Impact of Climate Change on an R-2000 and a Net Zero Energy Home

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This is to certify that the thesis prepared

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

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Ratnalee Patil

The impact of the predicted climate change on the energy use of a residential building is studied. For this purpose, an R-2000 home built near Montreal, Canada is simulated using TRNSYS environment based on the construction documents. In order to calibrate the model, the simulated total annual electricity use is compared with the actual energy consumption from the utility bills. The simulation results are found in agreement with the actual energy use, with less than 2% difference. The study involves four cases: (i) the R-2000 home, i.e. the Base case, in today's climate, (ii) the Base case under the predicted climate of 2050, (iii) the Base case converted into a Net Zero Energy Home (NZEH) in today's climate, and (iv) the NZEH in the predicted climate of 2050.

The projections in terms of monthly data for temperature, solar radiation, relative humidity, and wind speed for 2050 for Montreal are extracted from three different global climate models (CGCM2, ECHAM4, and HadCM3) with two scenarios each, A2 and B2. Hourly data is generated from this monthly data. To convert the R-2000 home into a NZEH, various energy efficiency measures and technologies are used, along with a liquid-based hybrid PV/Thermal combi-system. Finally, a complete life cycle analysis (LCA) of cost, energy, and emissions for both the houses including all their systems and components is conducted.

For the Base case, the heating loads reduce by 11 to 22%, while the cooling loads increase by 25 to 93% by the mid-century. For the NZEH, a change in the PV/T production is observed by -1 to 4% for electrical and by -10 to 1% for thermal energy, due to the climate change. The LCA comparison between the two houses indicates that although it initially costs more, the NZEH becomes cost competitive with the Base case over the life span of 50 years. In spite of 40% higher embodied energy of the NZEH, the life cycle energy for the Base case is 1.5 times to almost 3 times higher than the NZEH over the 30-50 year life span. The energy payback time is found to be 9.2 years for the PV, while 7 years for the combined PV/T. The life cycle emissions are found 14.5 and 29% less for the NZEH compared to the Base case over the life spans of 40 and 50 years, respectively.

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List of Abbreviations

AB	Alberta
AEE	Agence de l'efficacité énergétique
AGCM	Atmospheric General Circulation Model
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BC	British Columbia
BIPV	Building Integrated Photovoltaic
BOS	Balance of System
CCCma	Canadian Center for Climate Modeling
CCF	Cumulative Cash Flow
CCIS	Canadian Climate Impacts and Scenarios
CDD	Cooling Degree Day
CFC	Chorofluocarbon
CFL	Compact Fluorescent Lamp
CGCM	Coupled Global Climate Model
CICS	Canadian Institute for Climate Studies
CLTC	California Lighting Technology Center
CMHC	Canada Mortgage and Housing Corporation
COP	Coefficient of Performance
COP-	Conference of Parties-
CPBT	Cost Payback Time
CRCM	Canadian Regional Climate Model
CSTB	Centre Scientifique et Technique du Batiment
CWEC	Canadian Weather for Energy Calculations
DHW	Domestic Hot Water
DOE	Department of Energy
DSY	Design Summer Year
DWHR	Drain Water Heat Recovery
ECHAM	European Centre HAmburg Model
EERE	Energy Efficiency and Renewable Energy
EP	Engineered Plastic
EPA	Environmental Protection Agency
EPBT	Energy Payback Time
EPR	Energy Payback Ratio
EPS	Expanded polystyrene
FiT	Feed-in Tariff
FW	Future Worth
GCM	Global Climate Model / General Circulation Model
GDP	Gross Domestic Product
GFX	Gravity Film heat eXchanger

GHG	Greenhouse Gas
GHX	Ground Heat eXchanger
GSHP	Ground Source Heat Pump
GST	Goods and Services Tax
GWHR	Grey Water Heat Recovery
GWP	Global Warming Potential
HadCM	Hadley Centre coupled Model
HCFC	Hydrochlorofluocarbon
HDD	Heating Degree Day
HFC	Hydrofluocarbon
HRV	Heat Recovery Ventilator
HVAC	Heating Ventilation and Air Conditioning
IDP	Integrated Design Process
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kWh	kilo Watt hour
LBNL	Lawrence Berkley National Laboratory
LCA	Life Cycle Analyses
LED	Light Emitting Diode
MB	Manitoba
MEL	Miscellaneous Electric Load
MJ	Mega Joule
MNECC	Model National Energy Code of Canada
NAHB	National Association of Home Builders
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NRCan	National Resources Canada
NREL	National Renewable Energy Laboratory
NS	Nova Scotia
NWP	Numerical Weather Prediction
NZEH	Net Zero Energy home
NZEHH	Net Zero Energy Healthy Home
ODP	Ozone Depletion Potential
OEE	Office of Energy Efficiency
OGCM	Ocean General Circulation Model
OPA	Ontario Power Authority
ORNL	Oak Ridge National Laboratory
PEI	Prince Edward Island
PEX	cross-linked Polyethylene
PFC	Perfluocarbon
PIMA	Polyisocyanurate Insulation Manufacturers' Association
POPCDD	Population-weighted Cooling Degree Day
POPHDD	Population-Weighted Heating Degree Day

PST	Provincial Sales Tax
PV/T	Photovoltaic/Thermal
PW	Present Worth
RCM	Regional Climate Model
RSI	Measure of Thermal Resistance in SI units (m^2.K/W)
SEL	Solar Energy Lab
SHGC	Solar Heat Gain Coefficient
SIP	Structural Insulated Panel
SOP	Standard Offer Program
SRES	Special Report on Emissions Scenarios
TESS	Thermal Energy Systems Specialists
TMV	Thermostatic Mixing Valve
TMY	Typical Meteorological Year
TRNSYS	TRaNsient SYstem Simulation
UKCIP	U.K. Climate Impacts Program
UN	United Nations
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
WCF	Water Consumption Factor
WMO	World Meteorological Organization
WWF	World Wide Fund
XPS	Extruded PolyStyrene

1. Introduction

1.1 Thesis Overview: Climate Change and Buildings

The topic of climate change has gained significant attention over the past decade. The world has become increasingly aware of this impending environmental threat, and mitigation as well as adaptation strategies have been and are being thought-out in order to face its challenges. The use of fossil fuels to fulfill various energy needs such as for industry, transportation, and buildings, has grown exponentially since the industrial era and been identified as the main cause of this crisis.

The building industry and the issue of climate change are interlinked in various ways. The buildings have an impact on climate change through their embodied and operating emissions, while change in the climate affects buildings through, for example, change in heating and cooling loads. The interconnection between these two, the buildings and the issue of climate change, is the basis of this thesis. The goal of this research is thus two-fold: (i) to study the impact of climate change on energy use of buildings, and at the same time, (ii) to investigate the use of renewable energy for designing Net Zero Energy homes that would facilitate minimizing greenhouse gas emissions (GHG) in order to limit further climate change.

For the first part of this goal, a house - the Base case - built in the year 2,000, is modeled in TRNSYS and simulated in the current climate. Using the future climate data, the house is then simulated for the mid-century. Comparing these two, the impact on the house energy use due to climate change is evaluated.

For the second part of the goal, the selected house is converted into a NZEH using solar as the renewable energy source. Besides achieving energy independence, the main purpose of a NZEH is to use zero energy from the fossil fuels to operate, and consequently, to not create any emissions. However, this is only part of the picture, since the house actually consumes energy even before it starts operating, which is in the form of embodied energy.

This research, therefore, aims to shed light on the entire life span of these two houses, the Base case and the NZEH, in order to compare the true environmental benefits of building NZEHs. For this purpose, life cycle energy and emissions analyses are conducted. The life cycle cost analysis is also conducted besides the energy and emissions analyses in order to (i) evaluate economic feasibility of the NZEH, and (ii) evaluate the cost of saved emissions.

1.2 Climate Change

Climate change is a complex, highly politicized, and somewhat controversial issue that demands immediate attention and action from policy makers all around the world. In order to provide the related reliable information about this issue and propose adaptation and mitigation options, Intergovernmental Panel on Climate Change (IPCC) was established by World Meteorological Organization (WMO) and United Nations Environment Program (UNEP) in 1988. IPCC is now a Nobel Peace Prize winner scientific body. The key contributors to the work of IPCC are thousands of scientists from currently 194 countries, authoring and reviewing the technical work on voluntary basis (IPCC, n.d.). IPCC publishes periodic reports, the critical source of reference for climate change related information in this study.

1.2.1 Definition

According to IPCC, climate change is defined as 'significant variation in either the mean state of the climate or in its variability, persisting for an extended period (decade or longer)'. United Nations Framework Convention on climate Change (UNFCCC), the key international treaty to reduce global warming and the impacts of climate change defines it slightly differently, by linking it to anthropogenic emissions. As per UNFCCC, climate change is 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods' (IPCC, 2004).

1.2.2 Science Behind Climate Change

1.2.2.1 Earth's Atmosphere

Before beginning the discussion on climate change, a few relevant facts about earth's atmosphere are stated in this section. The earth's atmosphere is divided mainly into four layers, troposphere, stratosphere, mesosphere and thermosphere, extending 15, 50, 85, and 600 km respectively from the surface of the earth. (NASA, 1995). Most of the weather takes place in the troposphere. The dry atmosphere is mainly composed (by volume) of 78% nitrogen (N_2) and 21% oxygen (O_2). The minor components and their levels in the atmosphere are Argon (Ar) 9340 ppm, Carbon dioxide (CO_2) 380 ppm, Neon (Ne) 18 ppm, Helium (He) 5 ppm, Methane (CH_4) 2 ppm, Krypton (Kr) 1 ppm, and Hydrogen (H_2) 0.5 ppm. There is variable amount of water content in the atmosphere as well, but is normally less than 1% by volume (NASA, 2007).

1.2.2.2 Greenhouse Gases

The earth absorbs solar radiation (short wave) and radiates back in the form of long wave (infrared) radiation. Some of this infrared radiation is absorbed by the gases in the atmosphere and radiated back to the earth, just as the glass of a green house traps-in the long wave radiation; these gases are called greenhouse gases (GHGs). For billions of years the composition of the atmosphere was balanced in such a way that the heat balance was managed to keep the temperature of the earth warm enough to maintain life on the earth. However, since the industrial era, the composition of the atmosphere has been changing due to the pollutants that are being released to it. The percentage of anthropogenic GHGs in the atmosphere is constantly increasing. The most abundant gases in the dry atmosphere, nitrogen, and oxygen have no greenhouse effect; CO_2 and water vapor are the most important greenhouse gases

(IPCC, 2007.a). The GHGs addressed in Kyoto Protocol are CO_2, CH_4, nitrous oxide (N_2O), perfluocarbons (PFCs), hydrofluocarbons (HFCs), and sulphur hexafluoride (SF_6) (UN, 1998).

To measure and compare the warming effect due to various GHGs, a dimensionless weighting factor is used, called Global Warming Potential (GWP), which compares global warming impacts of 1 kg of any greenhouse gas and 1 kg of CO_2 over the same time period, normally 100 years (Masters, 1998). For example, GWP_{100} of methane is 21, which means 1 kg of methane is 21 times more effective in trapping heat compared to 1 kg of CO_2 over 100 year.

Today's atmosphere contains 390 ppm of $CO_{2,}$ while the pre-industrial value was about 280 ppm. This 39% increase is mainly due to burning fossil fuels and deforestation. The concentrations of methane and nitrous oxide have also changed significantly due to agriculture and fossil fuel use, while tropospheric ozone levels have increased due to emissions of ozone-forming chemicals. Although ozone in the upper stratosphere blocks ultraviolet radiation from reaching the earth, ozone in troposphere and lower stratosphere acts as GHG. Higher levels of halocarbons, used mainly as refrigerants, are responsible for stratospheric ozone depletion (IPCC, 2007.b).

1.2.3 Consequences of Climate Change

Global warming is the most prominent consequence of climate change. IPCC, in its Fourth Assessment Report, predicts an increase in average surface temperature of the earth (global mean surface temperature) by 1.1°C to 6.4°C compared to 1980-1999 level by the end of 21st century, because of climate change. (IPCC, 2007.b). Some of the observed impacts associated with climate change in various parts of the world are enlargement and increased number of glacial lakes, increasing rock avalanches in mountain regions, warming of lakes and rivers, earlier timing of spring events, adverse effect on crops due to warmer and drier conditions, increasing damage from coastal flooding due to sea level rise, increase in infectious disease vectors, increase in heat related mortality, etc. (IPCC, 2007.b).

With increasing global temperatures, land areas warm faster than oceans because of higher heat capacity of oceans, thus the temperature difference between land and ocean increases, in turn affecting the atmospheric circulation (Velling and van Verseveld, 2000). Changes in extreme weather events such as droughts, heavy precipitation, heat waves and the intensity of tropical cyclones have been observed. These extreme weather events are projected to become more frequent in the future (IPCC, 2007. c.). Besides affecting human population, these various changes in climate are also threatening numerous plant and animal species in various parts of the world. (WWF, n.d.).

1.2.4 Climate Change Skeptics

In spite of the agreement in the majority of the scientific community regarding the climate change, a few groups deny not only the adverse impact of human activities on the environment but also the very existence of global climate change phenomenon itself. Such groups condemn IPCC and Kyoto protocol; they focus on the media rather than publishing any scientific data. It is quite crucial to examine the organization, agenda, strategies, and funding sources of these groups. Since the attempt to lower GHG emissions bears financial cost to some groups, this entire issue of climate change has been a highly politicized issue. Along with these skeptic groups there are certain distinguished scientists that claim that climate change is just a perception and not a fact. Today the focus of most of the skeptics has shifted from science to economics, i.e. from completely denying the climate change to now arguing that the financial burden of the attempts of reducing GHG emissions to mitigate climate change is too much.

1.3 Climate Change Action

Brief History:

Due to the oil crisis in 1970s, the research activity on energy efficiency and renewable energy sources had gained significant interest during that era. As the oil prices dropped by 1982, this interest wore off and the research funding and consequently the activities in renewable energy field, got limited. But thanks to the report published in 1987 by Brundtland Commission, the idea of 'sustainable development' finally conceptualized. The commission was chaired by Norwegian prime minister Gro Harlem Brundtland, who pointed out that the thoughtless devouring of fossil fuels and endless consumerism by the developed world was much more threatening to the harmony of the planet than the higher population in the developing world with its limited consumption of natural resources and energy at the time. Following the Brundtland Report, the issues such as global warming, the depleting ozone layer due to CFCs, deteriorating air and water quality - all due to increased industrialization, acquired political interest (UN Documents, n.d., Center for a World in Balance, 2009).

The noteworthy milestones in climate change action are briefly listed below (Gouvernement du Quebec, 2009. a):

1. The first World Climate Conference, Geneva, 1979: Anthropogenic CO_2 emissions linked to climate change; fossil fuel use, deforestation, and changes in land use declared as the main contributing factors to climate change.
2. Intergovernmental Panel on Climate Change (IPCC) created, 1988: IPCC has published four reports so far in 1990, 1995, 2001, and 2007.
3. The second World Climate Conference, Geneva, Switzerland, 1990
4. United Nations Framework Convention on Climate Change, Rio de Janeiro, Brazil, 1992
5. Berlin Mandate: 1st Conference of the Parties (COP-1), Germany, 1995
6. Kyoto Protocol: COP-3, Japan, 1997
7. Kyoto Protocol came into effect, February, 2005
8. Montreal Protocol, Montreal, Canada, December, 2005
9. Bali Conference: COP-13, Indonesia, 2007
10. COP-15, Copenhagen, Denmark, December, 2009

Climate Action in Quebec:

The 2006-2012 climate change action plan for Quebec lists altogether 26 measures for reducing GHG emissions and adapting to climate change, with a total cost of $1,549,000. Quebec GHG emissions in 1990 were 87.5 Mt of CO_2-eq; by 2005 they increased to 92 Mt of CO_2-eq, and the projections for 2012 under Business As Usual are 96.9 Mt of CO_2-eq. With the Quebec Action Plan, a reduction of 14.6 Mt of CO_2-eq is expected between 2006 and 2012, thus resulting in 2012 emissions to be 82.3 Mt of CO_2-eq, which is 6% below 1990 levels (Gouvernement du Quebec, 2009. b).

Moving Forward:

There is no doubt that the earth, since its creation has been evolving, changing constantly; but nature has had a way of maintaining its balance. However, since the industrial revolution, the natural environment has been increasingly deteriorated. Therefore, research in energy efficiency and alternative energy sources has become quite crucial now and should seem so even to the skeptics, if not for the environmental concerns but at least for energy independence and the predicted end of fossil fuels.

2. Literature Review

2.1 Impact of Climate Change on Energy Demand of Buildings

Studies have been conducted in various parts of the world in attempt to estimate effects of climate change on heating and cooling demands of buildings. Two major types of studies in this area are encountered. The first type includes studies on regional or national scale, estimating the future demand under the changed climatic conditions. In the second type of studies, an individual prototype building is considered under current situation in a representative location and then the climatic conditions in the future are simulated to find the effects on heating and/or cooling demand of that building. The impact studies exist for various building sectors; the focus of this literature review is mainly on the residential sector. A few examples from other sectors, however, are also included.

Most of the studies that do not use detailed building simulation are based on changes in heating degree days (HDD) and cooling degree days (CDD), e.g. Belzer et al (1995), Rosenthal et al. (1995), Sailor (1997-1998) and (2001), Sailor and Munoz (1997), and Amato et al. (2005). The degree day method involves an assumption of a reference baseline temperature that represents the desired indoor temperature. The ambient dry bulb temperatures lower than this reference, contribute to HDDs, while higher than the reference contribute to CDDs. When the ambient temperature is equal to the reference temperature, there is no heat gain or loss through the envelope; the HDD as well as the CDD values are zero in such cases. The total values for HDD and CDD are calculated as follows:

$$HDD = (T_{ref} - T_{amb}) \cdot N \tag{2.1}$$

$$CDD = (T_{amb} - T_{ref}) \cdot N \tag{2.2}$$

where,

T_{ref} = the reference temperature, ˚C;

T_{amb} = average dry bulb temperature over the day, ˚C;

N = number of hours.

Only the positive values of the temperature difference are considered, e.g. during winter, if the average ambient temperature on a particular day is higher than the reference temperature, then the HDD for that day is zero. Similarly, the CDD for a summer day is zero if the average ambient temperature on that particular day is lower than the reference temperature.

For regional studies, population-weighted degree days (POPHDD and POPCDD) are considered better indicators of energy demand since the energy demand is significantly affected by the population size in that region besides the degree days.

2.1.1 Impact Studies on Global Level

Isaac and van Vuuren (2009) predict on the global level the repercussions of climate change on heating and cooling energy demand for residential sector. They considered the factors such as heating and cooling degree-days, the total number of households based on population, amount of conditioned floor area per household (m^2/capita), cooling appliance ownership, i.e. the penetration index of air-conditioning systems, equipment efficiencies, and house insulation. Since the most commonly used reference temperature in the past studies for HDD is 18°C, the same was used worldwide for both heating and cooling.

They predicted a decrease in heating energy demand by 34% and an increase in air conditioning energy demand by 72% worldwide by 2100 due to climate change. In the first half of the century, the decrease in heating energy demand is higher than the increase in cooling energy demand but vice versa in the second half of the century; the net effect being an increase in the total energy demand by the end of century. This trend is not uniform on regional level. The temperate regions are expected to have decreased demands, while the tropical regions are expected to have substantially higher energy demands.

2.1.2 Impact Studies on National Level

Rosenthal et al. (1995) estimate the impact of global warming on space heating and cooling in residential as well as commercial sectors in the U.S. The impact on HDD and CDD in 2010 due to a hypothetical 1°C increase in global temperature was studied. For heating, various sources of energy are considered such as natural gas, oil, etc., while for cooling, electricity is the only source. They estimated 14% decrease in the heating energy use and 20% increase in the cooling energy use in the residential sector. Taking into account the fact that the energy requirement in the U.S. is 10 times higher for heating than for cooling, they estimated a net cost reduction of $4.4 billion per 1°C warming for the residential sector in the U.S. by 2010.

Scott and Huang (2008) reviewed approximately 20 prior impact studies conducted for the U.S. They generalized that based on the collective summary of these studies, energy consumption is predicted to decrease in the northern U.S. having more than 4000 HDDs per year but increase in the southern U.S., with the net balance on the national level resulting in energy saving. They also presented seasonal predictions for temperature increase in the U.S., the data for which is based on Ruosteenoja et al. (2003) and is presented for western, eastern, and central U.S. for four seasons and three time steps, 2010-2039 (2020), 2040-2069 (2050), and 2070-2099 (2080). An earlier study based on this temperature data, Scott et al. (2005), predicted 6 to 10% reduction in space heating and 12 to 20% increase in space cooling consumption annually on the national level in the U.S., per °C warming.

Karl et al. (2009), in their report published through United States Global Change Research program, suggested that as an effect of global warming, the heating energy demand in the U.S. will decrease. The cooling energy demand, however, will increase, resulting in significant increase in the electricity and higher peak demands. Adverse impact is also predicted on the energy production and delivery due to the higher temperatures and limiting water supply as well as the extreme weather events. Electricity generation in the thermal power plants (nuclear, coal, natural gas, and oil) needs significant amounts of water for cooling and thus will have impact due to limited water demand caused by climate change. Hydroelectricity generation is also expected to be affected by the climate change. Higher air temperatures will increase water evaporation from the hydro reservoirs, thereby reducing the electricity production (Bull et al., 2007 cited in Karl et al. 2009).

Zachariadis (2010), in the study done for the eastern Mediterranean island country of Cyprus, assumed a uniform increase in temperature by 1°C over day and night, throughout the year. As a result of decrease in HDDs and increase in CDDs, a 6% net increase in degree-days by 2030 was estimated. Thus the electricity consumption from all the sectors by 2030 was predicted to increase by 3% in 2030. The increase in the energy consumption was found to be higher, i.e. 4%, in residential sector compared to the other sectors.

2.1.3 Impact Studies on Regional Level

Some scientists have focused on regional scale, i.e. provincial or state level rather than national scale. This section includes regional studies from various countries.

Canada:

Bhartendu and Cohen, in their study for Ontario, Canada (1987), considered the scenarios of climate change, specifically the global warming, due to doubling of atmospheric concentration of CO_2. Using the population weighted degree day method, the electricity consumption per household in Ontario was estimated to rise by 6 to 7% in cooling season (July-September) and decrease by 31 to 45% in heating season (October – March).

For the province of Quebec, using degree-day method, the residential heating demand was predicted to decrease by 8% by 2050 and 15% by 2100. The electricity demand for air conditioning is predicted to increase by 105% by 2050 and 288% by 2100. The net change predicted is a decrease in the total energy demand by 3% by 2050 and 12% by 2100 (Ouranos, 2004).

Barrow et al. (2004) presented future changes to climate in Canada as well as changes in HDDs and CDDs. The data for 10 different locations in Canada were reported for various parameters such as mean seasonal temperatures, length of growing season, and annual days with rain and snow. Using the climate model CGCM2, they predicted a decrease in the HDDs by 17% with A21 scenario and by 13% with B21 scenario for the location of Sept Iles, Quebec in 2050s compared to 1961-1990. An increase in the CDDs was predicted by 578% with A21 scenario and 367% with B21 scenario. It was observed that the magnitude of changes using B2 scenarios was consistently lower compared to those with A2 scenarios. The explanation about various scenarios and climate models is included further in Chapter 3.

In another study for the entire province of Quebec, the energy demand in residential sector is predicted to decrease by 11 to 21% for heating and rise by 6 to 12% for air conditioning, with a net reduction of 5 to 9% by 2050 (Lafrance and Desjarlais, 2006; cited in Bourque and Simonet, 2008).

Zmeureanu and Renaud (2008) employed a method based on house energy signature, correlating the historical energy use data from the utility bills to the HDDs. The future climatic data for 2040-2069 were generated by Coupled Global Climate Model (CGCM2) with A2x scenario, obtained from the same source as the current study, i.e. CCCma (2007). For a sample of 11 houses in Montreal, Quebec, using natural gas and heating oil, the heating energy use for the period of 2040-2069 was found to decrease by 8 to 17% compared to the present.

United States:

In their state level studies, Sailor (1997-1998) and (2001) and Sailor and Munoz (1997) used very similar methodologies for investigating the potential impact of global climate change on energy demand in the residential and commercial sector in the most energy consuming states in the U.S. These eight states representing 42% of the total energy consumption in the U.S. were California, Washington, Texas, Louisiana, Illinois, Ohio, New York, and Florida. The historical climate data from weather stations and the monthly energy data obtained from Energy Information Administration (EIA) were combined and used as a base-case. Monthly values of temperature variations due to global climate change were calculated based on three GCMs from IPCC (1992), the Canadian Climate Centre (CCC) model, the Geophysical Fluids Dynamics Laboratory (GFDL) model, and the United Kingdom Meteorological Office (UKMO) model. With these future temperature predictions, modified population-weighted HDD and CDD were calculated and then compared with the base-case. The use of only one parameter, temperature, was justified by stating that it is the most influential climate variable impacting energy consumption and that various GCMs are not as much in agreement in predicting variables such as humidity, precipitation, and cloud cover as they are with temperature. By dividing monthly electricity data from each state by the corresponding interpolated census data, per capita electricity use was calculated.

The study predicted per capita net increase in the residential electricity consumption in various states to be 3-19% depending on the climate model. Out of all the states under consideration, Washington was the only state for which, increasing temperature was found to decrease the net annual residential electricity consumption by 11-15%. Based on this, a possibility was suggested that other northern states not considered in this study would also exhibit similar savings. The relation between the percentage change in annual per capita electricity consumption and uniform temperature variations from 1 to 3 °C was also evaluated, which was found to be non-linear.

Hill and Goldberg (2001) quantified the potential impacts of climate change on electricity demand in the Metropolitan East Coast Region (New York, New Jersey, and Connecticut). Based on degree day method, compared to the time period of 1979-1996, heating degree-days were predicted to decline by 20-40% by the 2080s, while cooling degree days were predicted to increase by 45-135%.

Amato et al. (2005) assessed the influence of climate change on regional energy demand of Massachusetts. Using degree day method, their results suggested HDD decrease of 2, 9, and 12% and CDD increase of 4, 21, and 24% in 2010, 2020, and 2030 respectively. Consequently, decrease in natural gas and oil consumption and increase in electricity consumption was projected.

United Kingdom:

Homes and Hacker (2007) focused on implications of climate change on the low energy sustainable buildings that are entirely naturally ventilated for part of the summer or use mixed-mode, i.e. use natural ventilation but when it is inadequate employ mechanical cooling. The UKCIP02 scenarios, developed by the United Kingdom Climate Impacts Programme (Hulme, 2002; cited in Homes and Hacker, 2007) were used under the medium-high emissions. Compared to 1989, the heating demand for London, U.K. was predicted to reduce by 10% in 2020s, 20% in 2050s, and over 35% by 2080s.

In the same study simulations were carried out by using the program ENERGY2 (Homes, 1992; cited in Homes and Hacker, 2007) for assessing effectiveness of passive measures on cooling in school and office buildings in the current and future climates. Analysis for the buildings using night time cooling to keep indoor temperatures from exceeding 28°C showed that annually the number of hours above 28°C was 60 in 1980s, over 300 in 2050s, and 600 in 2080s. Considering the fact that the number of hours the indoor temperature exceeds 28°C is recommended not to surpass 1% of the time e.g. 20 occupied hours in a typical office building (CIBSE, 2002; in Homes and Hacker, 2007), some form of mechanical cooling was predicted to be essential for the future buildings in the U.K.

Australia:

Thatcher (2006), in the study done for Australia, modified a commonly used linear regression model between regional electricity demand and climate to estimate the impact due to

1°C increase in the average ambient temperature. In the four Australian states included in the analysis, the predicted change in the peak regional electricity demand from the combined residential, industrial, and commercial users was between -2.1 and 4.6%.

Switzerland:

Christenson et al. (2006) used data from IPCC Data Distribution Centre based on eight different Atmosphere-Ocean General Circulation Models (AOGCMs) with forcing scenarios. The changes in monthly mean temperatures for 2020s, 2050s, and 2080s were obtained relative to the 1961-1990 baseline, which is a similar method of extracting the weather data as used in this current study. This monthly data were then used to estimate changes in HDD and CDD for four locations in Switzerland. In the period 1975-2085, they estimated a decrease in HDD by 13-87% and an increase in CDD by up to 2100%.

Greece:

Another regional study, Mirasgedis et al. (2007) used a regional climate model PRECIS – Providing REgional Climates for Impact Studies (The PRECIS Regional Climate Modelling System, 2006). Using the same IPCC emissions scenarios as the current study, A2 and B2, they predicted the impact of climate change on electricity demand in Greece, taking two representative climatic regions in Greece, for 2071-2100. To predict the electricity demand, degree-day method was used. The results show an increase of 4 to 6 % in the annual electricity demand due to climate change. The decline in electricity use for heating during winter months is subsided by the increase in electricity use for cooling during summer months.

Thailand:

Wangpattarapong et al. (2007) analyzed the impact of climatic factors on the residential electricity consumption of Bangkok Metropolis in Thailand. A relationship was established between the monthly electricity consumption of the residential sector and the CDDs, relative humidity, and rainfall for 2002-2006. They estimated an increase of almost 7% in residential electricity consumption for every 1°C increase in the average ambient temperature in the future.

Hong Kong:

Lam et al. (2004) studied the repercussions of climate change on the building energy use in Hong Kong, where cooling loads are dominant over heating loads on an annual basis. They analyzed the measured hourly temperature data for 40 year (1961-2000) period and found a slight increase in the CDDs during the last 20 years of that time slice. They predicted an increase in electricity use for air conditioning if the trend in temperature increase continued. It was also reported based on the observed data that although an increase was detected in CDDs, it was not large since the increased temperature occurrences were more frequent in winters compared to summers.

2.1.4 Impact Studies using Building Simulation

Another category of impact studies includes investigation of climate change impact on the space energy demands of individual buildings using energy simulation. The studies included in this section as shown in Table 2.1, fall under this category.

Table 2.1 Impact studies using building simulation

	Impact Study	Building Type	Simulation Program	Location
1	Frank (2005)	Residential, Office	HELIOS	Switzerland
2	Gaterell and McEvoy (2005)	Residential	TAS	U.K.
3	Huang (2006; cited in Scott & Huang 2008)	Residential & Commercial	DOE-2	U.S.
4	Crawley (2007)	Office	EnergyPlus	U.S.
5	Iolova et al. (2007)	Residential	TRNSYS	Canada
6	Zmeureanu et al. (2009)	Residential	TRNSYS	Canada
7	Dénes-Béjat et al. (2009)	Office	CoDyBa	France
8	Xu et al. (2009)	Residential & Commercial	DOE-2	U.S.
9	Plokker et al. (2009)	Office	VA114	Netherlands
10	Capon and Hacker (2009)	Residential	OASYS Roomsuite	U.K.
11	Radhi (2009)	Residential	Visual DOE	UAE
12	Taylor et al. (2009)	Hotel	ESP-r	U.K.

Frank (2005) estimated climate change impact on heating and cooling energy demand for residential as well as office buildings in Switzerland. A single zone model was simulated using the program, HELIOS (Frank, 1982; cited in Frank, 2005) and a 4.4°C rise in mean annual air temperature was assumed for the period 2050-2100 relative to the baseline of 1961-1990. Gradual increases in the insulation level of the building façade were also incorporated reflecting the building code requirements between 1970 and 2003. For the multistory residential building, the results showed that due to climate change, annual heating energy demand decreased by 33-44%, while solar shading and night ventilation were deemed to be essential in order to avoid mechanical cooling.

Gaterell and McEvoy (2005) used the scenarios developed by UK Climate Impacts Program (UKCIP) in their analysis. A thermal model of a house built in 1968 was developed using TAS software (EDSL, 2009). To simulate for the UK climate in 2050, current weather data available within TAS was used. The Milan weather file was used to represent the low emissions scenario and the Rome weather file was used to represent high emissions scenario. As done in the current study, simulated cooling loads were converted to actual energy consumption values by dividing the cooling loads by coefficient of performance of a typical air-conditioning unit, using the value of COP equal to three. For 2050, the results estimated a decrease in heating demand by up to 53%, while the increase in cooling energy demand was found to be insignificant.

Huang (2006; cited in Scott and Huang, 2008), using four IPCC scenarios, A1F1, A2M, B1, and B2M, and the global climate model, HADCM3, presented changes in the climatic parameters, temperature, daily temperature range, cloud cover, and relative humidity for 18 locations in the U.S. and three time slices, 2020, 2050, and 2080. Prototype buildings from residential as well as commercial sectors representing the U.S. building stock were simulated using DOE-2 program (DOE-2, 2009). For residential buildings, on an average, the heating energy reduction was estimated as 12% for 2020, 24% for 2050, and 34% for 2080. The cooling energy was predicted to increase by 38% in 2020, 89% in 2050, and 158% in 2080.

Crawley (2007.a.) studied the impact of climate change on a 550 m^2 two-storey office building representing 25% of the U.S. office building stock. Using four IPCC scenarios, A1F1, A2, B1, and B2, simulations were performed using EnergyPlus (US DOE, 2007) for 25 locations worldwide. The prototypes developed included the base case conforming to ASHRAE Std. 90.1 (ASHRAE, 2004) and another low-energy prototype building with PV, consuming 50% less energy than the base case. It was found that for the low-energy building, the difference between the results under the baseline weather and the future weather due to the changed climate was only 5%, compared to the base case which showed 7% difference. Hence, it was suggested that the low energy office building was less susceptible to variations due to climate change. The study also reported that the total site energy consumption decreased in the heating-dominated regions, while it increased in the cooling-dominated regions. The generation of weather data for these 25 locations in 20 different climate regions worldwide is explained in Crawley (2007.b.).

Iolova et al. (2007), in their study using a triplex in Montreal, obtained the weather data from a previous study by the Ouranos group (Ouranos, 2005), which had predicted the mean monthly temperature increase for 2030 relative to the baseline, 1961-1990. They created a Typical Meteorological Year (TMY) for 2030 by adding the above-mentioned changes to the standard weather data for current climate from Canadian Weather for Energy Calculations (CWEC) database. Using TRNSYS as the simulation software, they estimated that compared to the baseline, heating energy was 17% lower and cooling energy tripled for the triplex in the year 2030.

Zmeureanu et al. (2009) compared two cases, a traditionally built house in Montreal, Canada having minimum allowable thermal resistance, e.g. exterior walls with RSI-value of 3.6

$m^2 \cdot K/W$ and another similar house in Lyon, France having exterior walls with RSI-value of 2.8 $m^2 \cdot K/W$. Both houses had electric baseboard heaters and heat recovery ventilators. Using TRNSYS for simulation they predicted that compared to present climate, the reduction in annual heating energy in the period 2040-2069 was 13% for the house in Montreal and 26-28% for the house in Lyon.

Dénes-Béjat et al. (2009) used the weather data from Météo France, called Arpège Climat for hourly simulation of an office building in La Rochelle, France. They used solar radiation, ambient and sky temperatures, and humidity as the climatic parameters and 25°C as the cooling set-point. Using the software called CoDyBa, for a 12 week summer period (July - September), the energy consumption in 2100 was found to be three times higher than the current value. The impact of night ventilation on the energy consumption was also assessed by increasing the air change rate per hour by four times. Although the natural ventilation at night reduced energy consumption in the current climate, it was not useful by the end of the century, since the night time ambient temperatures in 2099 were shown to be higher than those allowed by code inside the building.

Xu et al. (2009), in the report on impact study for residential and commercial buildings in California divided the state into 16 zones and used the downscaled GCM data with higher resolution up to 3 km for 63 locations across the state. The hourly weather data included the parameters, dry-bulb temperature, dew-point temperature, pressure, and total horizontal solar radiation with the IPCC scenarios A1F1, A2 and B1 for the time-slices, 2005-2014, 2035-2044, 2055-2064, and 2085-2094. Sixteen commercial and residential building prototypes, mostly developed in earlier LBNL research were used and the program DOE-2 was reported to be preferable over EnergyPlus for faster simulations. Under the IPCC's worst-case carbon emission scenario, A1F1, the electricity use for cooling was predicted to increase by 50% over next 100 years in some parts of California, while under A2 scenario, the increase predicted was

25%. Taking into consideration the reduction in the heating needs and the increase in cooling demand, a net increase of 2-8% in the total energy use was predicted.

Plokker et al. (2009) focused on the implications of climate change for only the cooling energy demand. They simulated an office building in Netherlands by using the simulation program, VA114 (Vabi, 2008; cited in Plokker et al., 2009). The updated weather files, NEN 5060:2008, that replace the older reference year data for simulating the buildings in Netherlands are combined with four climate change scenarios defined by the Royal Dutch Meteorological Institute (KNMI). Only the change in ambient temperature is considered as the parameter; all other climatic parameters were kept unchanged for the future. The cooling energy demand was reported to increase by 14 to 54% in the next 30 years, while the peak cooling load was found to increase by 70%.

Capon and Hacker (2009) in their study for U.K. climate, focused on the increasing cooling loads and the cooling strategies as adaptation measures to face the future overheating risks in the residential buildings. Simulations were carried out using the OASYS Room suite of software forced with the CIBSE weather data (CIBSE, 2009; cited in Capon and Hacker, 2009). The current data, Design Summer Year (DSY), is for London (1989) and the future data for the 2050s (2040-2069) is a DSY version adjusted as per UKCIP02 projections for London under medium-high emissions (also used in earlier study by Homes and Hacker, 2007). Simulations were only performed for the hottest month of the year, i.e. July. As a result of higher cooling load, the annual electricity costs and carbon emissions were found to be four times higher in 2050s compared to the current values. Various passive measures discussed in the study include external and internal shading, natural ventilation; ceiling or desk fans that have the effect equivalent to dropping the operative temperature by 2°C; increased thermal mass, e.g. concrete floors; light colored external walls; improved wall insulation, and double glazed windows with low-e coating.

Radhi (2009) evaluated the global warming impact on the air conditioning energy use of the residential buildings in the hot climate of United Arab Emirates. Weather data were created by assuming the annual average temperature increase in 2100 by 2.3 - 5.9°C compared to 1961-1990 baseline. The simulation program used was Visual DOE (Visual DOE, 2004). For warming scenario by 5.9°C, an increase in the cooling energy use by 24% was found. The study also suggested that incorporating thermal insulation and thermal mass can aid in coping with global warming.

Taylor et al. (2009) analyzed hotel buildings in Birmingham, U.K. and found a 12% decrease in the heating load of hotels by 2030. Hourly simulations were performed using ESP-r (ESP-r, n.d) and multiple zones were developed to account for thermal behavior of different spaces such as kitchens, laundry rooms, bedrooms, etc. Cooling was not included in the analysis. The weather data for 2030 was from another study, Jenkins et al. (2008), which included five representative locations in the U.K. and estimated approximately 1°C increase in ambient temperature and 3-4 W/m^2 increase in global radiation. For the baseline weather, the present-day design weather data, CIBSE Test Reference Year (TRY) was used. Different alternatives were discussed to cut down the emissions from the building by 50% by 2030. Similar to Capon and Hacker (2009), the climate change projections were from the U.K. Climate Impacts Programme (UKCIP 02) with medium-high projections for 2010-2040.

2.1.5 Summary

The literature review mainly focused on residential buildings but a few studies on non-residential buildings, e.g. Crawley D.B. (2007.a), Dénes-Béjat (2009), Plokker et al. (2009), and Taylor et al. (2009), were included as well. Based on these, it is observed that the methodology for obtaining and manipulating the weather data was independent of the type of building under consideration.

The literature review indicates that most of the earlier impact studies have used the degree day method, while in the recent years, energy simulation programs have been increasingly used for this purpose. Also, in the earlier studies, steady-state temperature increase was commonly assumed to represent the future climate, while in recent years the detailed weather data are used in impact studies since future predictions from advanced climate models can be easily obtained.

The prediction of decrease in heating loads and increase in cooling loads due to global warming seems to be consistent throughout the literature. At the macro level, the extent of impact varies based on the geographical location, the climate models and the scenarios used. At the micro level, the extent of impact varies based on the type of building, its specifications, as well as the heating, cooling, and ventilation systems. When the discussion is limited to only the loads and not extended to the energy use, then obviously the systems in the building do not affect the extent of impact.

If the impact study includes the financial analysis as well, then the type of fuel used for various systems is also a crucial factor in performing the complete investigation. Besides electricity, oil and gas are commonly used heating fuels while for cooling, electricity is the main energy source which is much more expensive than the other fuels. Therefore the impact due to certain amount of increase in cooling energy demand does not necessarily get nullified by the same amount of decrease in heating energy demand unless the same fuel is used for both the purposes.

It is also apparent, that the geographical location will be the deciding factor for the impact of global warming on heating and cooling energy demands. The countries in cold climates seem to benefit from it in terms of energy cost since in the first half of the century, the absolute decrease in heating loads seems more significant than the increase in cooling loads, in spite of considering the higher costs of cooling as compared to heating and the system efficiencies.

2.2 Net Zero Energy Homes (NZEH)

A NZEH is a home that produces at least as much renewable energy on-site as it requires on an annual basis. It is inherently an energy efficient building; it employs passive solar design principles to reduce energy demand and many a times, green design strategies are applied in its construction. The renewable energy sources can be solar, wind, geothermal, or biomass. Literature review indicates that the first grid-connected solar NZEH, Carlisle House in Massachusetts, dates back to 1980 with 7.5 kW PV system along with 14 m^2 of thermal collector area (Charron et al., 2005). Charron (2005) has summarized NZEH initiatives within Canada as well as internationally till 2005.

In recent years, Equilibrium program in Canada and Department of Energy (DOE)'s Building America program (Building America, 2008) in the U.S. have enabled a significant progress in this field. The following review only focuses on NZE homes and does not consider ultra-low or near-zero energy houses. Since no improvements are proposed in this study to the existing house for the envelope - insulation or windows, discussion about these items is not included here. Even though these items are omitted from this discussion due to the already energy efficient design of the existing house, their importance in NZEH design is very well recognized.

2.2.1 NZEHs Case Studies

Equilibrium Healthy Housing program started in 2006 by Canada Mortgage and Housing Corporation (CMHC) undertook 12 demonstrative energy efficient, healthy housing projects – four in Alberta, three each in Quebec and Ontario, and one each in Manitoba and Saskatchewan (Equilibrium Housing, 2008). The Riverdale NetZero Project is one of them, built in Edmonton, Alberta. It is a duplex with two housing units, each with an area of 165 m^2

(total heated floor area including the basement is 234 m^2). The estimated annual energy consumption is 14.43 kWh/m^2 for heating, 7.74 kWh/m^2 for DHW, 2.02 kWh/m^2 for ventilation, 16.54 kWh/m^2 for lighting and appliances, totaling to 40.73 kWh/m^2 (normalized by the total heated area). Besides the passive solar heating, the space heating is forced-air using a fan-coil, which, along with the DHW, is on solar thermal with electric back-up. The total electric back-up for space and DHW is a 14.4 kW resistance heater. The active solar thermal heating system includes seven glazed flat plate collectors with an area of 2.75 m^2 each of ZEN 28S, mounted vertically. The storage tank with a capacity of 17,000 liters is located under the basement. The expected solar heat production is 16,329 MJ (4,536 kWh), which is 91% of the total DHW and space heating loads (4,969 kWh). The electricity need for the entire house is expected to meet by a grid connected 5.3 kW PV system, made up of 24 modules by SunPower SPR-220 (17% nominal efficiency) with an area of 1.24 m^2 each, mounted at 53° (equal to the local latitude angle) from the horizontal, generating a total of 5,667 kWh of electricity annually. The inverter used is 5.1 kW Fronius IG 5100. The mechanical ventilation system uses an HRV, Venmar 1.8HE, with the ventilation rate of 48.23 L/s. A waste water heat recovery unit is used as well (Habitat Studio and Workshop Ltd., 2007).

Abondance le Soleil, another project from Equilibrium Housing program is built in Montreal (Verdun), Quebec (Ecocité Dévélopments, n.d.). This triplex has one 77m^2 apartment on each of the three floors and a mechanical room in the basement. The annual electrical energy requirement is 5,516 kWh for appliances, 3,285 kWh for plug loads, 1,521 kWh for DHW (for the auxiliary heater, solar system pump, and the desuperheater operation), 1,095 kWh for lighting, 931 kWh for HRV (748 kWh for the fan and 183 kWh for defrost-heating), 899 kWh for heating, 510 kWh for heat pump fan, 246 kWh for various pumps (175 kWh for DHW recirculation pump, 60 kWh for ground source heat pump, and 11 kWh for rainwater cistern pump), and 100 kWh for cooling, with the total of 14,103 kWh. To meet this need, a 12.7 kW

PV system with 73.2 m^2 of Sanyo HIP-205BA3 modules (17.4% nominal efficiency) installed at 30° produces 14,161 kWh. Hydro-Quebec's net-metering option is utilized.

The space conditioning in this project is a forced air system, composed of a 2-ton ClimateMaster's Tranquility 27™ Series geothermal water-to-air heat pump for each condo unit, collectively connected to a common ground heat exchanger (GHX). The GHX is made up of four 34.6 mm dia. tubes (two for downward and two for upward flow) buried to 100 m depth and surrounded by a high thermal conductivity grout (15 W/m.K) in a 150 mm dia. borehole. The average COP values for the ground source heat pump are 3.97 in heating and 5.84 for cooling compared to 1 with baseboard heaters and 3 with a standard air-conditioner. The heat pump also has desuperheaters to pre-heat DHW (Iolova et al., 2007). 10 m^2 of evacuated tube collectors mounted at 30° are used for solar thermal system along with two 600 liters of storage tanks. The estimated energy requirement for DHW is 5,500 kWh, out of which almost 25% is recuperated by the grey water heat recovery units connected to the shower in each of the three condos. The total solar thermal production is 7,120 kWh (Picard, 2007).

Another project from Quebec, Alstonvale Net Zero House in Hudson, suburban Montreal, is a 1,950 sq ft single family home. The design features of this house include a 7 kW roof integrated air-based BIPV/T (5.5 kW for domestic needs plus 1.5 kW to charge the electric car) with polycrystalline PV and a glazing section, generating 6,745 kWh electricity per year, connected to a 14 kW two-stage 3.5 ton air-to-water Climatemaster GSW036 heat pump recovering heat from behind the PVs on the roof and storing it in a 3,785 L (1,000 gal) storage tank. A solar thermal system with 40 evacuated tube collectors feeds to a Stiebel Eltron SBB300 Plus 80.6 gal tank for DHW and is also connected to the larger tank. Backup for DHW is provided by a Harman PB105 pellet boiler.

Other features in this project include the radiant floor heating, ventilation air heated by an additional hydronic heating coil, a solar chimney instead of air conditioning, and an HRV (Candanedo et al., 2007 and Sevag Pogharian Design, n.d.).

One of the Equilibrium Housing examples in Ontario is the project with three townhouses, each with 278 m^2 total floor area (210 m^2 heated area) on Davenport road in downtown Toronto with the total annual electricity demand of 6,197 kWh including 1853 kWh for heating, 313 kWh for cooling, 512 kWh for DHW, 573 kWh for ventilation, 1,376 kWh for large appliances, and the rest for lighting, small appliances, TVs, computers, and all other plug loads. To provide for this, 44 m^2 of NT-185U1 PV arrays by Sharp with 14.2% efficiency are installed at 20° tilt and an azimuth of 37° West of South, producing 6,600 kWh on an annual basis. This grid-connected PV system takes advantage of Ontario's buy-back policy. The solar thermal collection is exclusively for DHW with the system composed of 6 m^2 of SB64-9PV flat plate collectors by Thermodynamics Ltd., delivering 1.41 MWh/year. Oversized solar systems had to be considered since optimal tilt and azimuth angle could not be used. A waste water heat recovery unit is installed as well. An 8.5 kW water-to-water Encore Geosource 2000 GW/360/361 GSHP with the heat exchangers in vertical boreholes is used in combination with the radiant floors for heating and cooling. The COP is 4.23 for heating and 4.92 for cooling (Rad and Fung, 2007). A vanEE HRV 2000HE High Efficiency heat recovery ventilator is used (Rad and Fung, June 2007).

Biaou and Bernier (2008) present another NZEH in Montreal with a 156 m^2 two storey house with an unheated half basement. The study focuses on investigating the best option for DHW in NZEH and suggests that a system with solar collectors with an electric back-up is the best solution compared to other options such as all electric hot water tank, desuperheater of a GSHP with electric backup, or heat pump water heater indirectly coupled to a space conditioning GSHP.

Some examples of simulation studies of NZEHs are Biaou and Bernier (2006) using TRNSYS, Tse and Fung (2007) using HOT2000 and RETScreen. Snyder et al. (n.d.) used eQuest for energy simulation of a NZEH in the state of Michigan, U.S. The house has structural insulated wall panel system (SIP), ultra low-flow fixtures and appliances lowering the daily DHW need to be 151 L (40 gal), waste water heat exchanger, an HRV, radiant floor heating, evacuated tube collectors (20 tube), a 757 L (200 gal) DHW tank and a 3,785 L (1,000 gal) seasonal storage tank, both underground with R50 insulation.

2.2.2 Summary

Traditionally in Canadian climate, the highest contributor to the total residential loads has been heating loads, being around 60% of the total energy consumption, followed by DHW and then the appliances, lighting, and cooling loads. But as summarized in Table 2.2, the literature review indicates a different scenario for NZEHs. Because of the well-designed envelopes of the NZEHs combined with the other passive solar design principles, the heating loads are not a significant factor of the total loads; instead in many cases, the appliance load is the biggest load.

To achieve the net zero energy stage, all the options to minimize the energy needs are explored first, before making any decision on active energy generation, by employing better insulation and windows, superior air-tight envelope, various energy recovery technologies, efficient lights, appliances, and heating and cooling systems etc. All the NZEHs reviewed in the literature review are grid-connected. The net metering option in comparison with the Feed-in-tariff is discussed further in Chapter 7.

Literature review also indicated that sizing of the PV system should be done after completing the design of all other systems. This is to avoid over-sizing of the PV system, which has higher costs compared to the other technologies used in most of the NZEHs.

Table 2.2 Energy consumption for various needs in NZEHs

Project	Total Annual Energy Consumption	Percentage of total annual consumption							Reference
	(kWh/m^2 heated floor area)	Heating	Appliances	DHW	Lights	Cooling	Ventilation	Other	
Equilibrium Project									
Abondance le Soleil, Montreal (Verdun), Quebec	61	7	38	11	8	1	7	28	Picard (2007)
Eco Terra (Alouette Home), Eastman, Quebec	44	23	38 (including lighting)	33			6		Eco-Terra (n.d.)
Alstonvale NZH, Hudson, Quebec	45	49	43	2	5	0	_	1	Sevag Pogharian Design (n.d.)
Riverdale NetZero Project, Edmonton, Alberta	41	35	41 (including lighting)	19	_	_	5	_	Habitat Studio and Workshop Ltd. (2007)
Top of the Annex Townhome, Toronto, Ontario	30	30	22	8		5	9	26	Rad and Fung (2007)
Other studies									
Suburban Greater Toronto area, Ontario	36	16	19	7	5	17	_	24 (+12 for exterior)	Tse and Fung (2007)
Brampton Advanced House	31	39	32 (including lighting)	16	_	2	_	11	Hestnes et al. (2003)
Typical conventional Canadian house	124*	61	13	21	4	1	_	_	NRCan, 2005b cited in Charron R. (2007), *Zmeureanu et al. (1999)
R-2000 Home	30% less than conventional	53	23	19	4	2	_	_	NRCan, 2005b cited in Charron R. (2007)
Ray-vision house: Base case (simulated result)	75 (69 as per utility bills)	27	33	21	11	8	_	_	_

The NZEHs designed in the U.S. through Building America program use Building America (BA) Research Benchmark (Hendron, 2007) guidelines. These guidelines are mostly based on various ASHRAE Standards. The assumptions for user behavior such as appliance usage and set-point temperatures, etc. are based on average occupancy choices in the U.S. If the actual user behavior turns out to be similar in energy use, if not more conservative, then the house designed for NZE has a better chance of achieving that status, e.g. NREL/Habitat NZEH in Denver, in which, just as an example, the average daily hot water use was predicted to be 240 L (63.4 gal) while the actual measured consumption was 78 L (20.5 gal) (Norton and Christensen, 2006, 2008). The house designed as a NZEH at simulation stage cannot achieve its goal and ends up requiring more energy if the assumptions for the user behavior differs greatly from the actual consumption, as in the case of Armory Park de Sol in Tuscan, Arizona, where e.g. the daily measured energy consumption was 12.8 kWh as opposed to the expected 8.4 kWh (NAHB, 2004). The commissioning of these NZEHs aids significantly in providing the information about the net zero feasibility during the operation stage; it also provides an insight in to indentifying the mistakes made during the design process.

2.3 Hybrid PhotoVoltaic/Thermal (PV/T) System

This thesis attempts to explore the solar energy option as the renewable energy source in order to provide for all the loads in the proposed NZEH. The solar energy gain can be transformed into two useful components, the electrical energy converted by photovoltaics and the thermal energy which can be harnessed by solar thermal collectors using air, water, or both. Hybrid PV/T collectors combine these two functions and simultaneously generate electricity as well as heat. As a heat absorbing medium, the focus for this thesis is water instead of air, to supply for domestic hot water as well as space heating.

Literature review on NZEHs indicated that most of the NZEHs used solar collectors for thermal and PV panels for electrical energy generation. To the author's best knowledge, no example of NZEH was found that used liquid-based hybrid PV/T system. Therefore literature review is conducted separately on this topic as presented further in this section.

2.3.1 Liquid-Based Hybrid PV/T Flat Plate Collector

The liquid based hybrid PV/T collectors can be flat plate or concentrating. The flat plate collectors carry the fluid at the back of the PV layer in different ways. Accordingly the types of flat plate PV/T are sheet and tube, free flowing, or channel type. Out of these, this literature review mainly focuses on the flat plate sheet and tube collector.

2.3.1.1 Brief History of Research on PV/T Technology

Zondag (2008) has done an extensive 70 page review covering research done in the last three decades specifically on flat-plate PV/T collectors and systems, covering the topics starting from PV//T history and various design aspects to the current market scenario for PV/T. A short summary on the background on PV/T is presented here. The research on PV/T has been conducted since 1970s, with the first published work by Wolf (1976, cited in Zondag, 2008). Further work by Florschuetz (1979) on extending the Hottel-Whillier model to the analysis of combined PV/T flat plate collector became the basis of the current mathematical model used in TRNSYS, Type 50, which is used in this current study as further explained in Chapter 5.

During the infancy of PV/T technology, most of the research on it was carried out in the United States. But after 1982, as oil prices dropped and energy crisis seemingly tapered off, interest in solar technologies and renewable energy in general, also deflated; and by 1989 limited funding was available for any renewable energy research in the United States. After the publication of Brundtland Report in 1987 and increasing recognition of seriousness of the global warming issue, Europe took the lead in further research in renewable energy and consequently in the PV/T technology as well (Zondag, 2008).

2.3.1.2 Current Status of PV/T Research

Kalogirou (2001) used TRNSYS to simulate a hybrid PV/T system consisting of 5.1 m^2 of PV/T panels, inverter, batteries, hot water storage tank, a pump, and a thermostat. By varying the water flow rate through the collector from 0-150 L/h, the study found that the electrical output consistently improved with higher water flow rates, while the thermal production initially increased and then decreased. For the system under consideration in that study, the optimum value of flow rate was found to be 25 L/h.

