZEHs in Table 6.13 (comparing with the columns under 'including replacement costs'). This also changes the CCF payback of the 'NZEH before adding the solar system' from 39.3 years (or 41.7 years in Figure 6.24) to a significantly lower 22.6 years.

Using only PVs and baseboard heaters rather than radiant floors and solar collectors also has a significant impact on reducing the financial payback time. By avoiding the extra $13,472 cost of the radiant floors, the house requires about 597 kWh/yr more electricity with the baseboard heaters. This needs to be taken care of by installing 1.9 extra PV modules which increase the 40 year 'initial + replacement' cost of the PV system by $5,154. Therefore, the net life cycle cost reduction of staying with the baseboard heaters rather than installing radiant floors is $8,318, resulting in a new life cycle cost of the NZEH of $390,678. This reduces the CCF payback of the 'NZEH before adding the solar system' from 39.3 years to a significantly lower 25.4 years. However, as discussed above, this sacrifices the comfort in the house, which could be quite important to some people. This is not to say that baseboard heaters do not result in a relatively comfortable house, but to some homeowners, the extra cost for certain advantages are considered acceptable. In addition, since it is impossible to predict the future, one must always consider the possibility that the PV modules will not go down in price as much as is assumed in this thesis, in which case the use of solar collectors combined with PVs could be noticeably less expensive than just PVs. This would then require the radiant floor and also offset some of the cost differences between this option compared to only PVs with baseboard heaters.

Table 6.15: Life cycle costs and payback times for more cost effective versions of the NZEH

	Version of the NZEH			
Stage	**Original with 44.7 PV**	**Small Area of Triple Pane Windows (47.6 PV)**	**Baseboard Heating (46.6 PV)**	**Small Area of Triple Pane Windows + Baseboard Heating (49.5 PV)**
	40 Year Initial + Replacement Cost ($)			
♦Basic Construction	232,943	232,943	232,943	232,943
Energy Efficiency Modifications	34,287	18,012	20,815	4,540
PV System	131,766	139,630	136,920	144,773
Total Life Cycle Cost	398,996	390,585	390,678	382,256
	Payback Time (Years)			
Before Adding the Solar System	39.3	22.6	25.4	6.1
Complete NZEH*	83.8	79.8	79.8	75.71

* Since the payback times for the complete NZEH versions exceed the 40 year life of the house, these values are useful for comparison, but do not represent actual payback times. This is because replacement costs are only included up to the 40 year life of the house.

If both the larger window area and the radiant floors are left out of the final NZEH design, it reduces the 40 year 'initial + replacement' cost of the NZEH by a very significant $29,747. This is very significant since it is 87% of the extra cost associated with the energy efficiency changes to the NZEH (before adding the solar systems). Together, these increase the electricity load in the 'PV only' NZEH by about 1504 kWh/yr and thus require 4.8 extra PV modules (costing an additional $13,007 over 40 years). This results in a net life cycle cost reduction of the NZEH of $16,740 and thus this version of the complete NZEH has a life cycle cost of $382,256. In addition, this reduces the CCF payback of the 'NZEH before adding the solar system' from 39.3 years all the way down to 6.1 years.

Table 6.15 (above) summarizes the costs and payback times associated with the more cost effective, modified versions of the NZEHs described above.

6.3 LIFE CYCLE ENERGY

Just like the life cycle cost has its complexities from cost values that can quickly change and vary depending on location and local, national or world economic situations, due to many varying factors, it is also difficult to obtain accurate data for life cycle energy; perhaps even more so. In addition to operating energy, life cycle energy includes the embodied energy of all materials, components, sub-systems and equipment used in the house. Since embodied energy is the energy a product uses throughout its life, from cradle to grave, (i.e. from resource extraction, through transportation, transformation, production, delivery, maintenance, demolition and finally recycling/reuse/disposal), estimating these values can be quite complex. Since there are so many steps throughout the life of a product, the energy required for each step can vary significantly depending on many things such as where the product is produced and what type of energy source is used, how far the raw materials or final product needs to be transported (across a city or across the world), if recycled materials are used, etc.

In order to reduce the uncertainties regarding the embodied energy values used in this chapter, the data comes from a variety of sources that attempt to take the aforementioned complexities into account. For the embodied energy of the house construction, the Athena Institute Impact Estimator (Athena Institute 2008) is used. The results obtained from this software are based on Athena's large and detailed databases and internationally recognized life cycle analysis methodology. In addition to the fact that all of life cycle steps mentioned above are taken into account, the software also considers the location of the project, in this case Montreal. The solar collector and PV systems cannot be modeled with the Athena software. For these, a detailed literature review was undertaken in order to estimate the embodied energy of those systems. The details are presented in the following sections.

One term used often in this section is 'energy payback time'. There are in fact two ways that energy payback time can be calculated:

Energy Payback Time Based on Electricity Use Reductions. This is the amount of time that it takes for the annual reductions in electricity use from a change in the house to offset the total embodied energy contained in the materials needed for that change. This is calculated by dividing the total extra embodied energy in the materials of the change by the annual electricity use reductions from that change.

Energy Payback Time Based on Primary Energy Use Reductions. This is the amount of time that it takes for the annual reductions in primary energy use from a change in the house to offset the total embodied energy contained in the materials needed for that change. This is calculated by dividing the total extra embodied energy in the materials of the change by the annual primary energy use reductions from that change. This energy payback time is always shorter than the payback time based on the electricity use reductions. This is because the primary energy is all of the energy that it takes to supply electricity to the house, which comes from various sources (hydroelectric dam, fossil fuel power plant, etc) that have inefficiencies and transmission losses. Therefore, the quantity (in kWh) of primary energy is always larger than the associated electricity (in kWh) that it is creating.

An important difference between the energy payback times calculated with the two methods is that the values based on the primary energy use reductions highly depend on how the electricity is being generated. In Quebec, for example, where the majority of electricity is produced from highly efficient hydroelectricity, the values for primary energy are relatively similar to the associated electricity supplied to the house. However, if the house is located in an area where electricity comes mostly from a coal fired power plant, the primary energy will be much larger than the electricity and result in much shorter energy payback times. The method based on electricity use reductions is much less variable since those values are based on the on-site electricity use and don't depend on externalities such as the power generating facilities. In this thesis, based on information from the Athena Institute Impact Estimator for Buildings, the primary energy is estimated to be 1.074 times larger than the electricity use in Quebec.

Energy Payback Ratio (EPR) is another term used throughout this section. This term can also be calculated based on electricity use reductions or primary energy use reductions. The EPR (based on primary energy use reductions) shows the number of times during its useful life that a change in the house causes a reduction in primary energy use that is equivalent to the embodied energy of the change. An EPR of 1 means that the change is exactly net zero energy, however many changes do much better than that and over time they result in primary energy reductions much larger than their own embodied energy. The larger the EPR, the better. EPR is calculated by dividing the 'total life cycle primary energy use reduction' that results from a particular change by its life cycle embodied energy. The EPR based on electricity use reductions is calculated by simply replacing the primary energy use reduction with the associated electricity use reduction in the above explanation.

One important thing to note is that the EPRs calculated for the solar systems and many of the other changes are useful, but underestimated. This is because a consistent and conservative approach was taken such that the primary energy and electricity use reductions are all based on a 40 year time frame and all of the embodied energy values are from system/component changes that last at least 40 years (through replacements when necessary). Many of the changed systems/components will last longer than 40 years, such as the PV modules and solar collectors which are replaced after 25 years and are thus expected to last at least 50 years. This decision was taken since the solar systems are made up of components that are replaced at different intervals (e.g. 10, 15 and 25 years) and are not expected to cease functioning after the same number of years. Therefore, using one common year, consistent with the life cycle time used throughout this thesis is the best approach.

It is also important to note that the embodied energy values used to calculate the EPRs as well as the energy payback times are the net changes in embodied energy (compared to the BCH) for a particular change. This is why some changes, such as changing to energy efficient appliances, result in an energy payback time of zero years even though the appliances clearly do have embodied energy. However, they don't have more embodied energy than the standard appliances in the BCH.

6.3.1 Base Case House

6.3.1.1 Base Case House Construction

Based primarily on the construction details of the BCH provided in Chapter 4, the house was modeled in the Athena Institute Impact Estimator software. The resulting life cycle embodied energy of the materials are presented in Table 6.16 along with the operating energy. The table is broken into life cycle stages, and in each stage, it details the amount coming from hydroelectricity and from other primary fuels such as natural gas, petrol, coal, etc. The ratio of the sources of each energy come from statistical data compiled by the Athena Institute. Even though many people think that 100% of their electricity in Quebec comes from a hydroelectric dam, the electricity actually comes from a mix of sources. This is why only 90% of the operating energy is from hydroelectricity.

Aside from a few house components that need to be replaced prior to the end of the 40 year life cycle of the house, the embodied energy in the vast majority of the house components is a one time quantity embedded in the house materials. One significant exception to this is the energy from the operation of the house, i.e. the operating energy. This is measured on an annual basis and steadily accumulates over the life of the house. The total, 40 year operating energy listed in Table 6.16 is 1,100,629 kWh. This is from 27,516 kWh each year, which is the total primary energy required to provide the BCH with 25,615 kWh of electricity annually.

Due to a lack of reliable information in this new field, the embodied energy calculations do not include appliances, furnishings, electrical wiring and lighting, or general plumbing, with the exception of the baseboard heaters (with replacement after 20 years) and the DHW tank (including replacements every 15 years). It is assumed that the embodied energy in a regular hot water storage tank is 75% of that from a solar hot water storage tank equipped with a heat exchanger. The value used comes from Table 6.20.

Table 6.16: The 40 year life cycle energy (embodied & operating) for the BCH

Life Cycle Stage	40 year Life Cycle Energy		
	Hydroelectricity (kWh)	**Total Primary Fuels (kWh)**	**Total Energy (kWh)**
Manufacturing			
Material	32,707	160,393	193,100
Transportation	0	3,325	3,325
Total	32,707	163,718	196,425
Construction			
Material	612	1,167	1,779
Transportation	0	10,123	10,123
Total	612	11,290	11,902
Operations & Maintenance			
Material	18,073	51,630	69,703
Transportation	0	1,235	1,235
Total Operating Energy	993,862	106,767	1,100,629
Total	1,011,935	159,632	1,171,568
End-Of-Life			
Material	0	5	5
Transportation	0	1,922	1,922
Total	0	1,927	1,927
Total			
Material	51,392	213,195	**264,587**
Transportation	0	16,606	**16,606**
Total Operating Energy	993,862	106,767	**1,100,629**
Total	1,045,254	336,568	**1,381,822**

6.3.2 Net Zero Energy House

6.3.2.1 NZEH Construction

Similar to the previous table for the BCH, Table 6.17 shows the 40 year life cycle energy in the NZEH which is made up of the embodied energy of the materials as well as the operating energy. However, in the case of this NZEH, the operating energy is considered to be zero since it is all supplied by renewable solar energy. The table does not include the embodied energy in the solar system (the solar collectors and the PV modules). This data is presented in sections 6.3.2.3 and 6.3.2.4.

As in the BCH, the embodied energy values for the NZEH do not include appliances, furnishings, electrical wiring and lighting or the general plumbing, with the exception of those associated with the solar combisystem. The four radiant floor pumps and the manifolds are also not included, however the rest of the radiant floor system is.

The life cycle energy in the BCH and NZEH are compared in section 6.3.3.

Table 6.17: The 40 year life cycle energy (embodied & operating) for the NZEH (not including the embodied energy from the solar technologies)

Life Cycle Stage	40 year Life Cycle Energy		
	Hydroelectricity (kWh)	**Total Primary Fuels (kWh)**	**Total Energy (kWh)**
Manufacturing			
Material	39,348	196,227	235,575
Transportation	0	4,051	4,051
Total	39,348	200,278	239,626
Construction			
Material	581	1,164	1,744
Transportation	0	10,968	10,968
Total	581	12,132	12,713
Operations & Maintenance			
Material	27,376	67,677	95,053
Transportation	0	1,618	1,618
Total Operating Energy	0	0	0
Total	27,376	69,294	96,670
End-Of-Life			
Material	0	6	6
Transportation	0	2,101	2,101
Total	0	2,107	2,107
Total			
Material	67,304	265,074	**332,378**
Transportation	0	18,738	**18,738**
Total Operating Energy	0	0	**0**
Total	67,304	283,812	**351,116**

6.3.2.2 Individual Efficiency Improvements in the NZEH

Since reliable data is not available for the embodied energy contained in some of the individual efficiency changes that result in the NZEH (such as appliances, lighting and the TMV), a step by step comparison like that done in the cost analysis section is not possible. However, the estimated embodied energy for some of the efficiency improvements are presented here and summarized in Table 6.19.