Zondag et al. (2003) compared outputs of nine different designs of PV/T collectors. The most efficient design had transparent PV with channel below it. However, on an annual basis, it was only 2% better performing than a simple, easy to manufacture, sheet-and-tube design with PV on top, which was suggested as a good alternative.

Tripanagnostopoulos Y. et al. (n.d.) used the software SimaPro 5.0 for life cycle analysis of PV/T system. The life cycle analyses (LCA) were done for various combinations of PV/T system by adding components such reflectors and glazing and by varying the inclination angle. For various combinations of the system, the energy payback time (EPBT) ranged from 1.31 - 4.93 years and CO_2 payback time (CO_2 PBT) ranged from 1.67 - 4.97 years.

Tripanagnostopoulos et al. (2005) conducted experiments with hybrid PV/T prototypes and used SimaPro 5.1 for LCA. They found that by adding the heat recovery unit at the back of PV, as the part of PV/T module, its cost payback time (CPBT) was reduced by up to 50% compared to just the PV system. The study has reported that installing a PV/T on a tilted roof instead of a flat roof reduced the electrical yield but increased the thermal yield. The study concluded that compared to the standard PV modules, PV/T modules are an economically better option and cause less environmental impact.

Kalogirou and Tripanagnostopoulos (2006) used TRNSYS to assess the applicability of both passive and active hybrid PV/T systems for DHW. The life cycle cost analyses performed showed that with an electricity backup option, the PV system had PBT of 27-40 years, which was reduced in the case of combined PV/T system to 18-31 years.

Tripanagnostopoulos (2007) presented an experimental study on a dual type PV/T collector that used both water and air for heat extraction. Charalambous et al (2007) conducted a review of the literature available on PV/T including flat plate, concentrating, as well as water and air type collectors, along with their parameters. They concluded that PV/T collectors are a promising renewable energy technology. Erdil et al. (2008), in their experimental study on energy generation by PV/T system also found that in spite of electrical energy losses, the substantial gain in thermal energy made the hybrid PV/T system economically appealing.

Kalogirou et al. (2008) attempted to optimize various aspects of the design of heat exchanger at the back of the PV. Using TRNSYS as the simulation program and Type 50d as the component for the PV/T collector, they recommended copper as the most suitable material for the collector fin and tubes, compared to aluminum or steel. They also found the optimum values of collector parameters, e.g. 10 mm for the tube diameter, 8 cm for the tube spacing, and 0.2 mm for the fin thickness.

Chow (2010) presented a review on hybrid PV/T technology including the topics such as air- and water-type flat plate collectors, building integrated PV/T (BIPV/T), concentrating collectors, and overall development of PV/T technology over the last decade. The review mentioned that the product reliability and cost were the main reasons for limited market penetration of this technology at the present but also expected substantial potential for the near future.

2.3.1.3 Commercial Availability of PV/T Modules

Among the manufacturers of liquid-based PV/T, Millennium Electric from Israel, ICEC AG from Switzerland, Sekisui Chemical Co., Ltd. from Japan, SolarWerk and SolarWatt from Germany (IEA Task 7, 2002) as well as PVTWINS from Netherlands, SunWatt Corp. from USA, (IEA Task 35, 2008), Holtkamp Solar Energy Systems Co. from Germany have liquid-based PV/T collectors currently available in the market.

2.4 Research Objectives of the Current Thesis

Review of existing literature on the impact of climate change on buildings identifies the need for further research. Degree-day method, used in many impact studies, is an over-simplified steady-state method of calculating energy loads. It only considers the effect of dry bulb temperature on energy use. The goal of this thesis is to conduct an impact study using a transient energy simulation tool and to consider other climatic variables such as solar radiation, wind speed, humidity, besides the ambient temperature. Even though ambient temperature is the parameter influencing thermal loads the most, these other variables are also important. With this goal in mind, the objective is to obtain future climate data for the above mentioned four parameters and use TRNSYS as the energy simulation tool.

To assess the impact of climate change on a residential building in Montreal, Quebec, an R-2000 house is considered as the Base case. The future weather data for Montreal location is extracted using multiple global climate models and climate change scenarios. Comparing the simulation results with the current versus the future climate data, the impact on heating as well as cooling loads and the total energy use of this R-2000 house in 2050 is then estimated.

Literature review on NZEHs indicates that the option of liquid-based PV/T has not been much explored in designing NZEHs. Therefore, one of the objectives is to use hybrid PV/T technology to convert the R-2000 home into a NZEH. The R-2000 home only uses electricity to supply for all its loads. For the NZEH, since the PV/T produces both heat and electricity, the loads are split so that the thermal collector part of the PV/T supplies for space heating and DHW, while the rest of the loads are supplied by the electricity from the PV. The impact analysis is also conducted for the NZEH to see how it gets affected by the climate change.

Finally the last objective is to conduct comprehensive life cycle analyses of both, the R-2000 and the NZEH, including life cycle cost, energy, and emissions, in order to compare these two versions of the house.

3. Future Climate Projections for Montreal

In order to study the repercussions of climate change on buildings, future climate data is required for simulation purposes. This chapter presents the data obtained for Montreal, along with the methodology and the tools used to extract it. The term ‘future’ is used here to indicate mid-21st century, which is actually the 30-year time-slice 2040-2069, in short referred as 2050s for the middle decade.

The two main components of a climate change forecast are the climate models (the tool) and the emissions scenarios (the basis). For this reason, it is important to explain these two components. A brief description of the climate models and the emissions scenarios selected for this study is given in sections 3.1.2 and 3.2.2 respectively. The selection of the climate models and the emissions scenarios is mostly based on two prior studies, OURANOS for the province of Quebec (Ouranos, 2005) and a document on climate change in Canada, by WWF (2005), which reported the use of five climate models and two scenarios. At the time of this data extraction in the current study, very few comprehensive studies using multiple climate models and scenarios were available. The GCM and scenarios selection in this study is also affected by the data availability as mentioned further in section 3.3.

3.1 Weather and Climate Prediction Models

Numerical Weather Prediction (NWP) models are used for short range (1-2 days) and medium range (4-10 days) predictions, while Global Climate Models (GCM) are used for longer range (years or decades) predictions. Given the state of the atmosphere at a certain time and space, these transient models compute the state of the atmosphere in the future based on mathematical equations in fluid dynamics and thermodynamics. This is done by dividing the atmosphere and the ocean in a three dimensional grid.

Global climate models have the entire earth as the horizontal domain and therefore have much wider grid. For vertical resolution of the atmospheric component, the levels are not equidistant. The topmost level for most of the models under consideration is generally at the atmospheric pressure of 10 hPa (equal to 1 kPa or 10^{-2} atm), (Zwiers, n.d.) i.e. approximately at 30 km. Appendix A.1 demonstrates how vertical resolution of ocean and atmospheric components is defined. In the newer versions of GCMs, the topmost level of atmospheric components can be at even lower atmospheric pressures than 10 hPa, i.e. at higher altitudes and have more number of divisions (IPCC, 2007. a). The climate models covering smaller geographical regions are Regional Climate Models (RCM), which have only certain parts of the earth as the horizontal domain. Due to their restricted domain, the regional models use finer grid compared to the global models.

3.1.1 Global Climate Models or General Circulation Models (GCM)

A GCM simulates all heat flows and mass transfer (e.g. air, moisture). It simulates the entire passage of energy starting from solar radiation entering the atmosphere (short wave) till it leaves the atmosphere (long wave), as well as the effects of this radiation on the climatic system and its elements. It calculates the results in terms of climatic variables such as temperature, humidity, etc. This is done at a number of distinct points on a grid on the surface of the earth (horizontal direction) as well as in the atmosphere and ocean (vertical direction), as mentioned earlier. Since finer grid involves increased computation, leading to longer runs, a compromise is made between resolution and run-time. The three basic types of GCMs are as follows:

(i) **Atmospheric General Circulation Models (AGCMs):** AOGCMs simulate only the atmosphere, while the sea surface temperatures are imposed.

(ii) **Ocean General Circulation Models (OGCMs):** OGCMs only model the oceans including the ice coverage, ocean currents and temperatures, etc.

(iii) **Coupled General Circulation Models (CGCMs):** CGCMs, also called AOGCMs, i.e. Atmosphere-Ocean GCMs, are formed by combining the AGCMs and the OGCMs. These models simulate the mutual interaction between the atmosphere and oceans and hence are the most comprehensive models.

Out of over 23 coupled models available to date from different centers, IPCC does not single out any model as the best, but recommends the utilization of results from a range of coupled models. In all the models, processes such as formation of clouds and precipitation are still parametrized. Parametrization in a climate model is a method of replacing processes that are too small-scale or complex to be physically represented in the model by a simplified process. The uncertainty in parametrization is the leading cause of different AOGCMs giving different climate projections (IPCC, 2007.WG II).

3.1.2 Description of the GCMs used in the current study

For obtaining the future climate data, three coupled GCMs are selected, viz. CGCM2 (Canada), ECHAM4 (Germany), and HadCM3 (UK). The latest versions of all the models available at the time of data extraction have been used. A brief description of each of these models is presented in this section. Figure A.1.ii in Appendix A represents the improvements in GCMs over the past decades.

3.1.2.1 CGCM2 (2001)

This is the second generation coupled GCM developed by Canadian Center for Climate Modelling and Analysis, i.e. CCCma (Environment Canada, 2009). The horizontal resolution is 3.75° in latitude and longitude for the atmospheric component and 1.875° in latitude and longitude for the ocean component. For the vertical resolution, the atmospheric component has 10 levels, while the ocean component has 29 levels (Flato and Boer, 2001).

The previous version, CGCM1, had the same atmospheric component; the ocean model also had same resolution but the difference was in the parametrization of ocean mixing. The improved version, CGCM2, gives results better matching with the observed data compared to CGCM1 (Flato and Boer, 2001).

3.1.2.2 ECHAM4 (1996)

European Centre HAmburg Model is a fourth generation coupled global circulation model. Based on European Centre for Medium Range Weather Forecasts (ECMWF, Reading, UK), the model is developed and modified for climate forecasts at the Max Planck Institute for Meteorology in Hamburg and the German Climate Computing centre (DKRZ). The vertical domain has 19 atmospheric levels, with highest level at 31 km and spatial resolution is approximately 2.81° in longitude and latitude. The ocean resolution is 2.81° in longitude and latitude with 11 levels (Roeckner et al.1996, cited in IPCC, 2001.WG I).

The previous version, ECHAM3, had much coarser resolution, i.e. 5.6° x 5.6° for the atmospheric model with 19 levels and 4.0° x 4.0° for the ocean model with 11 levels (IPCC, 2001.WG I).

3.1.2.3 HadCM3 (1997)

This is a coupled atmosphere-ocean global climate model developed by UK Met Office (UKMO), Hadley Centre for Climate Prediction and Research, Bracknell, UK. The horizontal resolution for the atmospheric component is 2.5° in latitude by 3.75° in longitude, while for the ocean component 1.25° in latitude by 1.25° in longitude. For the vertical resolution, the atmospheric component has 19 levels, while the ocean component has 20 levels (Gordon et al., 2000).

The former version HadCM2 had the same vertical and horizontal resolution as HadCM3 in atmospheric model but the ocean model was coarser with horizontal resolution 2.5°

x 3.75° and the same vertical resolution (Johns, 1996; Johns et al., 1997 cited in IPCC, 2001.WG I).

The climate data used in the current study is obtained from a project, Canadian Climate Impact Scenarios that ran from October 1999 to June 2004 (CCIS, 2003). The procedure of extracting the data from CCIS project is explained further in section 3.3. The models used in the current study are the most recent versions available through CCIS project. However, it is recognized that for these same models, advanced versions have already been developed such as CGCM3 (2005), ECHAM5/MPI-OM (2005), and HadCAM1 (2004). These improved versions have a very fine resolution, but since the data using these recent models was not yet available, it could not be incorporated in the current study.

3.2 Emission Scenarios

Emission scenarios are basically the various assumed alternative states of the planet earth in the future. These are presented by IPCC in order to facilitate the prediction of GHG emissions in the future and are based upon mutually dependent interactions of socio-economic conditions, technology, energy use, resources, etc.

3.2.1 IPCC SRES (2001)

The earlier version of these IPCC scenarios called IS92 scenarios from the IPCC Second Assessment Report (1992) have been replaced by SRES scenarios, i.e. Special Report on Emissions Scenarios (IPCC SRES, 2001). The SRES scenarios suggest a higher warming compared to the IS92 scenarios (CICS, 2000). Figure A.1.iii in Appendix A is a flowchart summarizing the driving forces, storylines, scenario groups, and the scenarios derived in IPCC SRES (2001).

3.2.1.1 Driving Forces

Driving Forces are the various factors affecting the emissions of GHGs, which in turn, will affect the composition of atmosphere in the future. To forecast the climatic conditions in the future, the energy balance of the earth in the future needs to be understood, which will change according to the changes in its atmospheric components (CCIS, 2003). The population and economic growth, changes in - technology, cultural and social behavior, and land use – etc., are considered as the main driving forces. Hence, in IPCC SRES (2001), certain assumptions - to describe four storylines, A1, A2, B1, B2 - are made regarding these driving forces to create distinct emissions scenarios.

An example of estimation of emissions based on various driving forces is Kaya identity (Kaya 1990; cited in IPCC SRES, 2001) which calculates CO_2 Emissions based on the population, Gross Domestic Product (GDP), and energy use as follows:

$$CO_2 \text{ Emissions} = \text{Population} \cdot (\text{GDP/Population}) \cdot (\text{Energy/GDP}) \cdot (CO_2/\text{Energy}) \qquad (3.1)$$

3.2.1.2 Storylines

As seen in Figure A.1.iii in Appendix A, the two basic driving forces are globalization and regionalization, based on which, four storylines also referred to as families, have been developed. Each of the four storylines assumes distinctly different direction for future. Each storyline represents a distinct set of demographic, socio-economic, technological, and environmental development. A brief description of the storylines is presented below (IPCC SRES, 2001):

(i) A1
- increased cultural and social interactions
- focus on economic growth, reduced regional differences in per capita income
- global population at its peak by mid-century and then declining
- rapid introduction of new, efficient technologies

(ii) B1
- globalization and population description same as A1
- focus on environment, global solutions to environmental, social, and economic sustainability

- emphasis on technologies with clean energy, energy efficiency, sustainability, etc.

(iii) A2
- heterogeneous world, emphasis on preservation of local identities
- continuously increasing population
- slower and fragmented economic growth
- slower technological change compared to other storylines

(iv) B2
- focus on regionalization same as A2
- focus on environment, local solutions to environmental, social, and economic sustainability
- continuously growing population with growth-rate slower than that of A2
- slower but more diverse technological change as compared to A1 and B1.

3.2.1.3 Scenario Groups

The A1 family is further divided into groups based on three alternatives for technological change in energy systems:

A1F1 - fossile intensive energy sources (coal, oil, gas)

A1T - non-fossil energy sources

A1B - balanced energy systems, not relying on any particular source

Thus, there are six scenario groups in total, three from A1 family, and one each from A2, B1, and B2 storylines.

3.2.1.4 Scenarios

Each scenario group is further sub-divided into two categories:

HS - Harmonized Scenarios

OS - Other Scenarios exploring uncertainties in driving forces

Different scenarios are further developed under each category. Thus, altogether there are 40 distinct quantitative representatives derived from four qualitative scenarios. All scenarios are equally valid without any specific probability assigned (IPCC SRES, 2001).

3.2.2 Description of the scenarios used in the current study

The two scenarios used here are SRES A2 and B2, the selection of which is dictated mainly by the availability of data from CCIS project. As seen in Figure A.1.iii in Appendix A, both A2 and B2 scenarios focus on regionalization versus globalization, i.e. both of these scenarios describe the world in which solutions to various economic, social, environmental issues are found locally and the emphasis is on preservation of local identities. The key differences between A2 and B2 scenarios are in the population growth and the focus on economy versus environment. Compared to A2 scenario, B2 assumes moderate population growth. In A2 scenario, a world with more focus on economic development is pictured, while in B2 scenario the focus is on environmental protection and social equity (IPCC SRES, 2001). As a result, higher cumulative emissions of greenhouse gases are expected with A2 scenarios as compared to the ones with the B2 scenarios (WWF, 2005; Barrow et al., 2004).

3.3 Climate data for Montreal based on the GCMs

To obtain the monthly data for Montreal, with latitude 45.47 N and longitude 73.75W (ASHRAE Handbook), the Canadian Climate Impact Scenarios project of Environment Canada is used in this study (CCIS, 2003), as previously mentioned. The scenarios derived in CCIS are further based on the data from Canadian Center for Climate Modeling and Analysis. Climate data is available for four time slices, each with three decades, the base-line (1961-1990), 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). The 30-year time slices are referred to by their respective middle decades (CCCma, 2007).

For climate change impact studies, one of the first steps is to identify the relevant climate variables that would impact the system and the region under consideration (UNFCC, n.d.). Since the parameters, temperature, solar radiation, humidity ratio, and wind speed, are pertinent to heating/cooling systems, data for these same parameters are extracted from CCIS. Since different GCMs have different horizontal resolution, (e.g. HadCM3 uses 2.5° in latitude and 3.75° in longitude while ECHAM4 uses 2.81° in latitude and longitude) the grid box on CCIS tool is changed for each GCM in order to select the most precise grid box for Montreal location.

There are two possible approaches for obtaining future climate data based on GCMs:

i. Using observed data as the baseline and adding the change for the future from the climate models to it to obtain the future data is one approach. Although the observed data and the modeled baseline data do not necessarily match (see Appendix A.2), according to Canadian Institute for Climate Studies, this is an acceptable practice (CICS, 2000).

ii. Obtaining both, the change for the future climate as well as the baseline data, from the climate models, and using these two sets to obtain the future climate data is another approach, which is used in this thesis.

Thus, in order to obtain the monthly climate data for 2050s in terms of all the parameters for each GCM, first the data for the baseline climate, i.e. 1961-1990 (presented in Tables 3.1 to 3.4), and the data for the change in 2050s (presented in Tables 3.5 to 3.8) is obtained. The data for 2050s is then calculated based on the two and is presented in Tables 3.9 to 3.12.

3.3.1. Baseline Climate (1961-1990) Data

Table 3.1 Mean temperature (°C) for the baseline climate (1961-1990)

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	-9.44	-9.45	-15.28	-15.36	-11.00	-10.97	-11.92	2.72
February	-10.92	-10.90	-12.31	-12.36	-9.49	-9.37	-10.89	1.30
March	-6.30	-6.24	-6.51	-6.47	-3.78	-3.68	-5.50	1.37
April	-1.20	-1.15	1.88	1.77	4.52	4.47	1.72	2.54
May	5.19	5.22	10.68	10.68	10.81	10.84	8.90	2.87
June	13.69	13.78	16.55	16.57	15.35	15.28	15.20	1.27
July	18.20	18.23	19.66	19.56	17.70	17.64	18.50	0.90
August	18.94	18.92	19.20	19.14	16.59	16.58	18.23	1.28
September	14.88	14.96	14.53	14.57	12.56	12.50	14.00	1.15
October	8.20	8.27	5.98	5.99	6.08	6.13	6.78	1.13
November	1.90	1.93	-1.32	-1.21	-1.22	-1.28	-0.20	1.64
December	-0.61	-0.50	-9.42	-9.69	-6.93	-7.19	-5.72	4.16

Table 3.2 Incident solar radiation (W/m^2) for the baseline climate (1961-1990)

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	63.88	63.87	21.54	21.62	71.23	71.43	52.26	24.00
February	98.74	98.39	33.99	33.95	109.74	109.52	80.72	36.55
March	155.38	155.09	64.29	63.94	158.85	158.12	125.95	47.92
April	220.96	220.40	118.73	116.89	188.84	189.27	175.85	47.13
May	263.98	264.67	159.56	159.97	228.22	228.60	217.50	47.52
June	272.79	273.18	183.98	182.99	244.56	244.26	233.63	40.89
July	258.20	257.93	178.37	178.27	238.56	239.12	225.08	37.22
August	215.69	214.83	167.60	167.99	214.43	213.98	199.09	24.25
September	178.65	177.91	124.25	123.41	162.93	161.67	154.80	25.04
October	121.91	121.70	68.05	67.70	103.34	103.29	97.67	24.51
November	76.78	76.66	25.23	25.36	63.99	64.49	55.42	23.99
December	55.26	55.19	16.30	16.15	54.51	54.98	42.07	20.02

Table 3.3 Relative humidity (%) for the baseline climate (1961-1990)

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	99.08	99.20	83.26	83.20	97.23	97.22	93.20	7.77
February	95.71	95.56	85.17	85.17	95.24	95.10	91.99	5.29
March	93.34	93.53	87.93	87.99	88.69	88.27	89.96	2.71
April	89.94	89.91	89.15	89.29	80.50	80.47	86.54	4.70
May	97.99	97.89	78.76	78.87	78.11	78.26	84.98	10.04
June	98.46	98.46	70.97	71.19	80.90	80.99	83.50	12.40
July	98.75	98.72	70.07	69.98	81.77	82.26	83.59	12.90
August	99.00	98.97	69.10	69.10	80.79	81.04	83.00	13.46
September	99.84	99.91	73.90	74.19	79.44	80.21	84.58	12.13
October	99.87	99.87	85.97	86.01	84.57	84.81	90.18	7.53
November	96.43	96.33	93.34	93.39	92.33	92.17	94.00	1.91
December	93.06	92.86	88.00	87.89	96.06	96.30	92.36	3.71

Table 3.4 Wind speed (%) for the baseline climate (1961-1990)

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	2.57	2.57	4.37	4.36	3.46	3.46	3.47	0.80
February	2.66	2.67	4.36	4.34	3.59	3.56	3.53	0.75
March	2.90	2.89	4.44	4.46	3.55	3.59	3.64	0.70
April	3.13	3.14	4.39	4.44	3.63	3.61	3.72	0.58
May	3.27	3.28	4.20	4.21	3.46	3.44	3.64	0.44
June	3.54	3.52	3.91	3.93	3.38	3.37	3.61	0.25
July	3.20	3.20	3.71	3.70	3.23	3.23	3.38	0.25
August	2.85	2.86	3.66	3.67	3.03	3.02	3.18	0.38
September	2.68	2.67	3.86	3.85	3.19	3.20	3.24	0.53
October	2.60	2.63	4.34	4.36	3.42	3.42	3.46	0.78
November	2.53	2.50	4.48	4.48	3.59	3.59	3.53	0.88
December	3.09	3.10	4.62	4.62	3.50	3.50	3.74	0.71

3.3.2. Change in Climate in 2050s

Table 3.5 Mean temperature change (°C) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A21	B21	A21	B21	A21	B21		
January	6.58	5.27	7.42	6.84	2.60	1.88	5.10	2.33
February	4.78	2.57	3.69	4.70	1.73	1.11	3.10	1.54
March	3.26	2.52	3.08	4.71	2.08	1.95	2.93	1.01
April	1.75	1.06	4.39	3.83	1.88	2.70	2.60	1.29
May	3.85	3.57	2.82	2.02	3.19	2.85	3.05	0.65
June	2.90	2.43	2.99	2.58	2.83	2.90	2.77	0.22
July	3.14	2.52	3.51	3.34	3.74	3.05	3.22	0.42
August	2.27	1.89	3.92	3.71	4.06	3.78	3.27	0.94
September	2.93	2.12	3.37	2.56	3.53	2.35	2.81	0.57
October	2.48	1.63	4.14	3.39	3.29	2.04	2.83	0.94
November	1.59	0.90	3.43	3.19	2.79	2.48	2.40	0.97
December	1.00	0.89	5.43	5.26	1.58	1.99	2.69	2.09

Table 3.6 Incident solar radiation change (W/m^2) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A21	B21	A21	B21	A21	B21		
January	-0.97	-1.29	-2.23	-2.65	-4.55	-3.28	-2.50	1.32
February	-5.84	-2.59	0.39	-1.87	-1.97	-2.51	-2.40	2.01
March	-2.26	-1.40	4.84	7.49	-13.26	-10.51	-2.52	8.18
April	3.59	1.98	6.72	7.14	0.69	7.92	4.67	3.00
May	2.59	-3.11	3.09	1.53	10.96	6.62	3.61	4.77
June	0.16	-4.99	1.74	9.05	10.69	11.48	4.69	6.69
July	-20.14	-15.49	10.19	5.69	15.44	16.55	2.04	15.93
August	-9.11	-4.77	2.13	-1.91	18.18	20.52	4.17	12.34
September	-8.89	-6.85	3.85	0.76	4.74	11.22	0.81	7.56
October	-1.62	0.93	6.97	6.40	-2.88	0.60	1.73	4.09
November	-0.31	0.42	3.50	3.19	-6.89	-5.24	-0.89	4.31
December	1.29	-0.49	-1.49	-2.04	-2.32	-1.60	-1.11	1.33

Table 3.7 Relative humidity change (%) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A21	B21	A21	B21	A21	B21		
January	-3.11	-1.93	6.00	5.67	-0.81	-0.16	0.94	3.92
February	1.13	1.80	2.35	3.67	0.20	0.94	1.68	1.22
March	-1.29	-2.01	1.54	2.98	-3.19	-4.52	-1.08	2.85
April	5.09	2.51	-2.33	-1.81	-4.32	-3.83	-0.78	3.76
May	0.13	0.99	-0.71	0.51	-3.32	-2.67	-0.85	1.77
June	0.17	0.22	-1.07	-1.34	-4.40	-3.38	-1.63	1.89
July	0.32	0.26	-2.90	-2.65	-3.42	-4.18	-2.10	1.92
August	0.44	0.45	-2.66	-0.49	-6.55	-7.62	-2.74	3.57
September	0.10	-0.02	-3.84	-1.12	-3.58	-7.61	-2.68	2.96
October	0.13	0.03	-4.76	-2.33	-2.13	-3.47	-2.09	1.92
November	-0.02	-0.35	-1.01	-0.35	-1.45	-1.91	-0.85	0.73
December	-0.92	-1.23	4.71	4.55	-0.31	-0.54	1.04	2.80

Table 3.8 Wind speed change (%) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A21	B21	A21	B21	A21	B21		
January	13.16	19.63	1.05	3.25	1.10	1.18	6.56	7.93
February	7.00	3.84	4.25	1.96	1.69	2.36	3.52	1.99
March	7.98	11.07	-0.44	2.04	8.39	6.58	5.94	4.31
April	4.91	4.14	2.48	4.82	-1.32	-1.88	2.19	3.07
May	20.97	16.50	-0.78	1.10	-2.69	2.96	6.34	9.88
June	3.84	6.45	-0.16	-1.46	-0.65	1.04	1.51	3.04
July	-0.95	2.88	-6.96	-3.64	-8.16	-4.78	-3.60	4.06
August	1.16	3.82	-7.22	-7.86	-4.04	-1.78	-2.65	4.63
September	2.73	4.63	-0.59	1.32	-2.60	-0.40	0.85	2.59
October	5.92	-1.24	-2.86	-5.53	-1.47	-3.32	-1.42	3.91
November	0.31	8.86	3.22	1.16	-0.83	-1.62	1.85	3.82
December	-3.93	-1.17	-0.87	-3.08	-0.53	0.24	-1.56	1.60

3.3.3. Future Climate Data for 2050s

Table 3.9 Mean temperature (°C) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	-2.86	-4.18	-7.86	-8.52	-8.40	-9.09	-6.82	2.62
February	-6.14	-8.33	-8.62	-7.66	-7.76	-8.26	-7.80	0.89
March	-3.04	-3.72	-3.43	-1.76	-1.70	-1.73	-2.56	0.94
April	0.55	-0.09	6.27	5.60	6.40	7.17	4.32	3.21
May	9.04	8.79	13.50	12.70	14.00	13.69	11.95	2.39
June	16.59	16.21	19.54	19.15	18.18	18.18	17.98	1.34
July	21.34	20.75	23.17	22.90	21.44	20.69	21.72	1.07
August	21.21	20.81	23.12	22.85	20.65	20.36	21.50	1.19
September	17.81	17.08	17.90	17.13	16.09	14.85	16.81	1.16
October	10.68	9.90	10.12	9.38	9.37	8.17	9.60	0.86
November	3.49	2.83	2.11	1.98	1.57	1.20	2.20	0.84
December	0.39	0.39	-3.99	-4.43	-5.35	-5.20	-3.03	2.70

Table 3.10 Incident solar radiation (W/m^2) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	62.91	62.58	19.31	18.97	66.68	68.15	49.77	23.82
February	92.90	95.80	34.38	32.08	107.77	107.01	78.32	35.43
March	153.12	153.69	69.13	71.43	145.59	147.61	123.43	41.29
April	224.55	222.38	125.45	124.03	189.53	197.19	180.52	45.33
May	266.57	261.56	162.65	161.50	239.18	235.22	221.11	47.33
June	272.95	268.19	185.72	192.04	255.25	255.74	238.32	38.96
July	238.06	242.44	188.56	183.96	254.00	255.67	227.12	32.38
August	206.58	210.06	169.73	166.08	232.61	234.50	203.26	29.67
September	169.76	171.06	128.10	124.17	167.67	172.89	155.61	22.93
October	120.29	122.63	75.02	74.10	100.46	103.89	99.40	21.13
November	76.47	77.08	28.73	28.55	57.10	59.25	54.53	21.72
December	56.55	54.70	14.81	14.11	52.19	53.38	40.96	20.58

Table 3.11 Relative humidity (%) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	96.00	97.29	88.26	87.92	96.44	97.06	93.83	4.47
February	96.79	97.28	87.17	88.30	95.43	95.99	93.49	4.52
March	92.14	91.65	89.28	90.61	85.86	84.28	88.97	3.21
April	94.52	92.17	87.07	87.67	77.02	77.39	85.97	7.34
May	98.12	98.86	78.20	79.27	75.52	76.17	84.36	11.03
June	98.63	98.68	70.21	70.24	77.34	78.25	82.22	13.17
July	99.07	98.98	68.04	68.13	78.97	78.82	82.00	14.04
August	99.44	99.42	67.26	68.76	75.50	74.86	80.87	14.73
September	99.94	99.89	71.06	73.36	76.60	74.11	82.49	13.61
October	100.00	99.90	81.88	84.01	82.77	81.87	88.40	8.98
November	96.41	95.99	92.40	93.06	90.99	90.41	93.21	2.51
December	92.20	91.72	92.14	91.89	95.76	95.78	93.25	1.96

Table 3.12 Wind speed (m/s) for 2050s

	CGCM2		ECHAM4		HadCM3		Average of GCMs	Standard Deviation
	A2	B2	A2	B2	A2	B2		
January	2.91	3.07	4.42	4.50	3.50	3.50	3.65	0.67
February	2.85	2.77	4.55	4.43	3.65	3.64	3.65	0.75
March	3.13	3.21	4.42	4.55	3.85	3.83	3.83	0.59
April	3.28	3.27	4.50	4.65	3.58	3.54	3.81	0.61
May	3.96	3.82	4.17	4.26	3.37	3.54	3.85	0.35
June	3.68	3.75	3.90	3.87	3.36	3.41	3.66	0.23
July	3.17	3.29	3.45	3.57	2.97	3.08	3.25	0.23
August	2.88	2.97	3.40	3.38	2.91	2.97	3.08	0.24
September	2.75	2.79	3.84	3.90	3.11	3.19	3.26	0.50
October	2.75	2.60	4.22	4.12	3.37	3.31	3.39	0.67
November	2.54	2.72	4.62	4.53	3.56	3.53	3.58	0.87
December	2.97	3.06	4.58	4.48	3.48	3.51	3.68	0.69

3.4 Typical Meteorological Year (TMY) data for Montreal

Among the various weather data sets available in TRNSYS, the Typical Meteorological Year data set (.TMY files) is an older version of weather data derived from 1952-1975 data base, while TMY2 (.tm2 files) is developed later from 1961-1990 data base by National Renewable Energy Laboratory in the U.S. (TRNSYS 16, p 9.5, 9.53). The weather data in TMY2 format for the locations outside of the U.S. is from a global meteorological database, METEONORM, which is developed by a private company, METEOTEST, based in Switzerland (METEOTEST).

In the TMY2 data set, data for each individual month is actual observed hourly data. From the 1961-1990 observed data set, each month that represents an average over these 30 years, is selected and compiled together to make up the typical meteorological year (NREL (n.d.). For this study, the TMY2 file for Montreal is used from the METEONORM database to simulate the base case house for calibration purposes, as presented in Chapter 4.

3.5 Regional Climate Models (RCM)

For the impact studies using GCMs, the simplest and most commonly used method is to use values for the nearest grid box to the study area (Barrow E., 2001; UNFCC nd). This same method was adopted in obtaining data from GCMs in this study for Montreal. Although coupled models have been recognized by IPCC as most comprehensive and suitable tools to provide useful projections of future climates, these simulations are most accurate at large space scales (e.g. continental). But for regional studies, the resolution of these models is quite coarse. Most GCMs have their horizontal resolution of a few hundred kilometers, while regional climate is affected by factors working at a much smaller scale. Therefore, downscaling is necessary, which is a process of deriving regional climate data at a finer scale based on large scale climate conditions (Leung et al., 2005). The three basic options of downscaling include combining

GCM output with historical observations, statistical downscaling and regional climate models (UNFCC, nd).

3.5.1 Future Climate Data for Montreal Based on RCM

In this study, Canadian Regional Climate Model (CRCM) is used for the data for Montreal location (CCCma, 2006). At the time of this data extraction, CRCM3 was the latest version with CRCM 3.5 runs (available for three time slices of a decade each, 1975-84, 2040-49, 2080-89) and CRCM 3.6 runs (aal run for 1970-94 time slice and aaq run for 2039-63 time slice). The CRCM version 3.6 (aaq run) monthly data extracted in this study is presented in Table 3.9. This data is made available by Ouranos Climate Simulations Team via CCCma's data distribution web page (CCCma, 2006).

Table 3.13 Climate data obtained from RCM for 2050s

	Temperature (°C)	Wind speed (m/s)	Incident Solar Radiation (W/m^2)
January	-0.18	3.84	65.43
February	-0.55	2.60	101.20
March	-1.05	0.41	165.42
April	-1.20	1.84	245.05
May	10.13	1.86	277.85
June	19.73	2.08	295.56
July	20.39	0.79	258.98
August	22.33	2.67	209.35
September	17.03	0.77	175.62
October	9.99	2.02	110.32
November	4.48	3.10	75.00
December	0.49	4.20	57.03

In this regional model, the horizontal grid-size is 45 km which is significantly smaller compared to the global models, and there are 29 vertical levels. The model is nested with CGCM2, i.e. it is driven by boundary conditions computed by CGCM2, following the IPCC Scenario IS92a (Plummer et al., 2006). IS92a is one of the six scenarios developed by IPCC in

1992 and it suggests temperature increase in the 21st century by 2°C. This scenario, commonly used in impact studies and climate models, is also referred to as the 'Business-as-usual' scenario, meaning it assumes continuation of current trends in population growth, technology development, economy, and human behavior, along with absence of policy change affecting the future GHGs (IPCC SRES, 2001, section 1.4; CICS, 2000). To obtain the data for Montreal for the required parameters from CRCM v.3.6, the closest grid box to Montreal location with I value 132 (longitude 73.89 W) and J value 50 (latitude 45.82 N) was selected.

It should be noted that the RCMs have the limitation of not having a two-way interaction between RCM and GCM, i.e. there is no feedback from RCM simulation to the driving GCM, although the processes occurring at regional scale may have an impact on large scale circulation.

3.6 Discussion

In the data obtained for the change in 2050s, for all the global models under consideration, the values are in general higher with A2 scenario compared to B2 scenario. This observation seems rational, considering the fact that B2 scenario assumes the world in which environmental issues are given priority over the economy, as opposed to A2 scenario. This results in milder climate change in the future with B2 compared to A2 scenario. Thus the climate data derived here is in agreement with the fact that, from an environmental perspective, A2 scenario is generally referred to as a pessimistic scenario while B2 scenario as an optimistic scenario, in the climate change related literature.

The annual average values of the changes in all four parameters for 2050s are presented in Table 3.10. For the three parameters, radiation, relative humidity, and wind speed, the models provide contradictory predictions of increase or decrease i.e. some models expect increase while others forecast decrease in these parameters. However, all the models are consistent about predicting an increase in temperatures in 2050s.

Table 3.14 Annual average changes in 2050s compared to base line (1961-1990)

Model	Temperature (°C)	Radiation (W/m^2)	Relative Humidity (%)	Wind Speed (m/s)
CGCM2 A2	3.04	-3.46	0.18	5.26
CGCM2 B2	2.28	-3.14	0.06	6.62
ECHAM4 A2	4.02	3.31	-0.39	-0.74
ECHAM4 B2	3.84	2.73	0.61	-0.49
HadCM3 A2	2.78	2.40	-2.77	-0.93
HadCM3 B2	2.42	4.31	- 3. 25	0.05

Comparison between the GCM and RCM data:

For comparison purpose, the data from the GCMs is presented in Figure 3.1 along with the RCM data; only A2 scenarios are presented as an example. In general, the range of possible temperatures is much wider for the winter months, while between May and October, the models seem to be in better agreement. Also, compared to all GCM data (A2 and B2 scenarios), CRCM predicts much warmer winters, with a temperatures difference of 3 to 8°C.

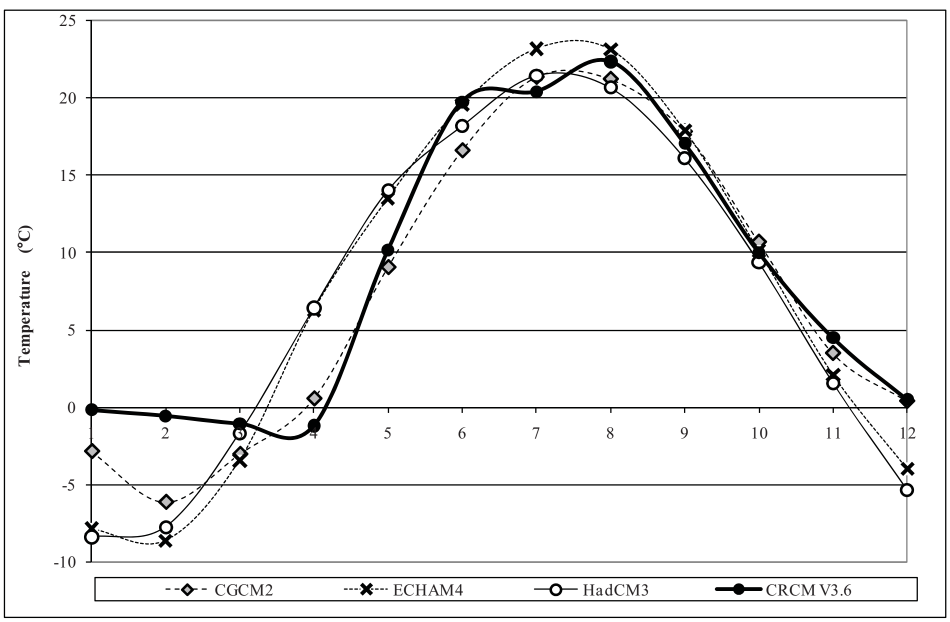


Figure 3.1 Comparison of 2050s temperature data for Montreal: GCM (A2) versus RCM

For further impact analysis in this thesis, however, only the GCM data is used since the global models utilize the current IPCC SRES scenarios, while CRCM data is with the older

IS92a scenario. Also, it is preferred to conduct an impact study with multiple global models versus only one regional model, in order to obtain a range of possibilities for the 2050s.

Extraction of the baseline data from CRCM and then the comparison between the impact results obtained by using GCMs and RCM is included in the recommendations for the future studies in Chapter 8.

Comparison between the GCM and the observed data:

The observed climate data for Montreal was obtained from Environment Canada (2009) for the baseline climate with the closest matching available time-slice of 1971-2000. This data, available for three parameters, temperature, wind speed, and humidity was compared individually with the GCM baseline (1961-1990) data sets. Figures 3.2 to 3.4 present the average data from GCMs along with the observed data for the three parameters; the observed data for radiation was not available.

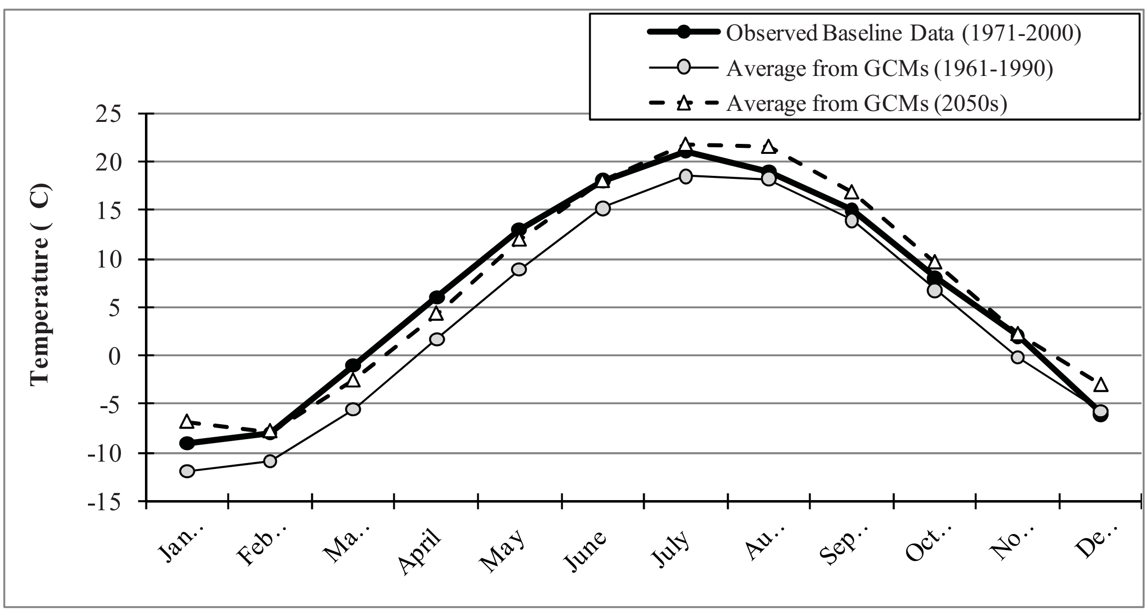


Figure 3.2 Average GCM data versus the observed data for Montreal

(Mean monthly temperature)

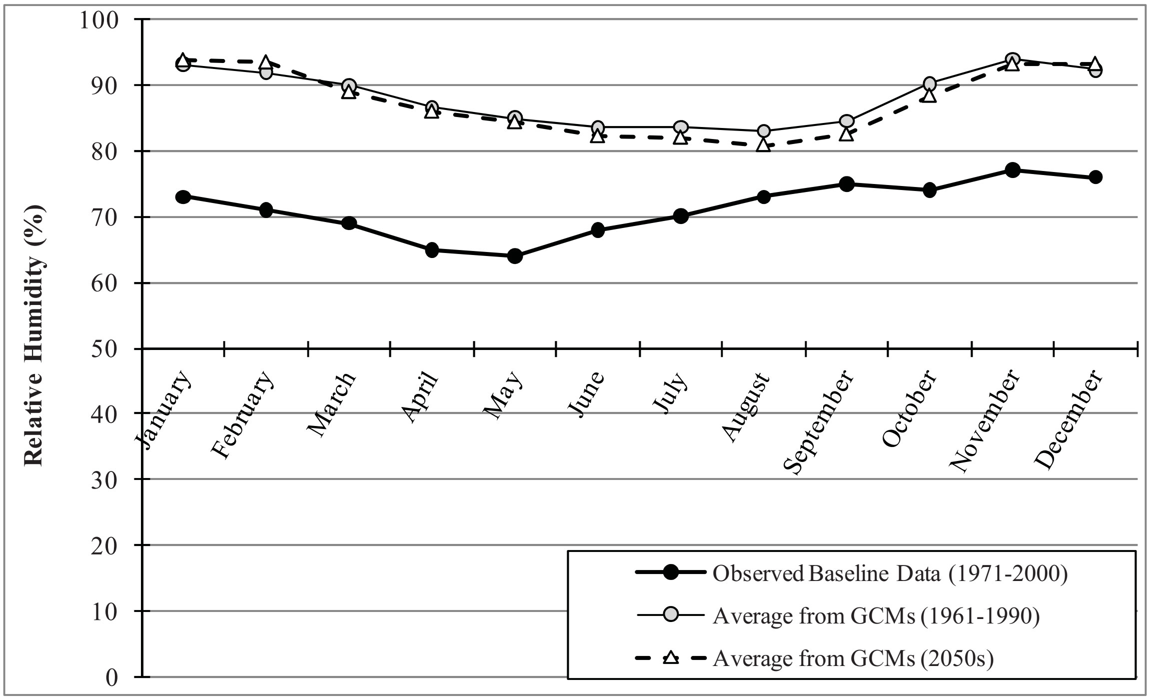


Figure 3.3 Average GCM data versus the observed data for Montreal (Mean monthly relative humidity)

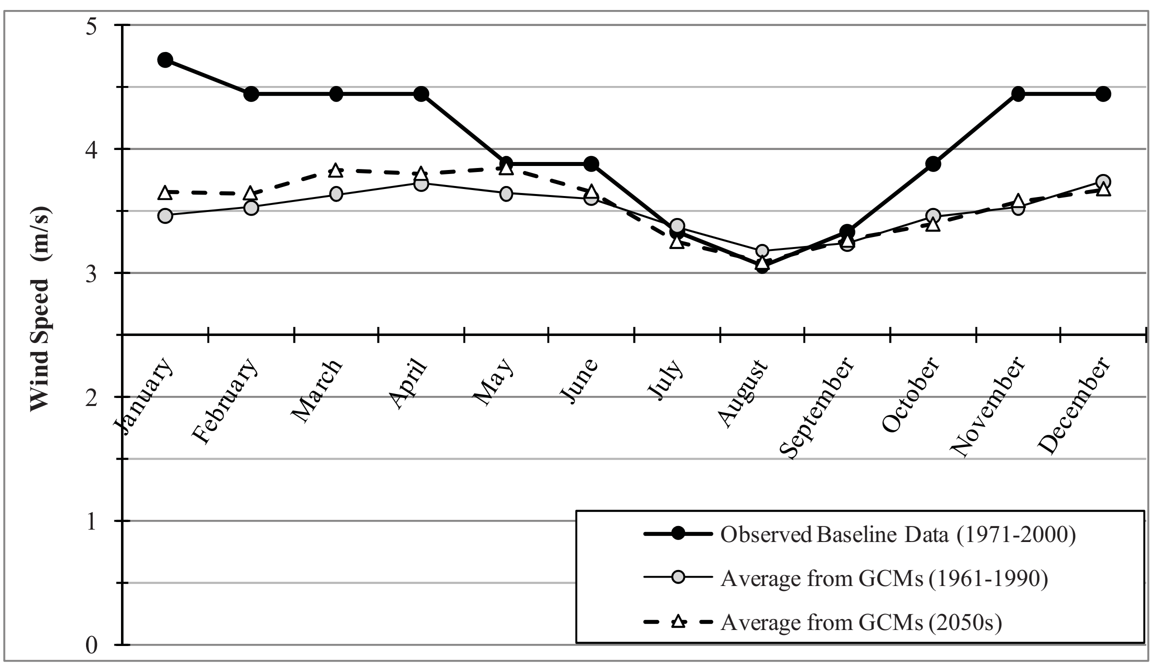


Figure 3.4 Average GCM data versus the observed data for Montreal (Mean monthly wind speed)

The comparison between the observed temperature data and the modeled baseline data, presented in Appendix A.2, show that in all the six cases (three GCMs with two scenarios each) the modeled baseline temperature is lower than the actual observed temperature. Thus the second approach taken in this current study (explained earlier in section 3.3), of using modeled data instead of observed data for the baseline and adding the change for the future to it to obtain the 2050s data will provide a conservative estimate of warming compared to the first approach of using the observed data as the baseline. This distinction between the two approaches is essential to note for the future studies that might compare the results from this thesis with other research.

Use of the climate data in the thesis:

Different sets of climate data are used at various stages in this thesis. First the TMY2 data for Montreal, mentioned in section 3.4, is used to simulate the Base case house in the current climate and compare the results with the utility bills as presented next in Chapter 4. Once the simulation model is calibrated, it is converted into a NZEH, as presented in Chapter 5, for which the same TMY2 file is used.

The data sets in Tables 3.1 to 3.4 are then used to simulate the base case house and the NZEH in the baseline climate, while the data sets in Tables 3.9 to 3.12 are used to simulate these two houses in the future climate, i.e. 2050s. Based on the results for the baseline climate and 2050s, the impact of climate change on these two houses is estimated as further explained in Chapter 6.

4. Simulation of the R-2000 Home in the Current Climate

The R-2000 home used as the Base case in this study is called Ray-Vision house (Kassab M., 2002). This chapter presents description of this house along with the development of its simulation model. TRNSYS 16 environment is used for the whole building simulation.

R-2000 is a voluntary, mainly performance based standard, set up to promote energy efficiency and indoor air quality as well as environmentally responsible material selection in new houses in Canada. It is applicable to single family as well as multi-unit residential buildings. It was created in 1981 with partnership between Canadian Home Builders' Association and Natural Resources Canada. Besides the performance requirement that R-2000 homes should consume 30% less than the conventionally built homes, the standard also includes some prescriptive measures such air-tightness requirement, minimum energy rating for windows, etc. The standard is updated periodically with the last update done in 2005 (NRC, 2009.a.).

4.1 Description of the Base Case

Ray-Vision house is a duplex apartment built in the year 2000 in suburban Montreal, in Longueuil (Quebec, Canada). It has a total built-up area of 310 m^2 including a basement (106 m^2), ground floor (103 m^2), and second floor (101 m^2).

The floor plans and the thermal zones assigned on each floor for the purpose of simulation are presented in Figures 4.1 to 4.5.