Radiant Floors

Changing from baseboard heating to radiant floor heating requires a significant change in the floor construction. Table 6.18 shows the additional materials required and leaves out the materials that are already in the BCH such as a concrete basement floor. The manifolds, thermostats, pumps and controls are not included due to a lack of reliable information for those components. The embodied energy in these missing components are not expected to make up a large part of the total for the radiant floors. With 13,171 kWh of embodied energy in the extra materials that make up the radiant floor (including the subtraction of the embodied energy of the electric baseboard heaters) and the 641 kWh of annual primary energy use reduction (597 kWh of annual electricity

Table 6.18: Embodied energy in the materials to change from baseboard heaters to radiant floors

Radiant Floor Component	**Added Embodied Energy (kWh)**
Radiant Floor tubing (all floors)	3,136
Concrete floors (ground floor and top floor)	8,959
Smaller Wood Floor Studs (reduction on ground and top floors)	-1,650
XPS Basement Floor Insulation	1,628
Mineral Wool Floor insulation (ground and top floors)	406
Extra Layer of Plywood (ground and top floors)	3,769
Manifolds	Not available
Thermostats	Not available
Pumps and controls	Not available
(Minus) Electric Baseboard Heaters	-3075
Total	**13,171**

Source: All values from Athena Impact Estimator use reduction) from the radiant floor, the energy payback time is 20.5 years. This is by far the longest energy payback time of all of the house components evaluated in this section, but is still only half of the life cycle of the house. The main purpose of the radiant floors are to be a more comfortable type of heating system that can make use of solar collectors. They sometimes result in lower thermostat set points due to the location of the heat, however, they are not a technology known to, on their own, significantly reduce energy use. The energy payback ratio (EPR) of the change to radiant floors is 1.9.

Insulation

From Athena, the extra insulation in the above ground walls and attic results in the increase of embodied energy by 11,770 kWh. In order to accommodate the increased insulation, extra wood is used which contains 1,147 kWh of embodied energy. Since this added insulation results in a primary energy use reduction of 3,000 kWh (2,793 kWh of electricity), the energy payback time is a relatively quick 4.3 years. The energy payback ratio (EPR) of the change in insulation is 9.3.

Drain Water Heat Recovery (DWHR)

The 12.25 kg DWHR device is essentially four long copper pipes wrapped around one larger copper pipe. Taking the average embodied energy of 22.3 kWh/kg from three studies (Hammond & Jones 2006, Lawson 1996, Victoria University of Wellington n.d.), the embodied energy in the material is 273 kWh. This is the embodied energy to make the copper but does not include the manufacturing of the device itself, which is unknown. The DWHR device is fairly simple and copper is highly malleable, and thus does not require high temperatures to form. Therefore, the embodied energy is doubled to include a rough estimation for the manufacturing energy. With an embodied energy of 546 kWh and the resulting primary energy use reduction of 1,897 kWh (1,766 kWh of electricity), the energy payback time is a mere 0.29 years (less than 3.5 months). Although the estimation of the manufacturing energy has a large margin of error, this shows that regardless of this potential error, the energy payback time for the DWHR is very fast. The energy payback ratio (EPR) of the DWHR is 139.

Low Flow Hot Water and Energy Efficient Appliances

Similar to the fact that low flow faucets and energy efficient appliances do not necessarily cost more than standard ones, the variations in embodied energy comes from which specific device is chosen, be it efficient or not. Therefore, there is no added embodied energy in these devices compared to standard equipment. This results in an immediate energy payback time, thus 0 years. Since the extra embodied energy is zero, the energy payback ratio (EPR) for these changes is calculated as infinity.

Table 6.19: The energy payback time for individual efficiency improvements in the NZEH

Efficiency Improvement	Added Embodied Energy (kWh)	Annual Electricity Use Reduction (kWh/yr)	Annual Primary Energy Use Reduction (kWh/yr)	Energy Payback Time (Years)	Energy Payback Ratio
Radiant Floors*	13,171	597	641	20.5	1.9
Insulation & Extra wood (walls & attic)	12,917	2,793	3000	4.3	9.3
DWHR	546	1,766	1897	0.3	139.0
Low Flow Hot Water	0	784	842	0.0	∞
Efficient Appliances	0	1,559	1674	0.0	∞

*Radiant Floor embodied energy value does not include manifolds, thermostats, pumps or controls. It is also the net value of the change, thus the embodied energy from the avoided baseboard heaters is factored into this value.

6.3.2.3 Solar Collector Systems

Table 6.20 shows a summary of values for the embodied energy associated with the components in a flat plate solar collector system. These values are specifically chosen from a larger literature review of embodied energy values of solar collectors since they consider the most complete life cycle analysis. The only significant part of the life cycle that is not included is the shipping of the final product from the manufacturing plant to the final destination in Montreal.

Table 6.20: Literature summary of embodied energy in flat plate solar collector systems

Collector kWh/m^2	Tank kWh/L	Installation kWh/m^2	Other kWh/m of pipe	Country	Reference
780	7.725	22.0		Italy	Ardente et. al. 2005
594		13.7	27	Cyprus	Kalogirou 2004
895	20.1			Australia	Crawford et. al. 2003
756	**13.91**	**17.9**	**27**		**Average**

Using the embodied energy values from Table 6.21, this missing energy portion from the final product shipment is accounted for. Based on information from Mark Gibson of HLT Energies who distributes Stiebel Eltron solar collectors in Montreal, the shipping route for the flat plate collectors is as follows: They leave the manufacturing plant in Holzminden, Germany and are trucked 420 km to a nearby port (assume Amsterdam). They are then sent 5,900 km by boat across the Atlantic Ocean to Boston, followed by 180 km of truck travel to West Hatfield, and finally another 450 km to Montreal by truck as well. Considering each solar collector weighs 49 kg, and assuming the shipping weight is 52 kg, the total embodied energy from shipping is 50 kWh/collector. Lacking more detailed information, it is assumed that the remaining components in the solar collector system (e.g. the tank, the piping, etc) are produced much closer to Montreal and thus any embodied energy from the shipping of these components is negligible compared to the total embodied energy in the system. Even if they are shipped from abroad, the shipping component of the embodied energy would still be very small relative to the total system embodied energy.

Table 6.21: Embodied energy from shipping

Method of Transport	Total Embodied Energy (kWh/ton/km)	Source
Coastal Shipping (Boat)	0.0639	Börjesson 1996
	0.1111	Lenzen
	0.0875	**Average**
Train	0.1944	Börjesson 1996
	0.2500	Lenzen
	0.2222	**Average**
Truck	0.3889	Börjesson 1996
	0.4722	Lenzen
	0.4306	**Average**

Table 6.22 shows the initial embodied energy (as of the initial installation) in different quantities of flat plate solar collector systems. Table 6.23 shows the complete 40 year life cycle embodied energy values for the same systems that include the impact of replacing the components at the frequencies specified in the table. Since many components need to be replaced, some several times, the difference between the initial values and the 40 year life cycle values are very significant. For example, the four flat plate solar collector system has an initial embodied energy of 11,479 kWh compared to the 40 year life cycle with 24,315 kWh, a 112% increase.

Table 6.22: Initial embodied energy for the flat plate solar collector system

		Initial Embodied Energy (kWh)					
No. of Collectors	Area of Collectors (m^2)	Collector	Tank	Installation	Piping*	Shipping	Total Embodied Energy
1	2.734	2,067	2,087	49	689	50	4,941
2	5.468	4,134	2,087	98	702	100	7,120
3	8.202	6,201	2,087	147	716	150	9,300
4	10.936	8,268	2,087	196	729	200	11,479
5	13.670	10,335	2,087	245	743	250	13,658
6	16.404	12,401	2,087	294	756	300	15,838

*Based on 25 m of piping between the collectors and the tanks and 0.5 m extra per collector

Table 6.23: 40 year life cycle embodied energy for the flat plate solar collector system

	40 yr life cycle embodied energy for solar collector systems (kWh)					
No. of Collectors	Collectors (0 & 25 yrs)	Shipping (0 & 25 yrs)	Installation (0 & 25 yrs)	Two Tanks (0, 15 & 30 yrs)	Piping (0 yrs)*	Total Embodied Energy
1	4,134	100	98	6,260	689	11,280
2	8,268	200	196	6,260	702	15,625
3	12,401	300	294	6,260	716	19,970
4	16,535	400	392	6,260	729	24,315
5	20,669	500	489	6,260	743	28,660
6	24,803	600	587	6,260	756	33,006

The numbers in brackets ( ) are the years of installation and replacement

*Based on 25 m of piping between the collectors and the tanks and 0.5 m extra per collector

The embodied energy for evacuated tube solar collectors are not included in this thesis since there does not appear to be any data on the subject in the available English literature. No attempt was made to estimate these values since such and exercise involves many complexities that are beyond the scope of this thesis. In addition, the detailed discussion in this thesis focuses instead on the flat plate collectors since the results indicate that when considering both cost and electricity reduction in the house, the flat plate collectors are the superior choice. Finally, based on the materials used in an evacuated tube solar collector, it does not appear that the embodied energy would be significantly different from that of flat plate solar collectors.

Table 6.24 shows the energy payback times for various sizes of flat plate solar collector systems. The table shows data based on the initial embodied energy values as well as the 40 year life cycle embodied energy values and does this for both methods of energy payback time described in the introduction to section 6.3. These numbers show that a flat plate solar collector systems does in fact significantly reduce overall energy use over its lifetime These numbers are discussed in more detail in section 6.3.2.5.

Table 6.24: The energy payback times for various sizes of flat plate solar collector systems

			Energy Payback Time Using Initial Embodied Energy (years)		**Energy Payback Time Using 40 Year Life Cycle Embodied Energy (years)**	
No. of Collectors	**Electricity Use Reduction (kWh/yr)**	**Primary Energy Use Reduction (kWh/yr)**	**Electricity Use Reduction Method**	**Primary Energy Use Reduction Method**	**Electricity Use Reduction Method**	**Primary Energy Use Reduction Method**
1	1292	1388	3.8	3.6	8.7	8.1
2	1945	2089	3.7	3.4	8.0	7.5
3	2440	2621	3.8	3.5	8.2	7.6
4	2818	3027	4.1	3.8	8.6	8.0
5	3042	3267	4.5	4.2	9.4	8.8
6	3195	3431	5.0	4.6	10.3	9.6

6.3.2.4 Photovoltaic System

Table 6.25 and Table 6.26 show the results from a literature review of the embodied energy in monocrystalline silicon and polycrystalline silicon PV panels respectively. These tables not only include the PVs modules themselves, but also the BOS (balance of system - all of the other main components in the PV system such as the inverter, wiring, racking, etc.) as well as the embodied energy that is associated with the operation and maintenance of the factory and the production equipment. The average result of 1496 kWh/m^2 of PV area used in the calculations for

Table 6.25: Literature summary of embodied energy in monocrystalline silicon PV systems

Total Embodied Energy (kWh/m^2)	**Module Production (kWh/m^2)**	**BOS (kWh/m^2)**	**Other (kWh/m^2)**	**Reference**
1334	976	233	125 Operation and maintenance	Nawaz & Tiwari 2006
720 to 2400	1320 (720 to 2400)	-	-	Hammond & Jones 2006
1235*	1235*	-	-	Krauter & Ruther 2004
664	664	-	-	Knapp & Jester 2001
1889	1556	194	139 Overhead operations & manufacturing equipment	Alsema & Nieuwlaar 2000
1496	1150	214	132	**Average**

Table 6.26: Literature summary of embodied energy in polycrystalline silicon PV systems

Total Embodied Energy (kWh/m^2)	**Module Production (kWh/m^2)**	**BOS (kWh/m^2)**	**Other (kWh/m^2)**	**Reference**
638	638	-	-	Stoppato 2008
540 to 1571	1130 (540 to 1571)	-	-	Hammond & Jones 2006
661*	661*	-	-	Krauter & Ruther 2004
1472	1139	194	139 Overhead operations & manufacturing equipment	Alsema & Nieuwlaar 2000
1225	892	194	139	**Average**

embodied energy in this section are from the monocrystalline silicon table since that is the type of silicon used in the Sanyo PV modules modeled in this thesis.

*The results from Krauter & Ruther (2004) presented in Table 6.25 and Table 6.26 are modified from the original values in their paper since they were only given in kWh/kWp and the area associated with 1 kWp was not given. Therefore they were estimated using the area and power of the Sanyo PV panel used in this thesis, 5.9 m^2/kWp. Also, the embodied energy to produce a certain type of PV panel (mono or polycrystalline) depends more on the area (quantity of material) than the efficiency. Therefore, since this data comes from 1996 PV modules which likely were closer to 11% and 12% efficient for polycrystalline and monocrystalline respectively as opposed to the 17% efficient Sanyo modules, the values were then weighted to reflect this difference. Ex: For the monocrystalline modules:

Weighted for area/power: (5144 kWh/kWp)/(5.9 m^2/kWp) = 872 kWh/m^2;

Then, weighted for efficiency: (872 kWh/m^2)·(17%/12%) = 1235 kWh/m^2.

Similar to the solar collectors, the PV embodied energy values in Table 6.25 and Table 6.26 also do not include the energy due to the final shipment from the PV manufacturing facility to the house in Montreal. Therefore, the embodied energy from shipping the PV modules is calculated using the values in Table 6.21. According to Sanyo customer support, the solar cells are produced in Japan and then shipped to Monterey, Mexico where the finished PV modules are assembled. Since the solar cells are extremely thin and their weight contribution to the final module weight is insignificant, the embodied energy from the shipment from Japan to Mexico is neglected. Therefore, the embodied energy from shipping is due to the 3750 km that they are trucked from Monterey, Mexico to Montreal. The 14 kg, 1.18 m^2 PV module is assumed to have a 15 kg shipping weight and thus results in a shipping embodied energy of 24 kWh/module.

The other main component for the PV system is the inverter. Xantrex inverters are manufactured in Shanghai, China and then shipped 11,000 km by boat to Hayward, CA, USA. From there they are trucked 4800 km to Montreal. Regardless of the inverter capacity (2.8 to 5 kW), they all weigh about 27 kg during shipping. This would require two inverters for any of the PV systems being used in the NZEH. Therefore, the shipping embodied energy for two inverters is 164 kWh. All other wiring and components in the PV system are assumed to contain negligible shipping embodied energy.

Table 6.27 shows the initial embodied energy (as of the initial installation) for PV systems of various sizes that match the quantities needed in the complete solar systems tested in the NZEH.

Table 6.28 shows the complete 40 year life cycle embodied energy values for the same PV systems that include the impact of replacing the components at the frequencies specified in the table. Since the PV modules are replaced once and the inverters several times, the difference

Table 6.27: Initial embodied energy for the PV system

	Initial Embodied Energy (kWh)		
No. of PV Modules	Complete PV System	Shipping	Total
44.7	78,908	1,237	80,145
40.6	71,670	1,138	72,809
38.6	68,140	1,090	69,230
37.0	65,315	1,052	66,367
35.8	63,197	1,023	64,220
35.1	61,961	1,006	62,968
34.6	61,079	994	62,073

Table 6.28: 40 year life cycle embodied energy for the PV system

	40 yr life cycle embodied energy for PV systems (kWh)				
No. of PV Modules	PV Module (0 & 25 years)	BOS (mostly the inverter at 0, 15 & 30 years)	Other	Shipping	Total
44.7	121,316	31,605	14,621	2,638	170,180
40.6	110,188	28,706	13,280	2,441	154,616
38.6	104,760	27,292	12,626	2,345	147,023
37.0	100,418	26,161	12,103	2,268	140,950
35.8	97,161	25,313	11,710	2,210	136,394
35.1	95,261	24,818	11,481	2,177	133,737
34.6	93,904	24,464	11,318	2,153	131,839

*This table assumes that 90% of the BOS is from the inverter and the 'Other' component (overhead operations & maintenance of manufacturing equipment) is 90% due to the PV modules and 10% for the inverters.

The numbers in brackets ( ) are the years of installation and replacement between the initial values and the 40 year life cycle values are very significant. For example, the 44.7 PV module system has an initial embodied energy of 80,145 kWh compared to the 40 year life cycle with 170,180 kWh, a 112% increase.

Table 6.29 shows the energy payback times for various sizes of PV systems. The table shows data based on the initial embodied energy values as well as the 40 year life cycle embodied energy values and does this for both methods of energy payback time described in the introduction to section 6.3. These numbers show that a PV system does in fact significantly reduce overall energy use over its lifetime. These numbers are discussed in more detail in section 6.3.2.5.

Table 6.29: The energy payback times for various sizes of PV systems

			Energy Payback Time Using Initial Embodied Energy (years)		Energy Payback Time Using 40 Year Life Cycle Embodied Energy (years)	
No. of PV Modules	**Electricity Use Reduction (kWh/yr)**	**Primary Energy Use Reduction (kWh/yr)**	**Electricity Use Reduction Method**	**Primary Energy Use Reduction Method**	**Electricity Use Reduction Method**	**Primary Energy Use Reduction Method**
44.7	14061	15102	5.7	5.3	12.1	11.3
40.6	12769	13714	5.7	5.3	12.1	11.3
38.6	12116	13013	5.7	5.3	12.1	11.3
37	11621	12481	5.7	5.3	12.1	11.3
35.8	11243	12075	5.7	5.3	12.1	11.3
35.1	11019	11834	5.7	5.3	12.1	11.3
34.6	10866	11670	5.7	5.3	12.1	11.3

6.3.2.5 The Combined Solar Energy System (Solar Collectors & PV modules)

Table 6.30 shows, for various configurations of the NZEH solar system, the total initial embodied energy in these complete solar systems (Solar collectors and PVs), as well as results both methods (electricity and primary energy) of energy payback time and energy payback ratio (EPR). Table 6.31 shows the same information but for the 40 year life cycle. These tables show that the solar system configuration with four flat plate solar collectors and 35.8 PV modules has the lowest embodied energy for the 40 year life cycle (160,709 kWh) and nearly the lowest (only

0.04% more) when based on initial values. This is important, since as seen in section 6.1.2.4.1 this same configuration with four solar collectors also has the lowest life cycle cost of the solar systems that contain solar collectors and thus has the fastest financial payback time. However, the overall lowest life cycle cost and payback solar system for the NZEH is the model with no solar collectors and 44.7 PV modules. The life cycle embodied energy for this case is 170,180 kWh, which is only 6% higher than the previously mentioned lowest option.

Table 6.30: The initial embodied energy and payback times for the complete solar system

Solar System Configuration		Total Initial Solar System Embodied Energy (kWh)	Based on an Electricity Use Reduction of 14,061 kWh/yr		Based on a Primary Energy Use Reduction of 15,102 kWh/yr	
No. of Collectors	No. of PV Modules		Energy Payback Time (years)	Energy Payback Ratio (EPR)	Energy Payback Time (years)	Energy Payback Ratio (EPR)
0	**44.7**	**80,145**	**5.7**	**7.0**	**5.3**	**7.5**
1	40.6	77,750	5.5	7.2	5.1	7.8
2	38.6	76,350	5.4	7.4	5.1	7.9
3	**37.0**	**75,667**	**5.4**	**7.4**	**5.0**	**8.0**
4	**35.8**	**75,699**	**5.4**	**7.4**	**5.0**	**8.0**
5	35.1	76,626	5.4	7.3	5.1	7.9
6	34.6	77,911	5.5	7.2	5.2	7.8

* See the introduction to section 6.3 for assumptions behind the calculation of the EPR

Table 6.31: The 40 year life cycle embodied energy and payback times for the complete solar system

Solar System Configuration		Total 40 Year Life Cycle Solar System Embodied Energy (kWh)	Based on an Electricity Use Reduction of 14,061 kWh/yr		Based on a Primary Energy Use Reduction of 15,102 kWh/yr	
No. of Collectors	No. of PV Modules		Energy Payback Time (years)	Energy Payback Ratio (EPR)	Energy Payback Time (years)	Energy Payback Ratio (EPR)
0	**44.7**	**170,180**	**12.1**	**3.3**	**11.3**	**3.5**
1	40.6	165,895	11.8	3.4	11.0	3.6
2	38.6	162,648	11.6	3.5	10.8	3.7
3	37.0	160,920	11.4	3.5	10.7	3.8
4	**35.8**	**160,709**	**11.4**	**3.5**	**10.6**	**3.8**
5	35.1	162,397	11.5	3.5	10.8	3.7
6	34.6	164,844	11.7	3.4	10.9	3.7

* See the introduction to section 6.3 for assumptions behind the calculation of the EPR

Figure 6.26 shows the energy payback time for the solar system and its individual components (the solar collector systems and the PV system) based on the electricity use reductions. This is the amount of time that it takes for the solar energy systems to convert and use a quantity of solar energy that is equal to the quantity of embodied energy in these systems. This is calculated by simply dividing the embodied energy by the annual electricity use reduction due to the system.

Similarly, Figure 6.27 shows the energy payback time for the solar system and its individual components based on the primary energy use reductions, which in this case, as explained earlier, are 1.074 times more than the electricity use reductions. This is the amount of time that it takes for the solar energy systems to convert and use energy that results in a quantity of avoided primary energy that is equal to the quantity of embodied energy in these systems. This is calculated by simply dividing the embodied energy of the solar system by the annual amount of primary energy avoided by using the solar system. The results in both figures show the energy payback time based on both the initial embodied energy as well as the 40 year life cycle embodied energy.

Aside from the inverter portion which is very small, the embodied energy for the PV system is a linear function of its area and so is the electricity it produces. Therefore, energy payback time is essentially constant, regardless of the number of PVs, at 5.7 and 5.3 years based on the initial embodied energy (for the electricity use and primary energy use reduction methods, respectively) and 12.1 and 11.3 years based on the 40 year life cycle embodied energy (for the electricity use and primary energy use reduction methods, respectively).

The solar collector system on the other hand is neither linear in energy capture and conversion nor in embodied energy. Therefore, in Figure 6.27, based on primary energy use reductions, the line showing the life cycle energy payback varies from 8.1 years for one collector to 9.6 years for six collectors and bottoms out at 7.5 years with two collectors. As more collectors are added to the same set-up, the energy payback time will continue to rise. This is because the

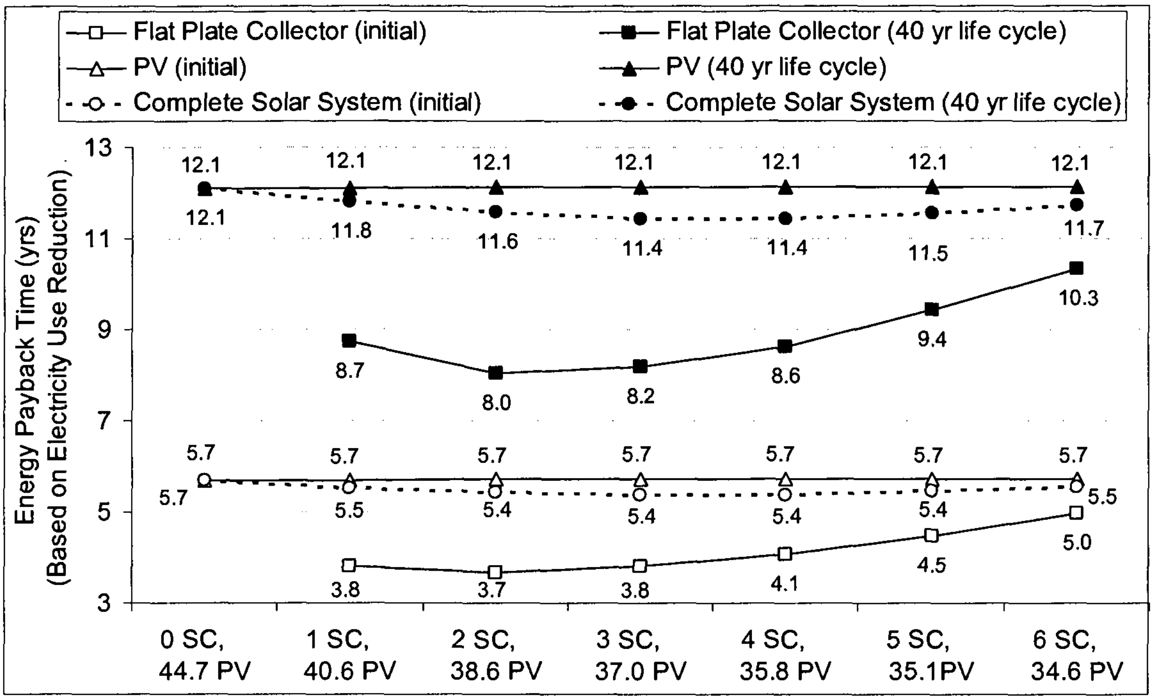


Figure 6.26: The energy payback time for the solar system as a whole and its components based on the electricity use reductions (initial and 40 yr. life cycle embodied energy)

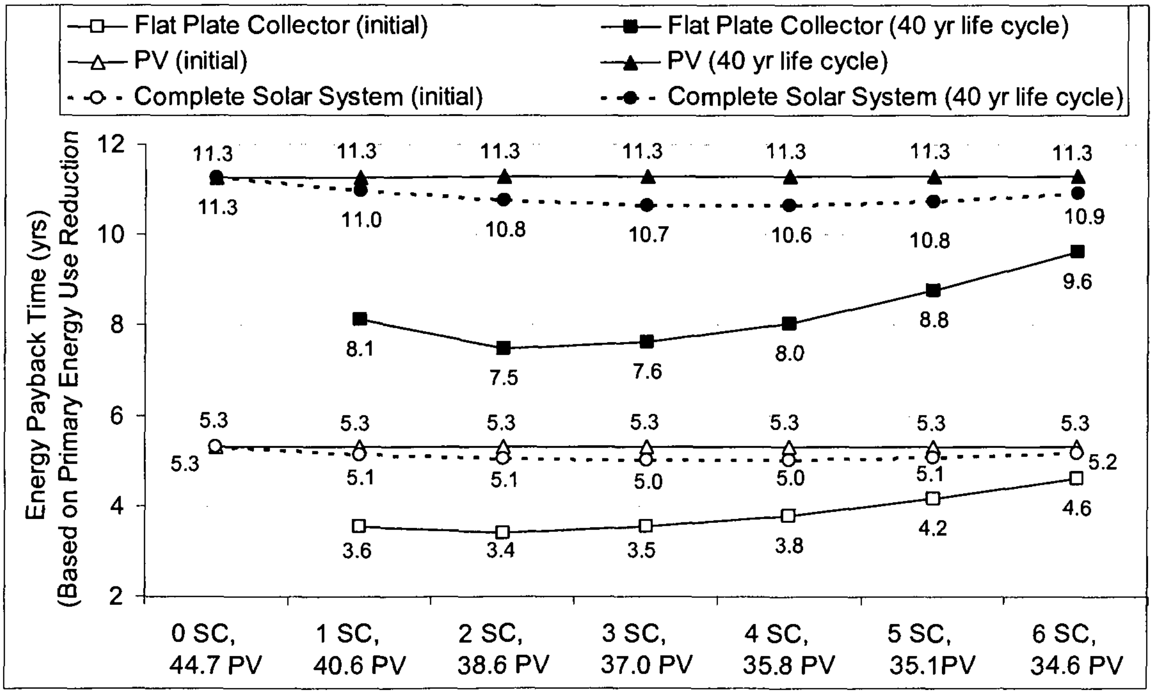


Figure 6.27: The energy payback time for the solar system as a whole and its components based on the primary energy use reduction (initial and 40 yr. life cycle embodied energy)

amount of energy that can be captured and used will increase more and more slowly and eventually plateau, while each new collector will contain the same amount of extra embodied energy. As expected, in Figure 6.26 the results for the energy payback time based on electricity use reductions follow an identical trend but are 1.074 times longer.