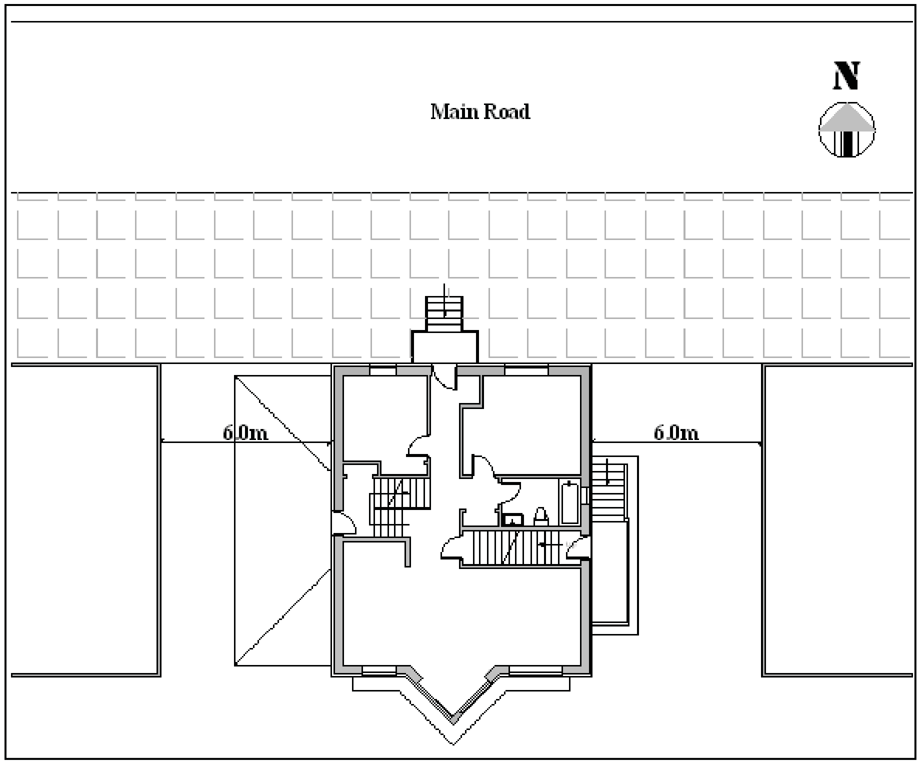


Figure 4.1 Site plan of Ray Vision house

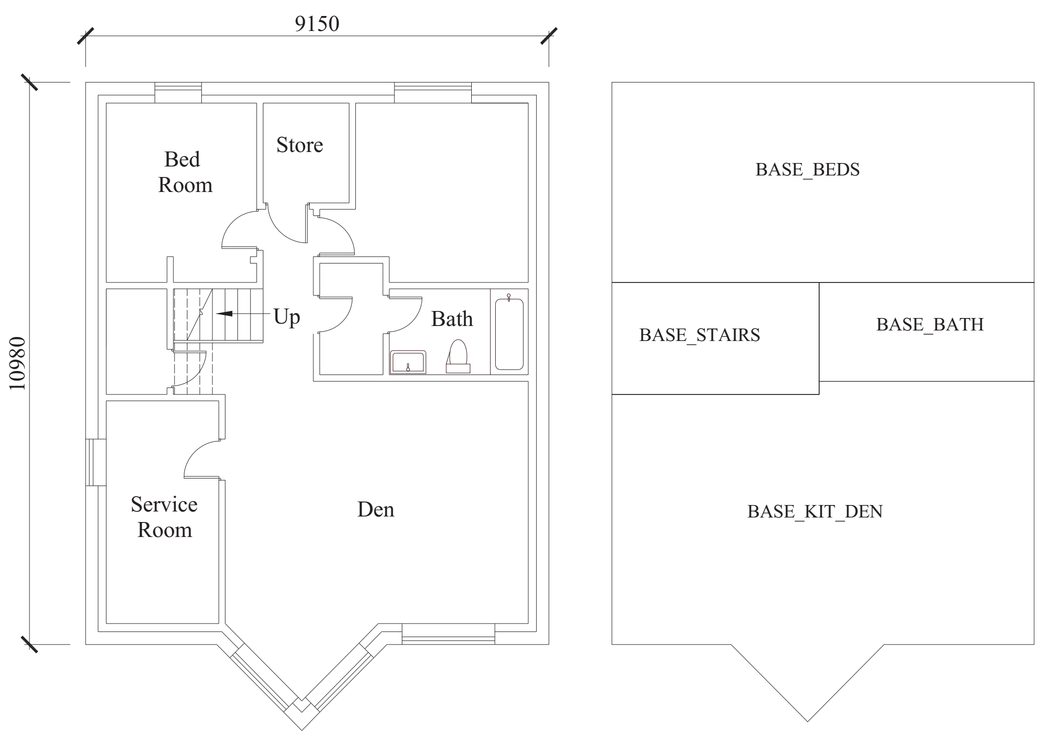


Figure 4.2 Basement floor plan with the zones

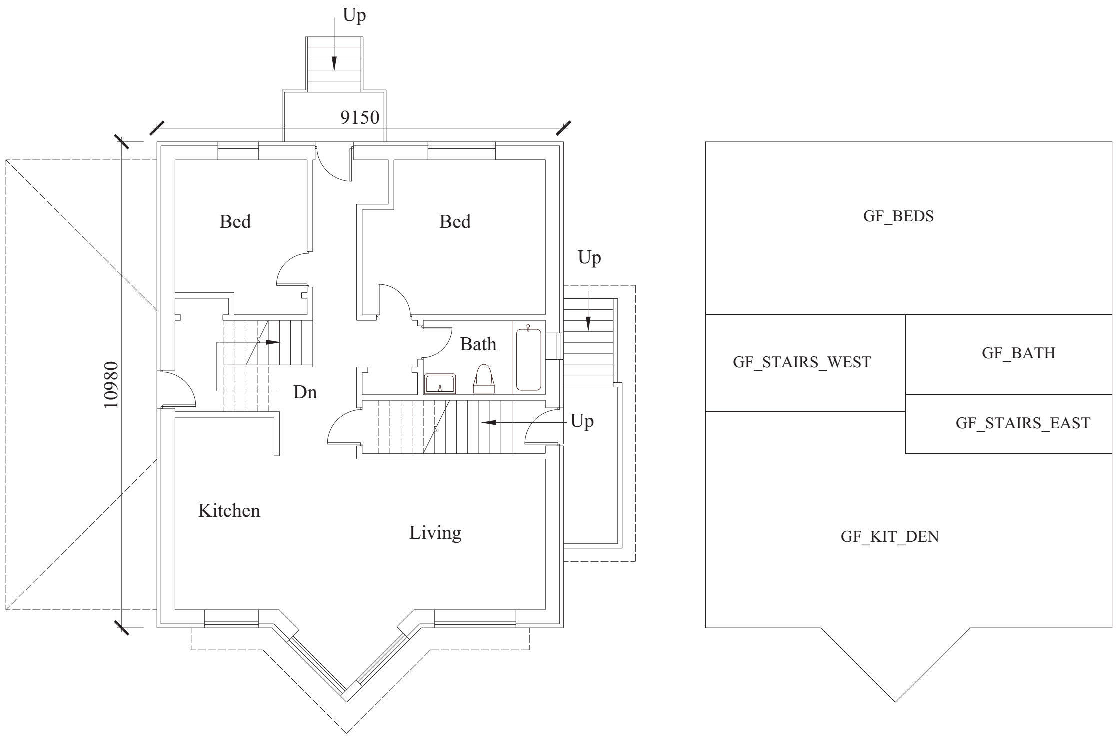


Figure 4.3 Ground floor plan with the zones

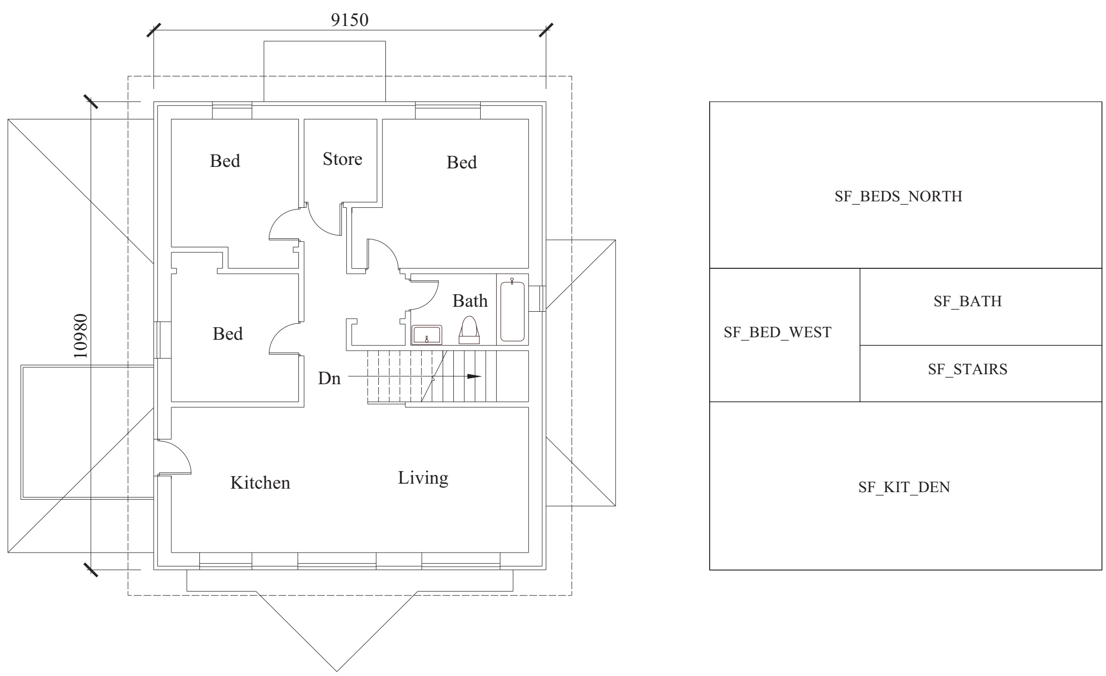


Figure 4.4 Second floor plan with the zones

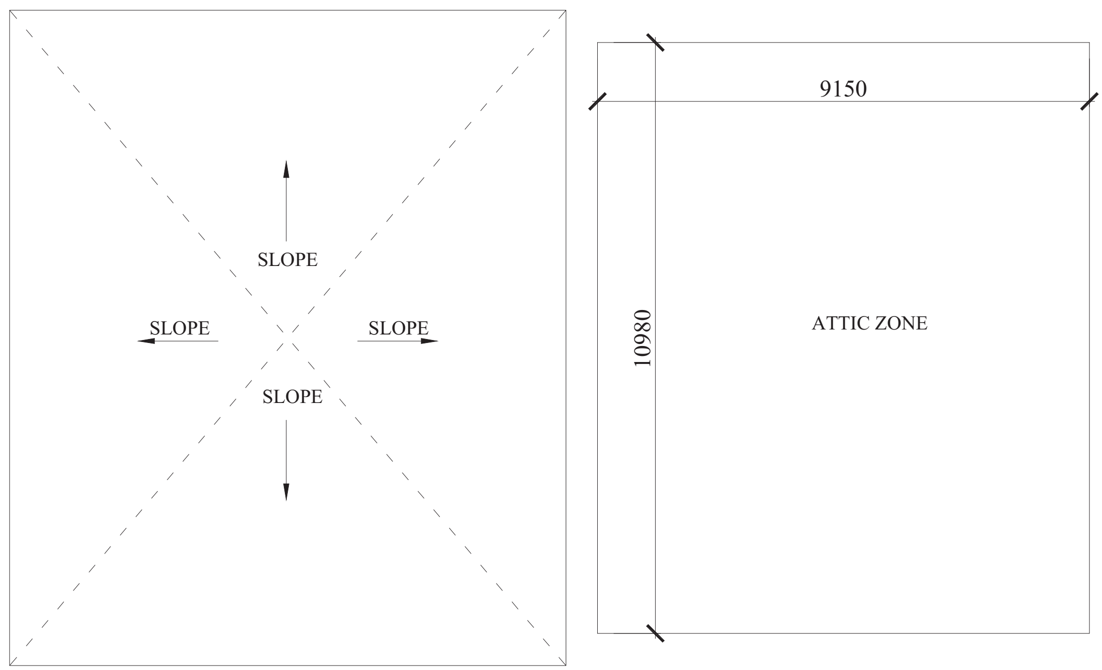


Figure 4.5 Roof plan and the attic zone

4.2 Existing Energy Efficiency Features in the Base Case

The features used for energy efficiency in this house are as follows:

1. The glazing area has been allocated to maximize the solar gains by having 29% glazing on the south facade and to minimize the heat losses by reducing the glazing on other facades, i.e. 1% on the East, 2% on the West, and 11 % on the North facade. The windows are Argon filled, double glazed with low-e coating.
2. Shading is provided to avoid overheating in summer.
3. The house is made air tight to minimize the infiltration by using continuous air barrier, sprayed-in-situ polyurethane insulation, 6 mm vapor barrier, continuous weather stripping and caulking around the door and window frames. The blower door test indicated the infiltration rate to be 1.25 ach at 50 Pa (Kassab M., 2002). This is a better performance than an R-2000 house, which requires the infiltration rate to be not more than 1.5 ach at 50 Pa (R-2000 Standard).

4. As presented in Table 4.1, the building envelope is designed in such a way to exceed the minimum values prescribed by the Quebec regulations (1992).

Table 4.1 Thermal resistance of the envelope

Building Component	Quebec Regulations (1992)		Ray-Vision house		
	RSI ($m^2.°C/W$)	R- value ($ft^2.F.hr/Btu$)	RSI ($m^2.°C/W$)	R- value ($ft^2.F.hr/Btu$)	Better than code by (%)
Roof (attic)	5.3	30.1	10.9	61.7	105
Walls: above ground	3.4	19.3	5.4	30.8	60
Walls: basement	2.2	12.5	4.8	27.3	119
Windows	0.4	2.0	0.6	3.2	63

4.3 TRNSYS: Simulation Software

TRNSYS stands for TRaNnsient SYstem Simulation program (Klein et al, 2006). It is a versatile, component-based, and extensible energy simulation tool that can be used for simulation of simple systems as well as complete energy simulation of multi-zone buildings. The software was originally developed by the University of Wisconsin's Solar Energy Lab (SEL) and has been commercially available since 1975. Since then this tool has been under continuous development; currently the joint team includes the Centre Scientifique et Technique du Batiment (CSTB) in France, Transsolar Energietechnik GmBH in Germany, and Thermal Energy Systems Specialists (TESS) in Madison, Wisconsin, along with the Solar Energy lab at the University of Wisconsin (TESS, n.d.).

4.3.1 Selection of TRNSYS as the Simulation Tool

Haltrecht et al (1999) have compared more than 30 energy analysis programs for the purpose of developing the next-generation HOT-2000 simulator, and concluded that the three software, ESP-r, TRNSYS and EnergyPlus, were good candidates as a starting point. In a later study, Crawley et al. (2005) have compared various features and capabilities of 20 major tools out of over 200 building energy simulation tools available to date. Based on this comparison, considering the features such as availability of components for renewable energy systems, the choice for the purpose of this study narrowed down to the same three programs, TRNSYS, ESP-r and EnergyPlus. Out of these three, TRNSYS is selected since it allows the generation of hourly weather data from monthly data as needed for this project and it has been used in several studies in related areas, e.g. Shariah et al. (1997), Florides et al. (2000), Kalogirou (2001), Jordan and Vajen (2001), Weiss W. (ed., 2003), Delisle et al. (2007), Harrison and Cruickshank (2007), Sibbitt et al. (2007), Iolova et al. (2007), Picard et al. (2007), Synnefa et al. (2007), etc.

4.3.2 TRNSYS Software Validation

For any building simulation tool, validation and testing provide essential quality control. These could be analytical tests - comparing against mathematical solution, comparative tests - comparing against other software, sensitivity tests - comparing small input changes against the baseline, range tests - testing over a wide range of input values, and empirical tests - comparing against experimental data (Witte et al., 2001). Some of the formal procedures established for testing of simulation tools that have been applied to TRNSYS, include (Kummert et al., 2004 a.; Kummert et al., 2004 b.; and Crawley et al., 2005, Table 13): (i) IEA HVAC BESTEST – analytical tests for space conditioning equipment (Neymark et al. 2001), (ii) IEA BESTEST/ASHARE 140 - a comparative validation suite for building envelope, (iii) IEA ECBCS Annex 21 / SHC Task 12 – empirical validation involving a simple mechanical system, three unoccupied test rooms and two 10-day experiments, (iv) RADTEST (Achermann and Zweifel, 2003) - validation suite for radiant heating and cooling system.

4.3.3. Overview of the TRNSYS Program

The extensive library of components in TRNSYS includes mathematical models for single- or multi-zone buildings, HVAC systems and equipment, hydronic components, control strategies, occupant behavior, renewable energy systems, weather data readers and processors, and so on. New components, if required, can be added, using common programming languages such as C, C++, PASCAL, FORTRAN, etc. The program can also be connected to other applications, such as Microsoft Excel, Matlab, etc., which is convenient for pre- and/or post-processing as well as interactive calls during the simulation (SEL, 2006). The link with Excel is found extremely useful in this research.

The TRNSYS simulation studio is the main visual interface in which the global simulation parameters such as the time step, start and stop time, etc. are defined and the required components called Types are added and linked to each other as shown in Figure 4.6. The studio provides access to the proformas, i.e. the description of inputs, outputs, and parameters of each Type to be able to view and/or edit them. After carrying out the simulation, the studio provides access to the input and the result files.

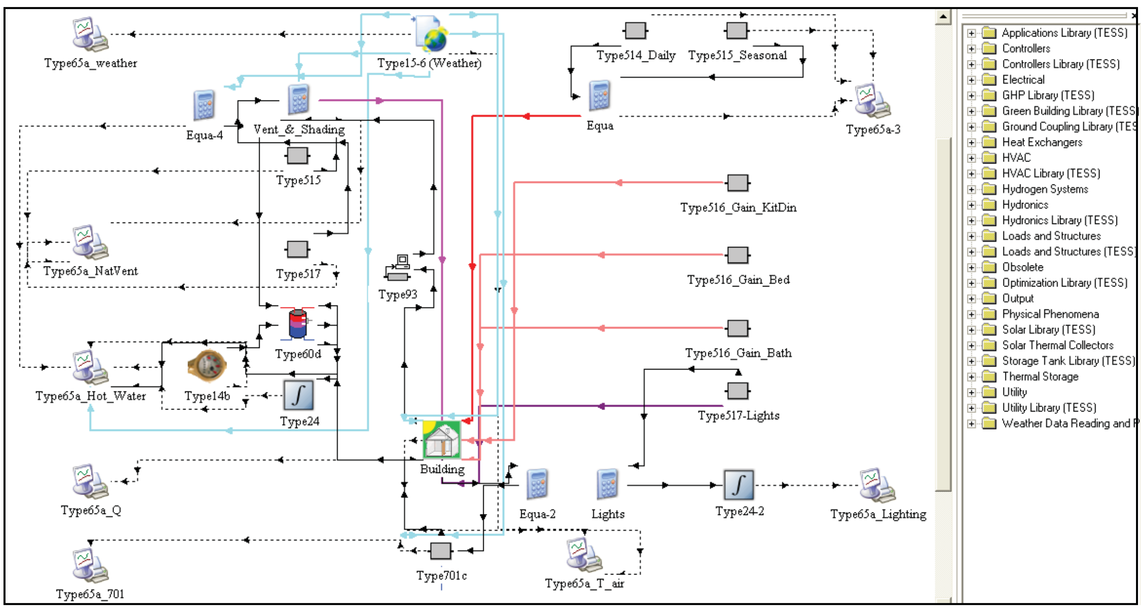


Figure 4.6 TRNSYS simulation studio

The simulation engine, composed of a large library of modules (i.e. the Types), is programmed in FORTRAN and it contains the mathematical models for simulation of HVAC system components, the heat balance equations for the envelope, and the equations at the air nodes, at each time step. The online plotters are enabled along with the simulation, which facilitate the view of multiple variables during the simulation.

4.3.4 Multi-Zone Building Model: Type 56

The visual interface for the building, TRNBuild, allows defining all aspects of the multi-zone building such as the size, orientation, physical and thermal properties of the envelope and glazing, etc. Since multi-zone buildings involve vast amount of information with complex details, instead of storing it in the TRNSYS input file, TRNBuild stores it by creating a separate building description (.bui) file. The component that models multi-zone buildings is referred to as Type 56.The mathematical description of various processes in Type 56 is presented in TRNSYS documentation (SEL, 2006), a brief summary of which is presented in this section.

Convection:

Each zone has one air node and the convective heat flux to it is calculated as:

$$\dot{Q}_{i} = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} \tag{4.1}$$

$\dot{Q}_{surf,i}$ = convective heat gains from all inside surfaces, kJ/h;

$\dot{Q}_{inf,i}$ = infiltration gains (air flow from outside only), kJ/h;

$\dot{Q}_{vent,i}$ = ventilation gains (air flow from user defined sources such as HVAC equipment), kJ/h;

$\dot{Q}_{g,c,i}$ = internal convective gains (by people, appliances, lighting, etc.) kJ/h;

$\dot{Q}_{cplg,i}$ = gains due to convective flows from adjacent zones, kJ/h;

Radiation:

The radiative heat flux to the wall surface temperature node is calculated as:

$$\dot{Q}_{r,wi} = \dot{Q}_{g,r,i,wi} + \dot{Q}_{sol,wi} + \dot{Q}_{long,wi} + \dot{Q}_{g,cwall-gain,i} \tag{4.2}$$

where,

$\dot{Q}_{g,r,i,wi}$ = radiative zone internal gains received by wall, kJ/h;

$\dot{Q}_{sol,wi}$ = solar gains through zone windows received by wall, kJ/h;

$\dot{Q}_{long,wi}$ = longwave radiation exchange between this wall and other walls and windows, kJ/h;

$\dot{Q}_{g,cwall-gain,i}$ = user specified heat flow to the wall, kJ/h

Conduction:

In Type 56, to model the walls, transfer function or response factor method (Stephenson and Mitalas, 1971; Mitalas and Arseneault, n.d.; and Lechner, 1992; cited in SEL, 2006) is used.

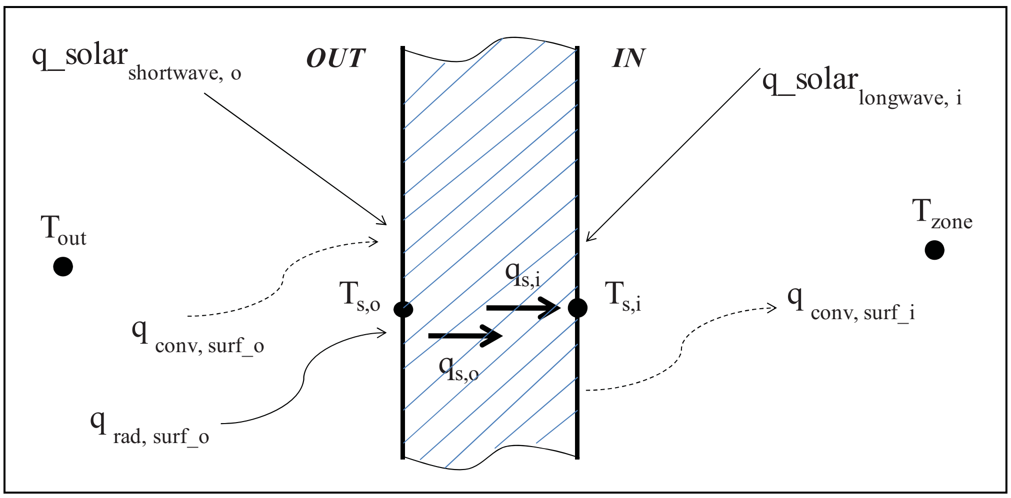


Figure 4.7 Heat fluxes and temperatures (SEL, 2006)

The expressions for heat conduction, at the inside and outside surfaces of walls are as follows:

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{bs}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{cs}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{ds}} d_s^k q_{s,i}^k \quad (4.3)$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{as}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{bs}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{ds}} d_s^k q_{s,o}^k \quad (4.4)$$

where,

$\dot{q}_{s,i}$ = conduction heat flux from the wall at the inside surface, kJ/h.m^2;

$\dot{q}_{s,o}$ = conduction heat flux from the wall at the outside surface, kJ/h.m^2;

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

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

The coefficients a, b, c, and d, are the transfer function coefficients of the time series, which are calculated by TRNBuild. The superscript k is a time series term with k = 0 indicating the current time-step, k = 1 the previous, and so on. Compared to thin walls, the number of time steps for heavier walls is more ($k \leq 20$) to account for the longer time lag due to their higher thermal mass. Taking into account all the radiative, convective and conductive heat fluxes such as shown in Figure 4.7, the surface and zone air temperatures are calculated for each time step.

4.4 The Base Case Simulation Model

To start with the building description, Type 56 is added to the studio.

4.4.1 The Building Model

The Base case building in this study, Ray Vision house, is mostly rectangular in plan with its length along the North-South axis as shown in the Figure 4.1. On the back side of the house, there are two short walls facing South-East and South-West. Thus there are 10 different orientations with six vertical facades and four sloping surfaces of the roof.

4.4.1.1 Zone Definition

The house in this case is divided in 15 zones: four in the basement (Figure 4.2), five each on the ground floor (Figure 4.3) and the second floor (Figure 4.4), and one in the attic (Figure 4.5). Based on their orientation, rooms on the same floor receive solar radiation differently and get affected by winds differently. Therefore, by having a thermostat in each room, a better control of indoor environment, leading to a better thermal comfort and energy savings, can be achieved. Dividing each floor into multiple zones allows the computer simulation to be slightly closer to the reality.

4.4.1.2 Envelope: Walls and Windows

Different components of the envelope including walls, floors, and roof are described by defining different ‘wall types’ through the ‘Wall Type manager’ in Type 56. For this house, there are altogether eight such types: the basement walls, the external walls above ground, the internal walls, the basement floor, the floor between the basement and the ground floor, the floor between the ground floor and the second floor, the attic floor, and the roof.

Each of these wall-types is made up of several layers, which are defined in the 'Layer Type manager'. The layers fall under mainly two categories: layers with thermal mass called 'massive' layers, e.g. concrete, and layers with R-value but no thermal mass called 'massless' layers, e.g. air cavity. Once all the required layers are defined, each wall-type is composed by including appropriate layers and their thicknesses.

All the windows in the house are double glazed with u-value of 1.4 W/m^{2}K. In Type 56, 'Geosurf', which is the short wave radiation distribution factor, is specified for the walls of the zones with windows. Out of the total short wave radiation received through windows, 70% is assumed to be received by the floor of that zone. The rest of the 30% is distributed among the walls, based on their location in relation to the position of the windows.

4.4.1.3 Thermostat Set-points

Kassab (2002) has presented the actual energy consumption of this particular house for a period of one year, from the electricity bills. Along with that, the additional information obtained from the owner related to heating energy use is also presented, e.g. the thermostat setpoint temperatures on the main floors and in the basement, setback temperatures and times, etc. This information is used to set the heating season and thermostat setpoints in the TRNSYS model of the Base case in this study in order to compare the simulated energy use with the actual from the electricity bills, as presented further in section 4.5.

Accordingly, the heating season for the house is assumed to be from October 17th to April 24th. The daily set-point temperature for heating is 21°C between 8 am to 8 pm and the setback temperature is 18°C on the ground floor and second floor. For the basement, a constant set-point of 10°C is used.

Although the existing house does not have mechanical cooling system, it is introduced in the simulation model in order to study the impact of climate change on the cooling loads. The cooling season is assumed to be for three months, from June 15th to September 15th. The daily set-point for cooling is 26°C between 9 am to 6 pm and the set-up temperature is 29°C. Only the ground and the second floor have cooling and not the basement.

The daily and seasonal schedules of heating and cooling are set up external to Type 56 in the TRNSYS studio. For both heating and cooling, Type 515 is used for seasonal schedules and Type 514 is used for daily schedules.

4.4.1.4 Internal Gains

Internal gains from people, computer, and lighting are considered in Type 56. Out of the two residential units in the building, each one is assumed to have two occupants. An occupancy schedule used (Type 516) allows to define separate occupancy loads for weekdays and weekends. The gains from occupants have been added only to the zones that are normally occupied at certain times, e.g. the zones with bedrooms have 100% occupancy at night but the zones with stairs have none. An internal gain of 150 W from each occupant is assumed based on ISO 7730 and is equally split between sensible and latent portions.

Each residence is assumed to have one computer placed in the bedroom zone on the North side. The computer is assumed to be a 230 W PC with color monitor. For the gains from the artificial lighting, 80% of the total sensible heat gain is assumed to be radiative and 20% to be convective, based on incandescent lighting (ASHRAE 2005, p. 30.22). No gains of any kind are assumed for the basement.

To account for the gains from appliances, the total annual appliance load is evenly distributed over the year. The electricity consumption for the appliances is assumed to be completely converted into sensible heat gain, which is distributed in respective zones depending on the contribution of particular appliance and its placement.

4.4.1.5 Infiltration

A similar methodology as Kassab (2002) is used for the purpose of calculating the infiltration. A blower door test result obtained of 1.25 ach at 50 Pa is converted for 4 Pa, which is equivalent to 1.25/20 = 0.0625 ach (LBNL, 1999, cited in Kassab, 2002). This infiltration is assumed to be entirely from the zones on the North and West side due to the prevailing winds. The details of calculation are explained below:

Total natural infiltration at 4 Pa = 0.0625 ach

Total volume of contributing zones = 796.21 m^3

Total contributing area (North and West side wall area above ground) = 126.33 m^2

Total ach converted to m^3/h: 0.0625/h * 796.21 m^3 = 49.76 m^3/h

This infiltration is distributed over the contributing area as follows:

(49.76 m^3/h) / 126.33 m^2 = 0.40 (m^3/h)/ m^2 of contributing wall area

This value is multiplied by the contributing area of each zone and infiltration for each zone in m^3/h is obtained, which in turn is divided by the volume of that zone to estimate the natural air change per hour as shown in Table 4.2. The infiltration values in terms of ach from the last column in this table are used in the TRNSYS model.

Table 4.2 Infiltration in North and West side zones

Zone	Total contributing wall area	Zone Volume	Infiltration	
	(m^2)	(m^3)	(m^3/h)	(ach)
BASE_BEDS	13.93	91.80	5.49	0.06
BASE_STAIRS	2.33	25.26	0.92	0.04
BASE_KIT_DEN	5.21	121.96	2.05	0.02
GF_BEDS	35.79	98.02	14.10	0.14
GF_STAIRS_WEST	6.00	26.97	2.36	0.09
GF_KIT_DEN	13.39	118.19	5.27	0.04
SF_BEDS_NORTH	32.23	88.25	12.69	0.14
SF_BED_WEST	7.73	27.10	3.04	0.11
SF_KIT_DEN	9.72	88.97	3.83	0.04
Total	126.33	796.21	49.76	

4.4.1.6 Shading

The windows are assumed to have a shading device, i.e. movable blinds. It is assumed that the occupants pull the blinds down throughout the year as soon as the room temperature reaches above 20°C. Type 56 requires information about the 'shading factor' of the windows, which is the ratio of non-transparent area of shading device to the glazing area of the window. The value of 1 indicates zero transmission of solar radiation to the room and zero indicates no shading.

The following sections from 4.4.2 to 4.4.8 present the components modeled in the studio outside of Type 56.

4.4.2 Natural Ventilation

There is no mechanical ventilation in the Base case. During the shoulder seasons (May - June and September - October) and at night during summer (June 15th to September 15th), the building is assumed to be naturally ventilated, whenever the zone air temperature goes higher than 26°C. Natural ventilation is modeled only in the zones with operable windows. It is not used during the day in summer, since the building is mechanically cooled during that period. Thus the schedule for natural ventilation is as follows:

April 24 to June 15:	during day and night
June 15 to September 15:	only during night
September 15 to October 16:	during day and night

The natural air flow rate due to wind is calculated for each zone individually by using the following equation (ASHRAE 2005, p.27.10):

$$R = C * A * V \tag{4.5}$$

where,

R = air flow rate, m^3/s;

C = effectiveness of openings, (0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds);

A = free area of inlet opening, m^2;

V = wind speed, m/s.

Out of these parameters, the value for the effectiveness of openings is assumed to be the minimum from the recommended range, i.e. 0.25 in order to avoid over estimation of effectiveness of natural ventilation. Eight zones are identified with operable windows and for each window, 50% of the area is assumed to be operable. The wind speed is supplied by the weather data reader and processor, Type 15, which is further discussed in section 4.4.4. The calculations for equation 4.5 are partly carried outside of TRNSYS and partly in the studio by inserting a component called ‘equation’. An ‘equation’ in TRNSYS is basically a calculator where the user can write his/her own equations.

In this calculator for ventilation, two conditions are inserted so that the ventilation is only allowed when the zone air temperature is higher than 26°C; and the ambient temperature, an input from the weather data reader, is higher than 18°C. Thus for each time step, the program needs to know the zone air temperature from the previous time step, verify if it meets the condition, and then calculate and provide the ventilation rate to Type 56. For this purpose, Type 93 is added, which is an input value recall device. It can store up to 10 inputs and values for each input for up to 500 time steps. For each zone, the air temperature from Type 56 is fed as an input to Type 93. It should be noted that Type 93 denotes the value for the current time step by t-1. Therefore, t-2 output is used to get the value for pervious time step and supply to the calculator. The calculated ventilation rate for each zone is then fed to the respective zones in Type 56.

4.4.3 Basement Heat Losses: Type 701

The basement has a concrete floor and four concrete walls. The heat transfer from these underground surfaces to the surrounding soil is simulated in TRNSYS using a three dimensional finite difference model (Type 701). For this purpose, the soil surrounding the underground portion of the house is divided into two sections, near-field and far-field as shown in Figures 4.8 and 4.9. The heat transfer from the basement only affects the near-field temperatures; it does not influence the far field. Since the far field is treated as an infinite heat sink/source its temperature is not affected by the energy flow to/from it but is only governed by depth and the surface conditions (SEL, 2004).

An important correlation employed by Type 701 is Kasuda correlation (Kasuda and Archenbach, 1965) presented in equation 4.6, to estimate the vertical temperature profile of the undisturbed field.

$$T = T_{mean} - T_{amp} \times \exp\left(-D\sqrt{\frac{\pi}{365\times\alpha}}\right) \times \cos\left(\frac{2\pi}{365}\left(t_{year} - t_{shift} - \frac{D}{2}\sqrt{\frac{365}{\pi\times\alpha}}\right)\right) \tag{4.6}$$

where,

T = soil temperature, °C;

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

T_{amp} = amplitude of surface temperature,

i.e. (maximum air temperature - minimum air temperature), °C;

D = depth below the surface (D=0 at the surface), m;

α = thermal diffusivity of the ground soil, m^2/day;

t_{year} = current time of the year, day;

t_{shift} = day of the year with minimum surface temperature, day.

The heat transfer from the basement boundary walls and floor to the near field is assumed to be strictly conductive and the moisture effects are ignored. The near-field is discretized with the grid size and the number and spacing of the temperature nodes specified as parameter in Type 701. The inside surface temperatures of all the boundary surfaces are the inputs supplied to Type 701 via Type 56. The u-values of the surfaces are calculated without including the inside or outside convective heat transfer coefficients and are provided as parameters. The other key parameters for Type 701 are listed below, out of which, the three parameters (i), (ii), and (iii) are used in Type 701 to set the initial ground temperature profile for the near-field and far-field based on Kasuda correlation (SEL, 2004).

(i) Mean surface temperature: A value of 3.875 °C is used which is calculated as the average from eight GCMs for the year 2000.

(ii) Day of minimum surface temperature: Hourly temperature data from Environment Canada (2009) for Montreal is extracted for each day of January, February and December in the year 2000. Out of these days, January 17, 2000 was found to be the day of minimum temperature, which is used for this parameter.

(iii) Amplitude of surface temperature: A value of 12°C is used based on latitude and longitude of Montreal (ASHRAE 2005, p.29.12).

(iv) Soil conductivity: The type of soil is assumed to be loam (mixture of clay and sand) with the thermal conductivity value of 8.1 kJ/h·m·K, i.e. 2.25 $W/m^2 \cdot K$ (ASHRAE 2005, p.25.14).

(v) Surface emissivity: A value of 0.94 recommended by ASHRAE (2005, p.3.9) for the surface emissivity of soil is used.

(vi) Nodes: The geometry of the grid used for discretization, showing the nodes along the boundary wall and in the near-field, is presented in Figures 4.8 and 4.9. The number of nodes is selected so as to balance the accuracy and the speed of simulation.

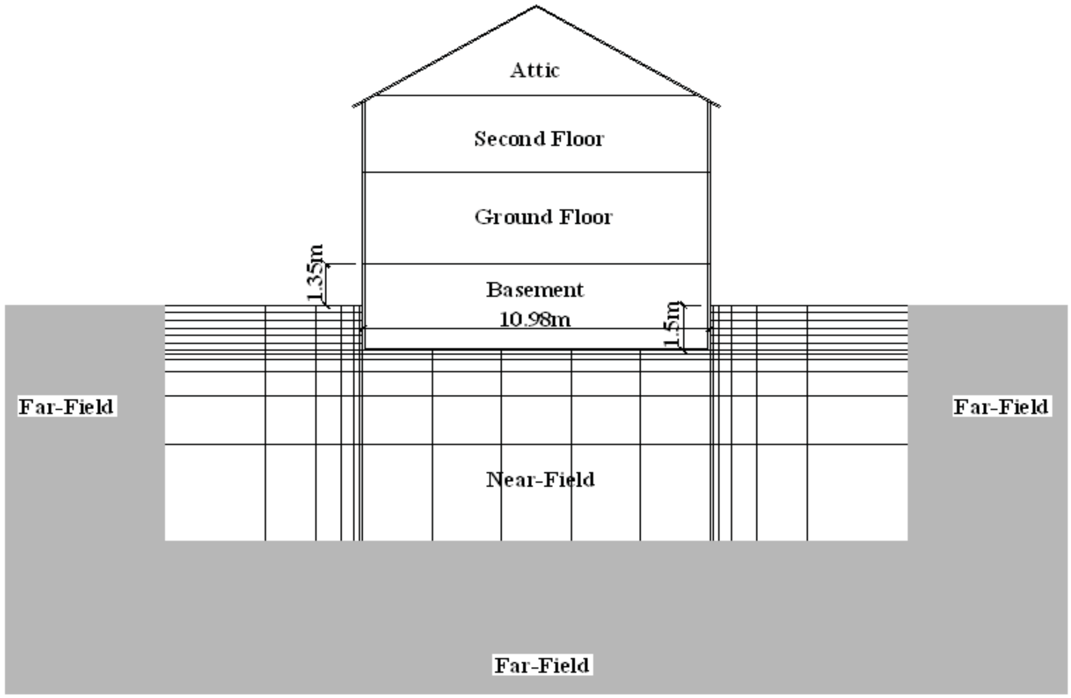


Figure 4.8 Section along the length of the house: x-axis (North - South Axis)

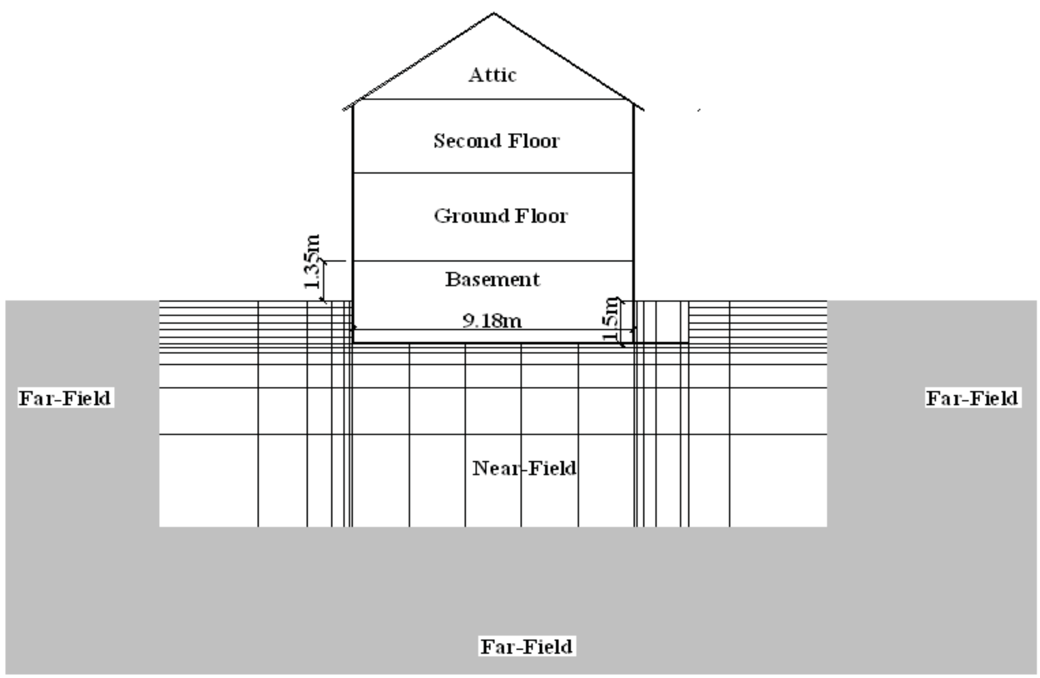


Figure 4.9 Section along the width of the house: y-axis (East -West Axis)

As seen in these two figures, the number of nodes is specified as follows (length, width, and depth below refer to the dimensions of the basement boundary walls):

Nodes along length: 5	Nodes beyond length: 6	Total nodes along x-axis: 6+5+6=17
Nodes along width: 5	Nodes beyond width: 6	Total nodes along y-axis: 6+5+6=17
Nodes along depth: 6	Depth nodes: 6	Total nodes along z-axis: 6+6=12

Table 4.3 shows the format in which this data is entered in Type 701. Each side is divided equally into the corresponding number of nodes, i.e. the length as well as the width of the basement is divided into 5 equal parts each (nodes 7 to 11), while the nodes 6 to 1 & nodes 12 to 17 are nodes going outwards from the edge of the building into the near field. The depth of the basement is divided into six equal nodes (nodes 1 to 6) and there are six more nodes going outward from the bottom of the slab into the near field (nodes 7 to 12).

Table 4.3 Dimensions of the nodes in the grid for near-field

Node	Length of soil node (m)	Width of soil node (m)	Depth of soil node (m)
1	3.2	3.2	0.25
2	1.6	1.6	0.25
3	0.8	0.8	0.25
4	0.4	0.4	0.25
5	0.2	0.2	0.25
6	0.1	0.1	0.25
7	2.196	1.83	0.1
8	2.196	1.83	0.2
9	2.196	1.83	0.4
10	2.196	1.83	0.8
11	2.196	1.83	1.6
12	0.1	0.1	3.2
13	0.2	0.2	
14	0.4	0.4	
15	0.8	0.8	
16	1.6	1.6	
17	3.2	3.2	

Out of the four different options available for Type 701, the two, 701a and 701c, both create output file at the end of simulation with the near field temperature data. The difference between these two models is that Type 701a needs an input file with near field temperatures while 701c does not. In order to ensure that the temperatures in the near-field were stabilized before using for further simulations, an input file for Type 701a was created. For this purpose, simulations were first carried out for five years using Type 701c. An output file thus created at the end of this simulation, which had the ground temperature profile (for the near-field) was then used as an input for Type 701a for further simulations. This was done to ensure that the appropriate input values of near field temperature were provided to the model.

The climate related data, including the ambient temperature, sky temperature, and the incident solar radiation on the soil surface, is provided to Type 701 by the weather data reader and processor Type 15, presented in the following section.

4.4.4 Weather Data Reader: Type 15

In TRNSYS studio, the Montreal weather file (.tm2) is accessed using the data reader and processor, Type 15-6. The added benefit of using this particular model is that it performs some additional functions like radiation processing and calculating the fictive sky temperature required by Type 56 for determining the long wave radiation exchange with the outside surfaces. The inputs from Type 56 include the number of surfaces of the building, their slopes, and their azimuth angles and the outputs to Type 56 include the ambient temperature, relative humidity, the tilted surface radiation for each surface, etc. Type 15 feeds information to various other components in the studio as well, e.g. Type 701.

4.4.5 Domestic Hot Water

The energy need for domestic hot water (DHW) is influenced by various factors, such as the DHW profile, specifications of the DHW tank, the supply temperature from the water mains, etc. The DHW profile is defined using the forcing function, Type 14, with its graphical plug-in. The graphical plug-in is an external executable program which can be accessed through the component's proforma. It allows the definition of time profile in a graphical way and then transfers the parameters to the main components, in this case Type 14. Residential hourly hot water use profile developed by Perlman and Mills (1985) from ASHRAE (2007, pp 49.11-12), is used, which specifies the hot water use of 236 L per day.

Type 60 is the component that simulates electric hot water tank with one or two internal auxiliary heating elements. For most of the TRNSYS components, typically, a time step of one hour is computationally convenient as well as accurate enough. But to simulate the heating element in the hot water tank accurately, Type 60 uses an internal time step that is independent of the global setting in TRNSYS. The component calculates a critical internal time step and it is recommended not to use the internal time step greater than (critical time step)/6 (Newton, 1995) for better accuracy. This is achieved by specifying the fraction of critical time step as one of the parameters in the component.

A 300 L (80 gallon) tank with 5.5 kW input power is used based on the size of the Base case house (ASHRAE 2007, p 49.10). A cylindrical tank with 1.52 m height, equipped with an inlet and an outlet is simulated. Only one internal auxiliary heating element with a thermostat is used. In ASHRAE 2007 (p.49.10), the set point temperature in the tank is recommended to be 60°C in order to eradicate Legionella bacteria; however, since it is stated that temperature does not have to be that high for prevention, the minimum temperature is set at 55°C.

One of the inputs for Type 60 is the temperature of the fluid entering at the inlet. For this purpose, the water supply temperature data measured for Montreal is used (Dumas and Marcoux, 2004). As shown in Figure 4.10, weekly data is available for the years 1994 and 2000 to 2003. An average daily temperature profile based on this data, which relates the day of the year to the temperature of the water supply that day, is presented in equation 4.7. Using the day of the year, which is an input from the weather file, the inlet temperature for the tank is calculated and fed to Type 60.

The trendline based on the average of the data from five years is a sixth-degree polynomial and it is expressed as follows:

T_{water} = $a \cdot x^6 + b \cdot x^5 + c \cdot x^4 + d \cdot x^3 + e \cdot x^2 + f \cdot x + g$ (4.7)

where,

T_{water} = municipal supply water temperature in Montreal, °C;

x = day of the year;

a = $-5.7912857188639*10^{-13}$;

b = $7.6821367525263*10^{-10}$;

c = $-3.6971602672816*10^{-7}$;

d = $7.569852502379*10\text{-}^{5}$;

e = $-5.840624355051*10^{-3}$;

f = $1.4518209154026*10^{-1}$;

g = 2.5662282218886

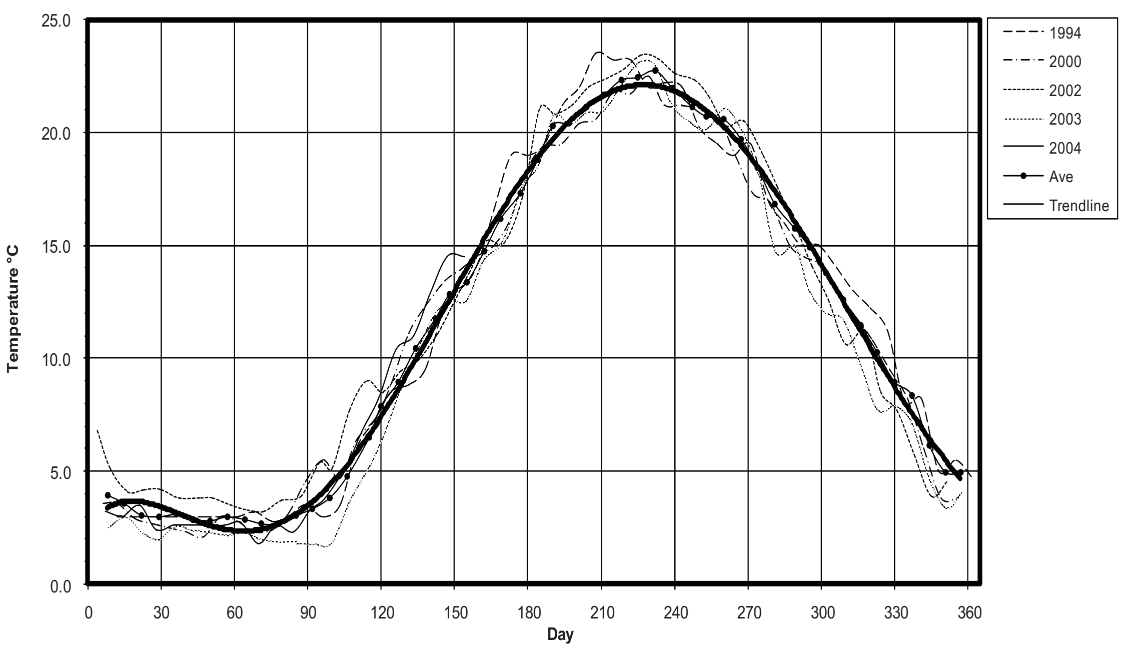


Figure 4.10 Municipal supply water temperature for each day of the year (Dumas and Marcoux, 2004)

4.4.6 Artificial Lighting

The artificial lighting for the Base case is provided by incandescent lights. It is assumed that 50% of the floor area needs artificial lighting at a time. The schedule is simulated with Type 517 and to establish the schedule, artificial lighting is assumed to be used for one hour in the early morning and four hours in the evening throughout the year. This represents an average between winter and summer need for artificial lighting, since the number of daylight hours is higher in summer than in winter. The instantaneous power is calculated by multiplying the lighting density, 5 W/m^2 and the lighted floor area, which in turn is integrated over the entire year, to find the total annual energy consumption for lighting. The total energy consumption for artificial lighting thus modeled, is presented in section 4.5.

4.4.7 Major Appliances

All the appliances considered in this study are electrical. Table 4.4 presents the average energy consumption for major appliances for a single family (NRCan, 2007). The values for the manufacturing year 1999 are used, since the house is built in the year 2000.

Table 4.4 Appliance load per family

Appliance per family	Description	Rated Energy Consumption (kWh/year)	Electricity demand (kWh/year)
Refrigerator	Top-mounted, 18 cu-ft	664	664
Dishwasher	standard	640	128
Clothes washer	standard	860	172
Clothes Dryer	standard	908	908
Stove	30-inch, self-cleaning	742	742
Total			**2,614**

The electricity demand listed in Table 4.4 for dishwasher and clothes washer is assumed to be 20% of the rated energy consumption. This is because a major portion of energy requirement for these appliances is for hot water, as discussed further in Chapter 5, section 5.3.

As there are two families in the building, the total electricity consumption for the whole building is doubled for the entire year, i.e. 5,228 kWh.

4.4.8 Miscellaneous Electric Load (MEL)

Table 4.5 Miscellaneous Electric Load (MEL)

Miscellaneous Electric Load (MEL)	No. of units in the building	Energy/unit [kWh/yr]	Total electricity need [kWh/yr]
Hard-wired			
Door bell	1	44	44
Smoke detector	3	3.5	10.5
Home Entertainment			
Cable box	1	153	153
Clock radio	2	15	30
Compact stereo	2	112	224
DVD player	2	50	100
Satellite dish box	1	132	132
Television	2	215	430
Home office			
DSL/Cable modem	2	17	34
Desktop PC w/Speakers	2	144	288
Printer (Laser)	2	93	186
Kitchen			
Blender	2	7	14
Coffee maker	2	61	122
Hand mixer	2	2	4
Microwave	2	135	270
Slow cooker	2	16	32
Toaster	2	46	92
Bathroom			
Hair dryer	2	41	82
Other			
Vaccum cleaner	2	41	82
Answering machine	2	34	68
Battery charger	2	15	30
Cell phone charger	2	77	154
Cordless phone	2	23	46
Iron	2	53	106
Portable fan	2	11	22
Total MEL			**2,756**

As opposed to large appliances, it is not very straight-forward to estimate the loads for small appliances and other plug loads since their number as well as usage varies a lot, depending on user behavior. The list of MELs assumed for the Base case in this study is presented in Table 4.5, in which the values for energy per unit are based on U.S. DOE's Building America benchmark definition developed by NREL (Hendron, 2008). Since these benchmark values are based on mid-1990s standard practice (EERE, 2009), they are appropriate for the Base case house built in 2000. The MEL totals to 1,378 kWh per household; which is equivalent to 2,756 kWh for both the families, i.e. for the entire building.

4.5 Simulation Results for the Base Case

After completing the model in the studio, simulation is carried out for the entire year. Simulation results obtained from various components are presented here. The annual energy consumption results obtained are compared with the actual energy consumption data of the house from the utility bills.

4.5.1 Monthly Loads for the Base Case

Figure 4.11 presents monthly values of all the loads for the Base case house along with the highest and lowest peaks for the ambient temperature. The baseload in the graph includes lighting, appliances, and miscellaneous electric loads, all assumed to be uniformly distributed over the year. The DHW load is less in February than in March in spite of the fact that the month of March is warmer than February, simply because of less number of days in February. January is the month with the lowest monthly average temperature, i.e. -10.1°C and it coincides with the highest monthly heating load. Similarly, July is the month with the highest monthly average temperature, i.e. 21.1°C, which coincides with the highest cooling load. The peak heating load is found to be 8.03 kW on January 15th and the peak cooling load of 11.48 kW occurs on July 20th.

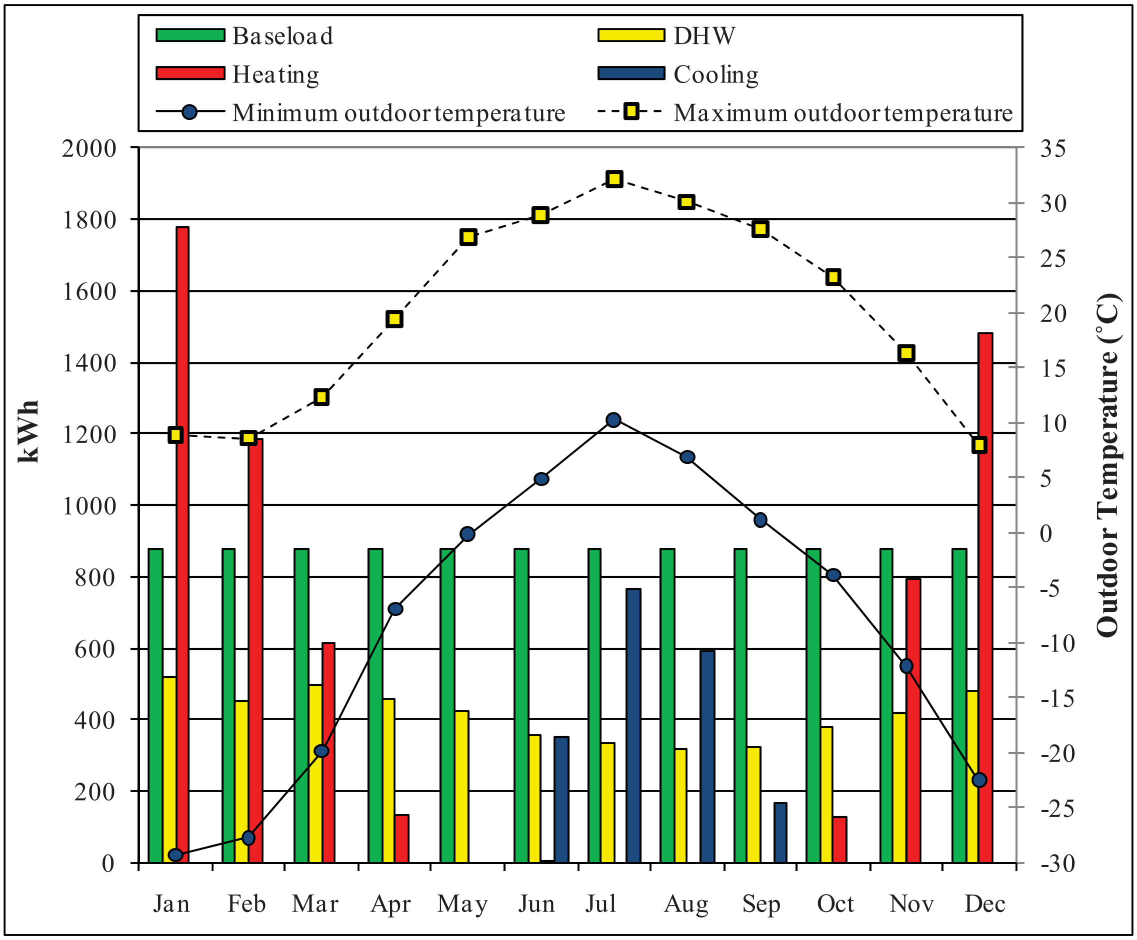


Figure 4.11 Monthly loads in the Base case

4.5.2 Annual Loads per Zone

The annual heating and cooling loads per zone are presented in Table 4.6. Based on these values, a few observations are made listed further in this section.

i. The basement zones contribute very little towards the total heating load. This is due to the lower set-point temperature for heating in the basement, i.e. 10°C.

ii. On the ground and second floors, the north side zones have higher heating load per unit floor area compared to the south side zones which receive more solar radiation. Another minor factor that contributes to this is that the south side zones on both these floors are kitchen zones which receive internal heat gains from the appliances. The area-weighted heating loads from the ground floor zones are on an average higher than those from the second floor zones.

iii. For cooling on the other hand, south side zones have higher cooling loads compared to the north side zones and second floor zones contribute more to the total cooling load compared to the ground floor zones.

iv. Out of all 14 conditioned zones, the highest area-weighted cooling load is from the second floor zone on the west side, i.e. SF_BEDS_WEST, since it receives higher solar radiation. The same zone has the smallest heating load among all the zones except the basement.

Table 4.6 Annual heating and cooling loads per zone

Zones		Loads (kWh)		Loads (kWh/m^2)	
		Heating	Cooling	Heating	Cooling
1	BASE_BEDS	13.37	_	0.37	_
2	BASE_STAIRS	0.00	_	0.00	_
3	BASE_BATH	0.00	_	0.00	_
4	BASE_KIT_DEN	4.39	_	0.09	_
	Total: Basement	**17.76**	_	**0.17**	_
5	GF_BEDS	1,579.00	128.10	44.16	3.58
6	GF_STAIRS_EAST	226.60	_	36.73	_
7	GF_STAIRS_WEST	423.30	_	43.02	_
8	GF_BATH	305.50	_	36.37	_
9	GF_KIT_DEN	1,732.00	610.50	40.17	14.16
	Total: Ground floor	**4,266.40**	**738.60**	**41.31**	**7.15**
10	SF_BEDS_NORTH	808.60	422.50	22.61	11.81
11	SF_BED_WEST	135.40	198.00	12.33	18.03
12	SF_STAIRS	105.60	_	14.12	_
13	SF_BATH	148.50	_	14.57	_
14	SF_KIT_DEN	641.10	518.10	17.78	14.37
	Total: Second floor	**1,839.20**	**1,138.60**	**18.31**	**11.33**
15	ATTIC	_	_	_	_
	Total: Enitre house	**6,123.36**	**1,877.20**	**19.94**	**6.11**

4.5.3 Total Annual Loads of the Base Case

The total annual load from all the needs of the Base case is 23,493 kWh. Table 4.7 and Figure 4.12 present the different loads that make up this total.

Table 4.7 Annual loads of the Base case

Load Type	Simulated Result (kWh)
Heating	6,123
Appliances	5,228
Hot water	4,955
Miscellaneous Electric Load (MEL)	2,764
Lighting	2,546
Cooling	1,877
Total	**23,493**

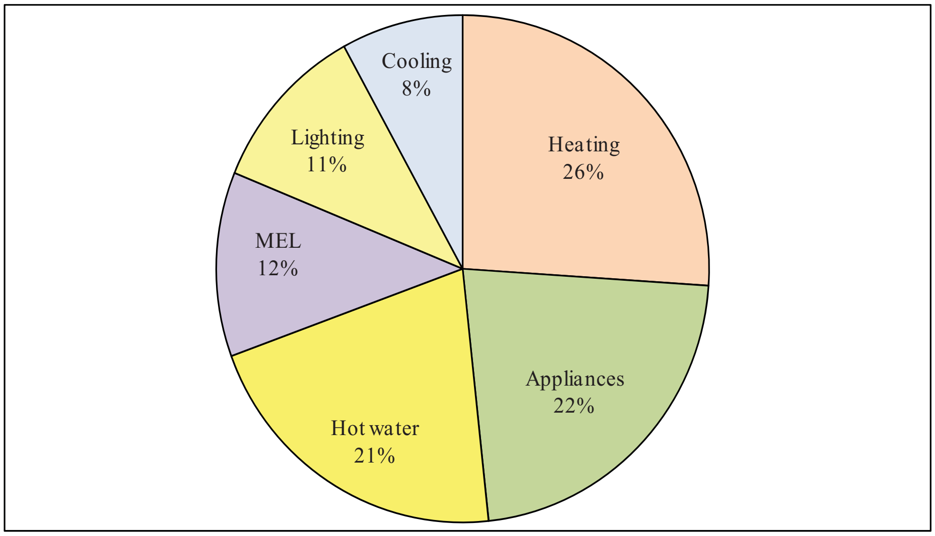


Figure 4.12 Distribution of annual loads in the Base case

The total annual DHW load is 4,955 kWh with the set-point of 55°C. At the set-point of 60°C, DHW load would be 11% higher, i.e. 5,560 kWh. The amount of heat removed from the house by natural ventilation is found to be 1,073 kWh; in absence of natural ventilation this would be an extra load on the cooling system.