When combining the solar collectors and PVs to make the complete solar system, the energy payback time inevitably falls between the results from the individual components. However, the solar system energy payback is much closer to the higher PV payback time since the system contains considerably more PVs than solar collectors. The four solar collector and 35.8 PV configuration results in the lowest life cycle energy payback time of 10.6 years (based on primary energy use reductions). This is good news since it shows that the complete solar system converts and uses considerably more renewable energy than the amount of non-renewable energy it takes to make it. Looking at it another way, the two NZEH solar system configurations focused on in this thesis avoid the use of 604,061 kWh of primary energy (562,440 kWh of grid electricity) over forty years but only contain 160,709 kWh to 170,180 kWh in embodied energy. Therefore, they avoids the use of 3.5 to 3.8 times more primary energy than was used to manufacture the systems (these are the EPRs). Again, the results from the analysis using the electricity use reduction values show identical trends with values just slightly (1.074 times) higher.

6.3.3 Comparison between the Base Case House and the NZEH

Since the NZEH is designed to produce exactly as much energy as it consumes in operating energy and does not account for the embodied energy, the house still indirectly uses a significant amount of energy over its 40 year life. This energy is not used by the house; rather it is embedded in the house materials and all of the processes associated with those materials. However, the amount of energy consumption avoided through energy efficient design changes and by capturing renewable solar energy is even more significant.

Table 6.32 shows the changes in embodied energy between the BCH and two versions of the final NZEH as well as two progressive steps in between. The table also contains the energy payback time and energy payback ratio (EPR) for those same steps. All of these results use the methods based on primary energy use reductions. The first step takes the BCH, changes the baseboard heaters to a radiant floor heating system, improves the envelope (windows as well as the insulation in the walls and attic) and adds the DWHR pipe. All of these changes increase the embodied energy in the house materials by 69,923 kWh (25%) to a total of 351,116 kWh of embodied energy in the NZEH construction (without the solar technologies). However, since these improvements also reduce the annual (primary) operating energy by 7,580 kWh (7,058 kWh of electricity from Figure 6.20), the 40 year life cycle energy of the house is reduced by 233,277 kWh (40 years x 7,580 kWh – 69,923 kWh). The energy payback time is 9.2 years and the EPR is 4.3. The next step (and row in Table 6.32) includes the remaining changes to complete the NZEH design before adding the solar system. This involves adding the low flow hot water faucets, efficient appliances, CFL lighting and the TMV. This is shown as a separate step for a few reasons. Firstly, low flow hot water and appliances do not necessarily result in a change in embodied energy since the less efficient versions are built with similar materials. Secondly, there is no reliable information on the embodied energy in CFL or incandescent lighting or for a TMV valve. Therefore, the embodied energy for these two changes were not taken into account. However, the TMV is a small valve and is certainly negligible. Also, since the CFL lights require replacement only ten times during the 40 years compared to 80 times for the incandescent lights, even if the individual CFL bulbs have more embodied energy, from a life cycle point of view, they probably end up reducing rather than increasing the embodied energy in the house. Therefore, leaving this out takes a conservative approach, although this one item is also not likely to have a big impact on the embodied energy in proportion to that of the entire house. Once this step is complete, it shows that all of the envelope and efficiency improvements prior to installing the solar system result in a reduction of 12,429 kWh of primary energy use (11,573 kWh of grid electricity). All of these changes together have an energy payback of just 5.6 years on a house that will last at least 40 years, and an EPR of 7.1. This is a very positive result.

The final step to complete the NZEH is to add the solar system. Compared to the BCH (281,193 kWh of embodied energy), the embodied energy increases 85% to 521,296 kWh in the completed NZEH when the 44.7 PV module system (170,180 kWh of embodied energy) is added to the envelope and efficiency improvements from the previous steps (69,923 kWh of embodied energy). It increases 82% to 511,825 kWh when the 4 solar collector and 35.8 PV system is used instead (160,709 kWh of embodied energy). However, these increases in embodied energy are more than made up for since the solar system eliminates the consumption of 1,100,629 kWh of (primary) operating energy over 40 years. This results in energy payback times of 8.7 and 8.4 years for these two complete NZEHs.

Table 6.32: Energy payback and changes in embodied energy between the BCH and NZEH

House Model	Total Embodied Energy	Increase in Embodied Energy compared to the BCH	Annual Operating Energy Reduction	40 Year Life Cycle Operating Energy Reduction	Net Change in Life Cycle Energy	Energy Payback Time	EPR
	kWh	kWh	kWh	kWh	kWh	Years	
BCH	281,193	0	0	0	0	-	-
NZEH (no solar system, missing some changes. See Note)	351,116	69,923	7,580	303,200	-233,277	9.2	4.3
* **NZEH** (no solar system)	351,116	69,923	12,429	497,179	-427,255	5.6	7.1
NZEH (with 44.7 PV)	521,296	240,103	27,516	1,100,629	-860,526	8.7	4.6
NZEH (with 4 Solar Collectors & 35.8 PV)	511,825	230,632	27,516	1,100,629	-869,997	8.4	4.8

* Note 1: This intermediate step between the BCH and NZEH is the NZEH design without the solar system and also without the low flow hot water, efficient appliances, CFL lighting and TMV

Note 2: All energy values in this table are of primary energy and the Energy Payback Time and EPR use the primary energy use reduction methods.

Table 6.33 shows that even though the improved envelope, efficiency changes and solar systems in the NZEH require considerably more embodied energy in the house materials, the effect of eliminating the operating energy (by meeting these needs with solar power) results in a house that uses over 62% less energy during its 40 year life cycle.

The next step (not done in this thesis) would be to design the house and renewable energy system such that it makes up for all of the embodied energy in the house as well.

Table 6.33: Total 40 year life cycle energy use comparison between the BCH and the NZEH

Energy Contributor	**Total Energy (Embodied & Operating)**					
	BCH		**NZEH (44.7 PV)**		**NZEH (4 Solar Collectors and 35.8 PV modules)**	
	kWh	**kWh/m^2**	**kWh**	**kWh/m^2**	**kWh**	**kWh/m^2**
Materials & Transportation	281,193	1,352	351,116	1,688	351,116	1,688
Operating Energy	1,100,629	5,291	0	0	0	0
Solar System	0	0	170,180	818	160,709	773
Total	1,381,822	6,643	521,296	2,506	511,825	2,461
Difference	0.0%		-62.3%		-63.0%	

* The value in kWh/m^2 is based on the heated floor area of the house, 208 m^2.

7. CONCLUSIONS

7.1 SUMMARY OF THE WORK IN THIS THESIS

The Scope and Contribution of This Thesis

This thesis is intended to be a contribution to the development of Net Zero Energy Home concepts. This is partly achieved by reinforcing certain accepted conclusions through a detailed and complete analysis but also adds to the body of knowledge by performing an up to date life cycle cost and energy analysis. The work in this thesis applies specifically to the realities regarding climate, energy and cost (electricity, labour and equipment) of a stand-alone house located in Montreal, QC, Canada. This work adds to the body of research that demonstrates the feasibility of NZEHs and which methods are some of the most cost effective in order to achieve the goal of homes that are environmentally benign in terms of their use of operating energy.

Due to the abundance hydroelectricity use in Quebec, the house models rely 100% on electricity as the source for the grid supplied operating energy. However, in order to correctly model overall energy use in Quebec, the energy data from Athena (Athena Institute 2008) attributes a very small amount to sources other than hydroelectricity. In addition, this research and analysis is performed to assess the feasibility of a house that uses relatively simple active solar technologies and it intentionally avoids the use of heavy HVAC equipment.

The Cost Effectiveness of Building a NZEH

The cost analysis in this thesis shows that certain changes required to turn the Base Case House into the Net Zero Energy House are much more cost effective than others. As a general rule, which is quantified here, it is always better to reduce the energy consumption of the house before installing systems designed to meet those energy needs. The most cost effective changes are: improving the wall and attic insulation, installing CFL lighting, installing a drain water heat recovery pipe (DWHR) and using efficient appliances. These will all significantly reduce the heating and electricity loads while providing financial paybacks ranging from instantaneous to

11.6 years. All of these improvements to the BCH design, along with a few others that encompass the complete changes to the house envelope and energy efficiency, result in changing the BCH electricity load from 25,615 kWh/yr to 14,061 kWh/yr for the NZEH design (without solar technologies). All of these changes add $34,287 to the 40 year life cycle cost of the house; coincidentally, these combined changes have a financial payback of just under 40 years, so they just pay for themselves during the life of the house. Only after those changes are done should the solar system be sized to the house so that this more costly system is as small as possible.

The less cost effective changes made to the house, from best to worst, are the solar collector and PV systems, the change to a radiant floor and the installation of a much larger area of triple pane windows. All of these systems are too expensive to achieve financial payback during the 40 year life cycle of the house. However, although not part of the final design, keeping the same area of windows as the BCH but changing them from double to triple pane, results in a 45 year payback for that one change, which is not much longer than the life cycle of the house. The overall financial payback time for the NZEH with all of the envelope, energy efficiency and solar system modifications far exceeds the 40 year life cycle of the house and thus payback is not achieved. This is mostly due to the cost of the solar systems. The financial payback time is much more encouraging for the combination of all the envelope and energy efficiency changes made to the NZEH but before actually adding the solar system. This results in a financial payback time of 39.3 years, but of course this version of the house is not net zero energy, but in fact uses 14,061 kWh/yr.

In hindsight, one way to improve the financial payback time a little could be to avoid implementing some of the less cost effective changes that were made. In terms of the envelope, this applies specifically to the large additional area of triple pane windows that cost $16,275. Avoiding these additional windows and adding more PV modules to account for the resulting extra electricity use results in a net savings of $8,411 for the 'all PV' NZEH. This changes the cumulative payback time of the combined envelope and energy efficiency device improvements from 39.3 years to 22.6 years (before installing solar technologies). Similarly, another more cost effective option (that would only work in the 'all PV' NZEH) is to use baseboard heaters which cost $13,472 less than radiant floors. All things considered (such as the extra PVs needed since this option also uses more electricity), this reduces the 40 year life cycle cost of the NZEH by $8,318 and changes the cumulative payback time of the combined envelope and energy efficiency device improvements to 25.4 years. Finally, combining these two design options reduces the 40 year life cycle cost of the NZEH by $16,740 and results in a significant reduction in the cumulative payback time of the combined envelope and energy efficiency device improvements, down to only 6.1 years from 39.3 years. It should be noted, however, that although using baseboard heaters is the most cost effective option, it will likely result in a less comfortable house compared to using radiant floors. In addition, other options that are more thermodynamically efficient, such as heat pumps and geothermal systems, might be worth looking into, although the costs and impact on energy use from those systems are beyond the scope of this thesis.

In terms of engineering design and building methods, other factors that could play a significant role in improving the cost effectiveness of NZEHs are prefabrication, pre-engineering and modular design.

Reducing the Grid Electricity Use with Solar Collectors and Photovoltaics

Although the solar collectors and photovoltaic panels are costly, they are an essential part of the NZEH in this thesis in order to reduce the grid electricity use to net-zero.