4.5.4 Total Energy Consumption of the Base Case

The value for the heating energy consumption is equal to the heating load, assuming the coefficient of performance (COP) equal to one for baseboard heaters. But the cooling load of 1,877 kWh translates to 626 kWh of electricity requirement, considering room air conditioning units (COP = 3). Therefore, even though the total load including cooling is 23, 493 kWh (Table 4.7), the energy requirement is slightly lower at 22, 242 kWh (Table 4.8).

The actual energy consumption for an entire year from the utility bills for this house without any air conditioning was 21,320 kWh (Kassab, 2002). To compare it with the simulation results, as seen in Table 4.8, consumption for cooling is separated from the total. The simulation results seem to be in a good agreement with the actual consumption, with a difference of less than 2%.

Table 4.8 Comparison of simulated and actual electricity consumption

	Electricity Consumption (kWh)
Simulated total with cooling	22,242
Simulated total without cooling	21,616
Actual consumption from Utility Bills	21,320

Kassab (2002) has attempted to separate the average base load from the total energy consumption using the utility bills for the period 2000-2001, in order to establish the heating consumption. According to his estimate, the heating consumption for this house was 6,118 kWh, which is very close to the simulation result obtained here with TRNSYS, i.e. 6,123 kWh.

The total electricity required for this house, including cooling is 22,242 kWh which is equivalent to approximately 72 kWh/yr·m^2 of conditioned floor area. Compared to this, Zmeureanu et al. (1999) found energy consumption of houses built in Montreal after 1990 to be approximately 108 kWh/yr·m^2. Thus, this R-2000 Base case house seems to consume 33% less energy compared to the existing building stock.

Once the total energy requirement of the house is estimated as presented in this chapter, an attempt has been made to further reduce these loads. The renewable energy system is then designed and sized accordingly, in order to achieve a Net Zero Energy Home, as discussed further in chapter 5.

5. Net Zero Energy Home in the Current Climate

The base case house is converted to a NZEH by proposing mainly two modifications which include, changing the heating system from electric baseboard heaters to radiant floor heating and using renewable energy technology, viz. hybrid photovoltaic/thermal (PV/T) system. The PV/T is designed to produce (i) heat for radiant floor heating and DHW and (ii) electricity to supply for all the rest of the electrical loads in the duplex. The backup electricity that is expected to be required intermittently for heating and DHW is also supplied by the PV/T. The description and details of these systems, along with the modeling of NZEH in TRNSYS as presented in Figure 5.1, are discussed in this chapter.

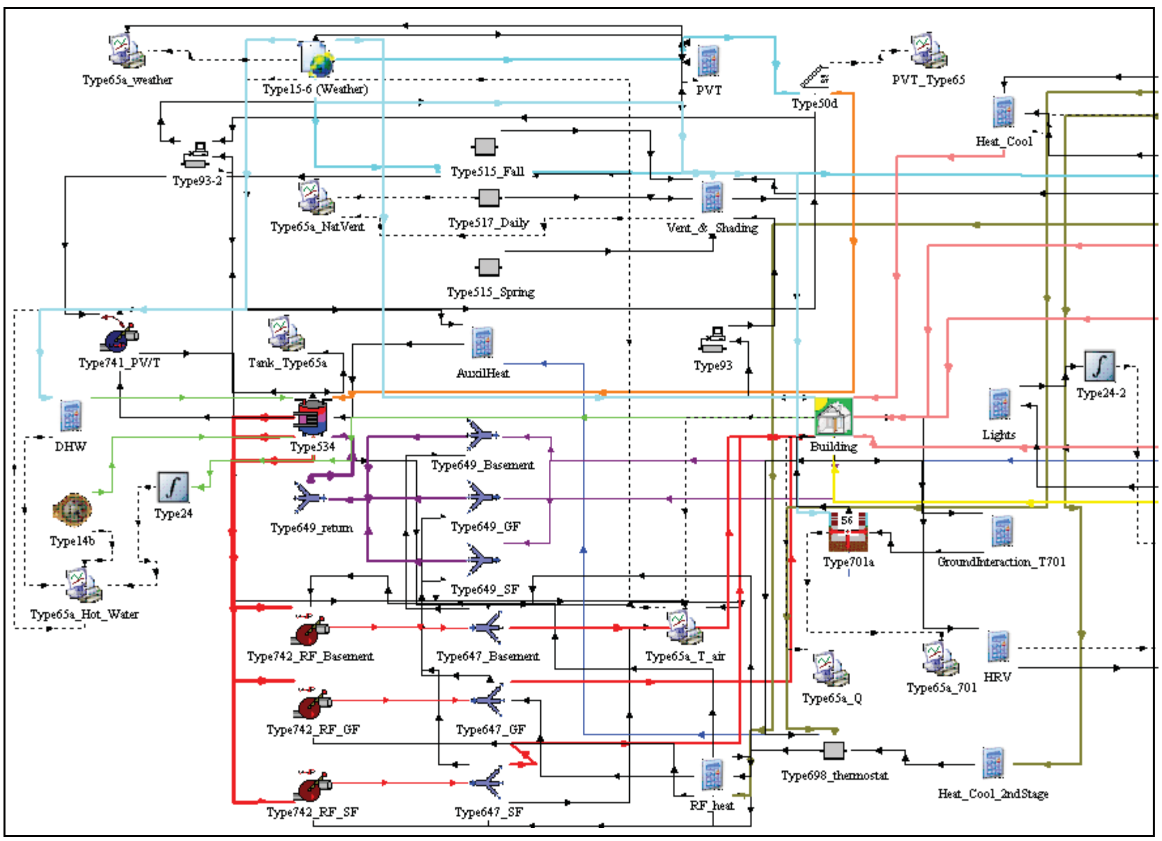


Figure 5.1 TRNSYS studio showing NZEH model

For a NZEH to be economically viable, it is essential to first reduce the onsite thermal and electric loads before sizing the renewable energy system; sections 5.3 through 5.6 describe various steps taken in this direction that include reducing appliance, DHW, and lighting loads.

5.1 Radiant Floor Heating System

Literature review indicates that the hydronic radiant floors are being selected consistently as the heating system in the NZEHs and near-NZEHs. Some examples of these include Avalon Discovery III, Echo Haven, Now House, The Laebon CHESS Project in Canada and Maine Solar House, Doub/Childs Residence, Graham-Jackson Residence, Lake Sammamish home in the U.S, mentioned earlier in Ch. 2, section 2.2. The percentage of radiant floor heating in the new residential applications is growing internationally in the last two decades. Radiant floor heating is used in 30 to 50% of the total number of new residential constructions in Germany, Austria, and Denmark and up to 90% in Korea (Olesen, 2002). In North America, it was introduced after World War II, and has seen some important advancements since then, in terms of new products and design techniques (CMHC, n.d., a).

Radiant floor heating is thermally more comfortable than forced air system and baseboard heaters. Radiant floors provide comparatively uniform warmer surfaces as well as uniform air temperature from floor to ceiling, have quiet operation, and do not cause drafts. Also, this type of heating allows for the room air temperatures to be slightly lower compared to other heating systems, which prevents indoor air from getting excessively dry (Olesen, 2002).

For the radiant floors using water as the heat transfer fluid, the design temperature range for supply is between 38 to 65°C for heating (ASHRAE 2000). As prescribed in ASHRAE Standard 55 (2004), floor surface temperature inside occupied zones with people wearing normal indoor shoes is maximum 29°C and minimum 19°C. This recommendation for thermal comfort is based on the criteria of 10% dissatisfied (Olesen and Brager, 2004). For the highest standard of thermal comfort listed, i.e. only 6% dissatisfied, the floor temperature has to be 24°C (ASHRAE

Standard 55, 2004). Some general guidelines that can be used for preliminary design, based on the average values of some of the parameters in residential radiant floor applications, are listed in Table 5.1 (Watson and Chapman, 2002 a).

Table 5.1 Preliminary guidelines for parameters in radiant floor system

Parameter	Recommended range of values
Water temperature	35-60°C (95-140°F)
Surface temperature	24-29°C (75-85°F)
Heat output	47-95 W/m^2 (15-30 Btu/h.ft^2)
Flow rate	68 kg/h (0.3 gpm)

5.1.1 The proposed system

In proposing the NZEH, it is assumed that it is a new construction and not a retrofit of the existing structure. This is mainly done to allow direct cost comparison between the base case house and the NZEH, without involving any demolition or retrofit costs etc., as further explained in Chapter 7. Most of the physical characteristics of the NZEH, i.e. floor plans, floor area, orientation, envelope, and windows are the same as the base case, but the space conditioning system is completely different. Accordingly, the necessary components of the structure that go along with this system are different than the ones in the original house. While the Base case has wooden floors, with concrete slab only in the basement, the NZEH with radiant floor system has concrete slab on all floors. Figures 5.2 and 5.3 present the sections through the floors.

The radiant floor system in this case is a closed-loop, forced, hydronic system with cross-linked polyethylene (PEX) tubing laid out within the flooring. There are various ways the hydronic radiant system can be incorporated in the buildings (Radiant Panel Association, n.d.), based on the budget of the project and whether the project is a retrofit or a new construction. A system with concrete slab and embedded pipes is preferred here, over a system with tubing installed in between floor joists. This is done mainly for two reasons, (i) higher heat transfer from the heating medium to the floor surface due to higher thermal conductivity of concrete, 0.8

W/m·K compared to that of floor wood, ranging from 0.1 to 0.2 W/m·K to take advantage of higher thermal mass of concrete.

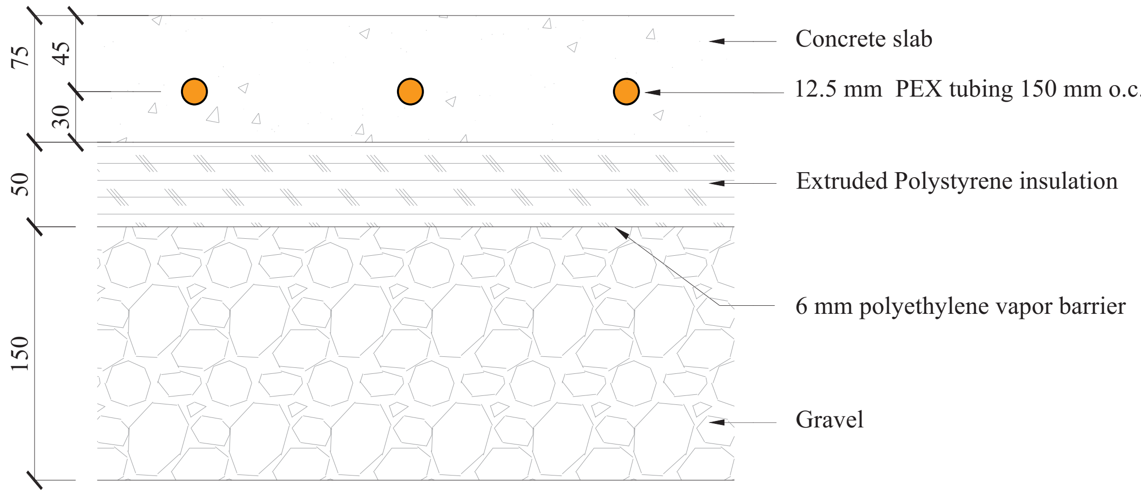


Figure 5.2 Section through radiant floor: Basement

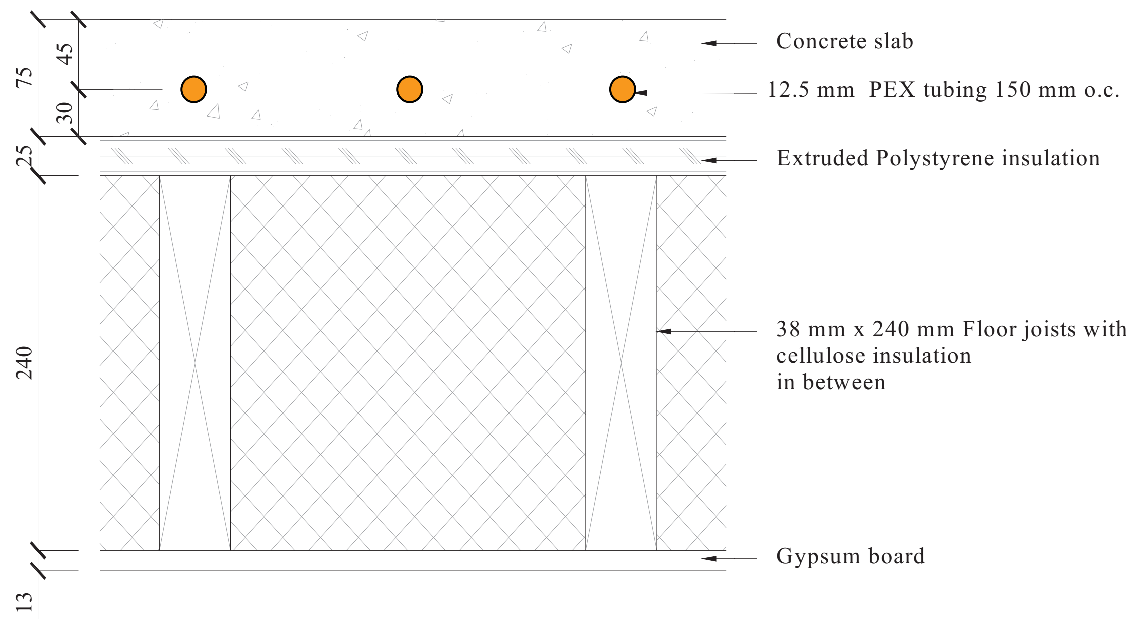


Figure 5.3 Section through radiant floor: Ground and Second floor

Exposed concrete slabs are proposed, which are an excellent option for radiant floors (Hertz, 1995 and CMHC, n.d.), as they can be very well finished by using any of the techniques such as polishing, staining, or painting (Wamberg, 2007). Specifically, ferrous sulfate stain is used, which is a non-toxic, low cost, low maintenance and durable green product (EcologyAction, 2008;

Owens, 2006; and Lile, n.d). An additional advantage of using exposed concrete floors is that the extra finishing material and the dead load as well as the cost associated with it are avoided.

5.1.2 Tubing

Developed in 1960s in Europe and introduced to North America in 1980s, PEX is an ideal tubing material for radiant floors, since it is noncorrosive and is not affected by the chemical composition of concrete. It is a strong as well as a flexible product that can withstand temperatures in the range of -17 to 93°C (0 to 200°F) (PPFA, n.d.; Watson and Chapman, 2002 b).

Based on the floor area of zones, 12.5 mm (½") tubing is selected and Uponor Wirsbo hePEX plus is the product used (Radiant Heat Products, n.d.). This tubing size is commonly used in residential applications considering the factors such as cost effectiveness, flexibility, and ease of installation (Woodson, 1999; Wirsbo, 1999). The minimum center to center spacing of these pipes depends on the turning radius, which in turn depends on the size of the pipes. The turning radius needs to be at least six times the tube diameter (Uponor, 2008; Starr, 2004). Therefore for the 12.5 mm (½") tubing used in this case, 75 mm (3") of turning radius and thus 150 mm (6") o.c. (on center) tube spacing is used.

5.1.3 Insulation

For rigid board insulation underneath the concrete slab, the material options include Extruded polystyrene (XPS), Expanded polystyrene (EPS), and polyiso-cyanurate, as presented in Table 6.2. Out of which, polyiso-cyanurate has the highest R-value followed by XPS (CMHC, n.d. b., Wilson A., 2005, and COenergy, 2008). The XPS is used here in order to keep the NZEH model similar to the base case for comparison purposes. It is recognized that polyiso-cyanurate, which used to be made with CFCs and then HCFCs, is now made with non ozone-depleting blowing agent, pentane, since 2003; while XPS is still made with HCFC blowing agents (PIMA, 2008 and Wilson, 2005). EPS also uses pentane blowing agent and has zero Ozone Depletion Potential (ODP) but its R-value is much lower compared to polyiso-cyanurate.

Table 5.2 Rigid board insulation

Insulation Type	**RSI value per 25 mm (R / in)**
	$m^2 \cdot K/W$ ($ft^2 \cdot h \cdot °F/Bu$)
Polyiso-cyanurate	1 – 1.36 (5.6 – 7.7)
Extruded polystyrene (XPS)	0.88 (5.0)
Expanded polystyrene (EPS)	0.63 – 0.77 (3.6 – 4.4)

An XPS layer of 50 mm (2") is provided under the basement slab and 25 mm (1") under the ground and second floor slab as seen in Figures 5.2 and 5.3.

5.1.4 Modeling in TRNSYS: Active Layer

The entire radiant floor system consists mainly of (i) the actual energy delivering network of tubing in the floor, (ii) the supply loop including the storage tank and the accessories including diverters, pumps, controller, manifolds and (iii) the return loop. Out of these, the first part, the tubing in the floor, is simulated in TRNSYS within Type 56 as 'active layer' and is described in this section. The components of the other two parts, the supply and the return loops are entirely modeled outside of Type 56, in TRNSYS studio and are discussed in the sections to follow. The entire radiant floor system with its main components is presented schematically in Figure 5.4.

The information required for some of the parameters in active layer definition are from the product specification from Uponor. Accordingly the inside diameter is 12.07 mm (0.475") with the pipe wall thickness of 1.9 mm (0.075"). Pipe wall conductivity for the PEX tubing is 0.38 W/m.K i.e. 1.37kJ/h.m.K (0.22 Btu/h.ft.°F) (Uponor, 2008). The other two inputs, the mass flow rate and the temperature of the fluid through the pipes, are calculated outside of Type 56 and are supplied to it.

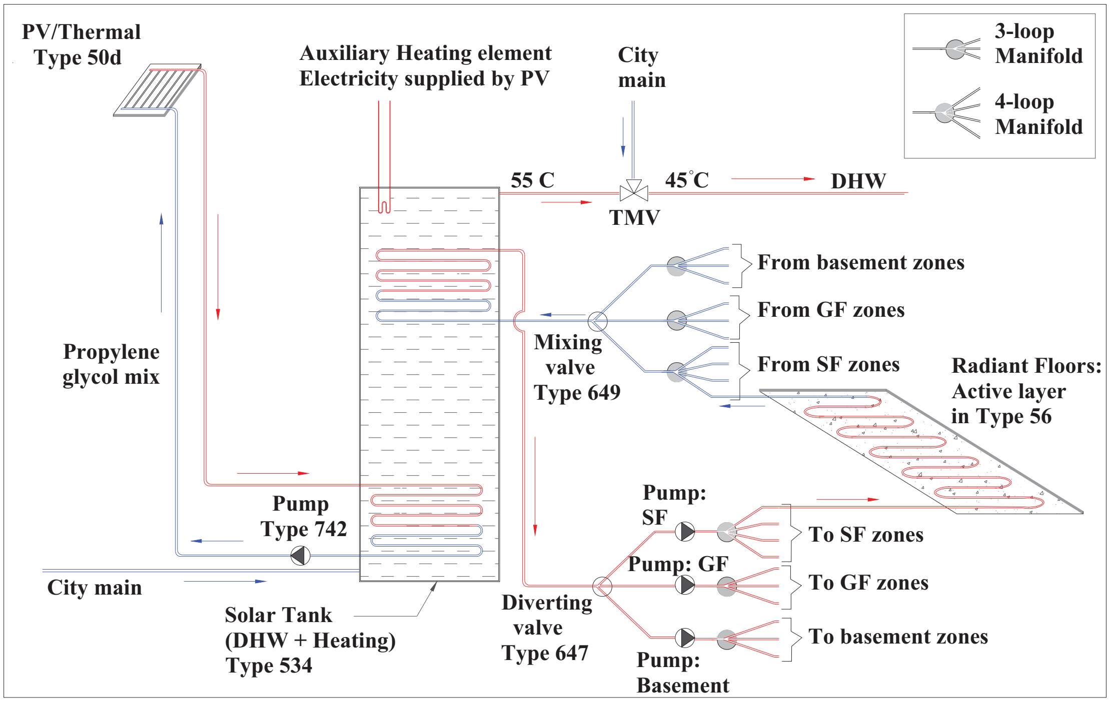


Figure 5.4 NZEH combi-system with the radiant floor system components

5.1.5 The Supply Loop

The main components of the space conditioning system on the supply side are the tank, the controller, the pumps, and the diverters as explained in the following sections.

5.1.5.1 Stratified Storage Tank

Only one tank is used for both DHW and radiant floor heating system. The tank used is SunMaxx Solar 80 S S2HX, which has two internal heat exchangers, auxiliary electric heating elements, an inlet for cold water from municipal supply and an outlet for DHW (SunMaxx Solar, personal communication). After the sensitivity analysis on the storage, the tank size is finalized as presented further in section 5.9.6.1. One heat exchanger is assigned for the radiant floor and the other one for the PV/T. The schematic representation of this tank is presented in Figure 5.5.

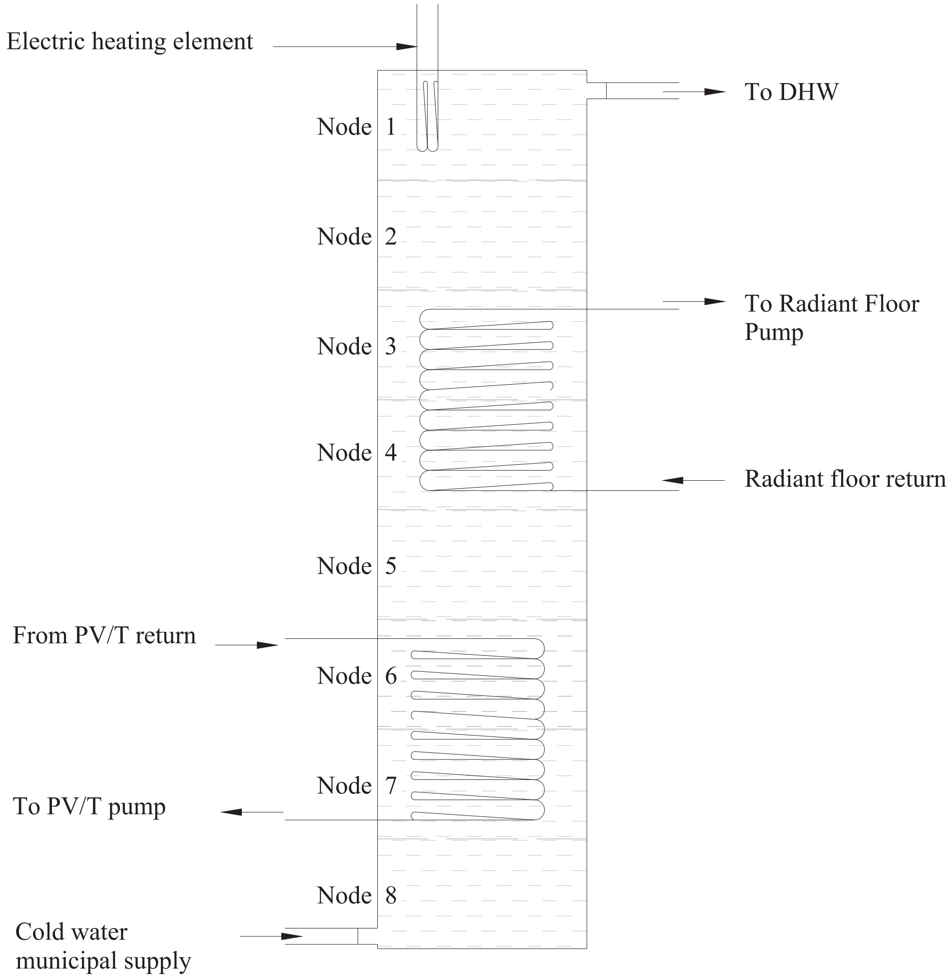


Figure 5.5 The stratified tank used in the NZEH

The solar tank is simulated in TRNSYS using Type 534, which models a cylindrical, stratified tank with coiled tube heat exchangers. The stratification is simulated by dividing the tank into eight equal-volume layers which are called nodes in TRNSYS. The tank is encased in 50 mm (2”) polyurethane foam insulation with conductivity of 0.46 W/m.K i.e. 1.67 kJ/h.m.K (0.27 Btu/h.ft.°F). Type 534 uses a plug-in for specifying most of the parameters and inputs. The zone air temperature of basement, where tank is placed, is supplied to Type 534 by Type 56 in order to calculate the heat losses to the surrounding. The top, bottom, and the edge losses are calculated in general as follows:

$$Q_{loss} = (A_{tank} * U_{tank}) * (T_{tank} - T_{environment}) \quad (5.1)$$

where,

A_{tank} = tank surface area for thermal losses, m^2;

U_{tank} = tank heat loss coefficient, $kJ/(h \cdot m^2 \cdot °C)$;

T_{tank} = temperature of the water in the corresponding node of the tank, °C;

$T_{environment}$ = temperature of the surrounding air around the tank, °C.

The DHW profile set up in Type 14, is explained further in section 5.5.3. The flow rates of the outlet to DHW and the inlet from municipal supply are the same since the tank is a constant volume tank. The calculation of this flow rate is further explained in the section 5.5.1.3. Also, the temperature of the municipal supply, mentioned previously in Chapter 4, section 4.4.5, is an input for the temperature at the inlet of the tank.

The placement of the heat exchangers takes advantage of the natural stratification occurring in the tank. As seen in the Figure 5.5, the outlet to DHW is in the topmost node, where the water temperature is the highest. Since the primary energy source for the heating and DHW is solar, a back-up energy source is required. Therefore, two auxiliary electric heating elements, 3 kW and 0.5 kW, are also placed in the topmost node, that prevent the temperature in the top node from dropping below 55˚C. The radiant floor heat exchanger is placed in the top half of the tank below the DHW outlet since the supply temperature required for the radiant floor is lower than that of DHW. The PV/T heat exchanger is placed in the bottom half of the tank where the water temperature is even lower, in order to improve the exchanger performance. And finally, the inlet from the municipal supply is at the very bottom of the tank where the temperature of the water is the lowest. The heat exchanger fluid in the radiant floor heat exchanger is water, while that in the PV/T exchanger is propylene glycol mix. The conductivity value is needed by the tank model, which is 383 W/m·K i.e.1379 kJ/(h·m·K) for copper exchanger pipes.

5.1.5.2 Controller

The extent of complexity of controls can vary a lot. Although a simple on/off control has less up-front cost, higher level of control is preferred since in the long run, it provides a more comfortable thermal environment, at the same time saving energy costs (Wirsbo, 1999). Type 698, which is a multi-zone thermostat model, is used to simulate the space thermostat.

Type 698 models hysteresis effect, for which, the dead band temperature difference of 2°C is specified. The inputs required are the setpoint temperatures at each stage and the zone air temperatures of all the zones for which the system needs to be controlled. The setpoint temperature for all the zones for heating is kept the same in NZEH, i.e. 21°C. The first stage heating setpoints for all zones are supplied to the controller by Type 514, which is a daily setpoint scheduler. The second stage setpoint temperatures are provided via an equation (Heat _2nd Stage) set up in the studio, in which the difference between the first stage and the second stage setpoint temperatures is set to be 2°C. This equation receives the setpoints from Type 514 as first stage setpoints, calculates the second stage setpoints and sends those to the controller. Thus, e.g. if at night, the setback temperature is set to 18°C for heating, which is used for the first stage heating, the equation will send 16°C as the second stage setpoint temperature to the controller.

The outputs of Type 698, i.e. the control signals at various stages, are then sent to another equation (RF_Heat) in the studio. This equation also receives signal from the heating/cooling season indicator, Type 515, based on the time of the year. The equation then calculates the flow rate for each zone. e.g. the flow rate for the zone GF_KitDen is calculated as follows:

GF_KitDen_heat = Heat_season_indicator* ((GF_KitDen_1stg*FlwRate_Stg1) + (GF_KitDen_2stg*FlwRate_Stg2)) (5.2)

where,

GF_KitDen_heat = flow rate for the zone GF_KitDen, kg/h;

Heat_season_indicator = 1 during heating season and zero otherwise;

GF_KitDen_1stg = control signal for 1st stage heating;

GF_KitDen_2stg = control signal for 2nd stage heating;

FlwRate_Stg1 = fixed value of flow rate specified, e.g. 300 kg/h;

FlwRate_Stg2 = fixed value of flow rate specified, e.g. 150 kg/h.

Since the zones with stairs do not have a radiant floor, there are in all 10 zones for which the flow rate needs to be defined as shown above, including three in the basement, three on the ground floor, and four on the second floor. Based on the signal from the controller, pumps are activated or deactivated, as explained in the following section.

5.1.5.3 Pump

In the radiant floor system of the whole house, there are three pumps used, one assigned per floor, as seen in Figure 5.4. Each pump is further connected to the respective manifold for that floor. The pumps are modeled using the TESS Type 742. Out of various pumps available in TRNSYS, the reason for using this particular model is that it assigns the same output mass flow rate as supplied to it through the input. Once the flow rates for the zones are defined as described in section 5.1.5.2, the flow rates for the pump for each floor are defined by adding the respective flow rates on that floor as follows:

Pump_basmnt_flow = Base_Bed_heat + Base_KitDen_heat + Base_Bath_heat (5.3)

Pump_GF_flow = GF_Bed_heat + GF_Bath_heat + GF_KitDen_heat (5.4)

Pump_FF_flow = FF_BedNoth_heat + FF_BedWest_heat + FF_Bath_heat

+ FF_KitDen_heat (5.5)

The flow rate calculated from either of the equations 5.3 to 5.5 is then supplied to respective pump as input. All the pumps are assumed to be located close to the tank in the basement. In order to estimate the pressure drop, one pipe is assumed to run from each pump to the corresponding diverter (manifold) located on its respective floor. In case of basement, the pump and the manifold are situated close-by with minimum pipe length in between. Normally for the hydronic systems, the value of the pipe friction loss used for design purpose ranges from 100 to 400 Pa/m. For this study, a value of 250 Pa/m is used, which is the mean to which most systems are designed. Also to take into consideration the fitting losses, each pipe length is assumed to be 50% longer (ASHRAE, 2005). The length of the pipe from each pump to the respective manifold is estimated based on the building drawings and using the shortest route possible to keep the pipe length to minimum. As a result, the pressure drop estimated for the ground floor pipe is 1.13 kPa and that for the second floor is 2.25 kPa. These pressure drop values are provided to the respective pumps as inputs. In case of the basement, since the pump and manifold have a very short pipe length in between as mentioned earlier, the pressure loss is assumed negligible.

The pump used is Taco Variable Speed Delta T 008 (Taco, 2008). An important output of Type 742 is the power input to the pump, which is taken into account to calculate the total electricity consumption of the house. The other outputs from each of the pump, i.e. the flow rate and the temperature of the fluid are then fed to the diverter assigned for the respective floor as described in the following section.

5.1.5.4 Diverter

The flow leaving the pump for each floor needs to be split among the zones on that floor. This is achieved with multi-loop manifolds, specifically Wirsbo EP manifolds (Uponor, 2009.b.), modeled with the diverting valve, TESS Type 647. The manifolds on ground and basement floors are three-loop manifolds, supplying to three zones each on these floors, while the manifold on the second floor is four-loop, supplying to the four zones on that floor.

Type 647 allows the diversion of the flow in more than two, in fact up to 100 outlet ports. The number of outlet ports is defined as the parameter. Each floor has one diverting valve and for that the number of outlet ports is set to be equal to the number of zones on that floor that need to be served by the flow supply. Thus the diverters of the basement and the ground floor have three each and that of the second floor has four outlet ports. The inlet temperature supplied by the pump is passed on by the diverter to each of the outlet ports, while the total mass flow rate fed by the pump is split among the outlet ports depending on the fraction designated for each port as an input, which is not a fixed value. This input for the fraction is calculated separately in an equation and fed to the diverter, e.g. the fraction of the flow going to the zone GF_KitDen is defined as follows:

Divert_GF_KitDen = GF_KitDen_heat / max (Pump_GF_flow, 1) (5.6)

where,

GF_KitDen_heat = flow rate for the zone GF_KitDen as per eqn. 5.2, (kg/h);

Pump_GF_flow = the total flow rate for the ground floor pump as per eqn. 5.4, (kg/h).

Thus, the flow goes to this particular zone only when it is called for, as shown in eqn 5.2. Once the fractions for all the zones are defined in the equation, they are supplied to the respective diverters (manifolds) on each floor. The outlet temperature and the flow rate from each port of the diverters are then finally connected to the respective zone inputs in Type 56 and are used in the active floor definition. The radiant floor supply system is thus completely defined.

5.1.6 The Return Loop

The design of the return side of the system is equally important as the supply side, in order to have the supply and return complete loop function properly. For the radiant floor return system, the flows from all the zones need to be connected back to the inlet of the radiant floor heat exchanger in the solar tank. For this purpose, mixing valves are used on the return loop.

5.1.6.1 Mixing Valve

The return flows from all the zones on each floor connect back to the return side of the manifold. This is simulated by delegating one mixing valve for each floor, modeled with TESS Type 649. Similar to the diverter, this particular mixing valve can have more than two and up to 100 inlet ports. The number of inlet ports for the mixing valve of each floor is equal to the number of zones on that floor that have radiant slab. The outlet temperature and the flow rate of the flow leaving the zones are the outputs from Type 56, which are fed as inputs to the respective mixing valve inlets. Based on the number of inlets to the mixer, the model calculates the output temperature and the flow rate.

A fourth mixing valve is needed further down the flow on the return loop, before the tank, with three inlets, one feeding from the manifold of each floor as shown in Figure 5.4. This last mixing valve supplies the final return temperature and the flow rate to the inlet of the heat exchanger coil located within the tank.

5.2 Mechanical Ventilation with HRV

In case of energy efficient houses, mechanical ventilation is quite vital since the air-tight construction restricts the infiltration, and thus indoor air quality can become an issue. The Base case house, although an R-2000 home, was simulated without it, since the house did not operate with a mechanical ventilation system during the year for which the utility bills were obtained (Kassab, 2002). Therefore, a mechanical ventilation system with an HRV is added to only the NZEH model.

The proposed mechanical ventilation system is a balanced system (supply equal to exhaust) with continuous operation. It is equipped with a Heat Recovery Ventilator (HRV) which transfers the heat between these two air flows. HRV is a commonly used energy efficiency measure, especially in NZEHs. The specifications used here are for Fantech HRV, designed for residential applications. Various models are compared for their sensible effectiveness versus power consumption and the particular model used here is VHR 1405R, with 73% sensible effectiveness and 72 W power consumption (Fantech, 2006).

The CSA Standard F326 – "Residential Mechanical Ventilation Systems" (1991), developed by Canadian Standards Association, prescribes ventilation requirements for each room (Haysom and Reardon, 1998). Based on these guidelines, ventilation rate in the building is calculated as presented in Table 5.3. The ventilation requirement for the master bedroom and the basement is higher than other rooms i.e. 10 L/s compared to 5 L/s. The supply air flow rate for the entire building is calculated as 280 kg/h, i.e. 65 L/s or 234 m^3/h. Considering the 722 m^3 volume of the house, this ventilation rate translates to 0.32 air change per hour (ach) for the whole house.

Table 5.3 Mechanical ventilation rates for HRV

Room Type	Recommended Capacity*			No of rooms	Total Capacity
	[L/s]	[m^3/hr]	[kg/hr]		[kg/hr]
Master bedroom	10	36	43.2	2	86.4
Other bedroom	5	18	21.6	3	64.8
Living room	5	18	21.6	2	43.2
Dining	5	18	21.6	_	_
Family room	5	18	21.6	_	_
Basement	10	36	43.2	1	43.2
bath rooms / other habitable rooms	5	18	21.6	2	43.2
Kitchen	5	18	21.6	2	43.2
Total					**324**
* As per CSA F-326					

5.2.1 Simulating HRV in TRNSYS: Type 760

The air-to-air sensible HRV is simulated in TRNSYS using Type 760. The weighted average of the temperature and relative humidity values of the zone air from all the respective zones from Type 56 is calculated and supplied as inputs for the exhaust air properties to Type 760. For this purpose, the values from all the zones except the attic and the bathrooms are used. It is assumed that the kitchen has a dedicated exhaust above the range which works intermittently, in addition to the ventilation provided. The bathroom and kitchen exhausts are not connected to the HRV due to the higher humidity in these areas and the possibility of contaminants such as grease particles.

Type 760 calculates the maximum possible sensible energy transfer as follows (TRNSYS 16 Documentation):

$$C_{min} = MIN\ (\dot{m}_{exhaust} * Cp_{exhaust}\ , \dot{m}_{fresh} * Cp_{fresh}) \quad (5.7)$$

$$\Delta T = T_{in,\ exhaust} - T_{in,\ fresh} \quad (5.8)$$

$$Q_{sensible,\ max} = \varepsilon_{HRV} * C_{min} * \Delta T \quad (5.9)$$

where,

C_{min} = minimum capacitance, kJ/(h·K);

$\dot{m}_{exhaust}$ = mass flow rate of the exhaust air from the zones entering the HRV, kg/h;

$Cp_{exhaust}$ = specific heat of the exhaust air, kJ/kg·K;

$\dot{m}_{fresh}$ = mass flow rate of the fresh air entering the HRV, kg/h;

Cp_{fresh} = specific heat of the fresh air, kJ/kg·K;

ΔT = temperature difference, °C;

$T_{in,\ exhaust}$ = weighted average temperature of the exhaust air from the zones entering the HRV, °C;

$T_{in,\ fresh}$ = temperature of the fresh air entering the HRV, °C;

$Q_{sens,\ max}$ = maximum sensible energy transferred between the exhaust and fresh air stream, kJ/h;

ε_{HRV} = sensible effectiveness of the device.

The desired outlet temperature of the fresh air exiting the HRV is set to be 20°C, which is the maximum temperature the HRV tries to reach. The outdoor air receives heat from the exhaust air while passing through the HRV and warms up in winter, and this fresh warmer air is fed to Type 56. In case, even after the heat exchange in the HRV, the air temperature is still lower than 20°C, a small electric internal heating element heats up the air till this temperature condition is met. In summer, as the two air streams pass through the HRV, heat is transferred in a reverse manner, i.e. from fresh air to the exhaust air, thus pre-cooling the fresh air before feeding it to Type 56.

In summer, whenever the natural ventilation is utilized, i.e. when the windows are opened, the HRV is turned off. Similar strategy is used in other NZEH examples in literature, e.g. Hendron (2008, p. 39).

5.3 Energy Efficient Major Appliances

As seen in literature review for NZEHs, appliances are the biggest contributors towards electricity use in most cases along with plug loads. Therefore this topic needs special attention while estimating the total electricity need of the house. For the base case house the appliance rating was used from the year 1999, since the house was built in the year 2000. In recent years, in order to promote energy efficient large appliances, audio-video equipment, as well as consumer electronics, Energy Star, the program run by United States Environmental Protection Agency (US EPA) and Department of Energy (US DOE) has been the most effective (Meier and Lebot, n.d).

For the NZEH, improved ratings for the Energy Star qualified appliances are used as shown in Table 5.4 (NRC, 2008), except for clothes dryer. Energy Star does not label dryers, since the energy consumption is almost similar for all the dryers on the market. In case of clothes washers, the information includes Water Consumption Factor (WCF) or Water Factor (WF), which is the ratio of total weighted per-cycle water consumption to the capacity of the clothes washer; lower the WCF value, higher the water efficiency (Energy Star, n.d., a).

Table 5.4 Major appliances per family in NZEH

Appliance	Description	Appliance Rating (kWh/year)	Electricity Demand (kWh/year)
Refrigerator	Kenmore 466797, 18.9 cu-ft, top-mounted freezer	393	393
Dishwasher	Fisher & Paykel DS605, compact built-in, hot water consumption 9.5 L/load	157	31
Clothes Washer	GE GCVH6600H, tub capacity 94L, WCF 0.56, 53 L/load	129	26
Clothes Dryer	GE PSKS333EB, 101L	398	398
Electric Range	Frigidaire CFEF 272DS, 24-inch, self-cleaning oven	397	397
Total		**1,474**	**1,245**

It should be noted that in Table 5.4, the energy rating and the electricity demand are not the same in case of the dishwasher and the clothes washer. For dishwashers, the majority of the energy need is for hot water, which is also true for clothes washers, which need 90% of their rated energy demand for hot water (EERE, 2009). Therefore, similar to the Base case, for these two appliances, 20% of their energy rating is considered as electricity demand and the hot water need for them is taken into account in DHW profile as explained further in section 5.5.2. Similar strategy has been used in other NZEH cases, e.g. Rad and Fung (2007). Table 5.5 presents the comparison of appliance load in the current NZEH proposal with other examples in the literature.

Table 5.5 Comparison of appliance load per family

Project name	Appliance load per family (kWh/yr)
Equilibrium Housing Projects:	
Alstonvale NZEH	1,435
Abondance le Soleil, Iolova et al. (2007)	1,839
Davenport road, Toronto	1,376
Other examples:	
Suburban Greater Toronto Feasibility study, Tse and Fung (2007)	1,979
Armory Park de Sol, NAHB (2004)	3,072
2003 Average for Canadian homes NRC (2005) cited in Tse and Fung (2007)	3,324
R-2000 Base case	2,614
Current NZEH proposal	**1,245**

Per family electricity load for major appliances in the base case was 2,614 kWh compared to 1,245 in NZEH. Thus, compared to the base case, in NZEH this load is reduced by over 52% due to the use of improved Energy Star appliances. Since there are two families in the duplex, the total load for major appliances is 2,490 kWh. The electrical energy used for the appliances is assumed to be added as heat to the respective zones. On the ground floor and the second floor, the gains from kitchen appliances are added to the kitchen zone and those from the washer and dryer are added to the bathroom zones since the laundry area is included in that zone. As per the occupancy schedule of kitchen the 821 kWh/yr of gain from kitchen appliances is added as 2,025 kJ/h for four hours (6:00 pm – 10:00 pm) daily. Similarly, 424 kWh/yr of gain is translated as 1,045 kJ/h for the same four evening hours in the bathroom zones.

5.4 Efforts in Reducing Miscellaneous Electric Load (MEL)

Among various items commonly comprising the total plug load or MEL in most of the houses, some electronic devices such as VCRs, DVD players, are equipped with timers; some like microwaves have clocks that continue to operate even when the appliances are turned off. Some devices like TVs and stereo systems work on remote control and even when they are turned off, they have to be in 'ready-state' or on 'stand-by'. The load from all such devices that are constantly consuming power is referred to as standby loss, vampire load, or phantom load; and the electricity loss due to standby load is referred to as leaking electricity or standby electricity. Sections 5.4.1 through 5.4.3 describe the measures taken in NZEH to reduce MELs in general as well as standby losses in particular.

5.4.1 Energy Star qualified products

In NZEH, Energy Star qualified home electronic products and personal electronic devices such as TVs, DVD/CD players, phone chargers, cordless phone adapters, etc. are used that are up to 30% more efficient than the standard models (Energy Star, 2008) used in the base case. Energy Star qualified printers are 25% more efficient than the standard ones (Energy Star, n.d., b). Therefore, compared to the base case, the energy/unit values presented in Table 5.6 for these items have been reduced by respective proportion.

Since the battery life is one of the key features of the laptops, compared to desktop computers, they are designed with the most energy efficient components. By replacing the PC and the monitor with a laptop can result in power saving of 50 to 80% (Energy Star, n.d., c).

5.4.2 Reducing electrical standby losses

Out of the total 2,764 kWh of the MEL in the base case, 50 W is assumed to be standby loss, which is 438 kWh/year. To support this assumption, following three studies are quite significant and are presented here: (i) In a study conducted by Natural Resources Canada, it was reported that typically, Canadian homes have at least 20 electric devices that consume 0.5 to 25 W each even when turned off. The standby power consumption in a typical Canadian home was found to be 44 to 59 W, totaling up to 389 to 513 kWh of standby losses annually, which is 3.2 to 4.3% of the total residential electricity consumption (UPI, 2008). (ii) Fung et al. (2003) conducted measurements in 75 houses in Halifax, Canada. They reported the average standby energy consumption per household to be 427 kWh, equivalent to a constant 49 W load. It was suggested that the value of 49 W was probably slightly lower than the actual one, since hard-wired appliances and major appliances were not included in the study (iii) In their research for California Energy Commission, Porter et al. (2006) used 50 houses in California to measure and characterize residential plug loads. They found that the average plug load electricity consumption per household was in the range of 1,069 to 1,207 kWh per year. Only 61- 78% of this annual energy was used in the active mode, with around 54 W as base load through standby consumption, which is equivalent to keeping an incandescent light bulb constantly turned on.

For NZEH, this 438 kWh of annual standby loss is reduced in three steps: (i) The occupants of the NZEH are educated to simply unplug the appliances/devices that are not in use, whenever possible. Although an important step, no formal reduction in losses is assumed for this step. (ii) The Energy Star devices used in NZEH have up to 50% less standby losses (NRC, 2007). For small kitchen appliances, although there is no Energy Star rating, the newer models have much lower standby losses compared to the ones manufactured a decade ago. Thus the 438 kWh/yr load in the base case is reduced by half to 219 kWh (iii) In the cases where unplugging the devices is not always practical, power strips are recommended. In NZEH, these are used for the home office as well as the entertainment equipment. Specifically, Smart Surge Power Bar SRG 7 by Woods Industries Canada is used that acts as a surge protector as well (Home Hardware, 2009). Although no research was found to date that estimates exact reduction in standby loss due to power strips, it is assumed to be further reduced by 20% to 175 kWh. This is a fair assumption, since wherever power strips are used they completely eliminate the standby losses.

By taking all of the above-mentioned measures the total reduction in standby loss is by 263 kWh, almost 60% reduction compared to the base case. This is not an over-estimation considering an LBNL (2009) statement that by employing various measures, it is feasible to reduce household standby power consumption by 75%.

Although many NZEH studies report the overall plug load to be a large part of the total electricity consumption, specific measures to reduce standby power or even separating standby loss from overall plug load was not found in any of the NZEH related studies except in Riverdale NZ Project, in which standby loss was assumed to be 555 kWh/yr (Habitat Studio and Workshop Ltd., 2007). Standby power has now become an important issue since International Energy Agency's (IEA) call to limit the standby power in all appliances to not more than one watt by 2010 (Meier and Lebot, n.d.). Efforts in this direction are currently being made by Canadian Government (UPI, 2008).

5.4.3 Total reduction in MEL for NZEH

After employing all the above mentioned measures, the final MEL equals to 1,128 kWh per year for both the families as presented in Table 5.6. This is a 59% reduction compared to the base case. Table 5.7 shows the comparison of plug loads in various NZEH examples in literature and the current proposal. In many cases, a lump-sum value e.g. 3 kWh/day was found to be used for plug load estimation.

Table 5.6 Items contributing to MEL in NZEH

Miscellaneous Electric Load (MEL)	No. of units in the building	Energy/unit [kWh/yr]	Total electricity need [kWh/yr]
Hard-wired			
Door bell	1	44	44
Smoke detector	3	3.5	10.5
Home Entertainment			
Cable box	1	45.9	45.9
Clock radio	2	4.5	9
Compact stereo	2	33.6	67.2
DVD player	2	15	30
Satellite dish box	1	39.6	39.6
Television	2	64.5	129
Home office			
DSL/Cable modem	2	17	34
Laptop	2	47	94
Printer (Laser)	2	23.25	46.5
Kitchen			
Blender	2	7	14
Coffee maker	2	61	122
Hand mixer	2	2	4
Microwave	2	135	270
Slow cooker	2	16	32
Toaster	2	46	92
Bathroom			
Hair dryer	2	41	82
Other			
Answering machine	2	10.2	20.4
Battery charger	2	4.5	9
Cell phone charger	2	23.1	46.2
Cordless phone	2	6.9	13.8
Iron	2	53	106
Portable fan	2	11	22
Surge protector/power strip	2	4	8
Total MEL for both the families			1,391
Final MEL (due to phantom load reduction by 263 kwh)			1,128

Table 5.7 Comparison of plug load assumptions

Project name	Area of the house (without the basement)	Plug load (kWh/day)	Area-weighted plug load (kWh/ m^2/yr)
Equilibrium Housing Projects:			
Abondance le Soleil, Montreal, Iolova et al. (2007)	3 apartments, $77m^2$ each	3	4.7
Davenport road, Toronto, Rad and Fung (2007)	Townhouse, 278 m^2	3	4
Base case	Two families, 204 m^2	7.6	13.5
Current NZEH proposal	Two families, 204 m^2	**3.1**	**5.5**

5.5 Domestic Hot Water for NZEH

The NZEH is designed to receive its DHW from the solar tank with an internal electric auxiliary heater backed by PV. Therefore before sizing the solar system, it is essential to first try to minimize the need for DHW.

5.5.1 Energy Efficiency Measures for DHW

There are various ways to reduce the DHW load, including ultra low flow faucets, grey water heat recovery, thermostatic mixing valve, and increased tank insulation, as presented in the following sub-sections. Table 5.8 lists some of the means undertaken by different NZEH projects found in the literature.

Table 5.8 DWH efficiency measures in various NZEH projects

DHW efficiency measures	NZEH Project employing the measure	Details
Gravity Film heat eXchanger (GFX)	Riverdale NetZero project (Picard, 2006)	62 L/day shower portion out of 101 L/day of total DHW is reduced by 36% due to GFX unit and subtracted from daily total DHW load, making it 78 L/day
	Abondance le Soleil, Montreal, Canada (Picard et al, 2007)	GFX model G3-60 recuperates 1,370 kWh/yr (25% of DHW needs)
Insulated tank	Solar Harvest: Boulder, CO, USA (Norton and Christensen, 2006)	22,700L (6,000 gal) stainless steel tank in basement, insulated with 0.8 kg (1.7 lb) low permeance foam RSI 16 (R-90)
	NZE Triplex, Montreal, Canada (Picard et al, 2007)	Tank heat loss coefficient 0.83 $W/m^2 \cdot K$, i.e. 3.0 $kJ/(h \cdot m^2 \cdot K)$
	NZEH, Montreal (Biaou and Bernier, 2008)	Solar tank insulation 2.8 $m^2 \cdot °C/W$
	Michigan NZEH (Snyder et al., n.d.)	757 L (200 gal) DHW tank and 3,785 L (1,000 gal) seasonal tank, both underground with RSI 8.8 (R50) insulation
Thermostatic Mixing Valve (TMV)	Abondance le Soleil, Montreal, Canada (Picard et al, 2007)	TMV used to ensure that the final hot water temperature does not exceed 50°C, Type 11d used in TRNSYS simulation
Low-flow faucets	Alstonvale NZEH (Candanedo et al.,2007)	Daily DHW use is reduced to 120 L (load of 2,500 kWh/yr) for a family of four.
	Suburban Greater Toronto Feasibility study (Tse and Fung, 2007)	DHW load reduced from 225 L/day to 98 L/day by using measures including low flow faucets
	Michigan NZEH (Snyder et al., n.d.)	DHW use reduced to 151 L/day (40 gal/day) for a family of four

5.5.1.1 Ultra Low Flow Faucets

The first step in the attempt to limit water use in general, and specifically hot water, is the use of improved water faucets. The comparison between the standard faucets, the low flow faucets used in the R-2000 base case, and the ultra low flow faucets available in the market that can be used for NZEH is presented in Table 5.9.

Table 5.9 Comparison of various faucets

Fixture type	Standard faucets	Low flow faucets used in the base case	Ultra low flow faucets available in the market
Kitchen and bathroom water faucets	15 – 26 L/min (4 – 7) gpm[1]	7 L/min (1.84 gpm)	2 L/min (0.5 gpm)[3]
Shower heads	19 – 30 L/min (5 - 8 gpm)[1]	8 L/min (2.15 gpm)	3 - 6 L/min (0.8-1.5 gpm)[1] 3.8 L/min (1.0 gpm)[2] 4.7 L/min (1.25 gpm)[3]

1. Flex your power (2009)
2. Habitat Studio and Workshop Ltd.(2007): Bricor
3. Coserv-A-Store (n.d.)

Minnesota Green Affordable Housing Guide (2007) provides detailed water consumption comparison charts. Based on these charts, the water saving percentage by incremental upgrades of the faucets is calculated and presented in Table 5.10. Based on this, for NZEH, an assumption of overall reduction in DHW by 35% by upgrading from low flow to ultra low flow faucets for kitchen and bathroom faucets and showerheads seems reasonable.

Table 5.10 Water saving as a result of efficient faucets

Faucet type	Base flow rate	Incremental Change		
Kitchen and bathroom water faucets	8.3 L/min (2.2 gpm)	7.6 L/min (2 gpm)	5.7 L/min (1.5 gpm)	0.95 L/min (0.25 gpm)
	Water reduction by	10%	31%	77%
Shower heads	9.5 L/min (2.5 gpm)	8.3 L/min (2.2 gpm)	5.7 L/min (1.5 gpm)	-
	Water reduction by	12%	40%	-

The DHW load is thus reduced to 153 L/day from the base case assumption of 236 L/day. This value is very close to the DHW requirement specified by CMHC during Net Zero Energy Healthy Home (NZEHH) competition (Picard, 2007), later called Equilibrium Housing, of 150.5 liters for four people, the same occupancy as the house in the current study.

5.5.1.2 Gravity Film Heat eXchanger (GFX)

Among the NZEH examples in the literature, use of GFX is very common. To further reduce the DHW load from 153 L/day, this option is explored here. This Grey Water Heat Recovery (GWHR) device is non-storage type, meaning the heat is extracted and used right away without storing it. In this device, the cold water supply pipe wraps around the grey water drain pipe and recuperates heat from it. To extract heat, water needs to flow simultaneously in the cold water pipe and the grey water pipe in counter directions at the same time. Out of the activities that require DHW, dishwashing, clothes washing, and baths require hot water in batches and only showers need simultaneous supply and return. Therefore heat recovery with non-storage type GWHR devices is only possible from the shower portion of hot water use.

Normally the residential plumbing system involves a mains supply pipe entering the house, and then diverting into two branches, one supplying the cold water to the tank and the other for cold water supply to the house. The GFX can be installed at three possible locations: (i) on the municipal supply pipe where it enters the house, (ii) after the diverter, on the supply pipe to the tank, or (iii) after the diverter, on the cold water supply to the showers. These three possibilities are considered by Picard et al. (2004) for evaluating GFX performance, using the data for water mains temperature for Montreal collected by Marcoux and Dumas (2004). The percentage of energy required to heat water for showers recuperated by GFX was found to be 49% by placing the GFX in location (i), 36% with location (ii), and 37% with location (iii).

Simulating the performance of GFX necessitates quite a few assumptions and simplifications, since the exact amount of DHW used for showers, the temperature at the showerhead outlet, the drain water temperature and flow rate, duration of showers, etc. vary significantly and thus need to be approximated. Therefore, in this case, the results from Picard et al. (2004) are used as a guideline. Although the percentage of energy recovered is higher if placed in location (i) compared to location (ii) and (iii), GFX is placed at location (iii), i.e. to preheat only the cold water supplied to the showers, thus reducing the hot water need for showers. The reason for this choice of placement is that if GFX is placed where it preheats the entire municipal supply draw to the house, the water temperature at the solar tank inlet will be higher, which will inversely affect the thermal performance of PV/T. The reduction in the shower portion of DHW due to GFX is assumed to be by 30% instead of 37% to be conservative. Similar strategy was used in Riverdale NetZero project (Habitat Studio and Workshop Ltd., 2007); they have used a reduction of 36%. U.S. Department of Energy reports up to 30% hot water energy saving by using DWHR system (U.S. DOE, n.d.).