This thesis compares one model of a flat plate solar collector (Stiebel Eltron SOL25) with one of an evacuated tube solar collector (Thermomax Solamax 20-TDS 300) to determine which type of collector would be better for the NZEH. Although the evacuated tube technology is generally more efficient based on the aperture area, when these two specific models are evaluated in terms of gross area, the solar energy they capture is almost equivalent for these two technologies. This is because most of the gross area of a flat plate collector is the aperture area, whereas an evacuated tube collector has spaces between the tubes as well as a large manifold at the top. The efficiency based on the gross area is what truly matters to a homeowner because that is the space that it occupies on the roof. Therefore, for these two models, in terms or capturing and using solar energy, the evacuated tube collector provides no significant benefit over the flat plate collector. Since evacuated tube collectors are much more expensive than their flat plate counterparts, this reveals that the flat plate solar collectors are the better choice between the two. Or stated another way, as shown in Figure 6.1, the cost per reduction in electricity use is much better for the flat plate solar collectors.

With four flat plate solar collectors installed with the combisystem, they are able to reduce the house electricity loads annually by 258 kWh/m^2 of gross collector area. Comparatively, the PV modules are able to produce 266 kWh/m^2 (of PV area) annually, regardless of the number of modules installed. The PV module electricity production depends only on the incident solar radiation as opposed to the solar collectors which depend on many variables. For the solar collector, the ability to capture and use solar energy can vary depending on storage capacity, collector and tank inlet water temperatures, desired tank outlet temperature, flow rates and hot water consumption rates. Therefore, the results from the solar collectors are specific to the type of combisystem set-up that is modeled in this thesis. However, that does not mean that general trends and comparisons concluded here cannot be applied to other systems that bear certain similarities.

The Cost of Solar Systems

One of the goals of this thesis was to make every effort to include as much detail as possible involved in the analysis of the systems being studied, within the scope of the work being done. One area of particular interest that appears to differ from some other studies and more so the claims commonly heard from companies in the solar industry, is the financial payback time for solar systems. The cost analysis in this thesis reveals that both solar collector and photovoltaic systems are still very expensive, and coupled with the low cost of electricity across Canada, the electricity cost savings they provide are not enough to offset the high price of the solar systems and never result in a financial payback. This conclusion is of course in the context of solar combisystems similar to the one presented in this thesis.

Although nobody disputes that solar technologies are still quite costly, the results here show that they are even more costly than expected. This can be attributed to the fact that this thesis goes very far to consider all aspects of the costs, and includes details such as realistic quotes from local suppliers, installation, all components needed for a functioning system, replacement costs and taxes as well as financial factors such as effective interest rates, the cost of electricity and its expected escalation rates. Other factors that actually help to improve the cost effectiveness of the solar systems are also considered, such as the expected aggressive cost reductions for PV modules as well as government or industry incentives. Regardless of these factors, the cost of solar technologies still needs to drop significantly to make them affordable to the average homeowner.

The Life Cycle Energy Analysis of the NZEH

As opposed to the life cycle cost analysis, the life cycle energy analysis results in only positive findings. All of the improvements in the design of the NZEH have relatively quick energy payback times. The only exceptions are the radiant floors (on their own, not including the impact of the solar collectors) which have an energy payback time of 20.5 years, still just half of the 40 year life cycle of the house. The energy payback times for the low flow hot water and efficient appliances are instantaneous since the analysis looks at the difference in embodied energy compared to the BCH, and this modified equipment is more efficient but not necessarily more energy intensive to manufacture. Other energy payback times are: added insulation (and wood studs to accommodate it), 4.6 years; DWHR, 0.3 years; any number of PV modules, 11.3 years; four solar collectors, 8.0 years; and finally, the NZEH with 35.8 PV modules and 4 solar collectors, 8.4 years. Using 511,825 kWh over 40 years, the life cycle energy use of this NZEH is 63% less than the BCH. Therefore, from an environmental point of view, the NZEH designs tested here are an overwhelming success and a large improvement over a typical house in Quebec built in 1994.

One caveat to the claim that the NZEH is environmentally superior to the BCH due to the large reduction in life cycle energy is that this depends where the energy comes from. Since the NZEH contains more embodied energy but less operating energy than the BCH, it is important to realize that if the houses are supplied with a relatively clean form of electricity, such as hydroelectricity, but the extra embodied energy in the NZEH materials come mostly from environmentally harmful energy sources like petroleum and coal, it is very possible that the overall environmental impact can be worse for the NZEH. This is a very complex issue since it is difficult to determine exactly how the materials are manufactured, in addition to considering the less obvious impacts of seemingly clean hydroelectricity (the impacts of flooding of large swaths of land) and the fact that reducing electricity use in Quebec allows Hydro Quebec to sell excess 'clean' electricity to neighbouring provinces and states which can replace their use of dirtier electricity production. So a reduction in hydroelectricity use in Quebec can actually indirectly result in a reduction of more polluting sources of electricity elsewhere. These are all important and complex questions to consider.

Incentives and Government Policy

As mentioned above, at current solar technology and electricity prices, the average homeowner cannot financially justify the expense of most solar technologies. However, the life cycle energy analysis in this thesis clearly shows that solar collectors and photovoltaic technologies reduce overall energy use and can be environmentally beneficial. In addition to reducing personal energy use, and thus greenhouse gases which have begun to cause dangerous climate change, reducing energy demand also reduces the likelihood that the growing demand exceeds current energy production capacity. This could help to avoid the need to build new energy generating facilities, such as large hydroelectric dams, nuclear power plants, natural gas production facilities, etc., all of which have their own costs and environmental implications.

One way to help resolve this disconnect between what homeowners would like to do to help reduce their negative impact and what they can actually afford to do, would be to follow the lead of other countries such as Germany. A country certainly not known for abundant sun, Germany has become a leader in solar technologies due to the political will of the government and the awareness of its citizens. The analysis in this thesis of the available incentives in Canada shows that although some are very weak (the $500 federal rebate) and some 'appear' at first glance to be quite aggressive (Ontario's $0.42/kWh Standard Offer Program), none come even close to making these systems cost effective. At current electricity prices, expected electricity price escalations and an annual 5% PV price reduction for the first 25 years, it requires an 81% rebate on the cost of a solar system for it to break even financially.

In addition to government and industry incentives, another factor that would make solar technologies much more cost effective would be to significantly increase the cost of electricity. This would not reduce the cost of the solar systems, but it would make them more desirable as they would be helping to offset larger electricity bills. Although electricity prices are often on the rise, it would be very difficult for the government to allow for a large increase since this would clearly be unpopular with the general public.

The conclusions in this analysis show that the currents financial costs of energy use do not adequately factor in the associated environmental, health and social costs. Therefore, although NZEH designs have many environmental benefits, until these costs are included in the price of energy, or until governments provide more effective programs or incentives, the general public will have difficulty justifying the extra costs involved in building NZEHs. The what-if scenarios for costs and incentives in sections 6.1.2.4.2 and 6.1.2.4.3 provide guidance regarding the changes required to make NZEHs cost effective.

The Best Design Options for the NZEH

Based on the life cycle cost and life cycle energy analyses, two Net Zero Energy House (NZEH) solar system configurations are considered to be the best options for the house and solar systems simulated in this thesis: the one with the lowest life cycle cost and the one with the lowest life cycle energy. Although the environmental impact of the house is very important (in this case as a function of life cycle energy use), most homeowners consider cost to be the driving factor in decision making. Therefore, assuming that a homeowner is willing to spend the extra money to have a NZEH with a combisystem, the lowest life cycle cost option is the one that uses 52.75 m^2 of PV modules (44.7 Sanyo HIP-200BA3 modules) and no solar collectors. Just the solar system (not the whole house) for this option has a total of 170,180 kWh of embodied energy, or 6% more than the NZEH solar system with the lowest life cycle energy. The 40 year life cycle energy use of the entire house for this same option (the one with the lowest life cycle cost) is 521,296 kWh, only 2% more than the house with the lowest life cycle energy. The solar system containing the lowest 40 year life cycle energy is the one comprised of 4 flat plate solar collectors (10.9 m^2) and 35.8 PV modules (42.2 m^2). Therefore, although both house options produce as much energy as they consume in operating energy, the embodied energy in their materials still differs by 9,471 kWh over the 40 year life cycle. The version of the NZEH with the lowest life cycle energy has a life cycle cost of $400,977 which is only $1,981 more than the NZEH with the lowest life cycle cost ($398,996). Therefore, although a little money can be saved by choosing the option with slightly more life cycle energy, the differences are not very large so both of these options are good choices.

Although the basis for this thesis is the design and analysis of a NZEH using a solar combisystem, the results point to a third option that cannot be ignored. Since the least expensive option uses only PV modules, this creates a situation where the house can be heated without the radiant floors, which are necessary when using the hydronic solar collectors. If so desired, the PV modules can be used to power the original electric baseboard heaters. Although there are some drawbacks to this (reduced comfort and likelihood of larger temperature fluctuations in the house from reduced thermal mass), the cost savings and reduced embodied energy make it a potentially desirable option. In terms of alternative options, the use of geothermal systems and heat pumps are also options that should not be ignored, but were not analyzed in this thesis since the goal was to look at the feasibility of simple, solar technologies and avoid large equipment of that sort.

7.2 FUTURE WORK

Achieving the goal of a net zero energy house, based on the operating energy of the house is actually only the first step in creating a more sustainable, low impact house. The next step is to transform the NZEH into a NZLCEH, or a Net Zero Life Cycle Energy House. This would not only produce as much energy as it uses in operating energy, but it would account for all of the life cycle embodied energy as well. It would also be interesting to have results for the embodied energy of evacuated tube solar collectors to compare to the flat plate solar collectors.

It is interesting to know the life cycle energy (operating and embodied energy) in this NZEH as well as that of a NZLCEH, but it would be even more useful to know how this energy is generated and in what quantities, i.e. how much of the life cycle energy comes from hydroelectric power, coal, nuclear power, natural gas, etc. Knowing not just the different percentages, but a detailed breakdown based on the materials used would lead to a better understanding of which materials are more sustainable than others. The most important differences between these sources of energy are the greenhouse gases generated. A given 'House A' with ten times as much life cycle energy as 'House B', but primarily generated from hydroelectric power, might produce only a fraction of the greenhouse gases that 'House B' emits from using energy from a coal fired power plant to make the materials or power the home. Given this detailed information, builders and homeowners would be empowered to make educated decisions to reduce their impact and make more sustainable homes.

Keeping with the eco-friendly, sustainable home theme, future work could focus more on the environmental impact of the materials used to make the NZEH. Although the design in this thesis did try to take that into account and use less harmful and more local materials, it was not the main focus of the work and was not discussed in much detail.

Finally, this thesis looked at one specific type of flat plate solar collector and one specific type of evacuated tube solar collector. It would be useful to do the same analysis with solar collectors from a wide range of manufacturers to see which are the better performing models and if generalizations can be made or if the performances from different collectors are erratic. The same can be done for the photovoltaic modules. This information should also be coupled with the gross area they occupy and a detailed and accurate cost analysis to determine which options give the homeowner the most bang for their buck. For example, simulations might reveal that a certain collector captures less energy than others, but it might also be smaller or cost much less. The important comparative conclusions would be denoted as [kWh of captured and usable energy]/[cost of the solar system · gross area of the solar system] or simply kWh/($$\cdot$m^2).

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APPENDIX A. BASE CASE HOUSE ENVELOPE AND CONTENTS

WALL INFORMATION IN TRNBUILD:

Solar Absorptance of Walls:

The values of solar absorptance for the front and backs of all walls was based on the following information taken from the help file of TRNSYS 16 - Volume 6 - Multizone Building modeling with Type56 and TRNBuild, page 28. This shows the following information:

Smooth surface- dark colour: 0.7–0.75

Smooth Surface – Medium colour: 0.6-0.65

Smooth Surface – white colour: 0.25-0.3

Rough surface and white color: 0.3-0.35

Rough surface, medium bright color: 0.65-0.7

Roofing Light Grey, bright: 0.3-0.4

Roofing Green (closest option to a dark colour): 0.6-0.65

Dark Brick: 0.65-0.7

Convective Heat transfer Coefficients of external walls and windows:

The coefficients a and b in the equations for the convective heat transfer coefficients from section 4.1.2.3 were taken as averages between the windward and leeward values since the wind direction changes often. This was determined by plotting wind direction, which was seen to vary widely on a daily basis.

TableA-1 Convective heat transfer coefficients (Yazdanian and Klems, 1994)

Wind Direction	a	b
Units	$[w/m^2 \cdot C(m/s)^b]$	-
Windward	2.38	0.89
Leeward	2.86	0.617

Table A-2 Surface roughness multipliers (Walton, 1981)

Roughness Index	R_f	Example Material
1	2.17	Stucco
2	1.67	Brick
3	1.52	Concrete
4	1.13	Clear pine
5	1.11	Smooth Plaster
6	1.00	Glass

Roughness factor used for walls: brick, 1.67. Roughness factor used for shingles: Stucco, 2.17

Garage Wall (Door)

The majority of the 15.71 m^2 south wall is made up of an 11.71 m^2 large single garage door. This garage door is based on an actual "Garaga" 35 mm insulated door with high-pressure injected polyurethane foam (RSI 2.1 $m^2 \cdot K/W$) (www.atbdoor.com/steel-insulated-garage-doors-toronto.htm). The remaining part of the wall is the type defined as OUTWALL in TRNBuild.

HEAT GAINS IN THE HOUSE

Occupants:

From ASHRAE 2005, p. 30.4, Table 1, each occupant performing moderately active office work creates 75 W of sensible heat. Assuming low air velocity, 58% of this is radiant heat which is 43.5 W. Finally, the convective heat is the remainder of the sensible heat, which is 75 W – 43.5 W = 31.5 W

In addition, TRNBuild requires an Absolute Humidity value for the gains in the room. This value comes from the latent heat in the same ASHRAE table 1 which is 55 W:

Absolute Humidity, kg/hr = (kJ/hr)·(kg/kJ) = (kJ/hr)/(kJ/kg).

This is equivalent to (Latent Heat)/(Evaporation Enthalpy of water) = (198 kJ/hr)/(2257 kJ/kg)= 0.08773 kg/hr.

The activity level was left constant during the night even though it is somewhat reduced when the occupants are sleeping (130 W vs. 95 W) because the difference is insignificant to the heating and cooling loads.

THERMAL MASS FROM THE HOUSE CONTENTS

The following list shows all of the contents in the house that were determined to be significant as thermal masses when they are combined. Each object is broken down into materials and sizes (area and thickness). This is an estimation, and slight differences in areas and thicknesses will not have any noticeable effect on the house heating loads. It should also be noted that certain areas and thicknesses are modified from these approximations of the actual objects because certain thicknesses cause transfer function coefficient errors in TRNBuild. This occurs when the thicknesses of certain materials are too thin. The thicknesses and areas are modified so that the result is the same volume of material. Table A-3 shows the properties of the materials used as thermal masses for the house contents.

Zone C1 (Top Floor):

Master Bedroom
  King-size bed, 2 Night tables w/ radio, lamp, Dresser, Drawer Chest, TV, Closet w/ clothes

Master bathroom
  Bath/shower, Sink, Toilet

Bedroom 1
  Bed, Night table, Dresser, Closet with clothes and games, Desk w/ papers

Bedroom 2
  Bed, Night table, Dresser, Closet with clothes, books and games, Desk and hutch w/ papers

Upstairs bathroom
  Bath/shower, Sink, Toilet

Linen Closet
  Linens

Plumbing

Zone B1 Ground Floor:

Kitchen
  Table, 4 chairs, Fridge/Freezer, Range, Counters and sink, Cupboards, Dishes and mugs, Glasses, Pots, pans and cutlery, Pantry with canned and boxed food, Appliances.

Washroom
  Sink, Toilet

Dining Room
  Table, 6 chairs, Credenza

Family Room
    3 seat couch, 2 seat couch, 1 Lazy-Boy, TV, Stereo w/ speakers, Wall Unit

Plumbing

Zone A1 (basement):

Laundry Room
    Washer, Dryer

Furnace room
    Furnace

Office/Play Room
    Desk and hutch w/ papers, Couch, Wall unit, TV, Toys, Books and games, Sink, Toilet

Plumbing

Table A-3: Properties of the materials selected as thermal masses

Material	**Conductivity**		**Capacity (Sp.Heat)**	**Density**	**Source**
	kJ/h·m·K	**W/m·K**	**kJ/kg·K**	**kg/m^3**	
Wood (Oak)	0.6336	0.176	2.39	750	1
Paper	0.468	0.13	1.3	930	1
Steel	163.08	45.3	0.5	7830	1
Foam (low density polyurethane)	0.08	0.0222	1.47	35	2
Textiles (average of Cotton and Wool)	0.1647	0.04575	1.35	1400	
Cotton	0.1512	0.042	1.34	1500	1
Wool Fabric	0.1782	0.0495	1.36	1300	1
Plastic	0.828	0.23	1.5	1300	3
Ceramic	4.32	1.2	1	2000	2
Marble	9.36	2.6	0.88	2600	1
Glass	3.6	1	0.75	2470	1
Granite	10.26	2.85	0.79	2880	4- Sp. Heat, 5- Cond., 6- Density
Liquefied foods	2.1672	0.602	3.77	998.2	7- Sp. Heat 1- Density & Cond. same as Water
Water	2.1672	0.602	4.18	998.2	1

Sources:
1- ASHRAE 2005, Ch. 39 Physical Properties of Materials
2- TRNBuild Library of Layers
3- Electronic Development Labs, Inc. 2000
4- The Engineering ToolBox 2005e
5- The Engineering ToolBox 2005f
6- ASHRAE 2005, p. 25.7
7- The Engineering ToolBox, 2005a

APPENDIX B. PARAMETERS AND INPUTS FROM TRNSYS TYPES

Table B-1: Properties for the DHW and radiant floor storage tanks

Property	DHW Tank	Radiant Floor Tank	Unit
Tank Properties			
Number of Tank Nodes	4	4	
Tank Volume	0.303	0.303	m^3
Tank Height	1.492	1.492	m
Top Loss Coefficient	1.181	1.181	$kJ/(hr{\cdot}m^2{\cdot}K)$
Bottom Loss Coefficient	1.181	1.181	$kJ/(hr{\cdot}m^2{\cdot}K)$
Additional Thermal Conductivity	0	0	$kJ/(hr{\cdot}m^2{\cdot}K)$
Top Loss Temperature*	20	20	°C
Bottom Loss Temperature*	20	20	°C
Flue Loss temperature*	20	20	°C
Inversion Mixing Flow Rate*	-100	-100	kg/hr
Edge Loss			
Nodal Edge Loss Coefficient (all 4 Nodes)	1.181	1.181	$kJ/(hr{\cdot}m^2{\cdot}K)$
Edge Loss Temperature (all 4 Nodes)*	20	20	°C
Paired Inlet/Outlet Ports			
Number of Ports	1	1	
Inlet Flow Mode	Locations of Inlets and Outlets Provided		
Entry Node	4	4	
Exit Node	1	1	
Temperature at Inlet*	5	30	°C
Flow Rate at Inlet*	4	100	kg/hr
Number of Misc. Heat Gains	0	0	
Tank Fluid	Pure Water	Pure Water	
Nodal Parameters			
Overall Flue Heat Loss Coefficient (all 4 nodes)	0	0	kJ/(hr·K)
Auxiliary Heat Rate (all 4 nodes)*	0	0	kJ/hr
Initial Tank Node temperature (node 1, 2, 3 & 4)	55, 12, 10, 8	all 35	°C

* These are inputs to the tanks and thus the values in this table are only the starting value.

Table B-1 (continued): Properties for the DHW and radiant floor storage tanks

Property	**DHW Tank**	**Radiant Floor Tank**	**Unit**
Immersed Heat Exchangers			
Number of Immersed heat Exchangers	1	1	
Heat Exchanger Type	Coiled Tube	Coiled Tube	
Number of Heat Exchanger Nodes	4	4	
Heat Exchanger Fluid	Propylene Glycol and Water		
Percent Volume of Additive	60	60	%
Multiplier for Natural Convection Correlation	1	1	
Exponent for Rayleigh Number	0.25	0.25	
Geometry Factor	1	1	
Geometry Factor Exponent	0	0	
Tube Inner Diameter	0.01587	0.01587	m
Tube Outer Diameter	0.018	0.018	m
Wall Conductivity	1415	1415	kJ/(hr·m·K)
Tube Length	36.6	36.6	m
Number of Tubes	1	1	
Header Volume	0.01	0.01	m^3
Cross Sectional Area	0.0254	0.0254	m^2
Coil Diameter	0.53	0.53	m
Coil Pitch	0.03	0.03	m
HX Temperature at Inlet*	20	20	°C
HX Flow Rate at Inlet*	1	1	kg/hr
Placement Parameters			
Tank Node for HX Node 1	3	3	
Tank Node for HX Node 2	3	3	
Tank Node for HX Node 3	4	4	
Tank Node for HX Node 4	4	4	
Fraction of HX Node (all 4 nodes)	0.25	0.25	

* These are inputs to the tanks and thus the values in this table are only the starting value.

Table B-2: TRNSYS Parameters for the Flat Plate and Evacuated Tube Solar Collectors

Solar Collector Parameter	Flat Plate	Evacuated Tube	Source
TRNSYS Type	1b	71	
Gross Area per collector	2.734 m^2	2.852 m^2	1, 2
Fluid Specific Heat*	3.370 kJ/kg.K	3.370 kJ/kg.K	3
Efficiency Mode	1	2	1, 2
Tested Flow Rate	75.9 $kg/(hr \cdot m^2)$	52.6 $kg/(hr \cdot m^2)$	1, 2
Intercept efficiency	0.649	0.58	1, 2
Efficiency slope or Negative of second order efficiency coefficient	3.1374 $kg/(hr \cdot m^2 \cdot K)$	1.21 $kg/(hr \cdot m^2 \cdot K)$	1, 2
Efficiency curvature or Negative of second order efficiency coefficient	0.0148 $kg/(hr \cdot m^2 \cdot K^2)$	0.0024 $kg/(hr \cdot m^2 \cdot K^2)$	1, 2
1st-order IAM	0.2824	-	1
2nd-order IAM	0.0111	-	1
Number of longitudinal angles for which IAMs are provided	-	10	2
Number of transverse angles for which IAMs are provided	-	10	2

* 40/60 water/glycol solution. Value taken at about 60 °C average.

1 - Solar Rating and Certification Corporation 2008.

2 - Solartechnik Prüfung Forschung 2008.

3 - The Engineering ToolBox 2005c.

Table B-3: Properties for the Sanyo HIP 200BA3 photovoltaic module, Type 94a

Parameter	**Value**
Module short-circuit current at reference conditions	3.83 Amperes
Module open-circuit voltage at reference conditions	68.7 Volts
Reference temperature	298 K
Reference insolation	1000 W/m^2
Module voltage at max power point and reference conditions	55.8 Volts
Module current at max power point and reference conditions	3.59 Amperes
Temperature coefficient of Isc at (ref. cond)	0.00088
Temperature coefficient of Voc (ref. cond.)	-0.172
Number of cells wired in series	96
Module temperature at NOCT	44.2 °C
Ambient temperature at NOCT	20 °C
Insolation at NOCT	800 W/m^2
Module area	1.179 m^2
tau-alpha product for normal incidence	-0.9
Semiconductor bandgap	1.12

Values from Sanyo Energy (USA) corp. 2006

Ground Coupling – TYPE 701a

Some of the more important parameters, inputs and outputs from Type 701a are detailed below.

Parameter 7, Mean surface temperature: This is 5.93°C based on the notes accompanying equation 36 on page 29.12 in ASHRAE 2005. It states that this value can be estimated using the average annual air temperature, which was generated from the TRNSYS weather file in this model.

Parameter 8, Amplitude of Surface Temperature: 11°C from ASHRAE 2005, p. 29.12 Fig. 2.

Parameter 9, Day of min surface temp: Day 34. This is based on ambient temperatures from a plot of the weather file. There is a colder day in January, but this was chosen since it may take some time for ground temperatures to cool. In addition, the default value in TRNSYS was 36.

The soil type in this model is defined as clay or clay loam since this is a common soil type around Montreal homes. This results in the following:

Parameter 10, Soil conductivity: 1.8 W/m·K. This value comes from ASHRAE 2005, p. 25.14 Table 5. It is based on the high conductivity values for clay and loam, but closer to the clay value since the soil is more clay. The high conductivity value was used to take the worst case scenario of maximum heat loss in winter conditions.

Parameter 11, Soil Density: 1250 Kg/m^3. This is an average between clay and earth from table 3 in ASHRAE 2005, p. 39.3.

Parameter 12, Soil Specific Heat: 875 J/Kg·K. Value taken between clay (920 J/Kg·K) and sand (800 J/Kg·K), but closer to clay (ASHRAE 2005, p. 39.3, table 3).

Parameter 13, Surface Emissivity: 0.94 (ASHRAE 2005, p. 3.9, Table 5).

Parameter 14, Surface Absorptance: 0.5. Note that Absorptance = (1 – Reflectance). ASHRAE 2005, p. 31.16, Table 10 shows solar reflectance for various surfaces: For bright green grass, at an incident angle of 60° -70°, absorptance is 1- 0.285 = 0.715. Snow reflectivity is 0.8 so the absorptivity is 0.2 (Albedo 2007). A weighted average is used assuming that there is snow 5 months of the year and green grass for 7 months (since brown grass also has a high absorptance). $(5/12)\cdot 0.2 + (7/12)\cdot 0.715 = 0.5$

Input 4, Convection coefficient: 29 W/m^2·K. From ASHREA 2005, p. 25.2, Table 1. This is the average of winter and summer for moving air.

APPENDIX C. DETAILED PRICING

All prices in Tables C-1 and C-2 include labour (installation) aside from the windows which list it separately.