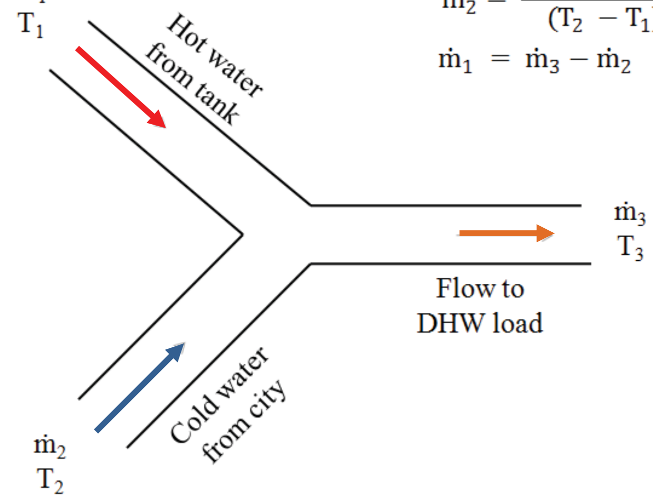
According to the CMHC guidelines, the shower portion accounts for almost 67% of total daily DHW use. Compared to this, Energy Star for Homes assigns almost 69% for showers and other use including sinks (Chinery, 2004). Thus out of 153 L/day of total DHW load, an estimated 103 L/day is the shower portion, which is further reduced by 30% due to GFX installation to 72 L/day. This value is used further in Table 5.12 for calculating the final DHW load for NZEH.

5.5.1.3 Thermostatic Mixing Valve (TMV)

A change in Plumbing Code was adopted by National Research Council Standing Committee on Building and Plumbing Services. Accordingly, in case of residential applications, the maximum supply temperature to plumbing fixtures, other than dishwashers and clothes washers, is restricted to 49°C (Cash Acme, 2003). To comply with this, having the water temperature in the tank set at 49°C is not an option because as mentioned in chapter 4, to prevent Legionella bacteria, the temperature has to be higher, with minimum 55°C. Therefore using a Thermostatic Mixing Valve (TMV) or a tempering valve is recommended, which also aids in saving energy since the entire daily DHW load is drawn at 49°C instead of 55°C. Another benefit of TMV installation is that it reduces potential losses through pipes since the water flowing through the pipes is at lower temperature. Besides being an energy saver, TMV is especially important in this case where there is no separate DHW tank and the solar tank is being used to supply for DHW. This is because the temperature in this tank can rise significantly high, over 85-90°C, and TMV is essential to avoid potential scalding.

ASHRAE (2007, p.49.10, Table 3) lists the temperature requirements for various activities in residential application ranging from 40°C to 45°C except for the dishwashing and laundry, for which the requirement listed is 60°C. For NZEH, laundry and dishwashing hot water supply temperature is also assumed to be 49°C instead of 60°C.

In TRNSYS, TMV is simulated with a valve and an equation. A tempering valve is placed near the outlet of the tank, which mixes cold water from the municipal supply to the hot water from the tank and sends the mixed flow to DHW load. Figure 5.6 shows this set up schematically, as well as the calculation of the two unknown flow rates, $\dot{m}_1$ and $\dot{m}_2$. T_1 is the tank outlet temperature, T_2 is the municipal supply temperature, T_3 is 49°C, and $\dot{m}_3$ is the modified DHW profile for daily consumption in NZEH, further explained in section 5.5.3.



$$\dot{m}_2 = \frac{\dot{m}_3 (T_3 - T_1)}{(T_2 - T_1)}$$

$$\dot{m}_1 = \dot{m}_3 - \dot{m}_2$$

Figure 5.6 Schematic representation of the TMV

5.5.1.4 Tank Insulation

The hot water storage tank in the base case has 51 mm (2") built-in polyurethane insulation. The preliminary results for NZEH show that with 51 mm (2") insulation there are significant edge, top, and bottom losses from the tank, in that order. Therefore for NZEH, SunMaxx Solar tank with 76 mm (3") built-in polyurethane insulation is used. Although the standby heat loss data from the manufacturer for the selected tank is not available, the technical documentation for a very similar Stiebel Eltron tank shows standby heat loss of 2 to 3 kWh per day (Stiebel Eltron, n.d.), which adds up to 730 to 1,095 kWh annually; while the preliminary simulation results showed 1,049 to 1,226 kWh of losses from the tank, depending on the size of the tank. Therefore the tank is further wrapped in an additional 100 mm (4”) insulation blanket especially made for water heating tanks by INFLEX. It is a vinyl backed polyurethane insulation; a thickness of 100 mm (4”) provides thermal resistance of 2.8 m^2.°C/W (R-16) (INFLEX, n.d.).

Also, to prevent the heat loss to the floor, a 50 mm (2”) rigid polyisocyanurate insulation board is placed between the tank and the basement floor instead of placing the tank directly on the floor. Polyisocyanurate insulation provides thermal resistance of up to 1.4 m^2.°C/W per 2.54 cm (R-8 per inch) and can withstand a wide range of temperature from -73°C to 121°C (-100°F to 250°F) (US DOE, 2009). Further discussion on effect of tank insulation on energy saving is continued in results section 5.9.

5.5.2 DHW for Appliances

In the DOE test procedures for dishwashers updated in 2006 and effective 2007, the number of average cycles is now 215, reduced from earlier 264 cycles per year (ENERGY STAR, 2006). Similarly, the average use for clothes washers is 392 cycles/year (e-CFR, 2009). Out of the total water use (hot + cold) of these appliances, the percent of hot water in case of dishwashers is almost 100%, while it is typically 28% in case of washers (DeOreo and Mayer, n.d.). Based on the rated total water use of the appliances selected for the NZEH, the hot water use is estimated as presented in Table 5.11. Since each family in the current study has only two members, the washing frequency of 392 cycles/year and hence the 16 L/day allocation of hot water for clothes washing is most likely a very safe estimate. This hot water need can be completely eliminated if the occupants decide to use only cold water for washing machines, since almost all the washers on the current market offer an option to do so. This is possible especially in summer, when the municipal supply water is warm enough. But for the simulation purpose, the hot water need for both of these appliances is taken into consideration.

Table 5.11 Hot water load from major appliances

Selected Appliances	ENERGY STAR rating	Average use	Total water need	Hot water need	
	L/Load	Loads/yr	L/year	L/year	L/day
Washer GE GCVH6600H	53	392	20,776	5,776	**16**
Dishwasher: Fisher & Paykel DS605	10	215	2,043	2,043	**6**

An alternative method of estimating the hot water load due to appliances is presented by Lutz et al. (1996) from Lawrence Berkeley National Laboratory by using the following equation:

$$T_{warm} = T_{hot}(x) + T_{cold}(1-x) \quad (5.10)$$

where,

T_{warm} = average temperature of warm water used, (33.5°C (92.3°F) in washers and 46.1°C (115°F) for dishwashers, based on 1,522 households survey done by Proctor and Gamble)

T_{hot} = hot water temperature, (set at 49°C, i.e. 120.2°F for NZEH)

T_{cold} = cold water temperature, °C (from mains temperature data)

x = fraction of total water that is hot

By finding x from the above equation and the total water need from the appliance specifications, daily hot water need for each appliance can be estimated.

5.5.3 DHW profile for NZEH

The final DHW load per day in NZEH after employing all the above mentioned measures is 104 L/day as shown in Table 5.12.

The occupancy schedule for NZEH is kept the same as in the base case and the total daily load is distributed only during the occupied hours.

Table 5.12 Comparison of DHW daily load and CMHC guidelines

Category	DHW consumption for four people (liters)	
	As specified by CMHC	**In the current NZEH**
Showers	100	72
Clothes washing	25	16
Dishwashing	15.5	6
Other uses	10	10
Total	**150.5**	**104**

Table 5.13 shows the daily DHW use distribution assumed for NZEH. The schedule differs for weekdays and weekends, with weekend daily load assumed to be 7.5% higher than that of weekdays. This is based on a report by Canadian Building Energy End-use Data and Analysis Center. The report mentions a 14-month study conducted by Goldner (1994), on 30 multi-family buildings in New York, with an average 2.2 occupants per apartment. Distinct variations in DHW use were observed with daily load during weekend being 7.5% higher compared to weekdays. Distinct seasonal variations were reported as well. Compared to summer, hot water usage was found 10% higher in the fall, and an additional 13% in the winter (Aguilar, 2005, p.30-31).

Table 5.13 Daily DHW schedule for NZEH

	Time	DHW use (liters)	Acivities
Weekdays	7:00 am - 8:00 am	3.0	sink
	8:00 am - 9:00 am	2.0	sink
	9:00 am - 6:00 pm	0.0	_
	6:00 pm - 10:00 pm	92.0	showers, clothes washing, sink
	10:00 pm - 12:00 am	6.0	dishwashing
	12:00 am - 7:00 am	1.0	sink
	Total daily use	**104.0**	
Weekend	7:00 am - 8:00 am	3.0	sink
	8:00 am - 9:00 am	2.0	sink
	9:00 am - 6:00 pm	23.8	clothes washing, sink (7.5% higher)
	6:00 pm - 10:00 pm	76.0	showers, sink
	10:00 pm - 12:00 am	6.0	dishwashing
	12:00 am - 7:00 am	1.0	sink
	Total daily use	**111.8**	

Seasonal variations in the hot water consumption are ignored in the current study, in order to avoid modeling complications. It should be noted that throughout the year, there is also seasonal variation in the energy consumption for heating the same amount of water, since water from the mains is colder in winter compared to summer. This is taken into consideration in the simulation since the water temperature profile used in the current study reflects this temperature gradient. Type 14 is used to simulate the DHW profile.

5.6 Improved Artificial Lighting

The electricity consumption calculated for artificial lighting in the base case was with the assumption that incandescent light bulbs were used. Incandescent lights are not very efficient, as they use only about 10% of the consumed energy to produce light while the rest is given off as heat (WBDG, 2008). Therefore to reduce the lighting load, compact fluorescent lamps (CFL) are used in NZEH, which need $1/4^{th}$ – $1/3^{rd}$ of the wattage required compared to the respective incandescent ones (CLTC, 2005), for the same amount of visible light, and have almost 10 times longer rated life (ENERGY STAR, n.d., d). Since in residential application temperature color is also important, warm-color CFLs, i.e. 2700K/3000K are recommended (higher Kelvin values indicate cooler and lower values indicate warmer color temperatures). Also instead of two-pin ballast, four-pin units are preferred, which are light weight and do not cause blinking or humming (CLTC, 2005), which is a common criticism against CFLs.

The lighting density for NZEH is thus reduced to 1.25 W/m^2 from 5 W/m^2 in the base case. The sensible heat gain from the CFLs is split into 67% radiant and 33% convective (ASHRAE 2005, p.30.22, Table 16). The lighting schedule in NZEH is kept the same as in the base case. Table 5.14 provides a comparison of the current NZEH lighting proposal with other examples in the literature.

Table 5.14 NZEH lighting load comparison with other projects

Project name	Area of the house (without the basement)	Lighting load	Normalized lighting load (kWh/ m^2.yr)
Equilibrium House competition:			
Abondance le Soleil, Iolova et al. (2007)	3 apartments, 77 m^2 each	3 kWh/day	4.74
Alstonvale NZEH, Candanedo et al. (2007)	Single family home, 181 m^2		2.25
Davenport Road, Toronto, Rad and Fung (2007)	Townhouse, 278 m^2	1 kWh/day	1.31
Other examples:			
Suburban Greater Toronto NZEH feasibility study, Tse and Fung (2007)	Single family, 196 m^2	0.75 kWh/day	1.40
Brahme R. et al (2008)		-	1.6
NREL/Habitat ZEH, Denver, CO. Norton and Christensen (2008).	119 m^2	970 kWh/year*	8.15
Armory Park de Sol NAHB (2004)	160 m^2	779 kWh/year	4.87
Current Study	Two families, 204 m^2		
Base case		2,546 kWh/year	12.48
NZEH proposal		**637 kWh/year**	**3.12**

*Performance data obtained by data acquisition system

Compact fluorescent lights are criticized sometimes for their mercury content, which is in the range of 3.5 to 15 mg per bulb. Although if CFLs are recycled, the mercury as well as almost all their other components can be recovered (EPA, 2008).

Another option for energy efficient lighting other than CFLs, is light-emitting diodes (LED), which are mercury-free, even more efficient than CFLs, and have longer rated life of up to 20 years. They need 85 - 90% less energy compared to incandescent lamps. But in residential applications, LEDs are not common yet due to their high cost. Energy Star has listed the qualified residential LED lighting manufacturers to date, but the only applications served in this list are recessed down-lighting and under-cabinet kitchen lighting (ENERGY STAR, 2009). From this list, as an example, the cost of one 4 W task light with efficacy of 34 lumens/W, by Kichler Lighting is $54 (Lighting Direct, 2009). Compared to that, a GE 13W CFL with similar efficacy costs approximately $8. LED technology and its versatility are growing at a very fast rate indicating its anticipated market penetration in residential sector, which should help in cost reduction in the near future.

5.7 Total Electric Load Reduction for NZEH

The reduction achieved for NZEH in appliance, miscellaneous electric, and lighting loads is presented in Table 5.15. A total reduction by almost 60% is achieved compared to the base case. This saving is quite significant, considering the fact that the base case house was already an energy efficient R-2000 house. This analysis was essential before PV/T system sizing. Even though additional electricity will also be required for cooling, pumps and HRV, this value provides a starting point for PV/T system design.

Table 5.15 Loads reduced in the NZEH compared to the base case

Load type	Base Case		NZEH proposal		Percent reduction in NZEH compared to the base case
	(kWh)	Reference	(kWh)	Reference	
Appliance	5,228	Table 4.4	2,490	Table 5.4	52.4
MEL	2,764	Table 4.5	1,128	Table 5.6	59.2
Lighting	2,546	Table 4.7	637	Table 5.14	75.0
Total	**10,538**	_	**4,255**	_	**59.6**

As mentioned in the earlier part of this chapter, the NZEH has radiant floors for heating. This radiant floor heating system, along with the DHW, is designed to be supplied by the thermal component of the proposed PV/T system, while the photovoltaic component of the PV/T system is used for the electric back-up.

5.8 Photovoltaic/Thermal System

Selecting the renewable energy technology is one of the most important decisions for NZEH design. In author's view, Ground Source Heat Pump (GSHP) in conjunction with solar thermal technology with PV for backup is an excellent option for DHW and space conditioning in NZEHs. It can use the ground as a heat sink whenever the solar system produces surplus heat especially in summer and as a heat source when the solar system fails to yield sufficient heat in winter. But one of the main goals of this research is to study the impact of climate change on building loads and the associated systems used. Since geothermal technology is hardly likely to be affected by climate change, its use is avoided in NZEH study here. The use of this technology with solar thermal system is recommended for future work.

A combined Photo-Voltaic/Thermal (PV/T) system is proposed for NZEH, which mainly consists of flat plate solar collectors with PV cells mounted on top of the absorber plates. Thus, a single PV/T module generates thermal as well as electrical energy. This section explains the logic behind this decision, the details of the selected system, integration of this system with the proposed heating system, and the simulation methodology.

5.8.1 Combined PV/T System

There are many reasons to prefer a combined PV/T over separate PV and solar thermal systems as listed below:

1. In residential applications the roof area is a limiting factor especially considering the fact that only the south side roof (in northern climates) is useful for installing solar systems. Therefore instead of individual solar thermal and PV modules, the combined PV/T can be a solution. PV/T modules can generate more energy per unit surface area as compared to side by side PV panels and solar thermal collectors (Kalogirou et al., 2008).
2. The efficiency of PV cells decreases with increasing temperature. The extent of the decrease depends on the type of PV, but in general, this temperature coefficient is in the range of -0.2 to -0.5% per °C (Affolter et al., n.d.). This means that with each degree increase in temperature of PV, its efficiency decreases by about 0.2 to 0.5%. PV/T systems provide the benefit of cooling down the PV panels, consequently, increasing their electricity conversion efficiency.

3. By combining PV and solar thermal technologies, the overall cost of PV/T system can be lowered because of shared mounting, packaging, and installation costs (IEA, 2002). Therefore, by using both the electrical and thermal systems together, the combined system becomes more economical.

4. Another reason from architectural point of view is that the combined system offers a more homogeneous appearance for the building than two separate systems. Even if in future both PV and solar thermal technologies develop in such a way that due to their higher efficiencies roof area is not a constraint, a combined product or system seems still preferable than two separate products side by side on the roof.

5.8.2 Water-Based Versus Air-Based System

PV/T system can use water, air or both, as a heat transfer fluid. PV/T system with water is more expensive, complex and needs proper care during installation to avoid leakage, as compared to air based system. But as presented in Table 5.16, compared to air, water has specific heat four times higher, thermal conductivity 24 times higher, as well as higher density. These properties of water make it a better heat transfer medium as compared to air.

Table 5.16 Thermo-physical properties of water and air (ASHRAE, 1981)

Material	Specific heat [J/kg.K]	Conductivity [W/m.K]	Density [kg/m^3]
Water	4180	0.6	1000
Air	1004	0.025	1.2

The other issue is related to the system application. In case of air-based system, the hot air is useful for space heating in winter but in summer, this hot air needs to be expelled outdoors, wasting the heat, unless used in an air-water heat exchanger. The need for hot water, on the other hand, is quite consistent throughout the year and hence installing a water-based system that will be used throughout the year makes more economical sense.

The usefulness of the recovered heat depends on its application and can be calculated by the 'use coefficient' Q_u such that

$$Q_u = \frac{\text{thermal energy delivered to the user (MJ/m}^2\text{)}}{\text{thermal energy recovered during PV system operation (MJ/m}^2\text{)}} \qquad (5.11)$$

In case of air-based PV/T this value can be as low as 0.2, while for water-based system it can rise up to 0.6 (Tripanagnostopoulos, 2006).

Based on the discussion above, a water-based PV/T system is proposed for the NZEH. It needs to supply for the total thermal load of 7,682 kWh and the electrical load of 6,132 kWh, as shown in Table 5.17. These total values are an estimate at this stage, not exact values, since in addition, electricity for the mechanical ventilation system and the pumps is also required which is unknown at this point and is presented further after carrying out the annual simulations.

Table 5.17 Annual thermal and electric loads for NZEH

Annual thermal loads		(kWh)
	Heating	6,123
	DHW	1,559
	Total thermal loads	**7,682**
Annual electrical loads		
	Cooling	1,877
	Appliance	2,490
	MEL	1,128
	Lighting	637
	Total electric loads	**6,132**

5.8.3 Mathematical model

Since the PV/T is the most important component of this NZEH design, it is discussed in detail here. The models for thermal collectors and photovoltaic cells are discussed first, which lead further to the model for combined PV/T.

5.8.3.1 Thermal Performance

As mentioned in ASHRAE (2007), the methodology for calculating the solar thermal collector performance is mainly based on the works of Hottel and Woertz (1942) and Whillier

(ASHRAE 1977). The efficiency of solar collector is the ratio of the useful energy output to the incident solar energy.

$$\eta_{th} = \frac{q_u}{G_t} \tag{5.12}$$

where,

η_{th} = thermal efficiency;

q_u = useful energy output per unit area of collector, W/m^2;

G_t = total incident solar radiation per unit area of collector, W/m^2.

The thermal efficiency can also be expressed as (ASHRAE, 2007, p.33.10):

$$\eta_{th} = F_R \left[\tau_g \alpha_p - \frac{U_L (T_{f,i} - T_a)}{G_t} \right] \tag{5.13}$$

where,

F_R = collector heat removal factor;

τ_g = transmittance of glass cover;

α_p = absorptance of collector plate;

u_L = upward heat loss coefficient, W/(m^2·K);

$T_{f,i}$ = fluid inlet temperature, °C;

T_a = ambient temperature, °C.

5.8.3.2 Electrical performance

The electrical efficiency of a photovoltaic module is expressed as a ratio of electrical output to the incident solar radiation,

$$\eta_e = \frac{I_m V_m}{G_t A_p} \tag{5.14}$$

where,

η_e = electrical efficiency;

Im = PV current at maximum power point, A;

Vm = PV voltage at maximum power point, V;

A_p = collector aperture area, m^2.

5.8.3.3 Performance of Combined PV/T

For analysis of PV/T, the work of Florschuetz (1979) is significant since it further extended the model for the thermal analysis of flat plate collectors to the analysis of combined photovoltaic/thermal flat plate collectors and is the basis for TRNSYS PV/T model (Type 50d) used in this study. Compared to the original Hottel-Whillier model, the only additional assumption made by Florschuetz was that the local electrical conversion efficiency of the photovoltaic can be represented as the function of the local absorber (PV cells) operating temperature and the photovoltaic performance is inversely proportional to the cell temperature, which is a valid assumption at least above 0°C.

Thus,

$$\eta_e = \eta_r[1 - \beta\,(T - T_r)] \tag{5.15}$$

where,

η_e = PV cell efficiency;

η_r = electrical efficiency of the PV cells at reference temperature (generally 25°C);

β = temperature coefficient of solar cell efficiency, $°C^{-1}$;

T = PV cell temperature, °C;

T_r = reference temperature, °C.

Florschuetz (1979) modified the parameters of the Hottel-Whillier model and used two PV cell parameters, viz. the electrical efficiency of the PV cells at reference temperature and the temperature coefficient of the cell efficiency. As discussed further in section 5.8.5.1, these parameters are included in TRNSYS Type 50d for PV/T. Thus Florschuetz facilitates direct calculation of electrical output of a combined PV/T in terms of the parameters used for the thermal output and in addition, the two above mentioned PV parameters. The modifications to the Hottel-Whillier model are discussed further below.

The modified values of heat loss coefficient and the absorbed solar radiation for the combined PV/T are calculated as presented in equations 5.16 and 5.17. In these two equations, U_L and S are the terms just for the solar collector, while $\tilde{U}_L$ and $\tilde{S}$ are the modified terms for combined PV/T.

$$\tilde{U}_L = U_L - \frac{S}{\alpha} \eta_r \beta \quad (5.16)$$

where,

U_L= overall thermal conductance for collector heat losses, W/(m^2·K) ;

S = absorbed solar radiation per unit area, W/m^2;

α = effective absoptance of collector absorber.

$$\tilde{S} = S\left(1 - \frac{\eta_a}{\alpha}\right) \quad (5.17)$$

where,

η_a = electrical efficiency of the PV cells at ambient temperature.

Due to these changes in the heat loss coefficient and the absorbed solar radiation equations in case of the combined PV/T compared to those in case of the solar thermal collectors, all other factors such as F, F', and F_R also get modified. These modified equations can be obtained simply by replacing U_L and S by the respective values from equations 5.16 and 5.17. Thus the thermal and electrical outputs for PV/T are given by Florschuetz as

$$Q_{th} = A_p \tilde{F}_R\left[\tilde{S} - \tilde{U}_L\left(T_{f,i} - T_a\right)\right] \quad (5.18)$$

$$Q_e = \frac{A_p.S.\eta_a}{\alpha}\left\{1 - \frac{\eta_r.\beta}{\eta_a}\left[\tilde{F}_R\left(T_{f,i} - T_a\right) + \frac{\tilde{S}}{\tilde{U}_L}\left(1 - \tilde{F}_R\right)\right]\right\} \quad (5.19)$$

where,

Q_{th} = total thermal output of PV/T, W;

Q_e = total electrical output of PV/T, W.

5.8.4 Modifications to the Base Case House for the PV/T Installation

As presented in chapter 4, the existing house (base case) has a hip roof with four surfaces: North, South, East, and West. To optimize the PV/T production, it is necessary to maximize the surface area of the south side roof. Hence in case of the NZEH, the house is assumed to have a gable roof with only two surfaces: north and south. With 45° slope, the surface area of the south side, available for PV/T panel installation is 89 m^2, which is significantly larger than the 25.86 m^2 south roof in the base case. The modification to the roof is presented in Figure 5.7.

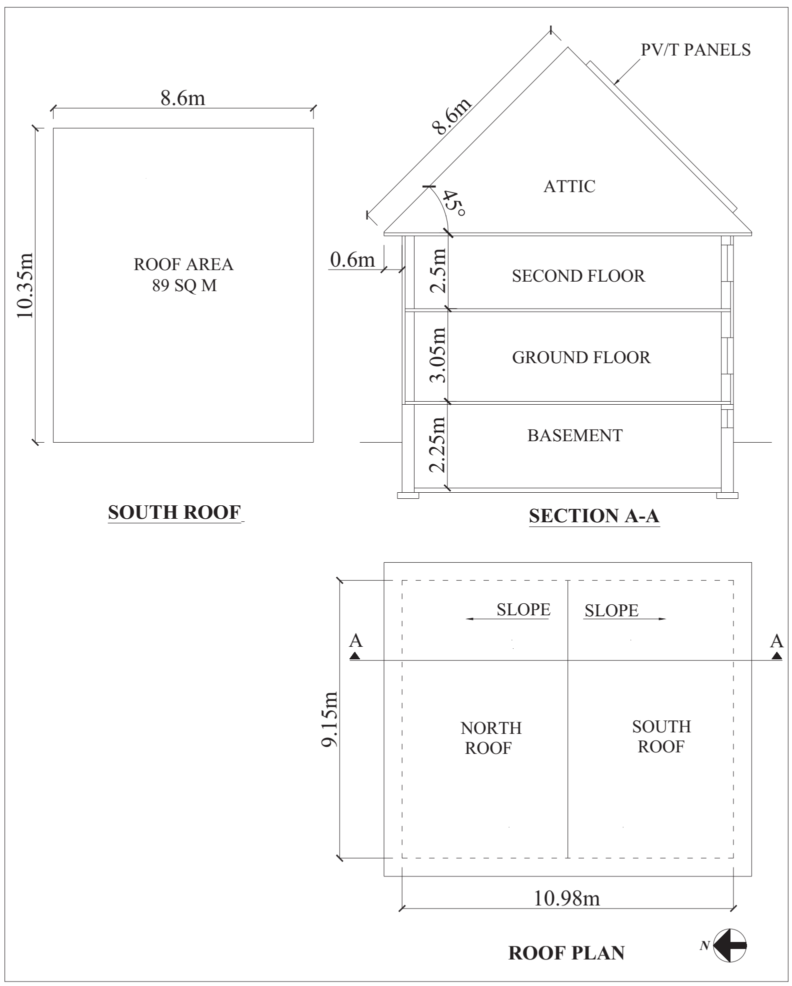


Figure 5.7 Roof modifications for NZEH

5.8.5 Modeling in TRNSYS

As mentioned earlier, there are two components to the PV/T system: electrical and thermal. The thermal side of the PV/T system is a closed loop, connected to the storage tank via the heat exchanger coil in the lower half of the tank. It is an active system, meaning a pump assists the flow in the loop. Thus the main constituents of the system are the PV/T panels, the controller, and the pump, which are explained in the sub-sections below.

5.8.5.1 PV/T modules

In TRNSYS, for PV/T using flat plate collectors, Type 50 offers four different modes of operation. With Type 50a (mode 1), both U_L and τ are assumed to be constant and their values are supplied as parameters. With Type 50b (mode 2), U_L is calculated as a function of operating temperatures, the wind speed, and the collector geometry, while keeping τ constant. With Type 50c (mode 3), τ is calculated as a function of incidence angle, with U_L being constant. With Type 50d (mode 4), neither U_L nor τ is constant; U_L is calculated similar to mode 2 and τ is calculated similar to mode 3 (TRNSYS Documentation). In this study, the PV/T system is modeled using Type 50d, which is the same model used in Task 35 of IEA SHC (Hansen et al., 2007). Figure 5.8 shows a typical PV/T module with flat plate collector using tube technology.

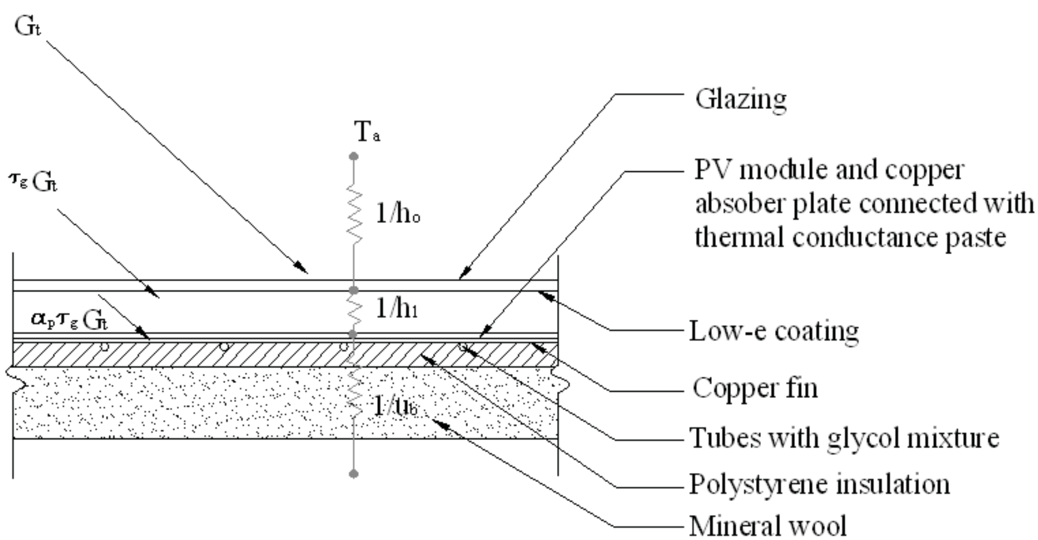


Figure 5.8 Section through a typical PV/T module

A PV/T module manufactured by a German company, Holtkamp SES, is used as a reference for the simulation purpose. It is a single glazed module with mono-crystalline PV cells having module efficiency of 10.9%. The PV cells are directly mounted on top of the copper plate with thermal conductance paste. Out of the parameters of Type 50d listed below, the information for the parameters, (i) to (iii) is obtained from the manufacturer. For the parameters (iv) and (v), the materials used are same as in the actual product but the material properties are obtained from other sources as indicated.

(i) Temperature coefficient of PV cell efficiency: As mentioned earlier, the efficiency of photovoltaic cells decreases with the increase in PV temperature. The temperature coefficient indicates the linear loss of performance per °C temperature increase of the module. In this case, this temperature coefficient is 0.0016 per °C temperature increase of the module and the reference temperature is 25°C.

(ii) Packing factor: The packing factor is a ratio of PV cell area and absorber area and this ratio is 0.94 in this case.

(iii) Insulation: The back of the PV/T is insulated with a combination of mineral wool and polystyrene with a total resistance of 0.93 $(h \cdot m^2 \cdot K)/kJ$.

(iv) Transmittance of glass: For the glazing of the PV/T module, glass with low iron content is preferred due to its low absorptance and high transmittance value, up to 90%, for the entering short wave radiation and almost zero transmittance for outgoing long-wave radiation (ASHRAE HVAC 2007).

(v) Absorptance and emittance of collector plate: The collector plate material is copper, which has emissivity of 7% (ASHARE 2005, p.39.3, Table 3). Sometimes to improve the absorptance of the solar collector, a black chrome coating is used, but it has emissivity of 15%. Therefore, a better coating material, TiNOX is used, which reduces the emissivity further to 5% (± 2%), with the absoptance of 95% (±2%). It is a mixture of Titanium and Quartz, with the solar absorption coefficient almost equal to the black chrome coating (TiNOX GmbH, 2007).

(vi) Heat transfer fluid: 55 % (by volume) propylene glycol solution which has freezing point of -41.6 °C, specific heat capacity of 3.44 kJ/kg·K, density 1,079.81 kg/m^3, and conductivity 0.34W/m.K (properties at 20°C), is used as heat transfer fluid in the solar collector loop (ASHRAE 2005, p.21.9, Table12). Even though ethylene glycol mixture has better thermo-physical properties, propylene glycol solution is preferred considering the application, since it is less toxic compared to ethylene glycol (ASH RAE 2005, p.21.4; The Engineering ToolBox, 2005).

The weather related inputs such as the ambient temperature, incident beam and diffuse radiation on the south roof, incidence angle of beam radiation, and wind speed are supplied to the PV/T model by Type 15.

5.8.5.2 Controller

The controller for the PV/T flow is simulated by inserting in the studio a component in TRNSYS called equation. The conditions imposed via the control signal, on the flow through the collectors are listed below; accordingly the PV/T pump only runs if both of these conditions are met:

(i) the total tilted surface radiation on the south roof is greater than zero. This is to ensure that the PV/T pump only runs during the day.

(ii) the water temperature in the tank, where the glycol mixture enters through the PV/T heat exchanger, is less than the PV/T outlet temperature.

Besides these two conditions, the pump stops working in summer whenever the temperature in the top node of the tank reaches higher than 90°C. This is to ensure that the PV/T pump does not operate unnecessarily, since in summer hot water is needed only for DHW use and not the heating.

The control signal takes value of either zero or one. The flow in the pump is regulated by this control signal, and is permitted only when all of these conditions are satisfied. The controller needs the values of tank nodal temperatures and the PV/T outlet temperature at each time step for comparison. For this purpose, an input value recall tool, Type 93 is used. At each time step, Type 93 receives values for the current time step, stores them and sends them to controller in the next time step. Type 93 is discussed earlier in chapter 4, section 4.4.2.

5.8.5.3 Pump

Type 741 is used to simulate the constant speed pump for the PV/T system. The pump manufactured by Grundfos, model UPS 15-42FR is used for reference. Out of the wide selection of Grundfos pumps, stainless steel and bronze pumps are for open systems, while cast iron pumps are for closed systems and hence used in this case. (Grundfos, n.d.).

Since The PV/T system is a closed loop, it needs an expansion tank and a pressure-relief valve, which are not simulated here.

5.8.6 Inverter

The Inverters have become increasingly efficient over the years. In 1980s the inverter efficiency was typically between 85 to 90%, but by 1990s it improved to over 95% (NREL, 2006). The inverter used in the proposed NZEH is by Mitsubishi with the efficiency of 97.5% (Mitsubishi Electric, 2009). Therefore the useful electrical energy produced by PV is assumed to be 2.5% lower than that actually produced.

5.9 Simulation Results and Discussion

After completing the NZEH model, simulations are carried out to extract results related to various aspects of the proposed design. These results, along with the relevant discussion are presented in this section.

5.9.1 Highlights of the Simulation Approach

1. The detailed model divided in 15 zones allowed temperature profiling of different zones and setting up the HVAC schemes and controls individually for all the zones to optimize thermal control while saving energy at the same time. Some examples of these independent settings are (i) bathroom zones are modeled without air conditioning and are cooled only with natural ventilation, (ii) mechanical ventilation from the bathroom zones is kept unconnected to the HRV, (iii) the stair zones are provided with baseboard heaters since radiant heating cannot be installed in these zones. Detailed zoning also allowed activities and the related gains to be assigned to appropriate zones, e.g. computer in bedroom zone, appliances in kitchen zone, tank in the basement zone, etc.

2. It is observed that the simulation time-step greatly affects the results obtained. To demonstrate this, two simulations with difference of only the time step are carried out, one with a time step of one hour, while the other with 10 minutes. As presented in Table 5.18, the results vary significantly with these two time steps. Especially, the results related to the tank vary by almost 60%, because, e.g. with one hour time-step, once the auxiliary heater in the tank turns on, it stays on at least till the end of the time-step, i.e. an hour; while in reality it might need to work for just a few minutes to raise the water temperature to match the set-point. Therefore, all the simulations discussed further in this chapter are run at 10 minute time-step unless otherwise specified.

Table 5.18 Impact of simulation time-step on the results

		Time step = 1 hr	Time step = 10 min	**Difference**
		(kWh)	(kWh)	(%)
Thermal	Q_aux_Tank	3,539	2,222	-59.3
	Q_PVT_therm_ received in the tank	5,756	6,902	16.6
	Q_losses_tank	978	1,037	5.7
	Q_RF_supply	6,772	6,530	-3.7
	Q_DHW_supply	1,551	1,559	0.5
Electrical	PV electrical production	13,048	12,993	-0.4
	Q_pump = Pump $_{PV/T}$ + Pumps_RF$_{Basement, GF, SF}$	27	19	-42.1
	Q aux_HRV	1,718	1,712	-0.4
	Q_HRV$_{fan}$	519	520	0.2
	Baseboard heat for stairs	333	297	-12.1
	Cooling	1,838	1,856	1.0

5.9.2 HRV

Figure 5.9 presents the monthly distribution of electricity required for HRV.

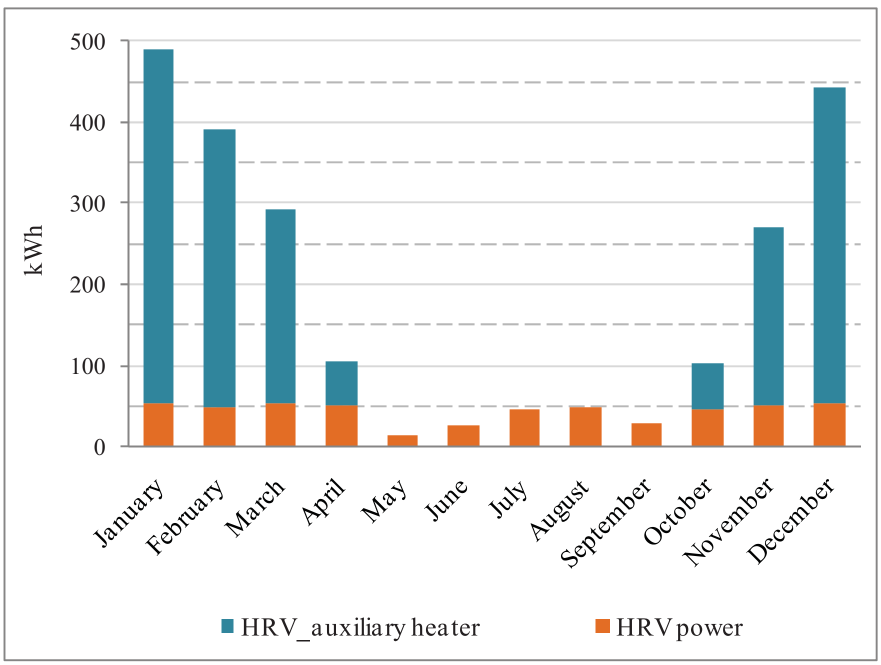


Figure 5.9 HRV monthly electricity consumption

The HRV runs throughout the year except when the natural ventilation is utilized by opening the windows. The results from annual simulation show that the HRV works for 7,228 hours out of 8,760 hours, with the windows being opened only for 1,532 hours a year. The 72 W HRV unit consumes 520 kWh of electricity for fan operation and approximately 1,723 kWh for preheating the air during winter. The total heat transfer by HRV between the exhaust air and the fresh air supply during its annual operation is 7,747 kWh.

The air temperatures entering and leaving the HRV in winter are presented in the Figure 5.10 for January 11th. As seen in this figure, the exhaust air at around 20°C from the building zones enters the HRV. The heat is extracted from this air in the HRV and its temperature drops to an average -3°C as it leaves the unit. On the other hand, the outdoor air at -13°C enters the HRV, receives the recovered heat, and warms up to an average 11°C. After this heat exchange, the supply air is further warmed up to 20°C by the internal heating element, before being delivered to the respective zones.

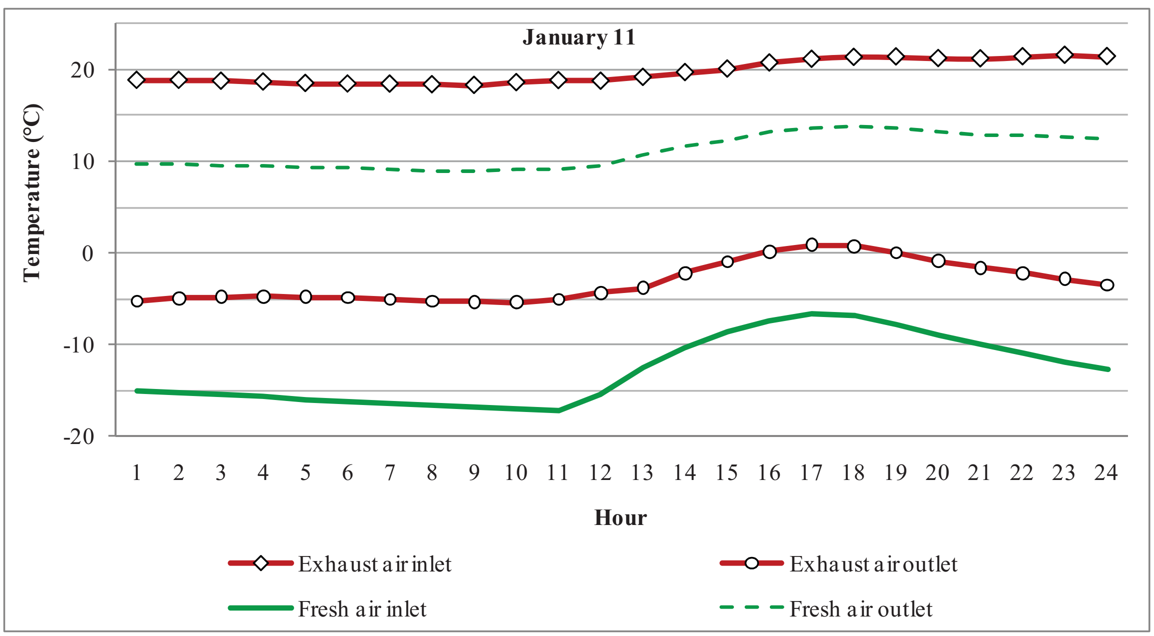


Figure 5.10 Temperature profile of air entering and leaving the HRV in winter

The air temperatures entering and leaving the HRV in summer are presented in the Figure 5.11 for July 20th. In this case, between midnight to 9:00 am and then from 10:00 pm to midnight the windows are open, and hence the HRV is turned off. So between 9:00 am to 10:00 pm, while HRV is functioning, it can be seen that the outdoor inlet temperature is high between 32°C to 27°C, but it is lowered by 4-5°C before exiting the HRV and being supplied to the zones, by passing that heat to the outgoing exhaust air. Thus the exhaust outlet temperature is higher than the exhaust inlet temperature.

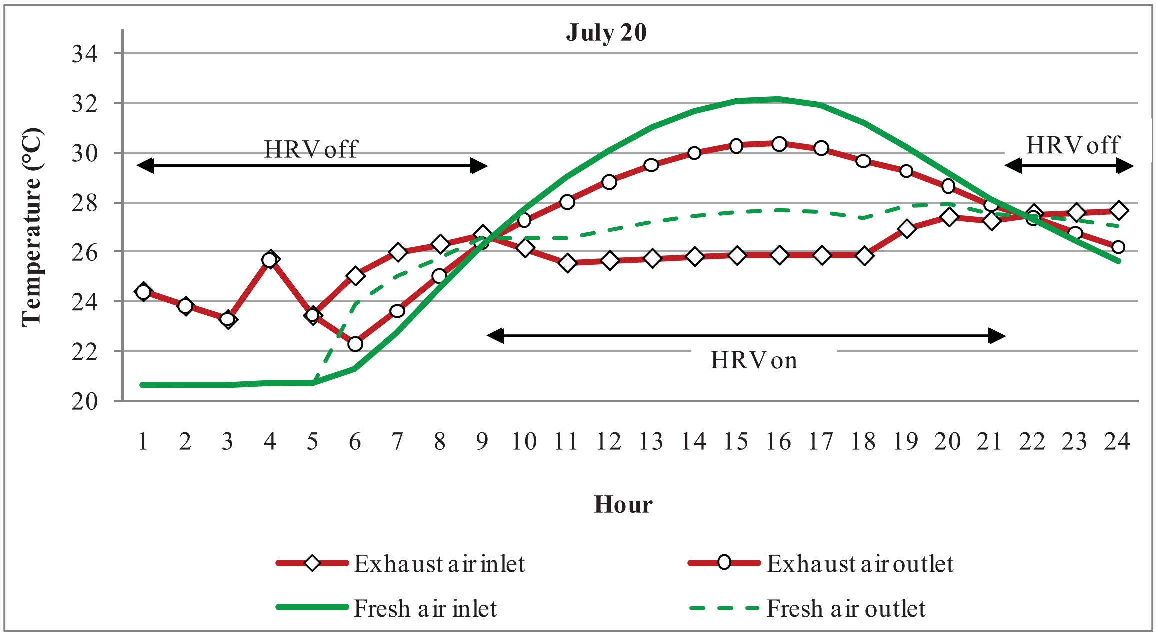


Figure 5.11 Temperature profile of air entering and leaving the HRV in summer

5.9.3 Reduction in Cooling Load

5.9.3.1 Attic ventilation

The temperature in the attic in the Base case reaches up to 43°C during summer. This adds to the cooling load on the second floor. Therefore, an option of cooling the attic is simulated by providing the attic with a fan with 6 ach. For the attic volume of 260 m^3, this translates to 495 L/s. The fan is modeled based on Air Vent Attic Aire 1050CFM gable mounted with 180 W power. It is equipped with an adjustable thermostat, so the fan turns on whenever the attic temperature in summer reaches above 35°C. To estimate the electricity consumption for attic ventilation, the number of hours the fan is on throughout the summer is multiplied by the fan power. Solar attic fans are also available in the market but since they are powered with the DC produced by PV, they rely on PV operation and turn off in cloudy conditions when PV stops operating.

The results, however, indicated that by adding the attic ventilation, the reduction in total cooling load was very minimal. In fact the fan power consumption exceeded the cooling load reduction by 14 kWh. Therefore this option is eliminated from the final design.

5.9.3.2 Natural Ventilation and Shading

This section focuses on the use of shading and natural ventilation to reduce the cooling energy use in summer and to avoid the overheating of zones during shoulder seasons when the air conditioning is off. The cooling season is the three month period from June 15th to August 15th and the cooling set-point in the habitable zones is 26°C, same as in the Base case. The natural ventilation and shading schedules are imposed; Table 5.19 lists the simulations carried out to implement these schedules, with case 1 being the worst in terms of cooling load and case 7 being the best option.

Table 5.19 Impact of shading and natural ventilation on cooling load and zone air temperatures

		Case 1 (Worst case)	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7 (Best case)
Shading		No	No	Yes	No	Yes	Yes	Yes
Natural ventilation								
	Spring: 24 hrs	No	No	No	Yes	No	Yes	Yes
	Summer							
	Day	No	No	No	No	No	Yes	No
	Night	No	No	No	Yes	No	Yes	Yes
	Fall: 24 hrs	No	No	No	Yes	No	Yes	Yes
Air conditioning in summer								
	Day	Yes	Yes	Yes	Yes	Yes	No	Yes
	Night	Yes	No	Yes	No	No	No	No
Cooling Load (kWh)		4160	3904	2871	2822	2735	0	1822
Highest Zone air temperature (°C)		41	41	36	36	36	36	32
***Combined occurrence frequency of zone air temperature ≥ 30°C**		6424	9542	3616	3265	4986	3766	462

*from all the zones

In this table, the temperature listed under the highest zone air temperature is from all the habitable zones on ground and second floor; while the occurrence frequency is the combined frequency of hourly zone air temperatures from all the zones, above 29°C, in the same habitable zones during spring, summer, and fall.

Case 1

In this case, air conditioning is used 24 hours a day during summer while shading and natural ventilation are never used. The annual cooling load is found to be over 128% higher compared to the best case scenario. Also as seen in Figure 5.12, the zone air temperatures go above 29°C very frequently (during the shoulder seasons), the highest value being 41°C.

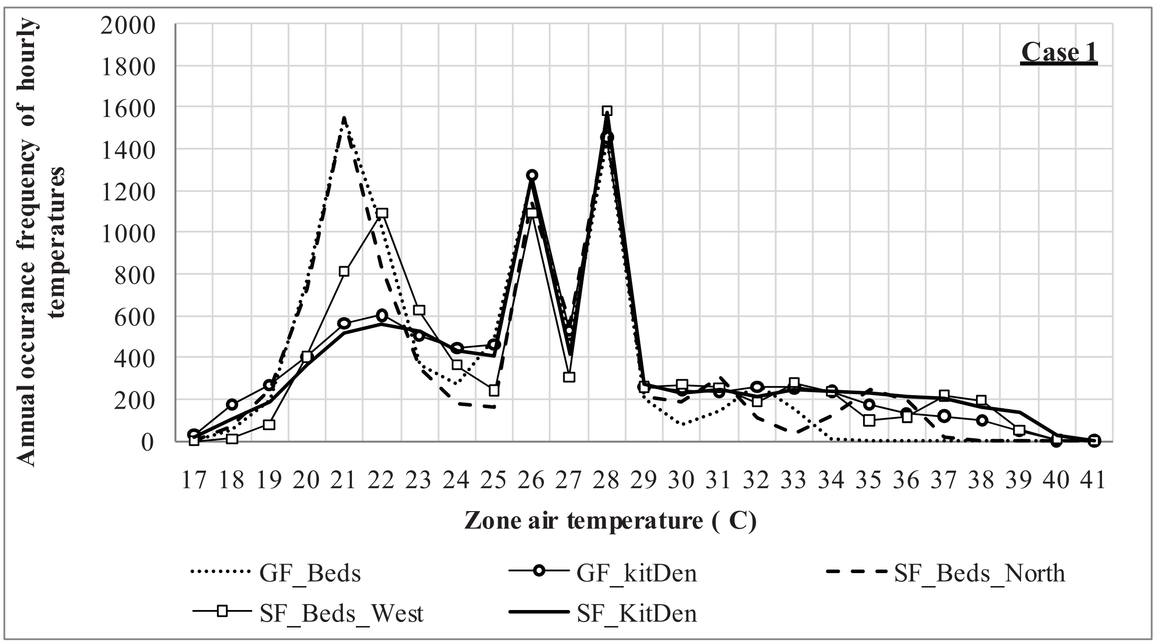


Figure 5.12 Frequency of temperature occurrences in Case 1

Case 2

With the same no shading or natural ventilation conditions as the Case 1, and by turning the air conditioning off at night during summer, the cooling load reduces only by 6% compared to Case 1, while the high temperature occurrence frequency increases considerably as seen in Figure 5.13.

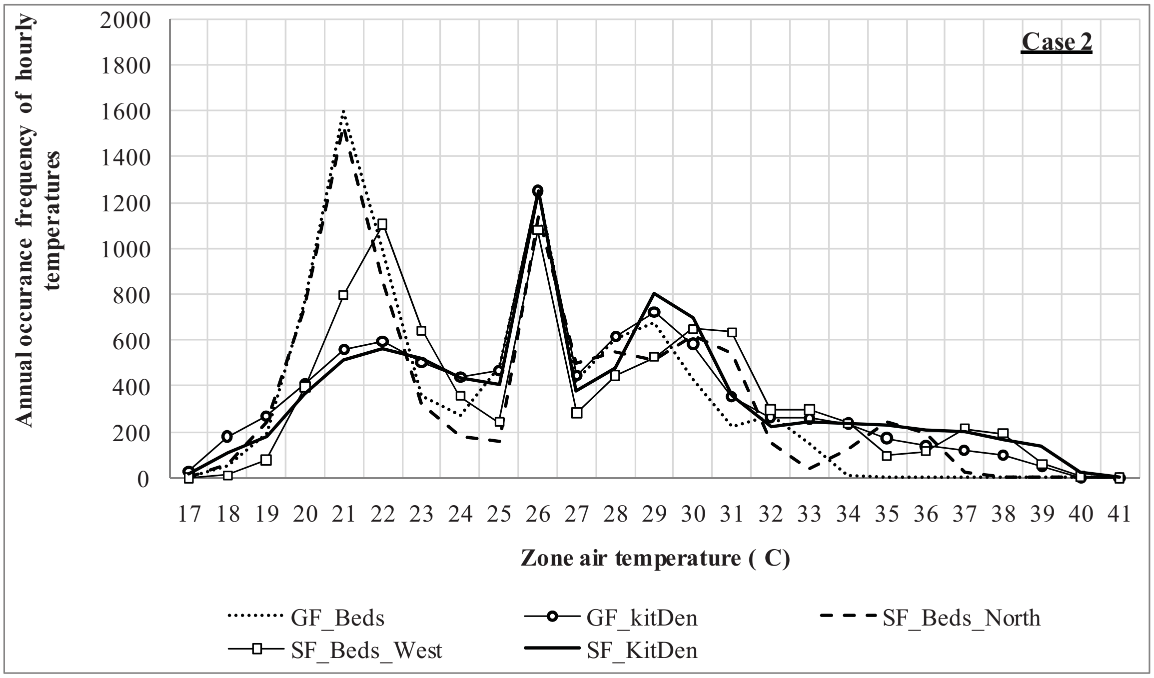


Figure 5.13 Frequency of temperature occurrences in Case 2

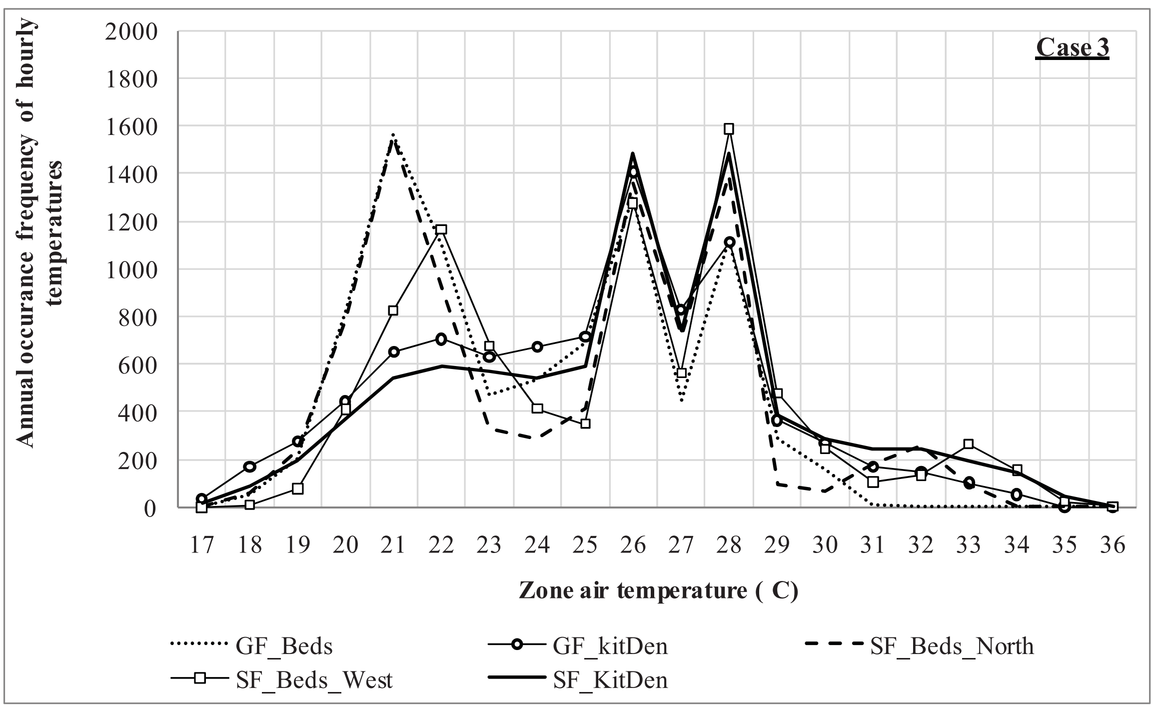


Figure 5.14 Frequency of temperature occurrences in Case 3

Case 3

Just by using shading, the cooling load reduces by almost 31% even though the natural ventilation is off. As seen in figure 5.14, the temperatures in some zones still go up to 36°C, but not as high as 41°C as in Case 1; and the occurrence frequency of temperatures above 29°C reduces by 44% compared to Case 1, proving the importance of shading.