Table C-1: Price breakdown of the Base Case House construction

Material	Price	per unit	Qty	Times to Install	Total Life Cycle Cost	Source
FLOOR ASSEMBLIES						
Footing						
200 mm thick x 460 mm wide	$48.56	m	39.36	1	$1,911	1
Basement Floor						
Hardwood floor (maple)	$71.80	m^2	41.23	1	$2,960	1
Plywood	$14.96	m^2	41.23	1	$617	1
Wood Floor Studs, 2x4 (38 mm x 89 mm)	$1.14	m	80.6	1	$92	1, 2
Concrete Floor Slab (76 mm thick)	$32.61	m^2	83.58	1	$2,726	1
B1 and C1 Floors						
2x10 x 400mm OC						
Hardwood floor (maple)	$71.80	m^2	167.16	1	$12,001	1
Floor Joist Frame (incl. plywood sheathing)	$79.65	m^2	167.16	1	$13,315	1
Gypsum, 13 mm (taped & painted)	$24.54	m^2	167.16	1	$4,102	1
Mineral wool insulation only for B1E, 235 mm	$16.17	m^2	42.37	1	$685	3
Attic Floor						
2x12 x 400mm OC						
Mineral wool insulation (260 mm thick)	$18.08	m^2	83.58	1	$1,511	3
Floor Joist Frame (incl. plywood sheathing)	$85.25	m^2	83.58	1	$7,125	1
Gypsum, 13 mm (taped & painted)	$24.54	m^2	167.16	1	$4,102	1
Roof						
Shingles (standard organic)	$12.07	m^2	137.2	3	$4,967	1
Truss (incl. sheathing)	$74.49	m^2	83.58	1	$6,226	1
WALL ASSEMBLIES						
Basement Exterior Wall						
Gypsum, 13 mm (taped & painted)	$29.92	m^2	74.82	1	$2,239	1
Mineral Wool Insulation, 89 mm	$8.63	m^2	74.82	1	$646	3
Wood Stud Frame, 2x4 (38 mm x 89 mm) 610 mm OC	$15.72	m^2	74.82	1	$1,176	1
200 mm Concrete & Rebar	$127.44	m^2	74.82	1	$9,535	1

Table C-1 (continued): Price breakdown of the Base Case House construction

Material	Price	per unit	Qty	Times to Install	Total Life Cycle Cost	Source
WALL ASSEMBLIES						
Basement Interior Walls						
Gypsum, 13 mm (taped & painted)	$29.92	m^2	22.66	1	$678	1
Wood Stud Frame, 2x4 (38 mm x 89 mm) 610 mm OC	$18.16	m^2	22.66	1	$411	1
Gypsum, 13 mm (taped & painted)	$29.92	m^2	22.66	1	$678	1
Basement/Garage Interior Wall						
Gypsum, 13 mm (taped & painted)	$29.92	m^2	22.66	1	$678	1
Mineral Wool Insulation, 140 mm, 24" OC	$11.19	m^2	22.66	1	$254	3
Wood Stud Frame, 2x4 (38 mm x 89 mm) 610 mm OC	$22.23	m^2	22.66	1	$504	1
Plywood	$14.96	m^2	22.66	1	$339	1
Gypsum, 13 mm (taped & painted)	$29.92	m^2	22.66	1	$678	1
B1 & C1 Exterior Walls						
Gypsum, 13 mm (taped & painted)	$29.92	m^2	215.7	1	$6,455	1
Mineral Wool Insulation, 140 mm, 24" OC	$11.19	m^2	215.7	1	$2,415	3
Wood Stud Frame, 2x6 (38 mm x 140 mm) 610 mm OC	$34.55	m^2	215.7	1	$7,453	1
Red Faced Common Brick	$184.06	m^2	215.7	1	$39,702	1
B1 & C1 Exterior Walls						
Gypsum, 13 mm (taped & painted)	$29.92	m^2	97	1	$2,903	1
Wood Stud Frame, 2x4 (38 mm x 89 mm) 610 mm OC	$18.16	m^2	97	1	$1,761	1
Gypsum, 13 mm (taped & painted)	$29.92	m^2	97	1	$2,903	1
Attic Side Walls						
Gypsum, 13 mm (taped & painted)	$29.92	m^2	25.92	1	$776	1
Wood Stud Frame, 2x4 (38 mm x 89 mm) 610 mm OC	$30.68	m^2	25.92	1	$795	1
Red Faced Common Brick	$184.06	m^2	25.92	1	$4,771	1
DOORS						
Garage Door, Overhead Sectional 4.88m x 2.13m	$2,161.00	each	1	1	$2,161	1
Header 2 x [2x8 (38 mm x 184 mm) double, 2.44 m long]	$111.63	each	1	1	$112	1
Front Door	1302.77	each	1	1	$1,303	1
Header, 2x8 (38 mm x 184 mm) double, 1.83 m long	41.83	each	1	1	$42	1
Interior Doors, Birch Fluch Door, Hollow Core	$711.02	each	10	1	$7,110	1
Header, 2x6 (38 mm x 140 mm) double, 0.914 m long	$18.47	each	10	1	$185	1
Basement/Garage Door, insulated fiberglass	$811.00	each	1	1	$811	1
Header, 2x6 (38 mm x 140 mm) double, 0.914 m long	$18.47	each	1	1	$18	1

Table C-1 (continued): Price breakdown of the Base Case House construction

Material	Price	per unit	Qty	Times to Install	Total Life Cycle Cost	Source
WINDOWS						
A1 Windows						
Double Pane 1000 mm x 1000 mm	$780.00	each	3	1.25	$2,925	4
Trim, paint, caulking, drip cap, labour	$146.00	each	3	1.25	$548	1
Header, 2x6 (38 mm x 140 mm) double, 1.22 m long	$24.66	each	3	1	$74	1
B1 & C1 Windows						
Double Pane 700 mm x 800 mm	$660.00	each	32	1.25	$26,400	4
Trim, paint, caulking, drip cap, labour	$146.00	each	32	1.25	$5,840	1
Header, 2x6 (38 mm x 140 mm) double, 0.914 m long	$18.47	each	32	1	$591	1
HEATING						
Baseboard Heaters (w/ controls), 15 kW	$221.84	kW	15	1	$6,655	1
DHW						
1 regular 300 L tank	$503.00	each	1	3	$1,509	1

TOTAL*	**$206,372**
TOTAL (incl. Tax)	**$232,943**

* Basic construction, not including plumbing, electrical or furnishings

Sources:
1- RS Means 2008
2- Rona Renovateur 2008
3- The Home Depot 2008
4- Glass Experts 2008

Table C-2: Materials added to or removed from the BCH to make the NZEH

LEGEND:
: New materials added to the NZEH
Ø : Materials removed from the BCH design to make the NZEH

Material	Price	per unit	QTY	Times to install	Total Life Cycle Cost	Source
RADIANT FLOOR COMPONENTS						
Radiant Floor tubing - All floors	$15.07	m^2	208.00	1	$3,134	1
Manifolds	$2,500.00			1	$2,500	1
Thermostats	$250.00	zones	6.00	1	$1,500	1
Pumps and controls	$375.00	pump	4.00	2.7	$4,000	1
Regular 300 L storage tank	$503.00	each	1.00	3	$1,509	8
Baseboard Heaters (w/ controls), 15 kW	$221.84	kW	15.00	2	$6,655	3
INSULATION & WALLS/FLOORS						
XPS Floor Insulation in A1, 41 mm	$18.84	m^2	41.23	1	$777	3
Ø Wood Floor Studs, 2x4 (38 mm x 89 mm)	$1.02	m	-80.60	1	-$82	2
Ø A1: 500 mm OC. 13 x 6.2 m = 80.6 m						
Ø Wood Floor Studs, 2x10 (38 mm x 235 mm)	$3.83	m	-334.80	1	-$1,281	2

Table C-2 (continued): Materials added to or removed from the BCH to make the NZEH

Material	Price	per unit	QTY	Times to install	Total Life Cycle Cost	Source
INSULATION & WALLS/FLOORS						
Ø B1: 500 mm OC. 27 x 6.2 m = 167.4 m						
Ø C1: 500 mm OC. 27 x 6.2 m = 167.4 m						
Wood Floor Studs, 2x3 (38 mm x 64 mm)	$0.89	m	248.00	1	$220	2
B1W: 500 mm OC. 13 x 6.2 m = 80.6 m						
C1: 500 mm OC. 27 x 6.2 m = 167.4 m						
Wood Floor Studs, 2x6 (38 mm x 140 mm)	$2.45	m	86.80	1	$213	2
B1E: 500 mm OC. 14 x 6.2 m = 86.8 m						
Ø Wood Floor Studs, 2x12 (38 mm x 286 mm)	$5.63	m	-167.40	1	-$942	2
Ø Attic: 500 mm OC. 27 x 6.2 m =167.4 m						
Wood Floor Studs, 3x16 (64 mm x 387 mm)	$8.08	m	167.40	1	$1,352	2
Attic 500 mm OC. 27 x 6.2 m =167.4 m						
Plywood floor, 16 mm	$14.96	m^2	167.20	1	$2,502	3
B1W: 41.23 m2	$15.07	m^2	208.00			
B1E: 42.37 m2						
C1: 83.58 m2						
Mineral Wool Floor insulation, 40 mm	$2.70	m^2	124.80	1	$337	4
B1W: 41.23 m2						
C1: 83.58 m2						
Ø Mineral Wool Floor insulation, 95 mm	$5.40	m^2	-42.37	1	-$229	4
B1E (NZEH): 140mm x 42.37 m^2						
Ø B1E (BCH): 235 mm x 42.37 m^2						
Mineral Wool Floor insulation, 160 mm	$5.70	m^2	83.58	1	$477	4
Attic (NZEH): 420mm x 83.58 m^2						
Ø Attic (BCH): 260 mm x 83.58 m^2						
Concrete floor, 75 mm	$20.88	m^2	167.16	1	$3,491	3
B1: 83.58 m^2						
C1: 83.58 m^2						
Wood Wall Studs, 2x10 (38 mm x 235 mm)	$3.83	m	320.00	1	$1,224	2
B1: 610 mm OC. 64 x 2.5 m = 160 m						
C1: 610 mm OC. 64 x 2.5 m = 160 m						
Ø Wood Wall Studs, 2x6 (1.5 x 5.5 = 38 x 140)	$2.45	m	-320.00	1	-$784	2
Ø B1: 610 mm OC. 64 x 2.5 m = 160 m						
Ø C1: 610 mm OC. 64 x 2.5 m = 160 m						
Mineral Wool Wall insulation, 229 mm	$12.94	m^2	157.00	1	$2,031	4
B1: 76.71 m^2						
C1: 80.3 m^2						
Ø Mineral Wool Wall insulation, 140 mm	$7.75	m^2	-157.00	1	-$1,217	4
Ø B1: 76.71 m^2						
Ø C1: 80.3 m^2						

Table C-2 (continued): Materials added to or removed from the BCH to make the NZEH

Material	Price	per unit	QTY	Times to install	Total Life Cycle Cost	Source
WINDOWS (Labour separate)						
Loewen Windows (Operable Casement) triple pane (HP3 Thermal Edge) argon filled						
800 mm x 1200 mm	$1,000.00	window	12.00	1.25	$15,000	5
Header, 2x6 double, 0.914 m long	$18.47	window	12.00	1	$222	3
400 mm x 1200 mm	$730.00	window	14.00	1.25	$12,775	5
Header, 2x6 double, 0.61 m long	$12.33	window	14.00	1	$173	3
400 mm x 1000 mm	$670.00	window	4.00	1.25	$3,350	5
Header, 2x6 double, 0.61 m long	$12.33	window	4.00	1	$49	3
1000 mm x 1000 mm	$910.00	window	3.00	1.25	$3,413	
Header, 2x6 double, 1.22 m long	$24.66	window	3.00	1	$74	3
Loewen Windows (Fixed Picture) triple pane (HP3 Thermal Edge) argon filled						
800 mm x 1200 mm	$700.00	window	12.00	1.25	$10,500	5
Header, 2x6 double, 0.914 m long	$18.47	window	12.00	1	$222	3
Ø Loewen Windows (Operable Casement) double pane (HP1) argon filled						
Ø 800 mm x 700 mm	$660.00	window	-32.00	1.25	-$26,400	5
Ø Header, 2x6 double, 0.914 m long	$18.47	window	-32.00	1	-$591	3
Ø 1000 mm x 1000 mm	$780.00	window	-3.00	1.25	-$2,925	5
Ø Header, 2x6 double, 1.22 m long	$24.66	window	-3.00	1	-$74	3
Window Installation						
(NZEH) Trim, paint, caulking, drip cap, labour	$146.00	window	45.00	2	$13,140	3
Ø (BCH) Trim, paint, caulking, drip cap, labour	$146.00	window	-35.00	2	-$10,220	3
LIGHTING						
CFL Lighting						
(4 x 1.25) W/m^2 x 208 m2 = 1040 W in the NZEH.						
Noma 13 W CFL 3-pack (39 W)	$8.49	3-pack (39 W)	27.00	10	$2,292	6
Ø Incandescent Lighting						
Ø (4 x 5) W/m^2 x 208 m2 = 4160 W in the NZEH.						
Ø Philips 60W Incandescent bulb 4Pk (240 W)	$3.98	4-pack (240 W)	-18.00	80	-$5,731	4
DHW DEVICES						
Thermostatic Mixing Valve	$160.77	valve	1.00	1	$161	3, 7
Drain water heat recovery (power-pipe)	$870.00	pipe	1.00	1	$870	3, 4