Case 4

If natural ventilation is used during shoulder seasons and at night time during summer, the cooling load is further reduced in spite of shading being not employed, by 32% compared to Case 1. Similarly, the high temperature occurrence also reduces further, as shown in Figure 5.15.

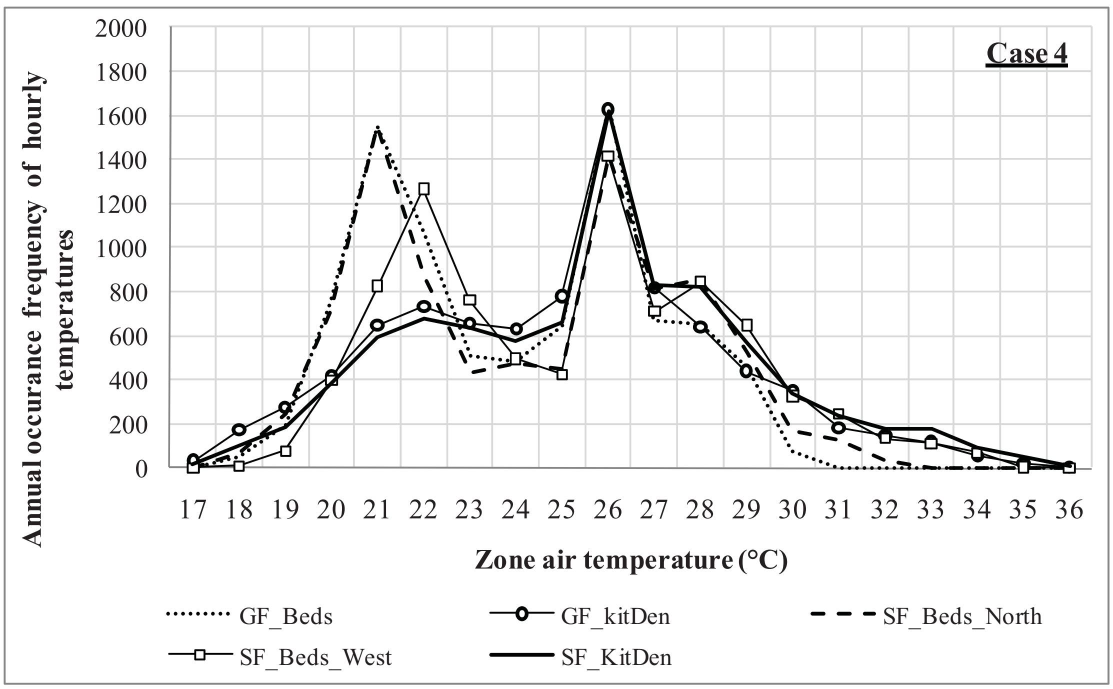


Figure 5.15 Frequency of temperature occurrences in Case 4

Case 5

Case 5 is same as Case 3, in which shading is used and not the natural ventilation, but it differs by not using air conditioning at night. It obviously results in slightly lower cooling load compared to Case 3 but as seen in Figure 5.16, temperatures go higher than 29°C much more frequently, i.e. 38% more than Case 3.

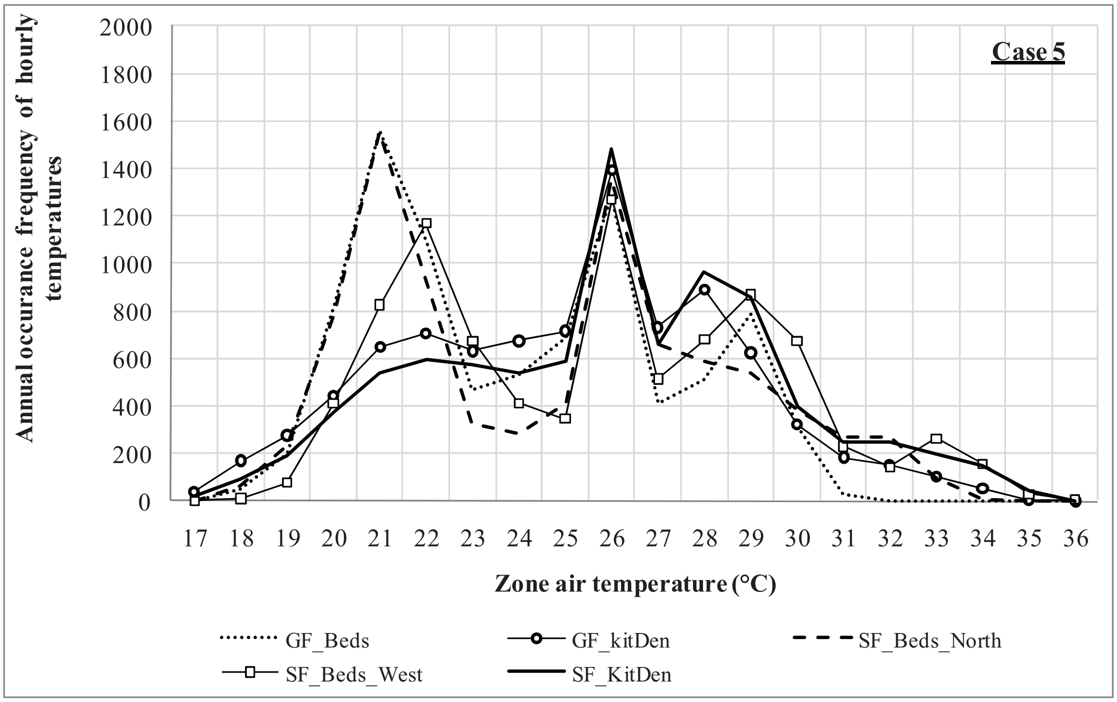


Figure 5.16 Frequency of temperature occurrences in Case 5

Case 6

This is an important case that explores the possibility of eliminating air conditioning completely with an effort to maintain the zones at comfortable temperatures by using both, the shading as well as natural ventilation. Although compared to Case 1, there is an improvement in the zone air temperatures, as seen in Figure 5.17, the hourly temperatures go higher than 29°C frequently in all zones and the highest temperature reached is 36°C. Thus the use of air conditioning is proved to be essential, along with shading and natural ventilation, and is simulated in the final proposal, Case 7.

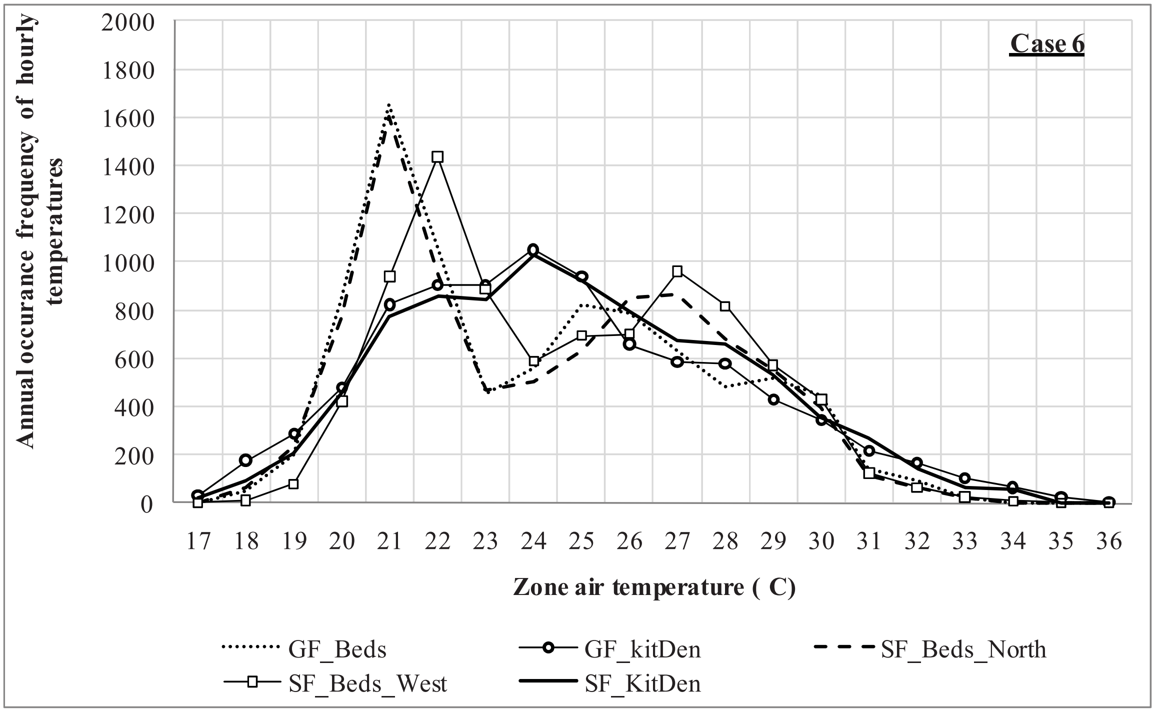


Figure 5.17 Frequency of temperature occurrences in Case 6

<u>**Case 7**</u>

In this last case, the goal is to keep the cooling load to minimum but not at the cost of thermal comfort. Shading is used throughout the year, air conditioning is used only during daytime in summer, and natural ventilation is used all day in shoulder seasons as well as during nights in summer. The cooling load is reduced by over 56% compared to Case 1, and this reduction is solely due to shading and natural ventilation. At the same time, the thermal conditions in all the habitable zones during shoulder season and at nights in summer are considerably improved. The highest temperature reaches to only 32°C compared to 41°C in cases 1 and 2. Also, the frequency of zone air temperatures rising to 30°C or more, is considerably low compared to all other cases as seen in Table 5.19, presented earlier. In all the zones the temperatures are most frequently between 20 - 22°C in winter and around 26°C the rest of year as seen in Figure 5.18.

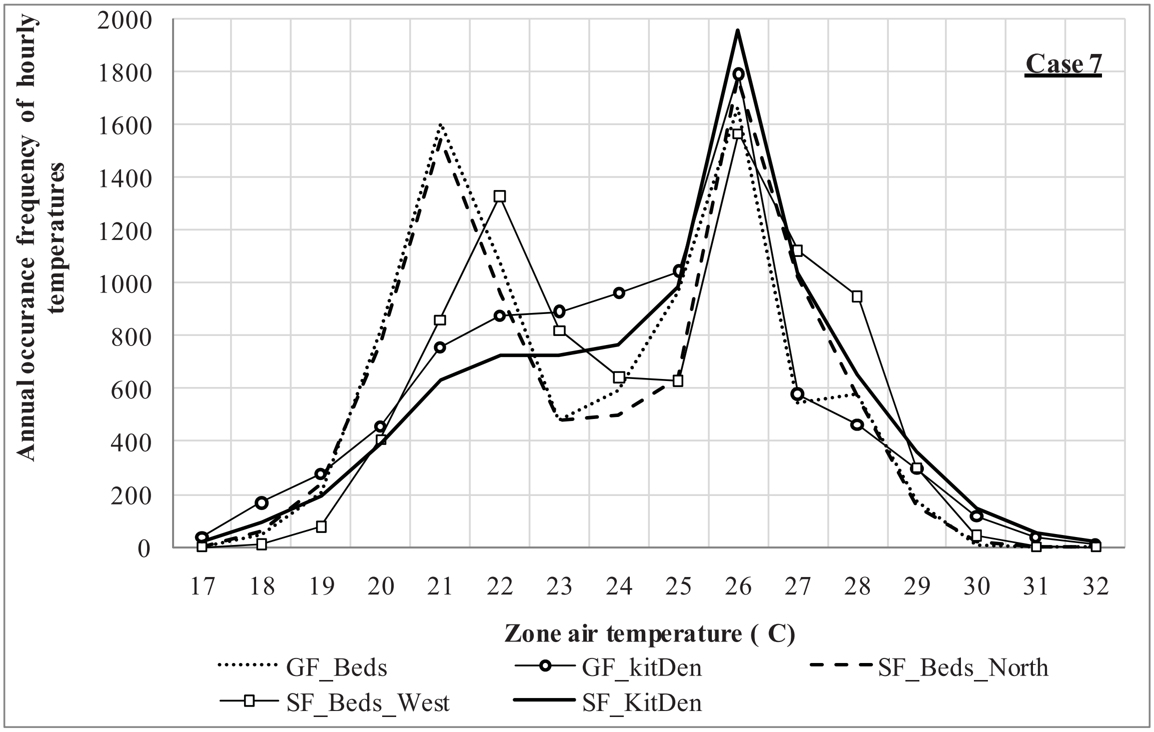


Figure 5.18 Frequency of temperature occurrences in Case 7

Figure 5.19 shows the zone air temperatures in case 7 with the occurrence frequency combined for all the zones. The cooling load from the zones normalized by their respective floor area is presented in Figure 5.20.

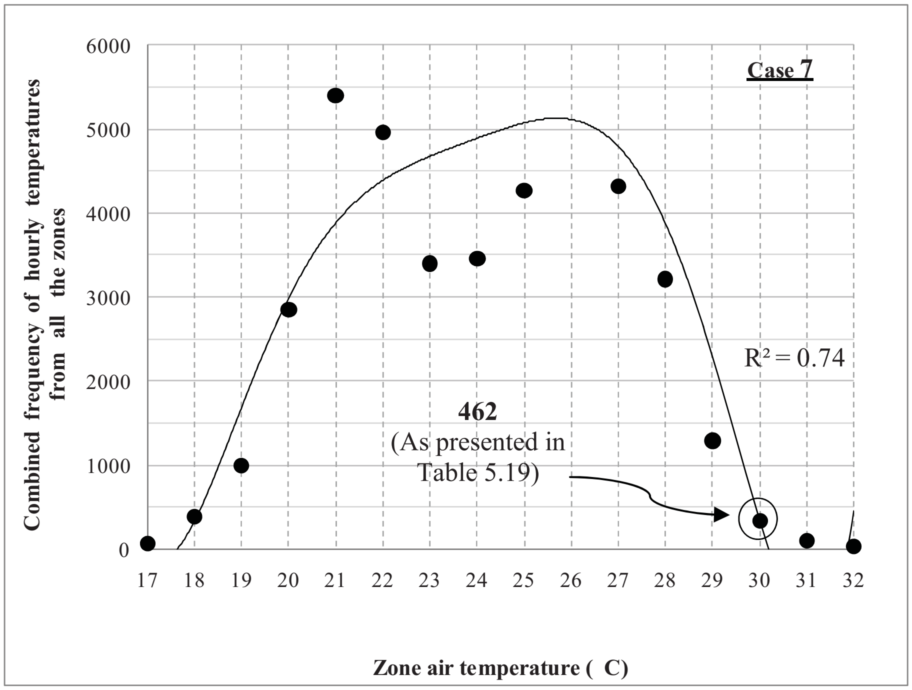
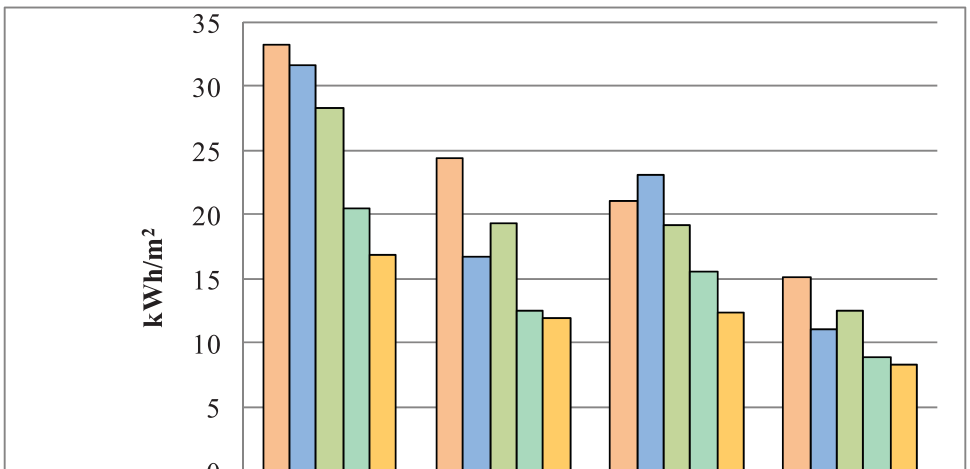


Figure 5.19 Temperature profile of the proposed NZEH



	Without shading or ventilation	With ventilation & without shading	With shading & without ventilation	With shading and ventilation
GF_KitDen	33	24	21	15
SF_BedsWest	32	17	23	11
SF_KitDen	28	19	19	12
SF_BedsNorth	21	13	16	9
GF_Beds	17	12	12	8

Figure 5.20 Normalized cooling load from various zones in NZEH

As shown in Table 5.20, the total cooling load for the NZEH is 1,822 kWh for the entire year. This translates to 5.88 kWh/m^2 of the entire 310 m^2 floor area of the house. The peak cooling load occurs in the zone GF_kitDen as 1.6 kW, while the total peak cooling load for the entire house is 4.88 kW.

Table 5.20 Annual cooling load distribution over various zones

Zones	Cooling load [kWh]	Cooling load [kWh/m^2]
GF_beds	289.83	8.10
GF_kitDen	649.33	15.06
SF_beds_North	315.75	8.83
SF_beds_West	118.26	10.77
SF_kitDen	448.81	12.45
Total	**1,821.98**	**11.27**

5.9.4 Initial Design of NZEH

The area of solar collectors supplying for DHW and space heating is generally in the range of 10 - 30% of the heated floor area (US DOE, 2003). This translates to the collector area of 31 - 93 m^2 for the NZEH, which has total heated floor area of 310 m^2. This is used as a guideline for the initial design, in which the PV/T has aperture area of 65 m^2. The flow rate of 52 kg/h·m^2 is used as per the PV/T product specification and the tank size used is 1,938 L (512 gal). Taking into consideration all the thermal and electrical loads, the results indicate that the house is still short of 851 kWh with the initial proposal. In order to reach the net zero energy goal and to reduce the PV/T system size as much as possible, sensitivity analyses are performed and the key findings are presented in the sections below.

5.9.5 Sensitivity Analyses for PV/T thermal and electrical energy generation

Various factors affect the solar thermal and electrical production of PV/T, e.g. the flow rate of the glycol mixture in the PV/T loop, area of PV/T, collector slope, number of glazing panels on PV/T etc. Following sub-sections, 5.9.6.1 to 5.9.6.5, focus on variations of these factors starting with the values in the initial design and the corresponding thermal and electrical production by PV/T.

In order to quantify the solar thermal energy production, there are two possible ways. The useful thermal energy gained by the glycol mixture at the outlet of the PV/T is one of the alternatives. From the outlet of the PV/T, this glycol mixture passes through the heat exchanger near the bottom of the tank and the heat is exchanged with the water surrounding the exchanger coiled tube in the tank. While presenting the solar thermal energy production for the NZEH, this later value, the amount of energy received in the tank after the heat exchange with the glycol mixture, is more significant and hence is presented in discussion in the sections to follow whenever accounting for the thermal energy produced by the PV/T panels. The difference between these two alternatives is apparent in the figure 5.23. At the same time, the electricity production by PV reported in the following discussions is the total useful electrical energy after deducting the inverter losses.

5.9.5.1 Tank volume and insulation

The sensitivity analysis for the tank volume, as presented in Figure 5.21, shows that bigger tank size has positive impact on PV/T thermal collection, resulting in reduced auxiliary heating requirement in the tank as well as higher electrical production. Higher tank volume allows more heat extraction from the PV/T heat exchanger, which increases PV/T electrical production slightly, due to the additional cooling of PV cells.

The tank insulation is increased in the NZEH compared to the Base case as discussed earlier. If the tank is further insulated, i.e. from RSI 0.6 (R 3.4) to RSI 1.1 (R 6.2), the losses from the tank seem to be further reduced by over 58%.

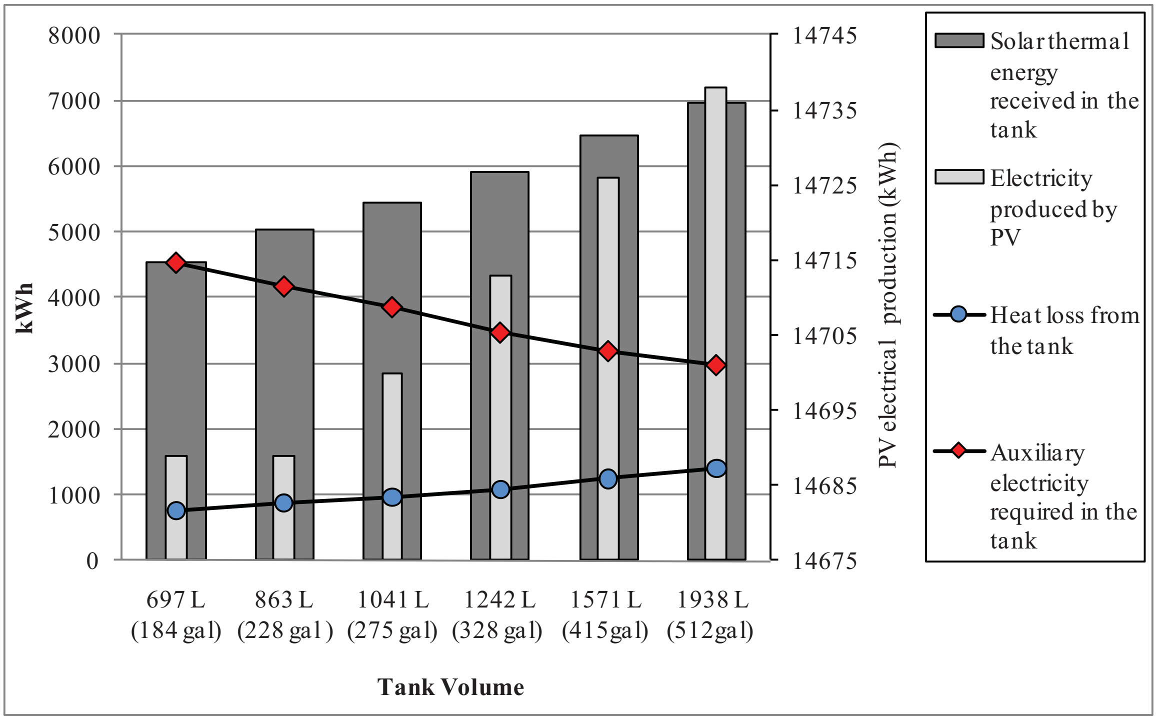


Figure 5.21 Impact of tank size on energy production

5.9.5.2 PV/T area

To size the PV/T that supplies for all the thermal and electrical loads for the NZEH, simulations are carried out with gradual increase in the PV/T area. The tank size used was kept constant during these runs as 1,041 L (275 gal) and the flow rate at 40 kg/h.m^2. As can be seen in Figure 5.22, the electrical energy produced by PV linearly increases with the increase in PV/T area but the thermal gain in the tank does not show similar trend. This is mainly due to the fact that even though larger PV/T area collects more thermal energy, the tank has limited volume and the entire thermal energy produced by the PV/T is not exchanged with the tank. Also, the PV/T pump stops operating whenever the tank temperature reaches over 90°C, although the PV still continues to work. It is observed that with PV/T area of 60 m^2, the system is still short of 231 kWh in order to satisfy all the thermal and electrical loads. With 70 m^2 PV/T area, the PV/T system is able to fulfill all the loads and produces 1,676 kWh of surplus electricity.

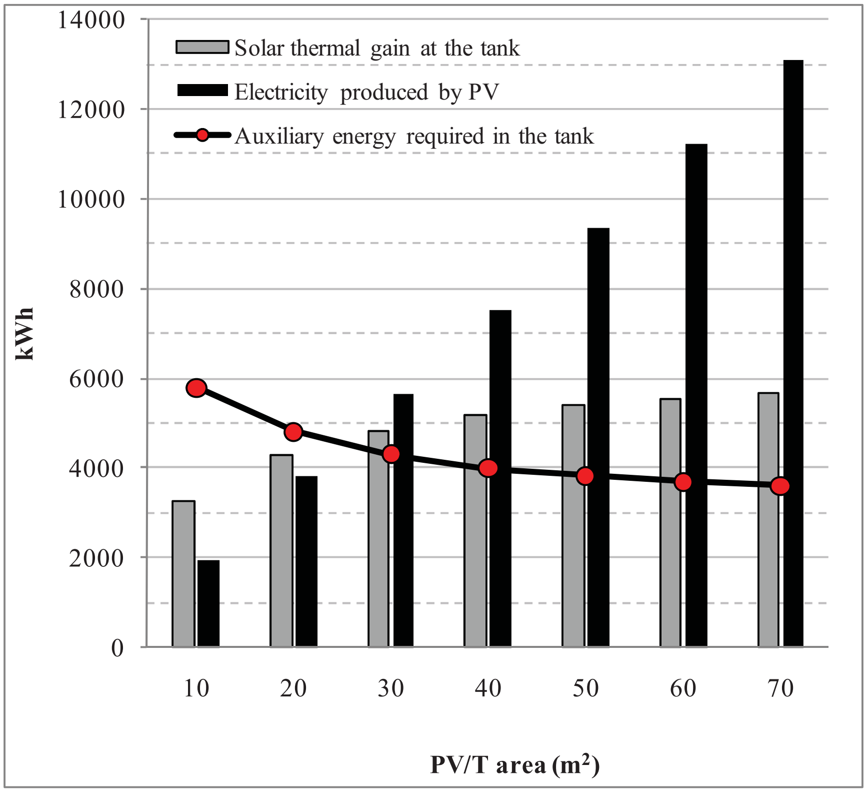


Figure 5.22 Thermal and electrical production trend with incremental PV/T area

5.9.5.3 Number of glass covers on PV/T

The PV/T modules used in NZEH proposal have single glazing. But since the number of glass covers affects the thermal and electrical generation, simulations are carried out with two and three glass covers as well. The values for other significant variables that are kept constant in these simulations are 1,041 L (275 gal) of tank volume, and 70 m^2 of PV/T area. The flow rate used in all three simulations is as per the recommendation by the PV/T manufacturer, i.e. 52 $kg/h.m^2$. Figure 5.23 shows the results obtained.

The additional glass covers reduce thermal losses to the environment, thus increasing the thermal energy gain slightly, but on the other hand, reducing the PV productivity significantly. The reduction of electrical generation can be attributed to the fact that higher number of glass covers also means higher PV temperature and more reflective losses. Compared to single glass cover, the electrical generation is reduced with double cover by 15%, while with triple cover it reduces by 29% for a gain of only 6.5% in the thermal energy. In all the simulations following this analysis, the PV/T used is therefore single glazed.

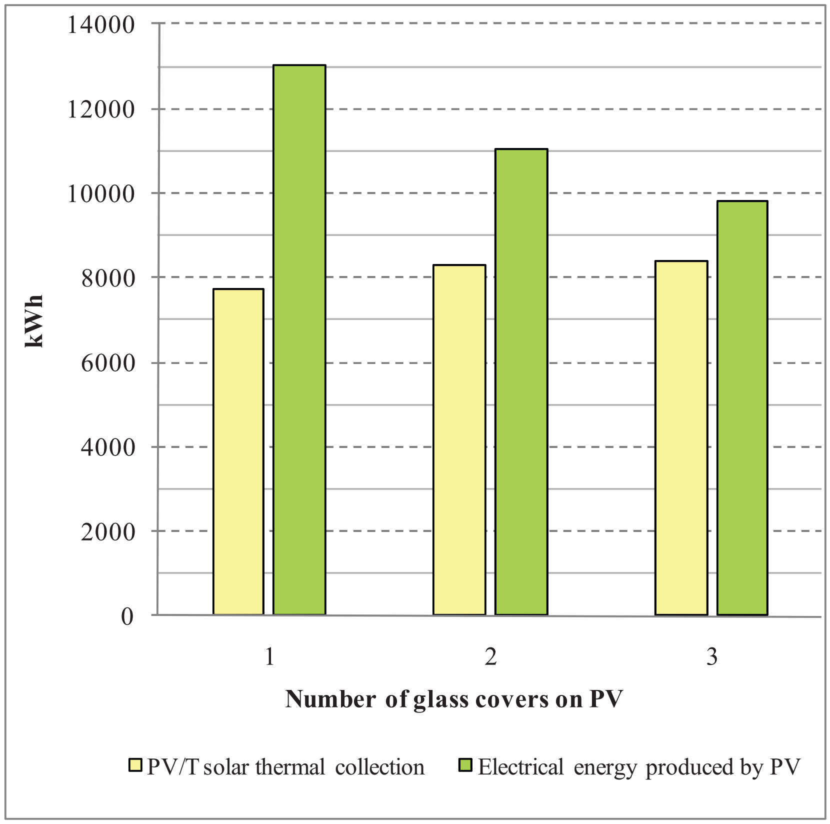


Figure 5.23 Energy production by PV/T with single, double and triple glazing

5.9.5.4 Collector slope

As the tilt angle of the collector changes, the incident radiation on the surface changes as well. To assess this, sensitivity analysis is carried out by changing the collector slope of PV/T. The optimum inclination angle for PV and thermal generation is supposed to be equal to the latitude angle ±15°. Since the latitude for Montreal is 45°, the range of 30° to 60° is selected in addition to horizontal (0°) and vertical (90°). As presented in Figure 5.24, the results indicate that on an annual basis, the optimum inclination angle for PV/T production is between 50 - 55°.

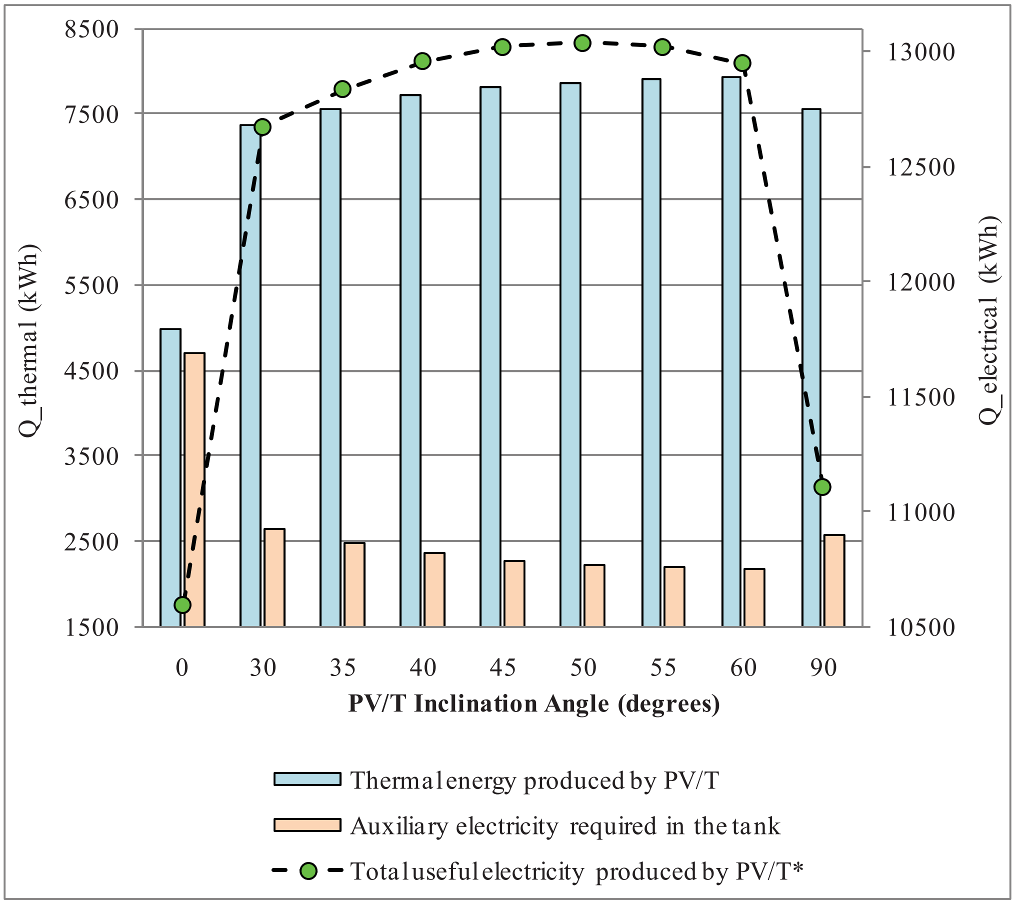


Figure 5.24 Electrical and thermal production with various PV/T inclination angles

5.9.5.5 Glycol mixture flow rate

Simulations are carried out to examine the impact of flow rate on the energy gain and the results are presented in Figure 5.25. The other parameters are kept constant, i.e. PV/T area of 57.6 m^2 (16 panels) and tank volume of 1,041 L (275 gal). The results indicate that increasing the flow rate significantly increases the thermal collection at the PV/T outlet and slightly increases the electrical production of PV/T as well. But considering the entire combi-system, increased flow rate in the PV/T closed loop induces more mixing in the tank nodes. Since the top nodes in the tank are at much higher temperatures, with a minimum of 55°C, increased mixing increases the temperature of water in the bottom nodes of the tank. This reduces the temperature difference between PV/T heat exchanger and the surrounding water, and ultimately reduces the heat transfer.

Thus with higher flow rates, the difference between the thermal energy collected by the PV/T and that exchanged with the tank is found to be increasing. The slight increase in electrical production can be attributed to the fact that the PV/T panels are better cooled down with higher flow rates.

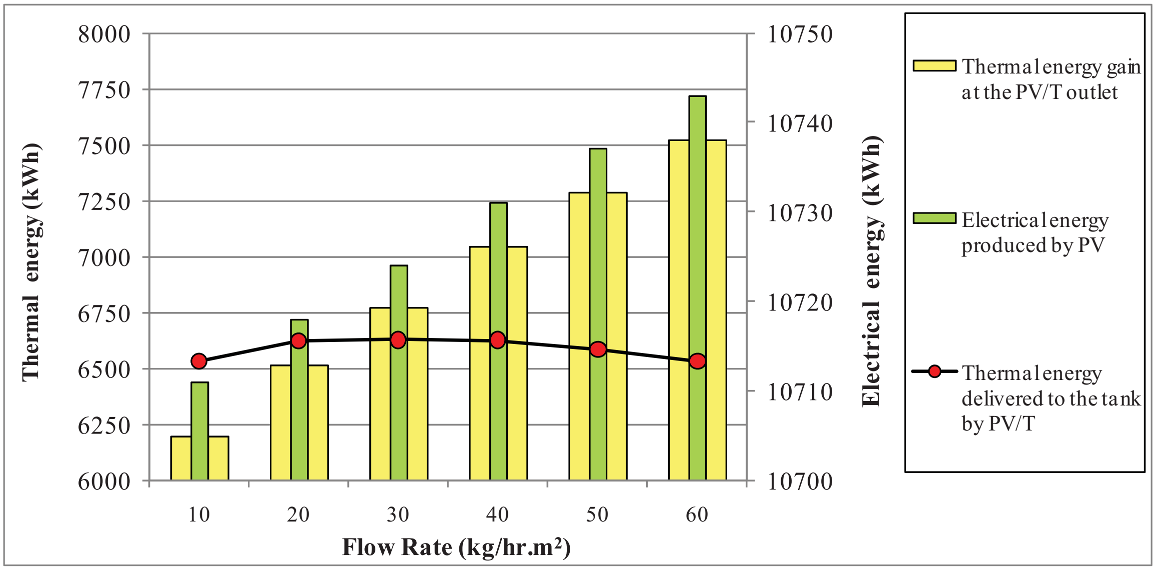


Figure 5.25 Impact of flow rate on thermal and electrical PV/T production

The surplus energy is calculated after taking into account the energy produced by PV/T and energy used for all the purposes in NZEH including the pumps, HRV etc., as well as losses such as from the tank. Based on that, the optimum flow rate is found to be 30 kg/h.m^2, which is used in the final design. It should be noted that this optimum flow rate is considering the entire combi-system and not just the PV/T panels. Figure 5.26 shows the total useful thermal plus electrical energy and the surplus energy produced by PV/T at various flow rates.

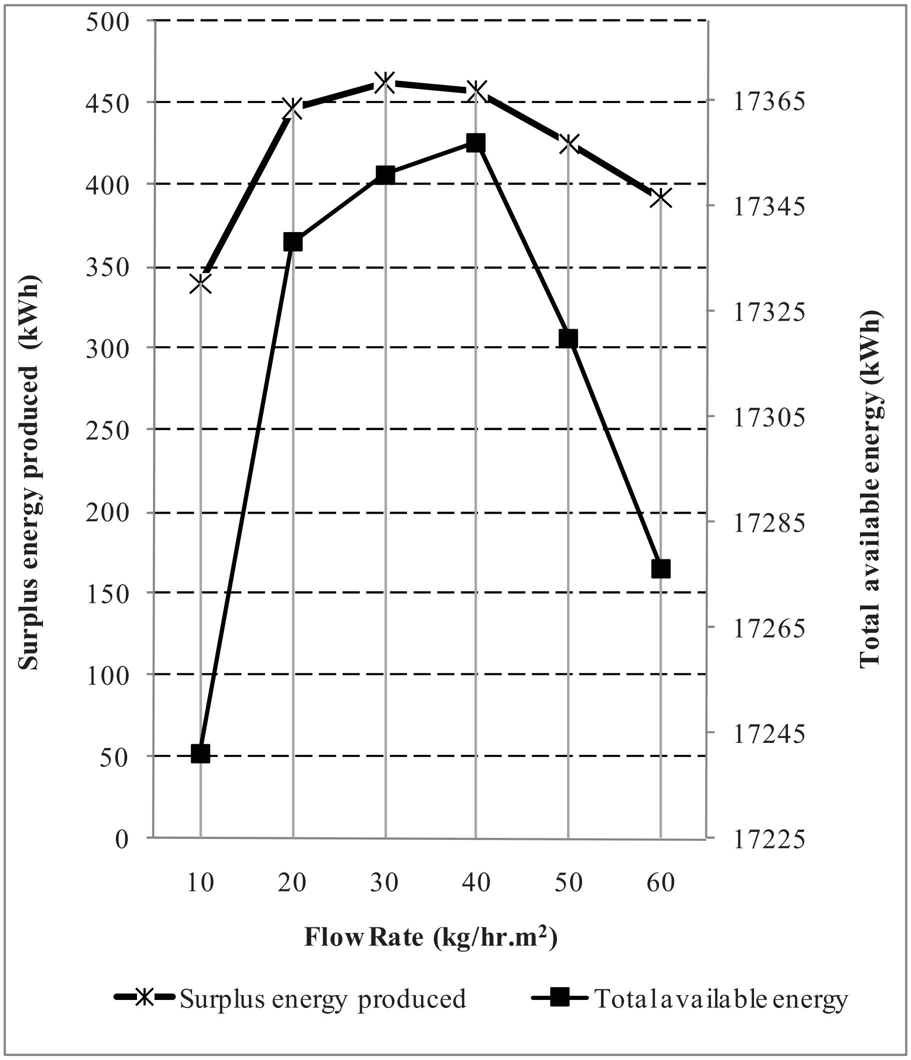


Figure 5.26 Total energy produced by PV/T at various flow rates

5.9.6 Final design of NZEH

Based on the sensitivity analysis, changes are made to the initial design and the final design is presented in this section along with the corresponding results.

5.9.6.1 Summary of the Final NZEH Proposal

The configuration of the final NZEH proposal includes 8.64 kW PV/T system having 57.6 m^2 of aperture area (65.3 m^2 of gross area), flow rate of 30 $kg/h{\cdot}m^2$ and the solar tank with volume of 1,041 L (275 gal). With this configuration, on an annual basis the thermal energy produced is 6,627 kWh, i.e.115 kWh/m^2 and the total electricity produced is 10,456 kWh, i.e. 182

kWh/m^2 of PV/T area. The value for electrical energy supplied by PV/T is after taking into consideration the inverter losses. Table 5.21 presents the thermal and electrical energy need and supply for the house by the PV/T. The PV/T produces 2,805 kWh of less thermal energy than needed but 3,270 kWh of extra electricity. The extra electricity supplies for the thermal load via the auxiliary heating element in the tank and still a surplus of 465 kWh is left. Thus the house produces as much energy as it needs, achieving the net zero goal with a slight surplus.

Table 5.21 NZEH annual energy balance

		Energy used in NZEH (kWh)	Energy supplied by PV/T (kWh)
Thermal	Space heating	6,846	
	DHW	1,559	
	Tank losses	1,027	
	Total thermal	**9,432**	**6,627**
Electrical	Cooling	607	
	Appliances	2,490	
	Lighting	637	
	HRV, pumps	2,324	
	Miscellaneous Electric Load	1,128	
	Total electrical	**7,186**	**10,456**
Total (thermal + electrical)		**16,618**	**17,083**
Surplus electricity produced by PV/T			**465**

Figure 5.27 presents the monthly distribution of thermal as well as electrical energy used for various purposes in the NZEH. Other than the three months in winter, i.e. November to January, the house produces more energy than it needs. Since the house is grid connected, it uses electricity from utilities for these three months and sells it back to the utilities during the rest of the year, thus achieving Net Zero goal on an annual basis.

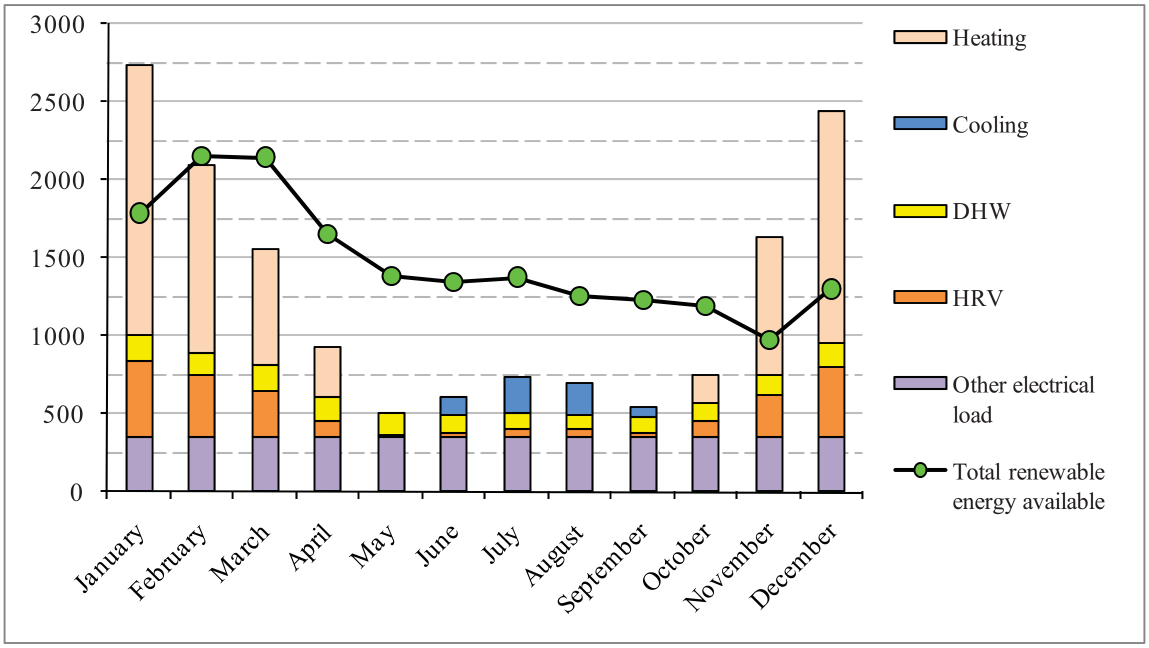


Figure 5.27 Monthly distribution of energy use for various needs in the NZEH (kWh)

To compare the results with other NZEHs, the most relevant study by Biaou et al. (2004) is presented here. They used 85.4 m^2 PV panels with nominal efficiency of 11.5% along with a GSHP for a 156 m^2 R-2000 house with unheated basement in Montreal to convert it to NZEH. Using TRNSYS for simulation, they reported the PV production of 159 kWh/m^2, while it is 182 kWh/m^2 in the current study. The peak loads reported were 9.0 kW for heating and 3.3 kW for cooling compared to 8.6 kW for heating and 4.9 kW for cooling in the current study. The total cooling load was found to be 1,742 kWh compared to 1,822 kWh in the current NZEH.

5.9.6.2 PV/T Production: Monthly and Daily

PV/T monthly production:

The monthly thermal and electrical energy production by the PV/T is shown in Figure 5.28. The highest total electrical plus thermal energy available for the NZEH is in the month of February, 2,152 kWh and the lowest is in November, 973 kWh. Since the total thermal loads (heating + DHW) are lower in summer compared to winter, the PV/T pump runs less frequently in summer, thus thermal energy collection and storage is less in summer than in winter.

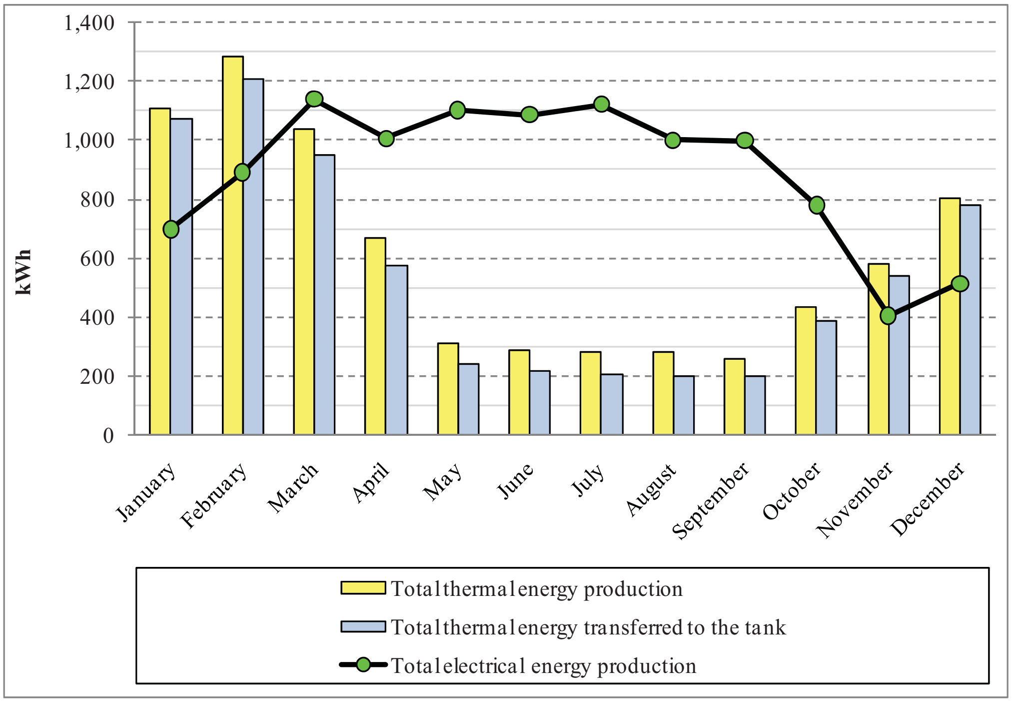


Figure 5.28 PV/T monthly electrical and thermal production

The electricity production by PV/T follows the trend of solar radiation received by the PV/T area, as seen in Figure 5.29. About 10 – 13% of total solar radiation received on the PV/T is converted into electrical energy by the PV/T.

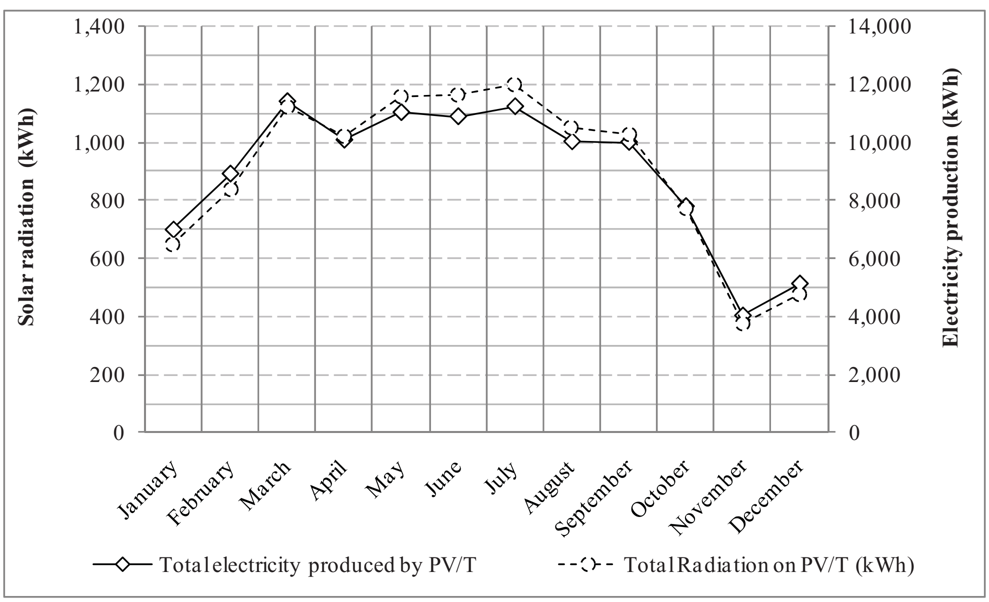


Figure 5.29 Comparison of surface radiation on and electricity produced by PV/T

PV/T daily production:

Figures 5.30 and 5.31 present the thermal and electrical production on the coldest and the hottest day of the year, respectively. As mentioned earlier, the hot water is needed only for DHW and not for the radiant floor in summer; hence the heat transferred to the tank is not completely utilized, resulting in higher tank temperatures, further reducing the heat exchange with the PV/T heat exchanger. The PV/T pump is shut off whenever the top node temperature in the tank reaches 90°C or the PV/T outlet temperature is lower by at least 2°C than the nodal temperature at the bottom of the tank where PV/T heat exchanger is located. Thus, as seen in these two figures, on the winter day, almost all the thermal energy produced by the PV/T is transferred to the tank, while in summer the thermal production is minimal.

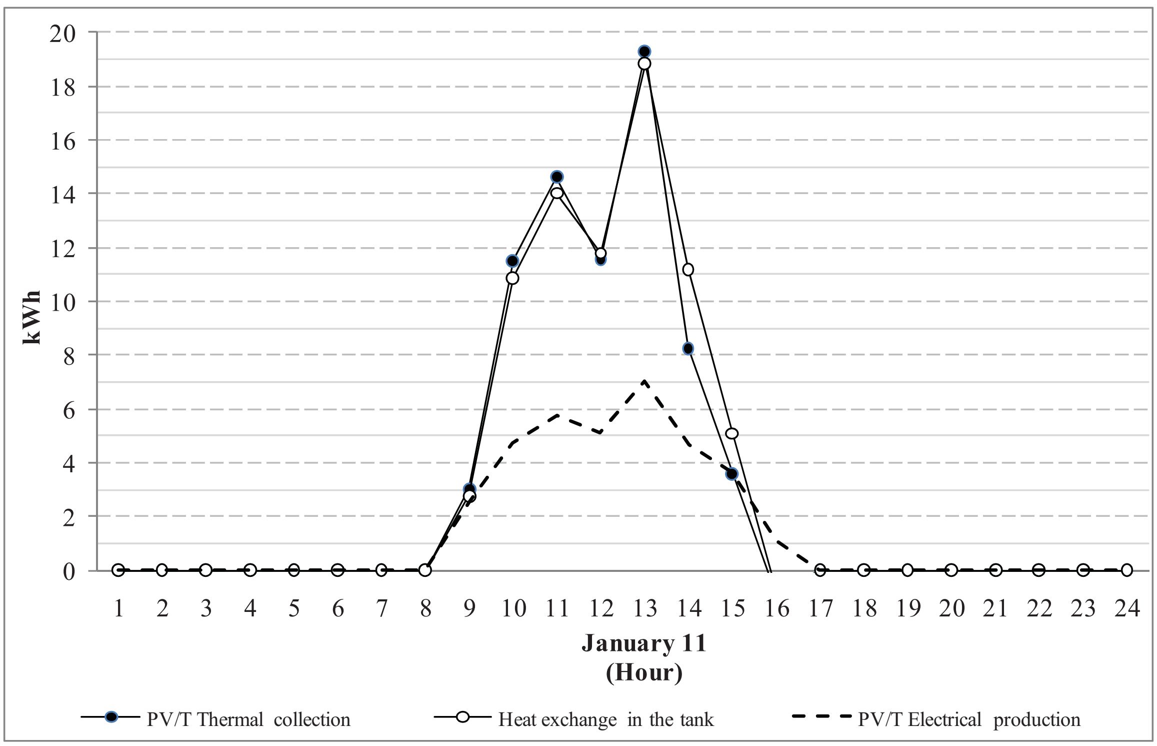


Figure 5.30 Daily PV/T electrical and thermal production in winter

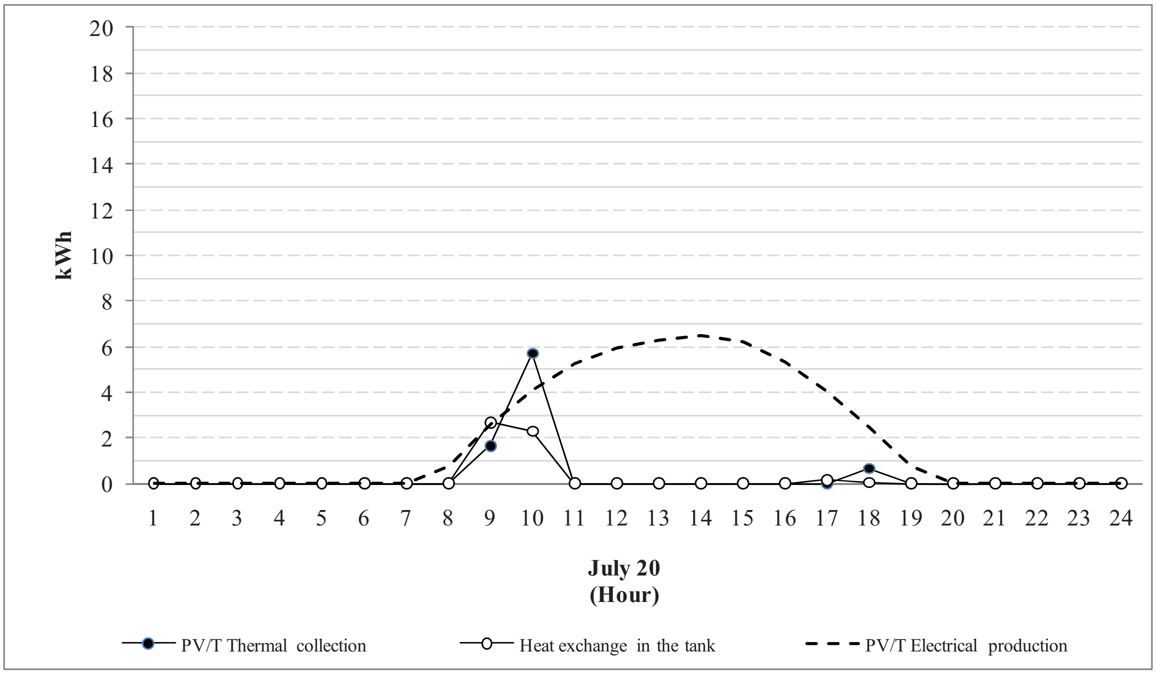


Figure 5.31 Daily PV/T electrical and thermal production in summer

In case of electrical production, its peak is slightly higher on the cold winter day compared to the hot summer day. The total daily electrical production, however, is lower on the winter day, i.e. 35 kWh, compared to 50 kWh on the summer day, due to longer daylight hours in summer. The PV production can be increased further if the PV/T pump runs continuously during daytime in summer, thereby lowering the PV cell temperature. This is only possible if there is an infinite heat sink available for all the heat produced by PV/T to be discharged, such as the ground.