TOTAL	**$30,376**
TOTAL (incl. Tax)	**$34,287**

Sources:

1- Beaulieu 2008, 2- Rona Renovateur 2008
3- RS Means 2008, 4- The Home Depot 2008
5- Glass Experts 2008, 6- Canadian Tire 2008
7- Cash Acme 2008, 8- Sears 2008

Table C-3: Solar collector prices

	Price	Adjusted Price	Location/ Currency	Source
Evacuated Tube Solar Collectors		$/20 tubes		
Thermomax Mazdon - 20 TMA 600 tubes	$2,948	$2,948	CAN (QC)	1
Thermomax - 20 tube	$2,000	$2,000	USA	2
Thermomax - 30 tube	$3,000		USA	2
***AVERAGE**		**$2,474**		
Thermomax Mazdon - 20 TMA 600 tubes	$1,922	$1,922	USA	3
Other Manufacturers				
Seido 1-16	$2,100	$2,100	CAN	4
SCGV 01 10 tubes	$1,200	$2,400	CAN	5
SCGV 02 20 tubes	$2,400	$2,400	CAN	5
SCGV 01 - 10 tubes	$945	$1,890	USA (NE)	6
SCGV 10 tubes x 2	$1,795	$1,795	USA (NE)	6
SCGV 10 tubes x 3	$2,636	$1,757	USA (NE)	6
Flat Plate Solar Collectors		$/m^2		
***Stiebel Eltron SOL25 Plus**	**$948**	$351	CAN (QC)	1
Thermo Dynamics G-Series Glazed	$864	$290	CAN (NS)	7
Thermo Dynamics G32-P collector	$864	$292	CAN (NS)	7
Stiebel Eltron SOL25 Plus 1-5 units	$697	$258	USA	3
Stiebel Eltron SOL25 Plus > 5 units	$627	$232	USA	3
EC-40 Sun Earth collector 4' x 10' (3.72 sqm)	$1,202	$323	USA (AZ)	8

*Values used in cost analysis.

Table C-4: Flat plate solar collector frame component prices

	Price	Location/ Currency	Source
Flat Plate frame components			
*Sensor well	$19	CAN (QC)	1
*Frame (1 panel)	$97	CAN (QC)	1
*Frame (2 panels)	$177	CAN (QC)	1
*Flush Mount Kit (per 2 panels)	$122	CAN (QC)	1
*Stainless steel connecting tube	$37	CAN (QC)	1
*Connector kit (attach 2 frames together)	$31	CAN (QC)	1
*Combined frame component price for 1 panel	$238		
*Combined frame component price for 2 panels	$386		
*Combined frame component price for 3 panels	$673		
*Combined frame component price for 4 panels	$821		
*Combined frame component price for 5 panels	$1,108		
*Combined frame component price for 6 panels	$1,256		
Sensor well	$11	USA	3
Frame (1 panel)	$56	USA	3
Frame (2 panels)	$114	USA	3
Flush Mount Kit (per 2 panels)	$74	USA	3
Stainless steel connecting tube	$24	USA	3
Connector kit (attach 2 frames together)	$20	USA	3
1- K1050 Mount kit	$31	CAN (NS)	7

*Values used in cost analysis.

Table C-5: Prices for components of both flat plate and evacuated tube solar collectors

	Price	Adjusted Price	Location/ Currency	Source
Storage Tanks with HX				
Stiebel Eltron SBB 300 S (single HX)	$1,730		CAN (QC)	1
Thermo 2000 - 80 gal tank	$2,500		CAN	4
***WHSC-300L (with HX)**	**$1,399**		CAN (QC)	5
Rheem Solaraide HE 80 Gal.	$1,353		USA (FL)	9
Rheem Solaraide HE 80 Gal.	$1,290		USA (AZ)	8
Regular Storage Tanks				
Kenmore®/MD Power Miser 6 Electric	$360		CAN	10
Kenmore®/MD Power Miser 9 Electric	$520		CAN	10
Kenmore® Power Miser 12 Electric	$630		CAN	10
*AVERAGE	**$503**			
Controllers				
***Stiebel Eltron SOM-6**	**$199**		CAN	1
Solar controler DeltaSol bs/3	$371		CAN	4
Stiebel Eltron SOM-6	$140		USA	3
Pumps				
***Stiebel Eltron - Flowstar Pumping Station**	**$726**		CAN	1
Pump flowconfa	$798		CAN	4
Stiebel Eltron - Flowstar Pumping Station	$496		USA	3
Glycol		**$/L**		
20 litres of Glycol	$146	$7.30	CAN	1
20 litres of Glycol mixed 40/60 with water	$128	$6.38	CAN	7
*AVERAGE	**$137**	**$6.84**		
20 litres of Glycol	$78	$3.90	USA	3
Piping (between the roof and the tanks)		**$/m**		
*1/2" copper pipe, 12' (3.7m) roll	$16	$4.32	CAN	11
*Rubber Tundra Seal pipe insul. 1/2'x384' (117 m)	$339	$2.90	CAN	11
*Elbows, fitting, and misc extras	$60		CAN	11
Installation				
***1 collector - new house**	**$1,200**		CAN (QC)	1
1 collector - renovation	$1,800		CAN (QC)	1
10 - 12 collectors	$3,000		CAN (QC)	1
2 collectors	$1,600		CAN	12
1 large collector	$3,400		USA - AZ	8

*Values used in cost analysis.

Table C-6: Photovoltaic system component prices

	Watts	Price	Price/Watt	Location/Currency	Source
PV Panels					
Sanyo HIP-200BA3	200	$1,240	$6.20	CAN (QC)	13
Sanyo HIP-200BA3	200	$1,421	$7.11	CAN (QC)	14
***AVERAGE**		**$1,331**	**$6.65**		
Sanyo HIP-200BA3	200	$1,100	$5.50	USA	15
Sanyo HIP-200BA3	200	$1,160	$5.80	USA	16
Sanyo HIT-200BA3	200	$1,100	$5.50	USA	17
Sanyo HIP-200BA3	200	$1,051	$5.26	USA	18
Sanyo HIP-200BA3	200	$1,050	$5.25	USA	19
Other Models					
Sanyo HIP-195BA3	195	$1,025	$5.26	USA	19
Sanyo HIP-195BA3	195	$1,355	$6.95	CAN (QC)	14
Sanyo HIP-190BA3	190	$1,305	$6.87	CAN (QC)	14
Sanyo 190	190	$1,300	$6.84	CAN (QC)	13
Sanyo HIP-186BA3	186	$1,221	$6.56	CAN (QC)	14
CAN AVERAGE			$6.75		
Other Manufacturers					
Sharp	200	$1,095	$5.48	CAN	13
Kyocera	200	$1,236	$6.18	CAN	13
SP150-12/24	150	$1,200	$8.00	CAN	20
Inverters					
Xantrex GT 2.8	2800	$2,498	$0.89	CAN	14
Xantrex GT 3.3	3300	$3,023	$0.92	CAN	14
Xantrex GT 4.0	4000	$3,291	$0.82	CAN	14
Xantrex GT 5	5000	$4,154	$0.83	CAN	14
***CAN AVERAGE**			**$0.87**		
Xantrex GT 2.8	2800	$2,312	$0.83	USA	21
Xantrex GT 3.0	3000	$2,100	$0.70	USA	19
Xantrex GT 3.0	3000	$1,800	$0.60	USA	22
Xantrex GT 3.3	3300	$2,000	$0.61	USA	22
Xantrex GT 3.8	3800	$2,166	$0.57	USA	22
Xantrex GT4.0	4000	$2,250	$0.56	USA	15
Xantrex GT 4.0	4000	$3,047	$0.76	USA	21
Xantrex GT 5.0	5000	$3,674	$0.73	USA	21
Xantrex GT 5.0	5000	$3,150	$0.63	USA	19
Xantrex GT 5.0	5000	$2,990	$0.60	USA	22
USA AVERAGE			$0.66		
Racking			$/panel		
$0.50/W, 3 panels = 600 W		$300	$100.00	USA	15
UNI-GR/04AH for 3 HIP		$255	$85.00	CAN	14
UNI-GR/08H 5 HIP		$475	$95.00	CAN	14
***AVERAGE**		**$365**	**$90.00**		

*Values used in cost analysis.

Table C-7: Complete solar collector system prices (based on Tables C3 – C5)

Total Evacuated Tube Collector System Prices	20 tubes	40 tubes	60 tubes	80 tubes
*Thermomax Evacuated Tube with average prices	$6,824	$9,526	$12,227	$14,928
Evacuated Tube from HLT Energies	$7,971	$11,348	$14,125	$17,302
Direct from Thermomax	$6,365	$8,593	$10,820	$13,047
Total Flat Plate Collector System Prices	1 collector	2 collectors	3 collectors	4 collectors
*Stiebel Eltron SOL25 with average prices	$5,523	$6,832	$8,281	$9,591
Stiebel Eltron SOL25 Flat Plate - HLT Energies	$6,194	$7,505	$8,954	$10,265

*Values used in cost analysis.

Sources for Tables C-3 to C-7:

1- HLT Energies (M. Gibson, Phone conversation & e-mails., May 2008)
2- Thermomax (L. Walsh, e-mails, January 2008)
3- Stiebel Eltron USA (E. Wilson, , e-mails, May 2008)
4- Energie Solaire (T & A Appelblom-Harriman, e-mails., May 2008)
5- Solair Quebec 2008
6- Nebraska Solar Solutions 2008
7- Thermo Dynamics 2008
8- EV Solar 2008
9- Energy Supermarket 2008
10- Sears 2008
11- The Home Depot 2008
12- Jory, L n.d.
13- MSM Electric (Phone conversation. May 2008)
14- Trans Canada Energies - Batteries Expert (Leclair, R, e-mail quote, May 2008)
15- The Alternative Energy Store 2008
16- Solar Home.org 2008
17- Wholesale Solar 2008
18- Affordable Solar 2008
19- Mr. Solar 2008
20- Windturbine.ca 2008
21- Sierra Solar 2008
22- The Solar Biz 2008

Table C-8: Photovoltaic system installation prices

	Watts	**Price**	**Price/Watt**	**Adjusted Price**
Installation			$/W	$/W, **Fit to curve**
5.6 kW system	5610	$5,680	$1.01	$0.95
3.1 kW system	3060	$3,610	$1.18	$1.20
2.4 kW system	2380	$2,973	$1.25	$1.33
1.7 kW system	1700	$2,478	$1.46	$1.51
1.2 kW system	1190	$2,093	$1.76	$1.73
0.7 kW system	680	$1,506	$2.21	$2.14
***Equation (see Fig. C1)**				$25.868/W^{0.3822}$

Source: Sun Volts Unlimited, Ontario, Canada. Mailed price quotes.

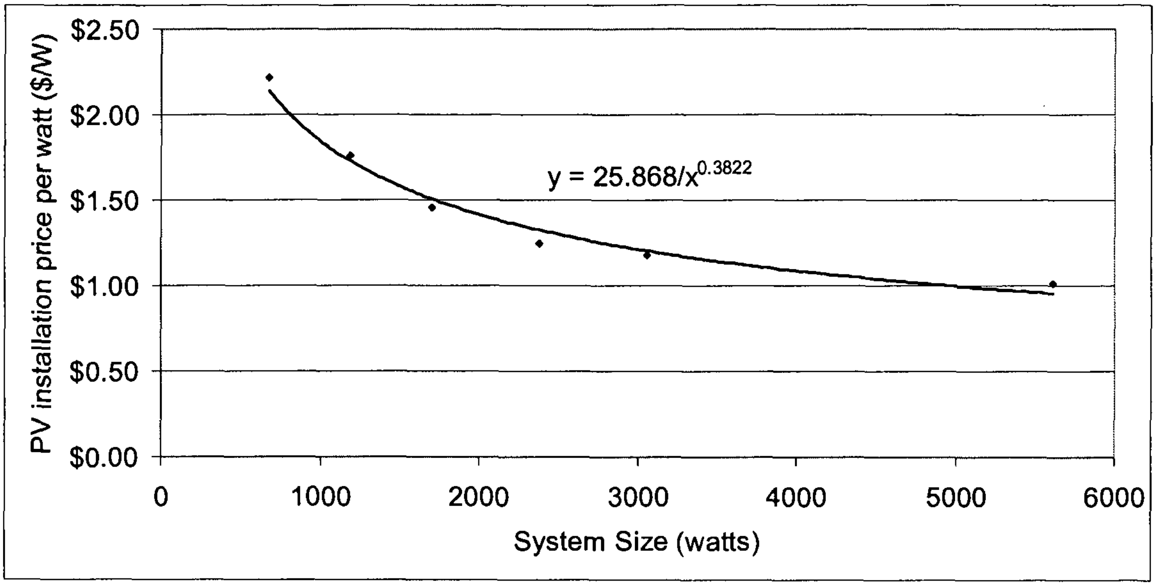

Figure C-1: PV installation price per watt (based on the installation costs in Table C8)