Figure 5.32 shows the PV cell temperatures during daytime on these two particular days in winter and summer. On the winter day the cell temperature goes above 60°C in spite of the ambient temperature being well below 0°C; while on the summer day it reaches up to 200°C. According to the manufacturer of the PV/T used, the modules do withstand temperatures over 200°C.

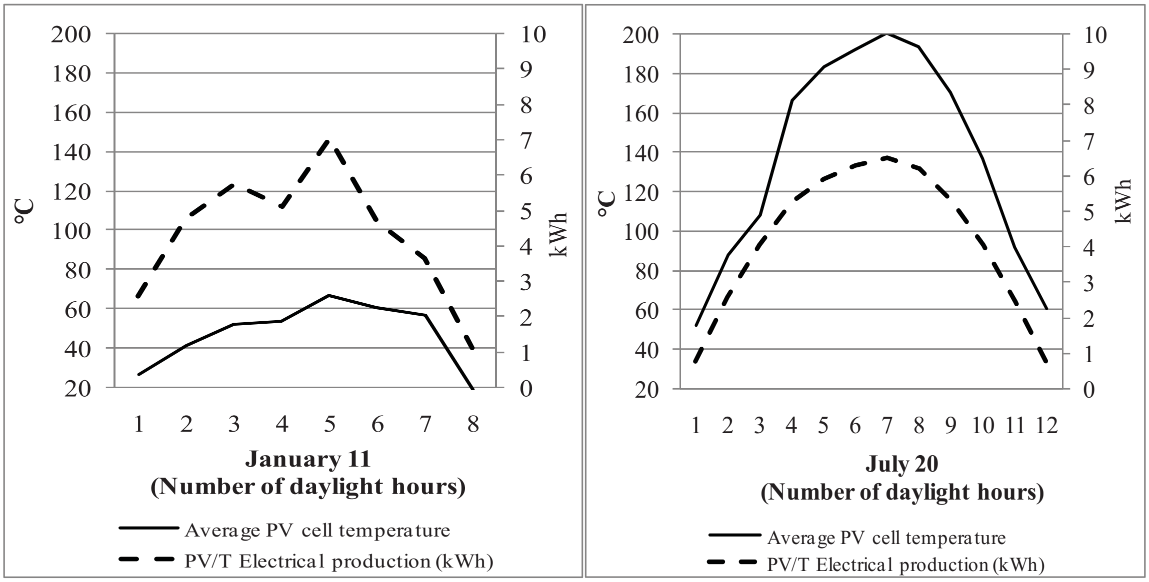


Figure 5.32 PV cell temperature and electrical production

5.9.6.3 Heating Energy Use: Monthly and Daily

The energy used for radiant floor heating is measured at the tank in terms of the energy transferred to the RF heat exchanger in the tank. The set-point temperature for all the zones during the day (between 6:00 am to 8:00 pm) is 21°C and the set-back at night is 19°C. On an annual basis, 6,561 kWh of thermal energy is required for radiant floors during the heating season, i.e. from October 17th to April 24th. Figure 5.33 shows the monthly distribution of heating energy required for radiant floors in the entire house along with the rest of the thermal energy outputs from and inputs to the tank.

The highest amount of energy is needed in the month of January, which is also the coldest month of the year. For the entire house, the heating peak of 8.58 kW occurs on February 13th at 6:00 am. The discussion about the energy balance in the tank shown in Figure 5.33, in order to avoid duplication, is presented in the following section, 5.9.6.4.

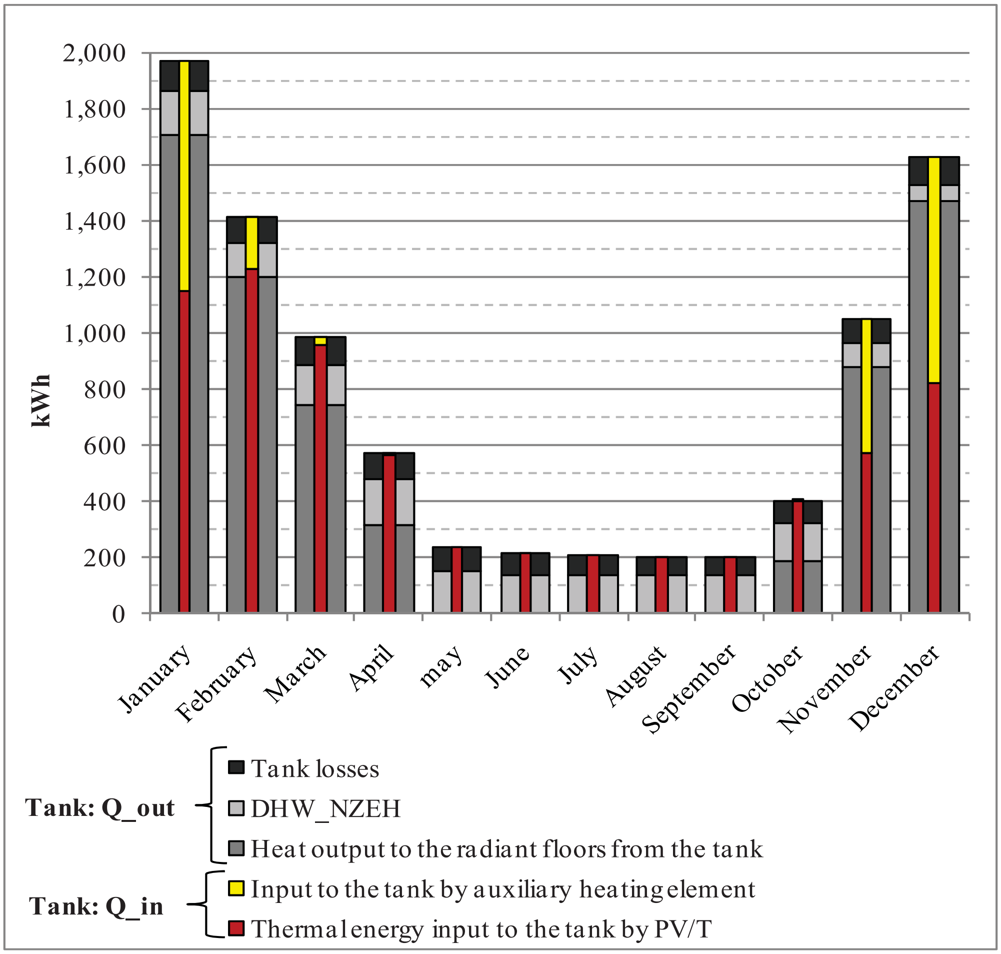


Figure 5.33 Monthly energy distribution related to heating and DHW and energy balance in the tank

Figure 5.34 shows the daily heating energy need for heating and auxiliary electricity required in the tank for January 11th, which is the coldest day of the year. Although the PV/T provides the thermal energy for heating between 8:00 am to 4:00 pm, auxiliary heating is still needed to supplement that. The radiant floor pump runs continuously from 3:00 am to 3:00 pm and charges the concrete floor. After 4:00 pm, the auxiliary heater turns on only intermittently for 1-2 time-steps (0.17 kWh, hence not apparent in Figure 5.34).

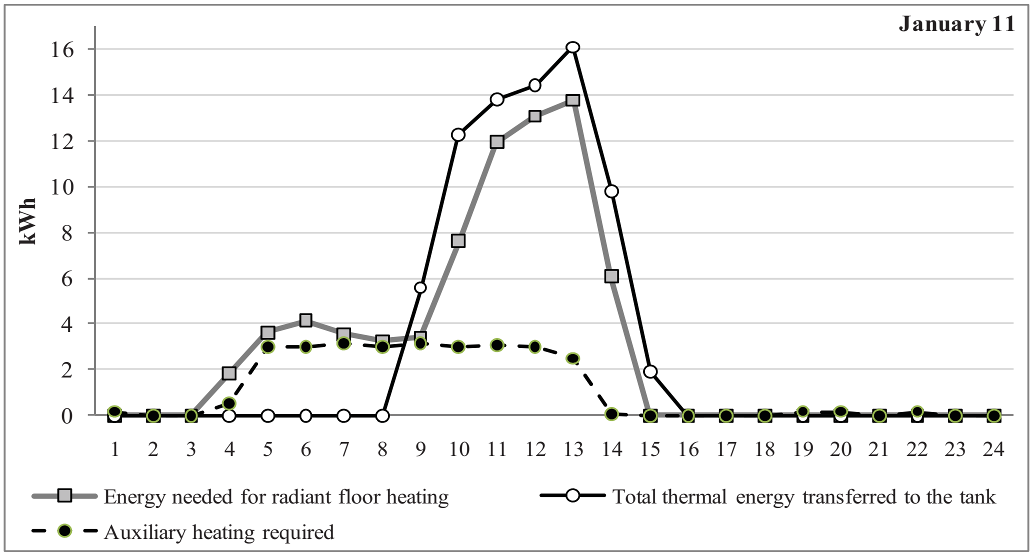


Figure 5.34 Daily energy distribution for heating on the coldest day of the year

After discussing the energy performance of radiant floors on this coldest day of the year, it is also crucial to verify the temperatures in the zones on this day. Therefore, for this winter day, the zone air temperatures in comparison with the floor temperatures are shown in Figure 5.35 for the south side Kitchen-Den zone on the second floor. For the same zone, the zone air temperature in comparison with the ambient temperature is presented in Figure 5.36.

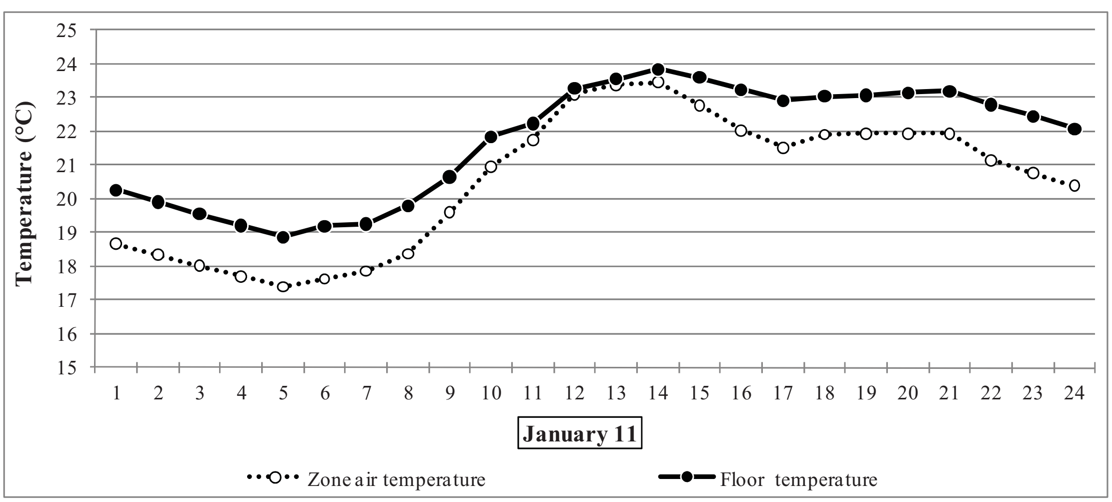


Figure 5.35 Zone air and floor temperatures on the coldest day of the year

(SF_KitDen zone)

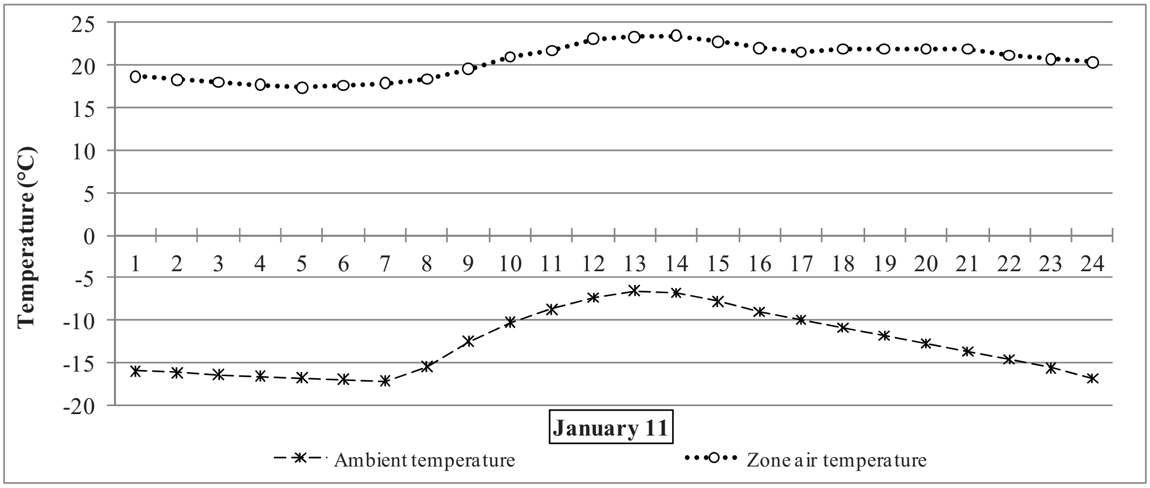


Figure 5.36 Zone air and the ambient air temperatures on the coldest day of the year (SF_KitDen zone)

5.9.6.4 Temperatures and energy balance in the tank

As mentioned earlier, the tank size used in the final proposal is 1,041 L (275 gal). Figures 5.37 and 5.38 show the nodal temperatures in the tank in winter and summer, respectively. The tank is well stratified during night time in winter in spite of the heat exchange with the radiant floor heat exchanger with its comparatively higher flow rates but lower temperature difference. But during the day, as soon as the exchange with the PV/T heat exchanger starts, significant amount of mixing is noticed. On the summer day, as shown in Figure 5.37, the temperature of the entire tank is higher than 70°C, even at night.

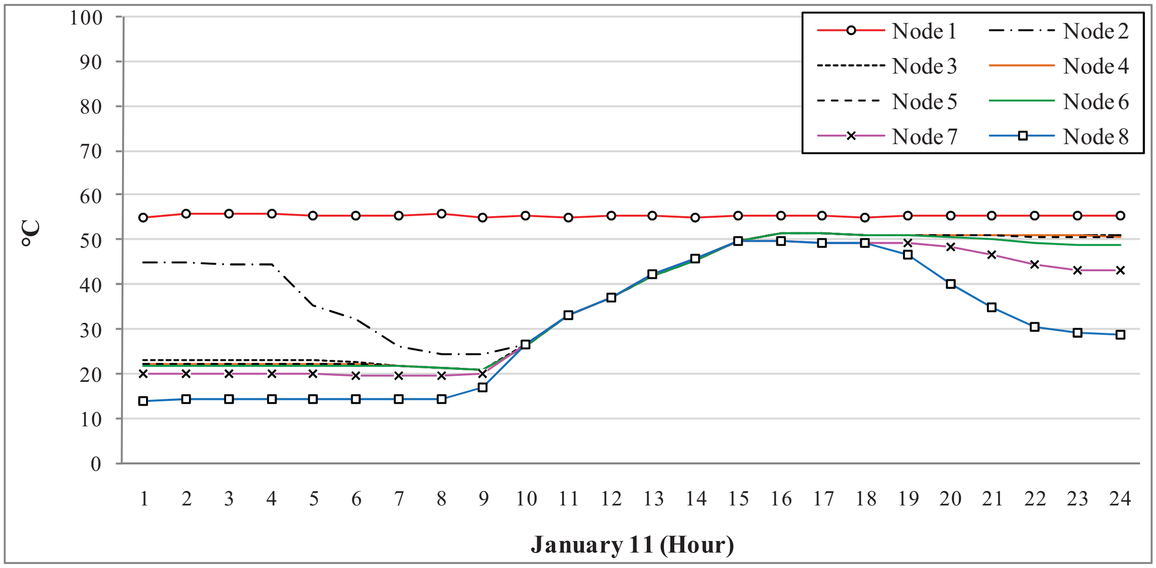


Figure 5.37 Daily tank nodal temperatures in winter

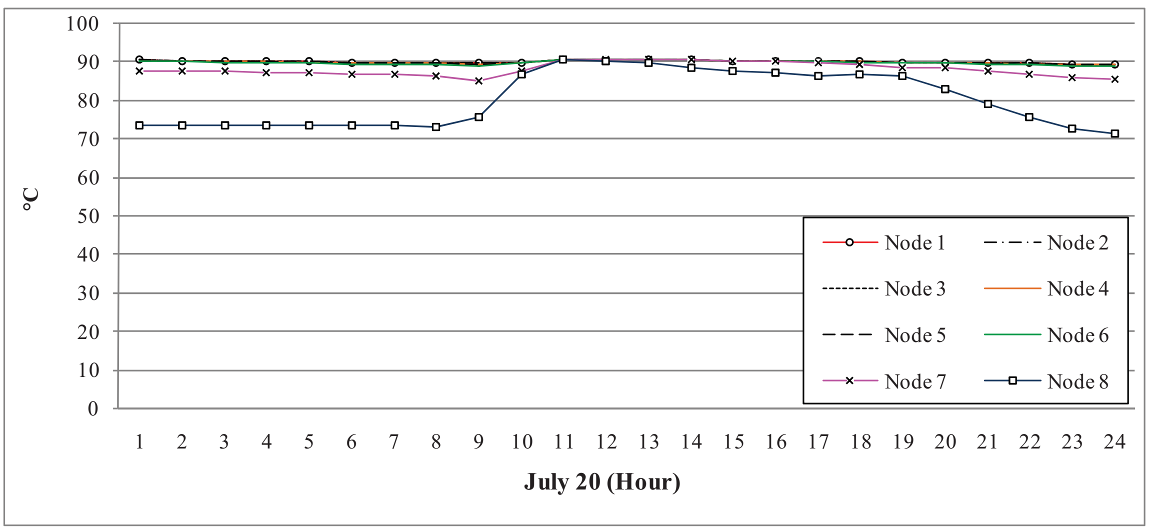


Figure 5.38 Daily tank nodal temperatures in summer

The energy related to various activities in the tank, on an annual basis, is presented in Table 5.22. The tank losses presented are with tank insulation of R 3.4.

Table 5.22 Annual energy balance in the tank

Tank_energy in		Tank_energy out	
Tank auxiliary heating	2528	Radiant floor heating	6567
PV/T thermal input in the tank	6627	DHW	1559
_	_	Thermal losses from tank	1027
Total	**9155**	Total	**9153**

The monthly energy balance is presented earlier in Figure 5.33 in section 5.9.6.3. The auxiliary heating is never needed in the tank in the summer months, as the DHW is taken care of entirely by PV/T.

5.9.7 Conclusion

The energy distribution for various loads in NZEH is presented in Figure 5.39. The highest percentage i.e. 41% of it is required for heating. Most of this 41% is for radiant floor heating with a very small portion for the baseboard heaters in the stair zones. Thus, this heating energy presented, along with most of the 9% for DHW and 6% in tank losses is mostly thermal energy, and the rest is electrical energy. It should be noted that although summed up together here for simplification, thermal and electrical energies have very different qualities.

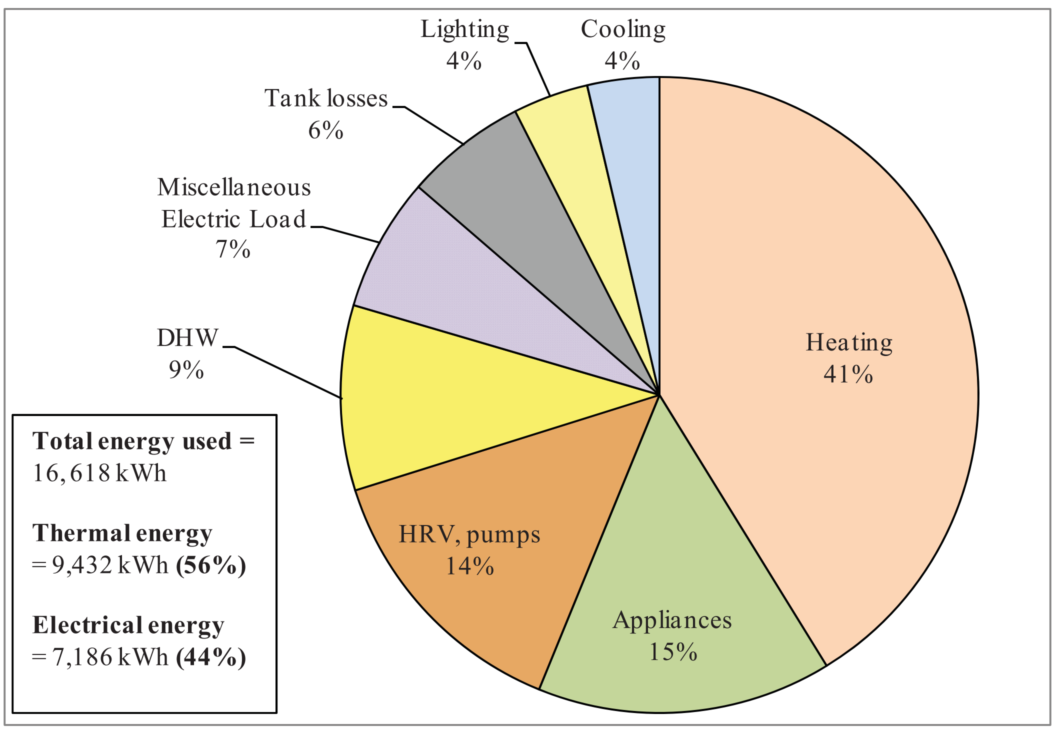


Figure 5.39 Distribution of combined thermal and electrical energy used in NZEH annually

Shading and natural ventilation play an important role in reducing cooling loads as well as maintaining the room temperatures in comfortable range, especially during shoulder seasons. They are even more important in NZEHs, for which every kWh counts.

In case of PV/T, the optimum tilt angle analysis is done on an annual basis. The smaller inclination angle (with horizontal) is desirable for summer months since the sun is high up in the sky in summer. On the other hand, during winter months better performance can be achieved with larger angles since sun is low in the sky. Thus, although the optimal angle found was 55° and not 45°, further analysis on seasonal or even monthly basis is desirable to choose and fix the inclination that is suitable for the entire year, keeping in mind that the energy required for this Montreal NZEH is higher during winter months.

The most important conclusion to this chapter is the significance of holistic approach to the design of NZEH. The key to efficient NZEH design is that none of the systems in it should be studied isolated. All the systems, including lighting, heating, air conditioning, ventilation, renewable energy generation, etc. are inter-linked and affect each other one way or the other, and their inter-dependence may not always be obvious.

The life cycle analysis of this proposal is presented further in chapter 7.

6. Base Case and NZEH in 2050

This chapter presents the impact of climate change on the Base Case house and the NZEH. For this purpose, the weather data extracted from the GCMs presented earlier in Chapter 3 is used.

6.1 Simulating the Weather for 2050 in TRNSYS

Several changes need to be made to the base case as well as the NZEH models in order to obtain the hourly weather data required for simulations. Following sections 6.1.1 through 6.1.3 present the TRNSYS Types used to replace the weather model Type 15.

6.1.1 Weather Generator

The weather data to be used for 2050 is in the form of monthly average values for all the parameters, i.e. ambient temperature, solar radiation, wind speed, and humidity. Since the simulation requires at least hourly weather data, Type 54 is used in TRNSYS, which generates hourly values from monthly data. The literature review indicated the use of Type 54 in many studies, e.g. Ghoneim (1992), Al-Rabghi and Hittle (2001), Datta(2001), Cardinale et al. (2003), Ghoneim (2005), Zogou (2007), and Oliveti et al. (2008).

The mathematical description of this component and the studies based on which the algorithm of this component is developed are presented in TRNSYS documentation (Solar Energy Laboratory, 2006, p. 5.302). Many of the correlations used in the development of this model are based mainly on data from temperate climate; therefore, it is most accurate for locations in temperate climates rather than e.g. tropical climate. The parameters include the latitude and altitude values, which are 45.47 W and 36 m respectively (ASHRAE, 2005). The average monthly values of temperature, radiation, humidity ratio, and wind speed are supplied as inputs to the model. The outputs, dry bulb temperature, percent relative humidity, and wind speed are directly fed to Type 56. Additional steps are required to obtain the radiation data needed by the building model Type 56, as explained below in section 6.2.

6.1.2 Radiation Data

The weather generator only provides hourly radiation only on horizontal. The base case as well as the NZEH building has surfaces including facades and roof with up to 10 different orientations. To calculate the radiation on each of these surfaces, a solar radiation processor is used, i.e. Type 16c. The hourly total horizontal solar radiation, ambient temperature, and relative humidity values are supplied to it by the weather generator. The other inputs include slope and azimuth of each of the surfaces. Based on these inputs, the component calculates radiation for each surface, which is then supplied to Type 56.

6.1.3 Sky Temperature

The effective sky temperature is calculated by using Type 69. The ambient temperature and dew point temperature values from the weather generator are used by this component to calculate the cloudiness of the sky. The calculated sky temperature output is then supplied to Type 56 as well as Type 701.

6.2 Base Case in 2050

This section presents the impact of climate change on the base case. For this purpose the weather data for 2050 as well as the baseline weather 1961-1990 is used, as explained further. The changes made specifically to the Base Case model are also presented.

6.2.1 Changes to the Base Case Model

After the Base Case model was calibrated using the electricity bills as explained in Chapter 4, a few changes are made to the model before simulating it for 2050. The heating set-point in the basement, which was previously 10°C as set by the owner, is now changed to 21°C during the day and 18°C at night. The second change is regarding the heating season, which was previously set strictly from October 17th to April 24th. It is kept the same; however, heating is allowed during shoulder seasons in case the zone air temperature drops below 15°C. The shading and ventilation strategies are improved by using different temperature criteria for each zone, in each season, depending on the position of the zone.

After the Base Case R-2000 model is thus ready, the same model is then simulated in the baseline climate (1961-1990) and in 2050. In order to compare the loads in these two climates effectively, no further changes are made to the model. The simulations for the current climate are carried out by replacing the TMY2 file with the baseline weather data (1961-1990) extracted from each of the GCMs. This allows a direct comparison between the results for the current climate and for 2050 using the same climate model.

6.2.2 Results and discussion for the Base Case in 2050

Table 6.1 presents the comparison of heating and cooling loads, and Table 6.2 presents the comparison of peak loads for the current, i.e. baseline climate and 2050.

Table 6.1 Annual heating and cooling loads for Base case: Current climate versus 2050s

	CGCM2		ECHAM4		HadCM3	
	A2	B2	A2	B2	A2	B2
Heating load in current climate (kWh)	7,972	7,966	13,276	13,321	8,428	8,428
Heating load in 2050 (kWh)	6,341	6,806	10,420	10,422	7,501	7,535
Absolute change in heating load (kWh)	-1,631	-1,160	-2,856	-2,899	-927	-893
Relative change in heating load (%)	-20	-15	-22	-22	-11	-11
Cooling load in current climate (kWh)	909	916	563	558	684	674
Cooling load in 2050 (kWh)	1,191	1,146	1,084	1,005	1,285	1,249
Absolute change in cooling load (kWh)	282	230	521	447	601	575
Relative change in cooling load (%)	31	25	93	80	88	85

Table 6.2 Peak heating and cooling loads for Base case: Current climate versus 2050s

	CGCM2		ECHAM4		HadCM3	
	A2	**B2**	**A2**	**B2**	**A2**	**B2**
Peak heating load in current climate (kW)	10.24	10.24	11.21	11.22	9.88	9.87
Peak heating load in 2050 (kW)	9.26	9.74	10.33	10.21	9.59	9.69
Absolute change in peak heating load (kW)	-0.98	-0.5	-0.88	-1.01	-0.29	-0.18
Relative change in peak heating load (%)	-10	-5	-8	-9	-3	-2
Peak cooling load in current climate (kW)	3.39	3.44	3.44	3.43	2.52	2.52
Peak cooling load in 2050 (kW)	4.38	4.32	4.69	4.41	3.96	3.83
Absolute change in peak cooling load (kW)	0.99	0.88	1.25	0.98	1.44	1.31
Relative change in peak cooling load (%)	29	26	36	29	57	52

Although the change in the cooling load in kWh is much smaller compared to that in the heating load, the indication that the earlier can increase by 80- 93%, under some scenarios, is alarming, considering the fact that most of the houses in the current building stock are not equipped with any cooling system.

To evaluate the effectiveness of night cooling and shading strategy, simulations are carried out in two stages without these measures. For the first stage, simulations are run with internal shading but without the night cooling, while for the second stage, simulations are run with neither the night cooling nor shading. The results show an increase in cooling load; for instance, if the base case house does not use night ventilation, under the CGCM2 A2 scenario, the cooling load increases from 1,191 kWh to 1,612 kWh in 2050, a 35% increase. Furthermore, under the same scenario, if neither the night cooling nor the shading is used, the cooling load increases by 112%, i.e. from 1,191 kWh to 2,523 kWh. All the basement zones maintain comfortable temperatures throughout the year in 2050 climate, never exceeding 29ºC, even without the shading or natural ventilation. Thus, the results indicate no need for cooling in the basement in the current or the 2050 climate.

Table 6.3 presents the comparison of total energy use for the base case house in the baseline climate versus 2050.

Table 6.3 Total annual energy use for space conditioning for Base case: Current climate versus 2050

	CGCM2		ECHAM4		HadCM3	
	A2	B2	A2	B2	A2	B2
Total energy use in current climate (kWh)	8,275	8,271	13,464	13,507	8,656	8,653
Total energy use in 2050 (kWh)	6,738	7,188	10,781	10,757	7,929	7,951
Absolute change in total energy use (kWh)	-1,537	-1,083	-2,682	-2,750	-727	-701
Relative change in total energy use (%)	-19	-13	-20	-20	-8	-8

In spite of the increase in cooling load in 2050 as presented earlier in Table 6.1, the total energy use for the base case house is predicted to decrease by 8-20% in 2050 climate. As the house under consideration is located in heating dominated climate, the decrease in heating load exceeds the increase in cooling load, resulting in net decrease in total annual energy use. The COP of the heating and cooling systems used, also play a role in reducing the impact of cooling load increase. As the COP for electric baseboard heaters is one, while it is three for air conditioners, the heating energy use is equal to heating load, while the cooling energy use is 1/3rd the cooling load.

The results from this research are compared with a few studies from the literature, which are found to be in the similar range. Using CGCM2, Barrow et al. (2004) have predicted 17% and 13% decrease in HDDs with A2 and B2 scenarios respectively in 2050 compared to 1961-1990 for the location of Sept Iles, Quebec. The increase in CDDs is much steeper, 578% with A2 and 367% with B2 scenarios. Similar to the current study, they also observed the magnitude of change with A2 to be higher than with B2 scenario.

Zmeureanu and Renaud (2008) have found an 8 to 17% decrease in heating energy use in 2050 for a sample of 11 houses in Montreal. Similarly, Iolova et al. (2007) using TRNSYS for simulation, have also reported a decrease of 17% in heating energy use in 2030 relative to the same baseline; the cooling energy is found to have tripled.

6.3 NZEH in 2050

This section presents the impact of climate change by 2050 on the space conditioning loads and total energy use of the NZEH; the impact on electrical and thermal energy production of the PV/T system is also included. The changes made to the NZEH model, before simulating it with the GCM data, are discussed first, followed by the results and discussion.

6.3.1 Changes Made to the NZEH Model for 2050

In order to obtain the hourly weather data from the monthly GCM data, similar procedure is used for the NZEH model as the Base case model, i.e. the three Types in TRNSYS - the weather generator, the radiation processor, and the effective sky temperature calculator are added to the NZEH model, replacing the weather data reader, Type 15. The pertinent weather information is supplied to the various components in the NZEH model via these three newly added Types. For example, the PV/T model now receives the ambient temperature and the wind speed information from the weather generator, Type 54, and the incident beam and diffuse radiation on the south roof as well as the incidence angle of beam radiation from the radiation processor, Type 16c. Similarly, the HRV receives the dry bulb temperature and the humidity information from the weather generator, Type 54. In addition, Type 56, Type 701 and numerous controllers in the model receive all the weather related information from Type 54, Type 16c and Type 69b, all of which was solely supplied earlier by Type 15.

As done in the case of the Base Case, NZEH is also simulated with the weather data obtained from the GCMs - first with the baseline climate data, 1961-1990 instead of TMY2 data, and then with the 2050 data. The combi-system configuration and the related details are kept the same as explained in Chapter 5 for all the cases.

6.3.2 Results and discussion for the NZEH in 2050s

Table 6.4 presents the heating energy use for the NZEH in the current climate and in 2050. All the climate models consistently show decrease in energy required for heating, ranging from 10 to 20%. It should be noted that the energy for radiant floor heating is thermal energy and the energy for baseboard heating in stairs is electrical energy, although the two are added to obtain the total heating energy.

Table 6.4 Annual heating energy use in NZEH: current climate versus 2050

	CGCM2		ECHAM4		HadCM3	
	A2	B2	A2	B2	A2	B2
Current climate (1961-1990)						
Radiant floor heating (kWh)	6,864	6,835	10,349	10,373	7,240	7,247
Baseboard heating in stairs (kWh)	296	297	1,178	1,189	302	300
Total energy for heating (kWh)	7,160	7,132	11,527	11,562	7,542	7,547
2050						
Radiant floor heating (kWh)	5,526	5,913	8,732	8,693	6,510	6,542
Baseboard heating in stairs (kWh)	205	228	688	704	263	265
Total energy for heating (kWh)	5,731	6,141	9,420	9,397	6,773	6,807
Change in the total heating energy						
Absolute change in total heating energy (kWh)	-1,429	-991	-2,107	-2,165	-769	-740
Relative change in total heating energy (%)	-20	-14	-18	-19	-10	-10

The cooling loads for the NZEH from each of the GCMs are presented in Table 6.5. The results from all the climate models indicate an increase in cooling load in 2050, with the range of increase being quite wide, from 26 to 123%. Although both the Base Case and the NZEH have similar envelope, there are some other factors that are different and that might contribute to different cooling loads in these two houses, e.g. NZEH has concrete floor instead of carpet and it has HRV. In addition, there are some differences in the shading and natural ventilation schedules, and various internal gains are different as well.

Table 6.5 Annual cooling load in NZEH: current climate versus 2050

	CGCM2		ECHAM4		HadCM3	
	A2	**B2**	**A2**	**B2**	**A2**	**B2**
Current climate (1961-1990) (kWh)	719	729	519	514	477	473
2050 (kWh)	953	921	1,052	976	1,063	1,032
Absolute change in cooling load (kWh)	234	192	533	462	586	559
Relative change in cooling load (%)	33	26	103	90	123	118

Although the relative change in cooling energy demand is much higher than the change in heating energy demand, due to higher absolute values of energy need for heating over cooling in Quebec, the net change predicted for 2050 is a decrease in the total energy demand. Combining the heating and cooling energy requirements, overall the house needs less energy in 2050 compared to the baseline temperature, with the reduction being 7 to 18%. Table 6.6 presents the total energy requirement for space conditioning in both the climates, current and future, using various models.

Table 6.6 NZEH annual total heating and cooling energy need: current climate versus 2050

	Total heating and cooling energy from various GCMs (kWh)					
	CGCM2		ECHAM4		HadCM3	
	A2	**B2**	**A2**	**B2**	**A2**	**B2**
Current climate (kWh)	7,400	7,375	11,700	11,733	7,701	7,705
2050 (kWh)	6,049	6,448	9,771	9,722	7,127	7,151
Absolute change in total energy for heating and cooling (kWh)	-1,351	-927	-1,929	-2,011	-574	-554
Relative change in total energy for heating and cooling (%)	-18	-13	-16	-17	-7	-7

Figure 6.1 shows the monthly percent change in the combined heating and cooling energy use in 2050 compared to the base line climate, 1961-1990. The amount of energy for space conditioning in 2050 decreases during the winter months while it increases during the summer months.

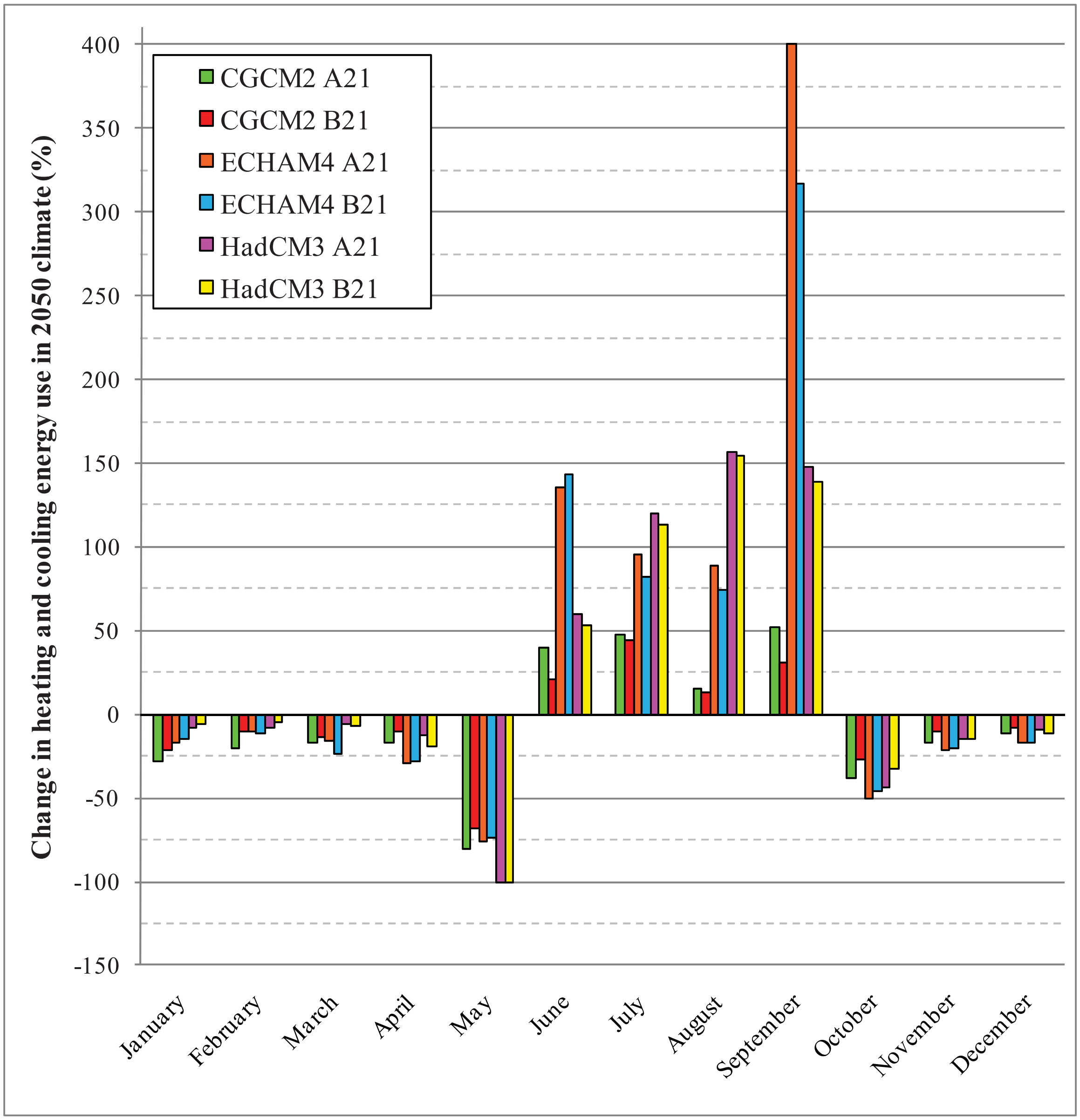


Figure 6.1 Percent change in monthly energy use in 2050 for space conditioning in NZEH compared to the baseline climate (1961-1990)

Table 6.7 shows the comparison between energy requirements for HRV fan, auxiliary heating for HRV, and pumps in the current versus 2050 climate. This total energy need decreases by 9 to 20% in 2050, mostly due to the decrease in the auxiliary heating for HRV which is almost 75% of the total energy required for the HRV.

Table 6.7 Energy requirement for HRV and pumps: current climate versus 2050

	CGCM2		ECHAM4		HadCM3	
Energy used for HRV and pumps	**A2**	**B2**	**A2**	**B2**	**A2**	**B2**
Current climate (1961-1990) (kWh)	2,403	2,400	3,201	3,211	2,477	2,475
2050 (kWh)	2,030	2,136	2,562	2,568	2,239	2,254
Absolute change (kWh)	-373	-264	-639	-643	-238	-221
Relative change (%)	-16	-11	-20	-20	-10	-9

The electrical and thermal energy production by the PV/T in the two climates is shown in Table 6.8. The results obtained by using data from both CGCM2 as well HadCM3 show a slight decrease in PV/T production, while results using ECHAM4 show slight increase.

Table 6.8 PV/T electrical and thermal production: current climate versus 2050

	CGCM2		ECHAM4		HadCM3	
	A2	**B2**	**A2**	**B2**	**A2**	**B2**
Electrical energy produced by PV/T						
Current climate (1961-1990) (kWh)	11,034	11,013	5,550	5,532	10,348	10,345
2050 (kWh)	10,792	10,819	5,763	5,705	10,276	10,453
Absolute change in electrical energy production (kWh)	-242	-194	213	173	-72	108
Relative change in electrical energy production (%)	-2	-2	4	3	-1	1
Thermal energy produced by PV/T						
Current climate (1961-1990) (kWh)	7,283	7,268	3,067	3,058	7,469	7,458
2050 (kWh)	6,675	6,805	3,110	3,083	6,737	6,802
Absolute change in thermal energy production (kWh)	-608	-463	43	25	-732	-656
Relative change in thermal energy production (%)	-8	-6	1	1	-10	-9

Tables 6.9 - 6.11 present the thermal and electrical loads of NZEH and the energy supplied by PV/T under each of the six scenarios. The thermal energy load not met by the PV/T is supplied as auxiliary electric heating element in the tank, for which the electricity is supplied by the PV/T. The total electricity values presented in these three tables include this auxiliary electricity supplied to the tank, besides all other the electric loads of the NZEH. The inverter losses are taken into consideration while calculating the surplus electricity produced by the PV/T.

The results from CGCM2 and HadCM3 are unanimous about the house reaching the net zero status with the same area of PV/T as discussed in Chapter 5, i.e. 16 PV/T panels with aperture area of 57.6 m^2 and gross area of 65.28 m^2. However, results from ECHAM4 with both A2 and B2 scenarios show that the energy produced by the house is much lower than its requirement, with the deficit being in the range of 10,000 to 13,000 kWh. It should be noted that in case of CGCM2 and HadCM3 the surplus is higher in 2050 than in the base line climate in spite of lower energy production in 2050, which can be attributed to the reduction in heating energy requirement. The increase in cooling load does not affect this situation much, due to the higher COP of air conditioners compared to baseboard heaters.

It should be noted that with ECHAM4, the house has a significant energy deficit in the current climate to begin with; it does not produce enough energy in the future climate either. Therefore even though the total space conditioning energy need decreases by 16 to 17% and the PV/T energy production increases by 1 to 4% in 2050, the house still does not achieve net zero goal in 2050.

Table 6.9 NZEH thermal and electrical energy annual demand and supply (kWh): Current climate versus 2050 using CGCM2 data

	CGCM2 A2			CGCM2 B2		
	Current climate	**2050**	**Change**	**Current climate**	**2050**	**Change**
Thermal energy needed (DHW + Heating + Tank losses)	9,490	8169	-1,321	9461	8550	-911
Thermal energy produced by PV/T	7,283	6675	-608	7268	6805	-463
Thermal energy shortcome (supplied to tank by auxiliary electricity from	2,207	1494	-713	2193	1745	-448
Total electricity needed	9,413	8322	-1,091	9394	8679	-715
Electricity produced by PV/T	11,034	10792	-242	11013	10819	-194
Surplus electricity produced by PV/T	1,345	2,201	855	1,344	1,870	526

Table 6.10 NZEH thermal and electrical energy annual demand and supply (kWh): Current climate versus 2050 using ECHAM4 data

	ECHAM4 A2			ECHAM4 B2		
	Current climate	**2050**	**Change**	**Current climate**	**2050**	**Change**
Thermal energy needed (DHW + Heating + Tank losses)	12,676	11,092	-1,584	12,698	11,048	-1,650
Thermal energy produced by PV/T	3,067	3,110	43	3,058	3,083	25
Thermal energy shortcome (supplied to tank by auxiliary electricity from PV/T)	9,609	7,982	-1,627	9,640	7,965	-1,675
Total electricity needed	18,393	15,815	-2,578	18,442	15,796	-2,646
Electricity produced by PV/T	5,550	5,763	213	5,532	5,705	173
Surplus electricity produced by PV/T	-12,982	-10,196	2,786	-13,049	-10,234	2,815

Table 6.11 NZEH thermal and electrical energy annual demand and supply (kWh): Current climate versus 2050 using HadCM3 data

	HadCM3 A2			HadCM3 B2		
	Current climate	**2050**	**Change**	**Current climate**	**2050**	**Change**
Thermal energy needed (DHW + Heating + Tank losses)	9,835	9,107	-728	9,843	9,143	-700
Thermal energy produced by PV/T	7,469	6,737	-732	7,458	6,802	-656
Thermal energy shortcome (supplied to tank by auxiliary electricity from PV/T)	2,366	2,370	4	2,385	2,341	-44
Total electricity needed	9,554	9,473	-81	9,572	9,451	-121
Electricity produced by PV/T	10,348	10,276	-72	10,345	10,453	108
Surplus electricity produced by PV/T	535	546	10	515	741	226

7. Life Cycle Analysis

Life Cycle Analysis (LCA), also referred to as Life Cycle Assessment, is an essential decision-support tool that can be used in construction industry for evaluating and/or comparing the alternatives of energy efficiency measures in buildings. This chapter presents the LCA of the Base case and the proposed NZEH. The three divisions of LCA included here are analyses of Life Cycle Cost, Life Cycle Energy, and Life Cycle Emissions. The analyses include the entire proposal of changes needed to convert the Base case house into a NZEH, along with focus on the individual systems as well as some selective system components, such as Gray Water Heat Recovery unit, Heat Recovery Ventilator etc. Finally, a comparison is made between the Base Case and the NZEH.

In order to estimate the replacement - cost, energy, and emissions - the life spans of various items are assumed based on either the information from the manufacturers or the specific references listed in the respective sections.

7.1 Life Cycle Cost

Life cycle cost of a building comprises of the initial cost as well as the operating costs during the life span of the building. Operating costs include the energy cost and the maintenance or replacement costs. Performing cost analysis on merely the first-cost basis presents only part of the picture. The other significant issues such as the life span of various components in the systems and the building as a whole, replacement costs, energy cost, energy cost escalation rate, inflation rate are various factors, all of which affect the complete life cycle cost analysis significantly.

The main source of information used for cost analysis here is RS Means (2009). The price quotes from various manufacturers and dealers are used whenever RS Means data are unavailable. The construction cost data from RS Means are based on the U.S. national average. In order to adjust these data to a particular location, the data need to be modified by using location factors, which are available for various locations in the U.S. and Canada. To obtain the costs for Montreal, the national average is multiplied by location factor/100, as recommended. The location factors for Montreal are 121.7 for material cost and 93.8 for installation cost. All the values taken from 2009 RS Means are the Bare Costs, i.e. including material, labor, and equipment costs but not including contractor profit and overheads. The cost data from RS Means presented anywhere in this chapter have been converted for Montreal location. Also, the currency sign $ refers to Canadian dollar. The total costs considered in the final cost analyses of both the cases include Provincial Sales Tax (PST) and the federal Goods and Services Tax (GST), a total of 12.875%.

The detailed cost breakdown of various items in the Base case and the NZEH, obtained from various sources, is presented in Appendix C.1.

7.1.1 Life Cycle Cost of the Base Case

7.1.1.1 Initial Cost of the Base Case

Part of the LCA of the Base case has been done in an earlier study by Kassab (2002), which mainly included the envelope but not any of the systems that are part of the analysis in this thesis such as the heating, DHW, lighting, or appliances. The total cost of envelope was estimated as $217,266 as per 2001 rates, which is assumed to be the same in this study, in spite of possible changes in material and labor costs or effects of inflation. The reason for not changing it is that the envelope for the NZEH is almost the same as in the Base case. Therefore any changes to the envelope costs would reflect equally in both the cases, thus nullifying the difference between the two. Some minor differences in the envelope between these two cases have been taken into consideration in respective sections. The total initial cost for the Base case is presented in Table 7.1.

Table 7.1 Total initial cost of the Base case

Item	Cost ($)
Envelope	217,266.00
Baseboard heaters	1,927.72
DHW Tank	1,286.05
Light bulbs: incandescent	29.84
Appliances*	8,916.75
Total initial cost (before tax)	229,426.36
Total initial cost (including 12.875% taxes)	**258,965.00**
*Two sets	

7.1.1.2 Maintenance & Operating Costs of the Base Case

Maintenance: Replacement Cost

To calculate the total operating cost of the base case, the replacement costs are estimated first as presented in Table 7.2 for three different scenarios with the building life span of 30, 40, and 50 years for comparison purposes.

Table 7.2 Total replacement cost for the Base case

Component	Life span of the component	Additional replacement cost besides initial		
		30 years	**40 years**	**50 years**
Baseboard heaters	20 years	1,927.72	1,927.72	3,855.43
Carpet	10 years	8,515.87	12,773.80	17,031.73
Parquetry flooring	30 years*	0.00	10,000.42	10,000.42
Ceramic tiles	30 years**	0.00	8,193.14	8,193.14
DHW Tank	15 years	1,286.05	2,572.10	3,858.15
Light bulbs: incandescent	750-1000 hours	1,790.40	2,387.20	2,984.00
Total replacement cost (before tax)		13,520.03	37,854.38	45,922.88
Total replacement cost (including 12.875%		**15,260.74**	**42,728.13**	**51,835.45**
*An average value used from the range found as 20-40 years (Antoli Efros, 1998)				
**Mithraratne & Vale (2004)				

It should be noted that the replacement costs are calculated only for the items that are different in the Base case and the NZEH. Some of the items such as air conditioners, windows, sanitary fittings, and wall paint need to be replaced during the life-span of the building (ASHRAE, 2007, p.36.3; Mithraratne & Vale, 2004), but are not accounted for here, since they are the same in both the cases and thus do not affect the comparison.

Operating energy costs:

In engineering economic analysis, to compare alternatives, their cash flows need to be converted and brought to a single point in time, either the present time or some point in the future. The terms used in this context, the Present Value (PV) or the Present Worth (PW) and the Future Worth (FW), as well as the processes called compounding and discounting are briefly explained below (Park et al., 2001).

The process of finding the FW of the present sum is called compounding and its equation is as follows:

$$FW = PW \cdot (1 + i)^{N} \tag{7.1}$$

where,

i = interest rate;

N = planning horizon.

The opposite of this is called discounting, which is a process of finding the PW of the future sum as follows:

$$PW = FW \cdot (1+i)^{-N} \tag{7.2}$$

The cost of changes made in the Base case in order to convert it to NZEH is considered as the up-front cost paid at the present time. Therefore, in order to have fair comparison between the two cases, the electricity cost required in the Base case throughout its lifespan at regular intervals needs to be converted to its Present Worth (PW). For this purpose, an equation from MNECC (1997), based on the discounting method is used:

$$PW = C \cdot (1-(1+a)^{-N})/a \tag{7.3}$$

where,

C = annual electricity cost in the first year;

a = effective interest rate = (d-e)/(1+e);

d = discount rate;

e = energy cost escalation rate;

N = planning horizon, in this case the life span of the building.

The annual electricity cost required to estimate the total life cycle energy cost can be calculated by two methods:

(i) by using the annual electricity consumption in the Base case and the average price of electricity for Montreal including tax. The average price of electricity in 2009 for residential customers with monthly consumption of 1000 kWh was 6.87¢ for Montreal while the average over North America being 13.59¢ (Hydro-Quebec, 2009.d).

(ii) by using the detailed electricity rate for residential customers (Hydro-Quebec, 2009.c.) which includes the following three components:

- fixed charge of 40.64¢/day,
- energy charge of 5.45¢ for first 30 kWh/day, and
- 7.46¢ for the remaining consumption

For the cost analysis in this thesis, the second method of detailed rate is used. The annual electricity cost is 4% lower if calculated by using the first method with the average rate, and thus could be misleading. For correct evaluation of the annual electricity cost, ASHRAE (2007, p.36.4) also recommends not to use simply the per unit electricity cost.

The other values used in the eqn. (7.3) are as follows:

1. Annual discount rate = 3.58%, for which is the average for the 'bank rate' between 1999 and 2009 (Bank of Canada, 2009.a).
2. Energy cost escalation rate = 1.97%, which is calculated as the average of energy escalation rate between 2004 and 2008 for residential use in Montreal (Hydro-Quebec, 2009.d).

The life cycle energy cost thus calculated, is accounted for in the total life cycle cost presented in Table 7.3.

Table 7.3 Total life cycle cost of the Base case

	Life span of the Base case house		
	30 years	**40 years**	**50 years**
Initial cost ($)	258,965	258,965	258,965
Operating cost			
Replacement cost ($)	15,261	42,728	51,835
Energy cost ($)	55,844	76,171	97,418
Total life cycle cost of the Base case ($)	**330,070**	**377,864**	**408,219**

7.1.2 Life Cycle Cost of the NZEH

In order to convert the Base case house to a NZEH, some modifications are done to the house as explained in Chapter 5. As a result, the initial investments as well as the operating costs are different for the NZEH compared to the Base case.

7.1.2.1 Initial Cost of the NZEH

The various components in the NZEH are divided mainly into two categories, the radiant floor heating system and the PV/T system. The initial cost calculations are presented individually for each system and the cost of appliances is presented separately as well. The total initial investment is then estimated.

Radiant floor heating system:

To estimate the quantity of some of the radiant floor system parts, a few guidelines are used, e.g. approximately 24.38 m of tubing is required per 9.29 sq m of floor area (80'/100 sq ft); four adaptors are needed for each zone, i.e. two each for supply and return to the manifold; and two couplings are required per zone (Radiant Floor Company, 2009). Thus the total length of tubing needed in the entire house is estimated at 813.8 m (2670'). Table 7.4 shows the total initial investment for the radiant floors in the NZEH.

Table 7.4 Initial cost of the changes made in the NZEH for radiant floor system

Item	Unit	Price ($)	Quantity	Total cost ($)
Radiant Floor Heating System				
Concrete slab	sq ft	2.63	2192.00	5,762.77
Floor finish: Stain, two coats	sq ft	0.73	3330.44	2,422.43
Floor finish: Acrylic sealer, two coats	sq ft	0.55	3330.44	1,840.73
Extruded polystyrene (XPS), 25 PSI compressive strength, 1", R5	sq ft	1.00	2192.00	2,182.95
Tubing: Uponor Wirsbo hePEX 12.7mm (1/2")	L.F.	1.49	2670.00	3,984.62
Manifolds: Wirsbo EP (Engineered Plastic)				
3-loop manifold for basement and first floor	each	267.45	2.00	534.89
4-loop manifold on second floor	each	315.60	1.00	315.60
Tubing accessories:				
Manifold connector kit including mounting brackets, couplings, end cap, air vent, valve, plug	each	182.06	3.00	295.73
Adapters: 3/4" to 1/2" PEX	each	7.44	40.00	297.46
Couplings	each	7.95	20.00	159.00
Mixing valves	each	179.34	2.00	292.08
Diverter	each	39.75	1.00	39.75
Thermostats: Wirsbo programmable set point controller, without floor sensor	each	218.24	10.00	2,182.38
Floor sensors: Wirsbo A3040079	each	47.03	10.00	470.27
Pump: Taco Variable Speed Delta T008-VDTF6	each	463.00	3.00	1,389.00
Copper				
1/2" dia.	L.F.	9.18		
1/2" dia.	each	_		
3/4" dia.	L.F.	12.13		
3/4" dia.	each	_		
1" dia.	L.F.	16.41		
1" dia.	each	_		
Piping: 1" Wirsbo AquaPEX	L.F.	6.44	38.70	249.39
Pipe insulation: 1" wall, for 1" pipe	L.F.	6.87	38.70	266.00
Subtotal				**22,526.02**

The initial estimate for the cost of the radiant floor system is $22,526. It does not include the cost of tank, which is part of the PV/T system and the cost of basement concrete slab, since it is already accounted for in the envelope cost, common to both the cases.

The average market price of a typical radiant floor system including a boiler or a water heater is $6-12/sq ft of the conditioned space (Radiant Floor Heating Guide, 2009; Anderson Radiant heating, 2006). To compare the estimated cost of the radiant floor system in this study with the market price, the radiant floor system cost per unit area is calculated as shown in Table 7.5, which includes the tank and the basement floor costs as well. Thus the cost estimate of the entire radiant floor system (not including taxes) appears to be $92/m^2, i.e. $9/sq ft of the heated floor area, which falls well within the market price range. The finished concrete slabs attributes to over half the cost of the entire radiant system.

Table 7.5 Initial cost breakdown for the radiant floor system

Main components of the radiant floor system	Cost per square unit floor area		Percentage of total radiant floor system
	($/m^2)	($/ft^2)	
Concrete floors	49.04	4.57	53
PEX tubing, manifolds, accessories	17.51	1.63	19
Valves, controls, pumps, and piping	15.77	1.47	17
Tank	10.10	0.94	11
Total	**92.42**	**8.60**	**100**

PV/T System:

The PV/t panels used in the NZEH in this study are by Holtkamp SES, which offers three different sizes of PV/T modules. The total module cost for the 8.64 kW system varies depending on the size of the modules used. The cost comparison with different modules is presented in Table 7.6. It is apparent that using the largest available panel size results in the most economical option.

Table 7.6 Total cost of PV/T modules using various module sizes

PV/T sizes available	Cost per panel		No. of panels needed	Total cost
	€	CAN$		CAN$
SES PVT 540/2300	2,000	3,152	16	50,432
SES PVT 360/1530	1,500	2,364	24	56,736
SES PVT180/750	950	1,497	48	71,866

Other than the modules, the PV/T system includes electrical and mechanical balance of system (BOS), as listed in Table 7.7.

Table 7.7 Initial cost of the PV/T system

Item	Unit	Costs ($)	Quantity	Total cost ($)
PV/T System				
Holtkamp SES PVT 540/2300 panels	each	3152.00	16.00	50,432.00
Balance Of System				
Pump package: WSE SOL-0100 (includes controller, 3-way valve, air-vent, BTU meter, flow meter, and Grundfos variable speed pump)	each	995.00	1.00	995.00
Fronius Inverter, Ig4500-Lv 4.5kW grid-tie	each	3179.00	2.00	6,358.00
Propylene glycol, inhibited anti-freeze	L	7.91	40.00	316.38
Collector panel mounting	each	357.89	16.00	5,726.22
Storage tank				
Tank: SunMaxx Solar, 1000L	each	1992.88	1.00	1,992.88
Tank insulation: 100 mm (4") polyurethane, INFLEX, R16	each	1123.50	1.00	1,123.50
Insulation between the tank and slab: polystyrene (XPS) board, 25 PSI compressive strength, 50 mm (2") thk, R14.4	sq ft	1.40	10.00	13.98
Accessories: Package includes expansion tank, air eliminator, fill and drain valves, pressure gauge and pressure relief valves, mounting hardware	each	341.33	1.00	341.33
Subtotal				**67,299.30**
Roofing material: for extra roof area in NZEH compared to Base case				
Plywood sheathing on roof, 1/2" thk, pneumatic nailed	sq ft	0.91	1212.867	1,099.93
Asphalt roof shingles: organic, pneumatic nailed	100 sq ft	103.34	1212.867	1,253.36
Subtotal				**2,353.29**

The total cost of the PV/T system including the complete balance of system (BOS) and the storage tank is estimated as $67,299. Based on 2008 PV average installed cost of $7.5/W (Wiser et al., October 2009), the 8.64 kW PV system in the current study would cost $64,800, while the actual estimate in the cost analysis is $67,299. Considering the fact that the proposed system is a combined PV/T system and not just a PV system, the 4% higher estimation seems acceptable. The inverter price index shows that the inverter cost has been constant around.$0.72/W throughout last year, i.e. 2008-2009 (Solarbuzz, 2009. a). The inverter price used here as seen in Table 7.7 translates to $0.74/W. As presented in Table 7.8, 75% of the total PV/T system cost is the module cost. The issues related to PV systems costs are discussed further in section 7.1.3.

Table 7.8 Cost breakdown of the PV/T system

PV/T system cost breakdown	Cost per square unit floor		Cost per square unit PV/T		Percentage of total PV/T system cost
	($/m^2)	($/ft^2)	($/m^2)	($/ft^2)	
PV/T modules	162.68	15.14	875.56	81.34	75
BOS	43.21	4.02	232.56	21.61	20
Tank	11.20	1.04	60.27	5.60	5
Total	**217.09**	**20.21**	**1,168.39**	**108.55**	**100**

Cost of appliances:

As discussed earlier in Chapter 5, all the appliances in the Base case are replaced by efficient Energy Star appliances. The costs for appliances for a single family in the Base case and the NZEH are presented together in Table 7.9 for easier comparison. The values presented are the average values calculated from the minimum and maximum costs available in RS Means (2009). The total cost of the Energy Star appliances seems to be 21% higher than those in the Base case.

Table 7.9 Cost comparison for appliances in the Base case and the NZEH

		2009 Bare Costs ($)		
		Material	Labor	Total
Appliances in the Base case:				
	Cooking range	1,183.53	47.37	1,230.90
	Refrigerator	958.39	88.64	1,047.03
	Dishwasher	313.99	270.61	584.60
	Clothes washer	861.03	243.88	1,104.91
	Electric dryer	369.00	121.94	490.94
Total				**4,458.38**
ENERGY STAR Appliances in the NZEH:				
	Cooking range	849.00	47.37	896.37
	Refrigerator	958.39	225.12	1,183.51
	Dishwasher	800.18	270.61	1,070.79
	Clothes washer	897.54	121.94	1,019.48
	Electric dryer	1,022.28	219.49	1,241.77
Total				**5,411.92**
Increase in appliance cost for NZEH				**953.54**

Cost of other energy efficiency measures:

Table 7.10 shows the costs of other items used in the NZEH to reduce the energy consumption associated with DHW, ventilation and lighting systems.

Table 7.10 Cost of miscellaneous energy efficiency items

Item	Unit	Costs ($)	Quantity	Addition for NZEH ($)
Thermostatic Mixing Valve:				
Honeywell RC-AM101C	each	110.94	1	110.94
Grey Water Heat Recovery unit:				
Power-Pipe R3-60, 3" dia., 60" long, includes drain connectors	each	680.00	1	680.00
Mechanical Ventilation:				
HRV: Fantech VHR 1405R	each	710.69	1	710.69
Air ducts, insulated	L.F.	5.26	200	1,051.89
Lighting:				
CFL bulbs: GE 13W, 6 pack	6 pk	16.96	5	84.80
Subtotal				**2,638.32**

After taking into consideration the costs of all the individual systems and their components, the total initial investment required to convert the Base case house into a NZEH is estimated at $72,002, as presented in Table 7.11. This includes the taxes as well as various rebates, which are further discussed in section 7.1.4.1. The majority of this initial investment is the PV/T module cost. Also, it should be noted that significant saving is achieved by avoiding extra floor finishes on top of the radiant floors. The appliances cost shown here is for two families.

Table 7.11 Total initial cost of the changes made for NZEH

Item	Cost Addition	Cost Reduction	Initial cost
Items added			
Radiant Floor Heating System	22,526.02		
PV/T System	67,299.30		
TMV, HRV, GWHR unit	2,553.52		
Roofing material for additional roof area of NZEH	2,353.29		
Lighting: CFLs	84.80		
Appliances: Energy Star (for both the families)	10,823.83		
Items to be deleted			
Lighting: incandescent light bulbs		-29.84	
Appliances from base case (for both the families)		-8,916.75	
Floor finish and baseboard heaters		-27,787.07	
DHW Tank: electric heater		-1,286.05	
Subtotal	105,640.77	-38,019.72	
Initial cost (without taxes) before rebates			**67,621.05**
Initial cost (including 12.875% taxes) before rebates			**76,327.26**
Rebates			
Hydro Quebec rebate for refrigerator		-50.00	
Hydro Quebec rebate CFLs		-25.00	
AEE rebate for Solar DHW		-4,250.00	
Total rebate		-4,325.00	
Total initial cost (including 12.875% taxes) after rebates			**72,002.26**

7.1.2.2 Maintenance & Operating Costs of the NZEH

For NZEH, the operating cost is mainly the replacement cost, since there is no annual energy cost. The costliest item that needs replacement during the life-span of the building is PV/T panels. The cost of PV/T panels is highly dependent on the PV itself. The study by Wiser et al. (2009), which is elaborated further in section 7.1.3, provides some insight for further cost analysis in calculating the replacement cost of PV/T panels at the end of their life, i.e. 25 years. Over the past decade, a reduction of 30% was observed in the U.S., based on which a further reduction by 50% in next two and a half decade is assumed here. Table 7.12 presents the total replacement cost for the NZEH based on this assumption.

Table 7.12 Total replacement cost for NZEH

Component	Life span of the component	Additional replacement cost besides initial cost ($) during life span of the building		
		30 years	40 years	50 years
Shingles	15 years	1,253.36	2,506.73	3,760.09
Pumps and controls	20 years*	1,852.00	1,852.00	3,704.00
PV/T panels	25 years	25,216.00	25,216.00	25,216.00
Inverter	15 years	6,358.00	12,716.00	19,074.00
Solar storage tank	15 years	1,992.88	3,985.76	5,978.64
Glycol mixture	3 years	2,847.41	3,796.55	4,745.69
Light bulbs: CFLs	6000-15000 hrs	593.60	848.00	1,017.60
Total replacement cost (before tax)		40,113.26	50,921.04	63,496.02
Total replacement cost (including 12.875%		**45,277.84**	**57,477.12**	**71,671.14**
*ASHRAE (2007)				

Considering the efforts being focused towards the cost reduction of PV technology, this assumption is plausible. To support this, another retail price survey (Solarbuzz, 2009. b) shows that the price of PV modules dropped from $\$27/W_p$ in 1982 to $\$4.31/ W_p$ in October 2009 in the U.S. and this is expected to drop further to $1.50 - 2.00 per watt over the next decade.

No change is assumed in the replacement costs of any other components in the NZEH. Other items that are different in the NZEH compared to the base case have longer life-span and thus do not add to the replacement cost, e.g concrete slabs have a life expectancy of 100 years (Mithraratne & Vale, 2004), PEX tubing is also expected to have a life span of 100 years (Uponor, 2009.a.). The total (initial + operating) cost of the NZEH is presented in Table 7.13.

Table 7.13 Total life cycle cost of the NZEH

Cost	Life span of the NZEH		
	30 years	40 years	50 years
Initial cost ($)			
Including envelope cost same as the base case & the changes made for converting to NZEH	330,967.26	330,967.26	330,967.26
Operating cost ($)			
Replacement cost	45,277.84	57,477.12	71,671.14
Energy cost	0	0	0
Total life cycle cost of the NZEH ($)	**376,245.10**	**388,444.39**	**402,638.40**
Life cycle cost of NZEH ($\$/m^2$)	1,213.69	1,253.05	1,298.83

7.1.2.3 Simple Payback and Discounted Payback Methods

In the decision making process for energy efficiency improvements, one of the frequently used terms is payback period. Payback period refers to the length of time required for an initial investment to be recovered. It can be calculated by using two methods, simple payback method and discounted payback method. There are mainly three sources of information used for the following analysis, ASHRAE (2007), Park (2001), and Leckner (2008).

Simple payback method:

This is the most basic method for screening projects on the basis of economic viability. The simple payback is calculated as follows:

Payback period (years) = Initial investment ($) / Annual saving ($/yr) (7.4)

The biggest drawback of simple payback method is that it assumes the annual savings to be uniform over the years, which is not necessarily true due to factors such as the inflation rate and energy cost escalation rate. Also, this method does not differentiate between the present and future value of money.

Discounted payback method:

This method takes into account the above mentioned factors. Payback is achieved when the cumulative cash flow (CCF) reaches zero, i.e. the initial cost is paid off from the savings achieved by the invested technology. From this point onwards, these savings accumulate as positive cash flow, i.e. profit. Table 7.14 below shows an example of calculation using this method for appliance upgrade, where the payback is achieved in the fifth year.

Table 7.14 Cumulative cash flow example showing calculation for appliance upgrade

Year	Discounted annual cost saving	Present Worth (PW) of the annual cost saving	Cumulative Cash Flow
0	0.00	0.00	-1,989.52
1	415.00	408.67	-1,580.85
2	423.30	410.49	-1,170.36
3	431.77	412.31	-758.05
4	440.40	414.14	-343.91
5	449.21	415.98	72.07

The CCF is calculated using following equations (Leckner 2008):

$$CCF = CCF_{n-1} + Spw_n + repl_n \quad (7.5)$$

$$Spw = \frac{S}{(1+a)^n} \quad (7.6)$$

$$S = E \cdot (1+e)^{n-1} \cdot R \quad (7.7)$$

where,

n = year, year 0 being the investment year;

Spw_n = present worth of annual saving, $;

$repl_n$ = replacement costs of various components at various intervals, $.

S = annual cost saving considering energy cost escalation rate, $;

a = effective interest rate;

E = cost of electricity, $/kWh;

e = electricity cost escalation rate;

R = annual reduction in electricity use, kWh.

7.1.2.4 Payback Periods for Various Energy Efficiency Measures in the NZEH

The profitability of various energy efficiency technologies is examined by using the discounted payback method; the results are presented in Figure 7.1.

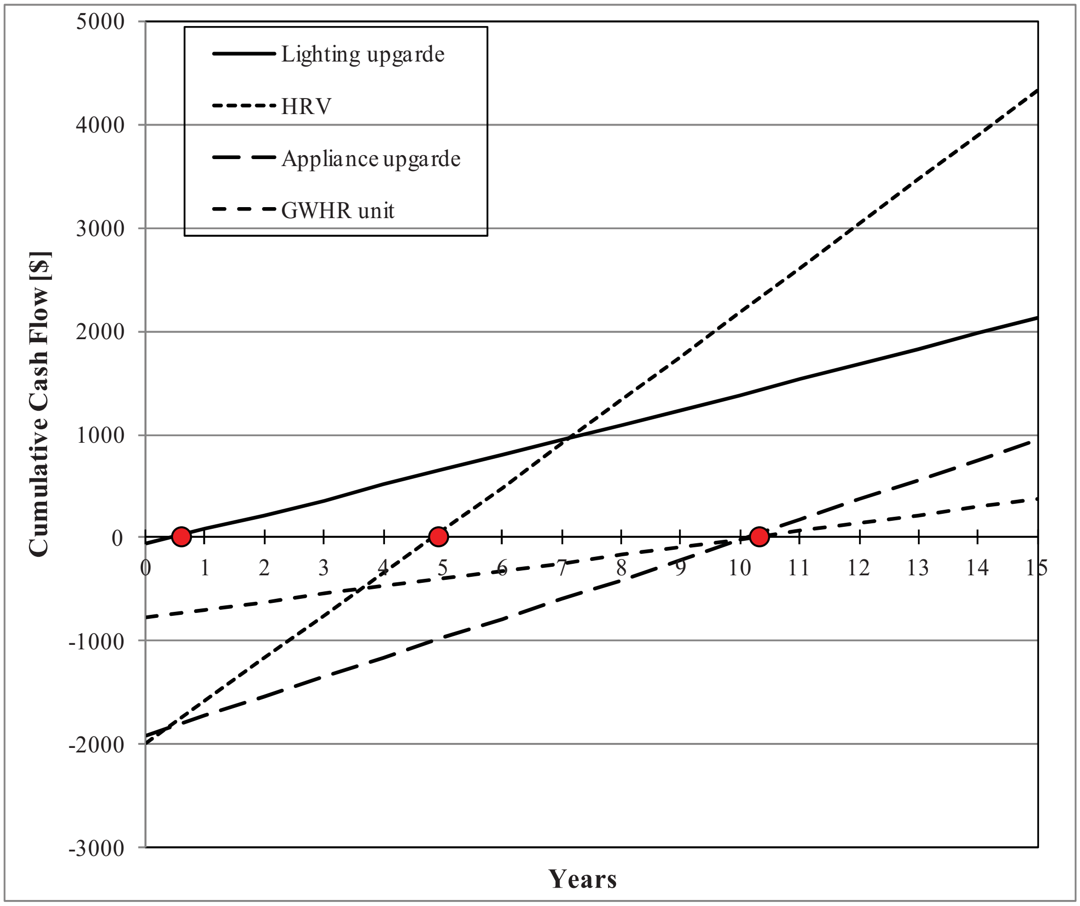


Figure 7.1 Discounted paybacks for various energy efficiency measures

As seen in the Figure 7.1, lighting upgrade is the most cost effective measure with almost instant payback of less than a year, followed by the HRV with payback being achieved by the fifth year. It should be noted that while calculating the payback for the HRV, material and labor cost for air duct installation was also included since the base case did not have any air ducts. The additional cost of appliances for both the families i.e. for two sets of appliances, due to upgrade to Energy Star, is $1907 including taxes. The payback analysis of the upgraded appliances shows the payback being achieved just after 10 years.

The payback for the GWHR unit, i.e. GFX is also achieved just after 10 years. Compared to this, a field evaluation by ORNL (2005) using simple payback method and $500 as the cost of GFX showed the payback could be achieved by up to 5 years for a U.S. location and the energy saving due to GFX was shown to be 30-45% of the shower portion. Considering the fact that the actual cost of GFX used for the cost analysis in this current study is $768 including tax ($680 plus tax), and the comparatively lower electricity costs in Quebec, the estimate of 10 year payback seems reasonable. Although, it should be noted that there are two main assumptions used here, the percentage of DHW used for shower portion, and the percentage of heating energy saved due to GFX. Out of these, the assumption used here, that the GFX saves 30% of energy required for showers is a conservative assumption and so the 10 year payback period can be considered as the maximum amount of time by which the GFX pays for itself.

The initial cost of changes made for the NZEH is $72,002 as shown in Table 7.11 and the payback for it is achieved in the 38th year of the life-span of the building. A profit of total $10,055 is made once the cash flow turns positive during the 40-year lifespan. If the surplus of 465 kWh of electricity produced by the NZEH is not considered in the CCF analysis, then the payback is achieved in the same year but the profit made is slightly lower at $6,295. The payback considering the replacement costs is not achieved during the life-span of the building and hence is not discussed further in this study.

7.1.3 Current Solar Market Costs

The trend of the PV cost reduction is discussed in this section to support the assumption of reduced cost of PV/T at the time of replacement in this thesis. Wiser et al. (2009) conducted a study at the U.S. Department of Energy's Lawrence Berkeley National Laboratory on the installed cost of PV systems in the U.S. It shows a decline in the average cost of PV systems by more than 30% from 1998 to 2008. Based on the observation of 52,000 grid connected PV installations between 1998 to 2008, the cost reduction from 1998 to 2007 is mainly due to the reduction in non-module costs such as labor costs, cost of inverters, balance of system, marketing and overhead costs, while over 4% decline in PV systems costs between 2007 and 2008 is mainly due to the direct impact of decreasing PV module costs.

Among the systems installed in 2008, the average cost of the smaller systems (less than 2 kW) was $9.2/W, while for the larger systems (500 - 750 kW) it was $6.5/W. Looking at the trend, the average installed cost was $10.80/W in 1998, while it was reduced to $7.5/W in 2008. Compared to this, the cost of the entire PV/T system in this study is estimated at $7.79/W. Another important observation in their report is that the cost reduction over a decade was largest for the residential PV installations such as systems for individual households.

Another study by Alsema (2003) discusses how increase in the demand for PV can result in the PV cost reduction. In the PV manufacturing process, silicon purification is a highly energy-intensive step (see Appendix C.2.iv). The current production of silicon is determined by the electronic industry, since 90% of the silicon production is consumed by it. As a result, the purification process has a very high purity criteria required by the electronic industry, which is not really necessary for the PV industry. As the demand for PV goes higher, it will be commercially feasible to produce the ‘solar-grade’ silicon meant for only the PV industry, which will bring down the energy requirement in the PV production and consequently result in the cost reduction.

7.1.4 Financial Incentives for Energy Efficiency and Renewable Energy Use

In the cost analysis of NZEH, a few relevant rebates are taken into account. This section focuses on how government subsidies and incentives are crucial for new technologies and industries that require high up-front costs. The impact of government subsidies and incentives on the success of an emerging industry is evident from the examples of Japan and Germany. The incentives started for solar industry in 1994 by the government of Japan allowed that country to make solar energy systems 72% cost effective by the end of 2003, at which time the program was ended. The same strategy was followed by Germany with its feed-in tariff program started in 2004 that ended in 2006, by which time Germany became the world leader in the solar industry

(Rowlands, 2005). The initial help by government in market penetration leads to increase in demand, which eventually results in the cost reduction.

7.1.4.1 Incentives Available in Quebec from Various Sources

This section is an overview of incentives available in Quebec for energy efficiency technologies and solar heat and power systems. The incentives offered by the federal government, provincial government, and utility companies are all taken into consideration.

In Quebec, among the renewable energy options, hydro power has been the most explored option. Out of the total electricity produced in Quebec, over 96% is hydro power (Gouvernment du Quebec, 2008). The focus of the government is still more on hydro-power (CBC, 2009), followed by wind power (Gouvernment du Quebec, 2008). In spite of having fair amount of solar insolation in Quebec, the solar power has not gained significant support from public sector yet. The main reason for that is not just the high cost of PV but also the existing low electricity cost. Also, another reason is the fact that the existing power supply, the hydro power, is competitive with PV power in terms of GHG emissions, with 15 $ktCO_2$ eq/TWh versus 13 $ktCO_2$ eq/TWh respectively (Gagnon et al., 2002).

On the federal level, solar is considered as one of the significant renewable energy sources. To promote solar thermal technology, ecoENERGY for Renewable Heat program was set up for four years that ends on March 30, 2011, by which time it will have supported solar air and water based heating system installations in estimated 700 buildings. But this program only includes industrial, commercial, and institutional sectors and does not support residential installations (ecoENERGY, 2009). Residential applications are covered under ecoENERGY Retrofit program which is for retrofit projects. On the solar power side, incentives do exist for non-residential sectors via ecoENERGY for Renewable Power program. For residential sector, PV applications are considered as economically non-viable (NRC, 2008).

Office of Energy Efficiency (OEE) provides the directory of all the provincial as well as Canadian federal grants, rebates, and funding options for renewable energy and energy efficiency (NRC, 2009). Some of the incentives listed below are applicable to the NZEH in the current study and were used while estimating the cost of NZEH.

7.1.4.1.1 ecoENERGY

Various cash incentives have been offered by Canadian Federal Government's ecoENERGY Retrofit program starting July 01, 2009 (NRC, 2009) for increasing energy efficiency of the existing homes. The grants for the low-rise multi-family residential units are listed below. These are only applicable in retrofits and could be utilized if the NZEH was proposed as a retrofit to the existing R-2000 house.

1. For replacing the window air conditioners with Energy Star qualified units: Grant amount of $25 per window unit is available for maximum of two units per dwelling
2. For installing the HRV: Grant amount of $375 is available per unit installed.
3. Drain water heat recovery (DWHR): Grant amount of $165 per unit installed is available for selected models from various manufacturers such as Power-Pipe.

Incentives are also available for installing solar DHW system but although the list of eligible manufactures of solar collectors is quite extensive (ecoACTION, 2009), it does not include hybrid PV/T systems.

7.1.4.1.2 Hydro Quebec

Hydro Quebec (2009, a.) offers a few incentives for its residential customers as listed below, out of which, the last two rebates, on refrigerator and CFLs, are taken into account for the cost analysis of the proposed NZEH.

1. The program RYCLC-FRIGO that will be effective till December 31, 2010, offers $60 for free pick-up of old refrigerators (at least 10 years old), which are then recycled up to 95% of their material content.

2. Till December 31, 2009, Hydro Quebec offers a cash rebate of $50 on the purchase of Energy Star qualified refrigerators.
3. Until April 30, 2010, Hydro Quebec offers up to $25 rebate on Energy Star qualified CFLs in residential application.

7.1.4.1.3 Gaz Metro

Energy Efficiency Fund is available till 2012 for Gaz Metro customers that use natural gas for heating or DHW. Through this fund, a rebate $5 per square foot is offered on Energy Star windows and another rebate of $250 to $400 is available on drain water heat recovery units (EEF, 2008).

7.1.4.1.4 NovoClimat

Under this program by Government of Quebec, on-site construction of new homes by a contractor accredited by Agence de l'efficacité énergétique (AEE) and certified by AEE, qualifies for $2000 in financial aid. The proposed NZEH could qualify for this aid based on the energy efficiency and better ventilation criteria except the program requires the house to be single-family, semi-detached, or a row house.

7.1.4.1.5 AEE Rebate for Solar DHW

Agence de l'efficacité énergétique (Gouvernment du Quebec, 2008-2009) has started a project to provide financial assistance to first 600 homes installing solar collectors for DHW by October 2010. The financial aid offered under this program is taken into consideration for cost calculation of NZEH.

7.1.4.2 Feed-in Tariff and Net-metering

In Quebec, net metering is the only option available to any renewable power producers, however, Ontario offers Feed-in-Tariff. This section describes the difference between these two programs. Feed-in Tariff (FiT) is the rate set by the regional or national government at which utility companies are obligated to buy the electricity generated from various renewable sources.

This program has been implemented in Europe and is partially responsible for the successful market penetration of renewable power generation, especially in countries like Denmark, Germany, and Spain (Rowlands, 2005).

Feed-in tariff allows the power producer to sell all the generated power to the utilities at the rate pre-set by the law, which is higher than the retail electricity price. In Ontario, the earlier Standard Offer Program (SOP) provided a rate of $0.42/kWh for solar power. Now under the new Feed-in Tariff program, in Ontario, the home-owners with PV roof top systems have option to sell all the PV-generated electricity to Ontario Power Authority with 20 year contract at the rate of 80.2¢/kWh for systems up to 10 kW (OPA, 2009). These selling rates vary depending on the system size and are lower for larger systems. The buying rate of electricity is 5.8 ¢/kWh for first 1000 kWh and at 6.7¢/kWh for the rest, if bought from Ontario Hydro (Ontario Hydro, 2009). Thus on an average, the home-owner can make a profit of almost 74¢/kWh with feed-in tariff option and apply that towards the huge up-front cost required for PV systems. The Feed-in Tariff rate in Ontario is the highest rate in North America, followed by California (OPA, 2009).

In Quebec, the existing net-metering option is not as profitable for the home owners with the PV roof-tops as the feed-in tariff. Because in case of net-metering, only the surplus power produced by the PV generation is fed to utilities, i.e. Hydro Quebec. Hydro Quebec then gives the credit to the power producer, in this case the home owner, for the amount of kWh fed, which is used to reduce the home owner's draw from the grid. The credits are accumulative for up to 24 months after which period, they become invalid and the account is reset. Thus the surplus electricity can only help in reducing the payment to Hydro Quebec over the two year period; it does not allow the home owners to generate any profit based on the supplied PV power.

7.2 Life Cycle Energy

Life cycle energy is composed of embodied energy and operating energy. The embodied energy for building materials includes the energy required for raw material extraction and processing, manufacturing, transportation of the materials to construction site (cradle to gate) and finally recycling/reuse/disposal at the end of life (cradle to grave). The operation and maintenance energy is composed of the energy associated with replacement of components as part of maintenance and the annual electricity required during the life span of the building. The specific embodied energy values used in this study that are obtained from various sources in the literature are presented in Appendix C.2.

7.2.1 Life Cycle Energy of the Base Case

7.2.1.1 Embodied Energy of the Base Case

The embodied energy estimate for the envelope of the Base case was previously done by Kassab (2000) using mainly two resources, ATHENA Impact Estimator (2003) and Alcorn (1998). The plumbing, electrical, heating, cooling, or ventilation systems in the house were not included in that analysis. The current study does attempt to include some of these systems in the analysis besides the envelope, but is mainly focused on comparison between the base case and the NZEH as discussed in the earlier section of cost analysis. Thus the items that are the same in both the cases are not included in this analysis, i.e. air conditioning units, plumbing for DHW and cold water, and electrical system in the house. The appliances and lighting are not the same in the base case and the NZEH, but are not included either, due to lack of information.

The embodied energy for the base case was estimated by Kassab (2000) as 707,863 MJ. In this estimate, the embodied energy for floor finish and floor paint was 19160 MJ. This value was calculated by assuming wooden floors as the floor finish on both ground and second floor; no floor finish in the basement was accounted for. Therefore in this study, the embodied energy of the base case is recalculated by first subtracting the 19160 MJ, and then taking into consideration the ceramic floors in the basement, parquetry on the ground, and carpet on the second floor. These are the floor finishes used in the simulation of the base case in this study. These, along with the other components added to the analysis of base case are shown in Table 7.15.

Table 7.15 Total initial embodied energy of the base case

Items	Embodied energy (MJ)
Embodied energy without floor finish	688,703.00
Ceramic tiles in the basement, 105.78 m^2	15,421.67
Parquetry flooring on ground floor, 103.28 m^2	4,849.00
Carpet on second floor, 100.46 m^2	18,755.88
Baseboard heaters	16,466.90
DHW tank 300 L (80 gal)	2,187.70
Total initial embodied energy	**746,384.15**

7.2.1.2 Maintenance & Operating Energy for the Base Case

As part of maintaining the house, some items as shown in Table 7.16, need to be replaced at certain intervals during the life span of the building.

Table 7.16 Maintenance energy for the Base case

Components needed to be replaced in the Base case	Life span of the component	Embodied energy (MJ) due to replacement of components during the life span of the building		
		30 years	40 years	50 years
Ceramic tiles	30 years	0.00	15,421.67	15,421.67
Parquetry flooring	30 years	0.00	4,849.00	4,849.00
Carpet	10 years	37,511.76	56,267.65	75,023.53
Baseboard heaters	20 years	4,574.14	4,574.14	9,148.28
DHW Tank	15 years	2,187.70	4,375.40	6,563.10
Total maintenance energy		**44,273.60**	**85,487.85**	**111,005.57**

Reliable information for the embodied energy of the DHW electric tank used in the base case was not found in the literature. Therefore it is calculated as explained further in section 7.2.2.1.

While estimating the life cycle operating energy of the base case, it is recognized that the electricity received by the user is lower than the actual primary energy consumed by power plants due to the transmission and distribution losses and the losses related to the plant efficiencies. The amount of primary energy consumption thus depends largely on the fuel mix of the supplied power generation.

In Quebec, over 96% of the electricity produced is hydroelectricity (Government of Canada, 2008), which has much higher fuel conversion efficiency compared to the other resources such as coal, natural gas or oil. The primary energy required for the base case house is estimated based on three factors: (i) losses incurred during transmission and distribution of electricity from the power generation location to the site, (ii) the resource mix for electricity generation in Quebec, and (iii) the conversion efficiencies for various fuels under consideration.

As shown in Table 7.17, to supply the annual 23,493 kWh of electricity for the base case house, the primary energy required is 32,966 kWh. Thus the ratio of primary energy to on-site electricity consumption appears to be 1.4 for Quebec. This ratio will be much higher for other locations such as the U.S., where almost half of the electricity produced is from coal, and one fifth each from natural gas and nuclear, a mere 5.8% from hydro, and the rest from petroleum and other resources (EIA, 2007, see Appendix C.3.iii). The total life cycle primary energy required for the base case is presented in Table 7.18.

Table 7.17 Annual primary operating energy required for the base case

	Hydro	**Nuclear**	**Natural gas**	**Petroleum and other**	**Total**
*Average electricity mix for Quebec (%)	96.20	2.50	0.20	1.10	100.00
Annual energy split considering T&D losses (kWh)	23,956.28	622.56	49.81	273.93	24,902.58
**Fuel conversion efficiency (%)	80.00	30.00	43.10	33.00	_
Total primary energy required (kWh)	29,945.35	2,075.22	115.56	830.09	**32,966.21**
Annual electricity consumption for the base case: 23493 kWh					
**Transmission & Distribution (T&D) losses: 6%					
Electricity required considering the T&D losses: 24902.58 kWh					
References:					
*Government of Canada (2008)					
**Zmeureanu & Wu (2007)					

Table 7.18 Total life cycle energy of the Base case

Primary Energy required in the Base case	Life span of the Base case house		
	30 years	40 years	50 years
Initial embodied energy (MJ)	746,384	746,384	746,384
Maintenance energy (replacement of components) (MJ)	44,274	85,488	111,006
Operating energy (MJ)	3,560,351	4,747,134	5,933,918
Total life cycle energy (MJ)	4,351,009	5,579,006	6,791,308
Total life cycle energy per unit area (MJ/m^2)	14,057	18,025	21,941
Total life cycle energy (kWh)	1,208,613	1,549,724	1,886,474
Total life cycle energy per unit area (kWh/m^2)	**3,905**	**5,007**	**6,095**

7.2.2 Life Cycle Energy of the NZEH

7.2.2.1 Embodied Energy of the NZEH

As mentioned earlier, the embodied energy values for various materials and components related to the NZEH and obtained from the literature are presented in Appendix C.2. In case of some of the components for which embodied energy values are not directly available from either ATHENA or the literature, they are estimated by using LCA Calculator by idc (2008). This tool allows the user to enter information related to the product, such as different materials that the product is composed of and their masses, geographical location, packaging material, transportation from the manufacturing to the destination, life expectancy of the product, and the percentage of the product that can be recycled at the end of its life. The results are produced in terms of embodied energy and carbon footprint for various stages in the life-cycle of the product.

The components for which the embodied energy is calculated by using this tool are the PEX tubing in the radiant floors, supply and return AquaPEX piping between the radiant floors and the hot water storage tank, concrete stain and sealer, manifolds, TMV, and the GWHR unit, etc. as shown further in Table 7.20. The information regarding the make-up of the components such as presented for the manifold in Table 7.19 is gathered from the individual manufacturers. Some assumptions are made whenever data were not available, e.g. no recycling is assumed at the end of life of the non-metal components. Almost all the items evaluated by using this tool are manufactured in North America. For some of the components in the mechanical balance of system, the manufacturing location is Germany, which is taken into consideration during estimation of embodied energy, e.g. support structure of PV/T modules for tilted roof.

Table 7.19 Wirsbo engineered plastic (EP) manifold and its accessories

Component	Material	Mass	
		kg	lbs
EP (Engineered Plastic), 3-loop manifold assembly	Main component: EP Axel and spring: Stainless steel Inserts: Brass Flow meter: Glass	1.89	41.6
Thermal actuator: Provides individual loop flow control, mounts on the manifold and connects to the control	EP	0.10	0.22
Actuator adapter	EP	0.02	0.04
Manifold mounting bracket: A set of two brackets attach to a wall and hold the manifold.	EP	0.18	0.4

An example of a component evaluate by using this tool is PEX tubing for radiant floors. For a standard 304.8 m (1000') PEX tubing roll weighing 27.22 kg (60 lbs), the embodied energy is estimated at 2416 MJ, i.e. 88.77 MJ/kg. Out of this, 95% is for material extraction and manufacturing including packaging, 2.5% is for transportation, and the rest of 2.5% for the disposal at the end of life. Thus the total embodied energy for the PEX tubing required for the whole house is 6450.7 MJ. For all other components, the results obtained using LCA Calculator by idc (2008) are presented in Table 7.20.

Table 7.20 Embodied energy & emissions estimates using LCA Calculator by idc (2008)

Component	Extraction & Manufacturing	Transportation	Disposal	Total
Concrete sealer: 3.4 kg (per gal)				
Embodied energy (MJ)	320	50	8	378
Emissions (kg eq-CO_2)	130	4	3	137
Concrete stain: 4.54 kg (per gal)				
Embodied energy (MJ)	440	50	11	501
Emissions (kg eq-CO_2)	170	4	4	178
Wirsbo Manifold: EP 3-loop, Engineered Plastic, values shown per unit				
Embodied energy (MJ)	160	50	6	216
Emissions (kg eq-CO_2)	66	4	3	72
Wirsbo AquaPEX pipe: 1", straight length, mass 0.26 kg/m (35 lbs/200'), values shown per 30 m				
Embodied energy (MJ)	710	51	20	781
Emissions (kg eq-CO_2)	120	4	4	128
Thermostatic Mixing Valve: Brass, values shown per unit				
Embodied energy (MJ)	57	50	2	109
Emissions (kg eq-CO_2)	23	4	1	28
GWHR: Power-Pipe R3-60, 1.5 m (60") long with 75 mm (3") dia., copper, weighs 15 kg (33 lbs), values shown per unit				
Embodied energy (MJ)	1,100	51	34	1,185
Emissions (kg eq-CO_2)	440	4	14	458
Heat exchanger coil in the solar storage tank, 48 kg total mass, values shown per unit				
Embodied energy (MJ)	3,500	60	300	3,860
Emissions (kg eq-CO_2)	1400	4.4	120	1,524
Support structure for PV/T: 173 kg galvanized iron and 53 kg aluminum, values shown are for 57.6 m^2 PV/T system				
Embodied energy (MJ)	4,300	64	1,300	5,664
Emissions (kg eq-CO_2)	_	_	_	_
Solar storage tank: SunMaxx Solar SM-275, stainless steel, 1000 L, weighs 85.73 kg (189 lbs), values per 1000L				
Embodied energy (MJ)	2800	70	1000	3870
Emissions (kg eq-CO_2)	1100	5.1	400	1505

7.2.2.1.1 Embodied Energy in the Radiant Floor System

Table 7.21 shows the breakdown of the embodied energy for various parts of the radiant floor heating system. Reliable information was not available for the embodied energy of the pumps used in this system. Also, the details from the manufacturer showed the complexity of the electronic parts of the controls inside; so the pump could not be evaluated by using the LCA Calculator either. Therefore the embodied energy of the three pumps is ignored. The total embodied energy for the radiant floor system as estimated by using various sources as shown in Table 7.21 is 65,931 MJ, i.e. 213 MJ/m^2 of heated floor area.

Table 7.21 Embodied energy in the radiant floor heating system

Item	Total embodied energy [MJ]	Reference
Concrete slab	29,491.37	Athena Impact Estimator
Concrete sealer	6,426.00	idc (2008)
Concrete stain	5,010.00	idc (2008)
Extruded polystyrene (XPS)	17,315.99	Athena Impact Estimator
Tubing: Uponor Wirsbo hePEX 12.7mm (1/2")	6,450.72	idc (2008)
Manifolds: Wirsbo EP (Engineered Plastic)		
3-loop manifold for basement and first floor	432.80	idc (2008)
4-loop manifold on second floor	501.47	idc (2008)
Piping, 1" Wirsbo AquaPEX straight length	302.25	idc (2008)
Total	**65,930.58**	

7.2.2.1.2 Embodied Energy in the PV/T System

In order to account for the total embodied energy of the PV/T system categorically, it is broken down into four parts:

(i) PV modules

(ii) Electrical balance of system (BOS)

(iii) Solar thermal panels

(iv) Mechanical BOS

Out of these, the embodied energy values for the first three components are obtained directly from the literature, while the energy in the mechanical BOS is evaluated separately. Since the modules are manufactured in Germany, there is also the transportation energy required in addition, which is discussed further. For types of PV cells, various abbreviations are used in the literature and some of those are used interchangeably, e.g. m-Si is used to indicate mono-Si PV in some studies, while it is used to denote multi-Si in others. Therefore, these abbreviations are not used here to avoid any confusion; the terms mono-Si and poly-Si are used instead.

A study done by Tripanagnostopoulos et al. (2005) gives detailed LCA account for various PV/T systems analyzed from raw material extraction to the end of life disposal. The embodied energy values of the solar thermal panels in terms of primary energy from this study are used as a reference in the current analysis. But for the PV modules, the embodied energy estimated by Tripanagnostopoulos et al. (2005) is 3043 MJ/m^2, while the current study uses the value of 6100 MJ/m^2 as shown further in Table 7.24. The difference is mainly due to the fact that Tripanagnostopoulos et al. (2005) use poly-Si modules, while the PV/T used in the current study is composed of mono-Si modules, for which the embodied energy is much higher. Alsema (2000) has estimated the embodied energy values for both mono- and poly-Si modules as shown in Appendix C.2.iv, which shows the embodied energy for mono-Si to be almost 33% higher than that of poly-Si modules.

The mechanical BOS is further composed of multiple components and the embodied energy for it is presented separately in Table 7.22.

Table 7.22 Breakdown of mechanical BOS

Mechanical BOS: Components		**Total embodied energy [MJ]**
Expansion tank: Steel, 7.6 gal (5.4 kg)		155.50
Pumps: Brass, 0.9 kg		55.80
Heat transfer fluid: Propylene glycol and water mixture		1,252.80
Support structure for tilted roof: Galvanized iron rods & aluminum		5,664.00
Pipes for water circulation: Wirsbo AquaPEX		302.25
Storage tank		12,238.03
Stainless Steel, 1000 L (265 gal)	7,292.34	
Heat exchanger coils in the tank: copper	3,860.00	
Polyurethane insulation wrap, 100 mm thk	1,006.70	
Extruded Polystyrene (XPS), 0.93 m2 (10 sq ft)	79.00	
Subtotal		**19,668.38**

Transportation of the PV/T panels:

Energy associated with the transportation of the PV/T panels from the manufacturing plant in Schüttorf, Germany to the destination in Montreal, Canada is estimated separately. A transportation route is assumed due to the lack of detailed information from the manufacturer. The 16 PV/T panels, each weighing 95 kg, are assumed to be first transported by truck from Schüttorf, Germany to the closed port Amsterdam, Netherlands, which is at a distance of 233 km from Schüttorf. From there, they are assumed to be shipped by boat to Montreal, which is at a distance of 5978 km (3228 nautical miles) from Amsterdam port (Farnel Capital, n.d.). The embodied energy values used for these two shipping modes, i.e. by truck and by boat, are average values from two studies, Börjesson (1996) and Lenzen (1999), cited in Leckner (2008). The total embodied energy for transportation of PV/ T panels is thus estimated at 3,411 MJ, i.e. 213 MJ per panel or 59 MJ/m^2 of the PV/T area.

Table 7.23 Embodied energy associated with transportation of PV/T panels from Europe

	Mode of transportation	Distance (km)	Embodied energy (MJ/ton per km)	Total embodied energy (MJ)
Schuttorf, Germany -	Truck	233	1.550	2862.39
Amsterdam Netherlands -	Sea freighter	5978	0.315	549.00
Total energy for transportation of 16 PV/T panels				**3411.39**
Total energy for transportation per m^2 of PV/T area				**59.23**

As shown in Table 7.24, the total embodied energy in the PV/T modules used in this study is estimated at 464,219 MJ, i.e. 8,059 MJ/m^2 or 2,239 kWh/m^2 of PV/T area. Out of this, over 75% is for PV modules, 13% for solar thermal collectors, 7% for electrical BOS, 4% for mechanical BOS, and 1% is for transportation. From the description in Tripanagnostopoulos et al. (2005), they estimated the embodied energy in the PV/T modules as 4,612 MJ/m^2 using poly-Si modules, which is less than the estimate in the current study by 3,447 MJ/m^2. Considering the fact that the main difference of 3,057 MJ/m^2 is due to the type of PV modules used as explained earlier, the estimation here seems reasonable.

Embodied energy in other energy efficiency measures:

Table 7.25 presents the embodied energy associated with the rest of the energy efficiency measures in the NZEH.

Table 7.24 Breakdown of embodied energy in PV/T System

PV/T system component	Embodied Energy (MJ/m^2)	Total Embodied Energy (MJ)	Percentage	Reference
mono-Si PV modules	6,100.00	351,360.00	76	Alsema (2000)*
BOS (electrical)	542.00	31,219.20	7	Mason et al. (2005) sited in Sherwin et al. (2010)
Solar thermal panels	1,016.67	58,560.00	4	Tripanagnostopoulos et al. (2005)
BOS (mechanical)	341.46	19,668.38	13	Table 7.22
Transportation	59.23	3,411.39	1	Table 7.23
Total embodied energy in the PV/T system		**464,218.97**	**100**	

Table 7.25 Embodied energy related to miscellaneous energy efficiency items

Item	Specific embodied energy [MJ/kg]	Total embodied energy [MJ]
Thermostatic Mixing Valve:		
Honeywell TMV, RC-AM101C, Brass, weighs 0.86 kg (1.9 lb)	126.98	109.20
Grey Water Heat Recovery unit:		
Power-Pipe R3-60, 1.5 m (60") long with 75 mm (3") dia., weighs 15 kg (33 lbs).	79.00	1185.00
Mechanical Ventilation:		
HRV, galvanized steel (27.7 kg)	28.80	798
Ductwork	28.80	843
Total		**2935.20**

The total initial embodied energy in the NZEH thus estimated is presented in Table 7.26.

Table 7.26 Total initial embodied energy in the NZEH

Items	Embodied energy
Embodied energy without floor finish (MJ)	688,703.00
Shingles for the larger roof area compared to the base case (MJ)	31,561.59
Radiant floor heating system, including concrete floor finish (MJ)	65,930.58
PV/T system (MJ)	464,218.97
Other energy efficiency measures (MJ)	2935.20
Total embodied energy (MJ)	1,253,349.35
Total embodied energy per unit area (MJ/m^2)	4,049.33
Total embodied energy (kWh)	348,152.60
Total embodied energy per unit area (kWh/m^2)	**1,124.81**

7.2.2.2 Maintenance & operating energy for the NZEH

As shown in Table 7.27, the maintenance and operating energy of the NZEH only consists of the energy related to the replacement of components as part of maintenance and no operating energy, as opposed to the base case which needs operating energy from the utilities.

Table 7.27 Maintenance & operating energy for the NZEH

Component needed to be replaced in the NZEH	Life span of the component	Additional embodied energy for replacement besides initial embodied energy (MJ)		
		30 years	40 years	50 years
Shingles	15 years	31,561.59	63,123.19	94,684.78
PV/T system (without electrical BOS & tank)	25 years	420,761.74	420,761.74	420,761.74
Inverter & cabling	15 years	31,219.20	62,438.40	93,657.60
Solar storage tank	15 years	12,238.03	24,476.06	36,714.09
Glycol mixture	3 years	11,275.20	15,033.60	18,792.00
Total energy for replacement		**452,323.34**	**483,884.93**	**515,446.53**

Table 7.28 shows the total life cycle energy of the NZEH; the embodied energy is 73, 72, and 57% over 30, 40, and 50 year life span of the building respectively.

Table 7.28 Total life cycle energy of the NZEH

Energy required	Life span of the Base case house		
	30 years	40 years	50 years
Initial embodied energy	1,253,349	1,253,349	1,253,349
Maintenance energy (replacement of components)	452,323	483,885	515,447
Operating energy	0	0	0
Total life cycle energy (MJ)	1,705,673	1,737,234	1,768,796
Total life cycle energy per unit area (MJ/m^2)	5,511	5,613	5,715
Total life cycle energy (kWh)	473,798	482,565	491,332
Total life cycle energy per unit area (kWh/m^2)	**1,531**	**1,559**	**1,587**

7.2.2.3 Energy Payback for the PV/T system

Payback for PV/T system is calculated using two commonly used terms, Energy Payback Ratio (EPR) and Energy Payback Time (EPBT). It is desirable to have higher EPR and lower EPBT as explained further in this section.

1. Energy Payback Ratio (EPR)

EPR is calculated as follows:

$$\frac{E_{out}}{E_{in}} = \frac{E_{out}}{E_{PV/T} + E_{Transportation} + E_{BOS\_mechanical} + E_{BOS\_electrical} + E_{Replacement}} \quad (7.8)$$

The E_{in} term in the denominator in this equation refers to the life cycle energy input, which also includes the replacement of the components such as modules after 25 years and inverter, tank, heat transfer fluid etc. at various intervals. The calculations show that the EPR is 2.1 years over 30 year life span, 2.8 years over 40 year life span, and 3.6 years over 50 years life span. The EPR over 50 years is the highest and over 30 years is the lowest due to the PV/T module replacement after 25 years.

2. Energy Payback Time (EPBT)

EPBT is calculated as follows:

$$\text{EPBT (years)} = \frac{\text{Life-cycle primary energy consumed by the generation system (kWh)}}{\text{Annual energy generation by the system (kWh/year)}} \quad (7.9)$$

The EPBT calculated for just the PV system is 9.2 years, while for the combined PV/T it is reduced to 7 years. Thus the EPBT is almost 24% less with a combined PV/T rather than just the PV system. EPBT for PV found in the literature is from 2.5 to 8 years (Alsema & Nieuwlaar, 2000; Battisti & Corrado, 2005; Muneer et al., 2006 & Kannan et al., 2006 cited in Sherwin et al., 2010). Out of these studies the systems with mono-Si modules had higher EPBT values, i.e. 4.5 to 8 years, compared to those with poly-So modules. Tripanagnostopoulos et al. (2005) have estimated the EPBT of PV as 2.7 years, while for PV/T it is reduced to 2.2 years.

7.3 Life Cycle Emissions

The amount of GHG emissions during the life span of a building depends on various factors such as the total embodied energy in the building, the fuel mix of the electricity used for manufacturing of materials and components used in that building, as well as the fuel mix of the local electricity generation in that area.

7.3.1 Life Cycle Emissions of the Base case

For GHG emissions of the base case, the embodied energy in terms of primary energy is first converted to electricity. Assuming all the materials and components are produced in Quebec, the emissions are calculated as shown in Table 7.29, based on the electricity generation mix for Quebec.

Table 7.29 Initial embodied emissions of the Base case

	Hydro	**Nuclear**	**Natural gas**	**Petroleum and other fuels**	**Total**
*Average electricity mix for Quebec (%)	96.2	2.5	0.2	1.1	**100**
Electricity used (kWh)	142,464.59	3,702.30	296.18	1,629.01	148,092.09
**Emissions (gCO_2 eq/kWh)	15	15	443	778	_
Emissions ($kgCO_2$ eq)	2,136.97	55.53	131.21	1,267.37	**3,591**
Primary energy = 746,384 MJ = 207,329 kWh					
Electricity used = Primary energy (kWh)/1.4 = 148,092 kWh					
*Government of Canada (2008)					
** Gagnon et al. (2002)					

Similarly, the emissions from the maintenance and operating energy are calculated. The emissions from the electricity consumption of 23,493 kWh plus the 6% distribution and transmission losses are estimated at 603.86 kgCO_2eq per year. The total life cycle emissions are then estimated as presented in Table 7.30.

Table 7.30 Life cycle emissions of the Base case

Emissions of the Base case (kg CO_2 eq)	**Life span of the Base case house**		
	30 years	**40 years**	**50 years**
Initial embodied emissions	3,591	3,591	3,591
Emissions due to maintenance (replacement of components)	213	411	534
Emissions during Operation	18,116	24,155	30,193
Total Life Cycle Emissions	21,920	28,157	34,318
Specific emissions (kg CO_2 eq/m^2)	**71**	**91**	**111**

7.3.2 Life Cycle Emissions of the NZEH

In case of the NZEH, the procedure for calculating the emissions becomes slightly complex compared to the base case, since the PV/T modules are produced in Germany, for which the electricity generation mix is entirely different than that of Quebec. Therefore, there are mainly four components to the emissions calculations of NZEH as shown below:

(i) Emissions due to the initial embodied energy in the envelope and all the systems and components in the NZEH except the PV/T panels: emissions calculated using Quebec electricity generation mix

(ii) Emissions due to PV/T panels: emissions calculated using German electricity generation mix

(iii) Emissions due to transportation of PV/T from Germany to Quebec

(iv) Emissions during maintenance: separate calculations are carried out for the replacement of the PV/T panels and the replacement of the rest of required parts.

Various sources (Tahara, 1997 & Mauch, 1995 cited in Krauter and Ruther, 2004; Chalvatzis & Hooper, 2009; IEA, 2009; and Eurostat, 2009) suggest the electricity generation portfolio for Germany. Out of these, the latest data are used in this study that suggested Germany's electricity production for 2006 was 30% from coal and ignite, 31.5% from nuclear, 10.3% from natural gas, 2.5% from oil, and 15.5% from renewable. The total electricity from renewables was composed of 76.4% biomass and waste, 12.5% wind, 8.1% hydro, 2.2% solar, and 0.8% geothermal (Eurostat, 2009).

In Quebec, the electricity to primary energy ratio is established earlier as 1.4. The calculations performed in order to establish a similar ratio for Germany is presented in Table 7.31. It shows that for 100 kWh of on-site electricity use, assuming 6% transmission and distribution losses, the primary energy required with German electricity generation scenario is almost 306 kWh.

Thus the ratio of electricity to primary energy for Germany is approximated as 3. Using this ratio, the embodied primary energy for PV/T is converted to electricity, assuming that all the primary embodied energy in the PV/T was due to electricity. Then the embodied emissions for PV/T are calculated based on the German electricity production portfolio and fuel conversion efficiencies of various fuels as shown in Table 7.32.

Table 7.31 Calculations to establish the ratio of electricity to primary energy ratio for Germany

	Coal & Ignite	Hydro	Nuclear	Natural gas	Oil	Other renewables	Total
***Average electricity mix for Germany (%)**	39.00	4.50	31.50	10.30	2.50	12.20	**100.00**
Annual electricity split considering T&D losses (kWh)	41.34	4.77	33.39	10.92	2.65	12.93	**106.00**
****Fuel conversion efficiency (%)**	40.00	80.00	30.00	43.10	33.00	25.00	–
Total primary energy required (kWh)	103.35	5.96	111.30	25.33	8.03	51.73	**305.70**
* Eurostat (2009)							
**Bradsher K. (2009), Zmeureanu & Wu (2007)							

Table 7.32 Embodied emissions for PV/T with German electricity generation portfolio

	Coal & Ignite	Hydro	Nuclear	Natural gas	Oil	Other renewables	Total
Electricity used (kWh)	14,802.67	1,708.00	11,956.00	3,909.42	948.89	4,630.58	**37,955.56**
Specific emissions (gCO2 eq/kWh)	960	15	15	443	778	9	_
Emissions (kg CO_2eq)	14,210.56	25.62	179.34	1,731.87	738.24	41.68	**16,927.30**
Emissions (kg CO_2eq/m^2 PV/T area)							**293.88**
Primary embodied energy in PV/T (kWh) =			113,866.67				
Primary energy/Electricity ratio for Germany =			3				
Embodied energy in PV/T in terms of electricity (kWh) =				37,955.56			

Hammond & Jones (2008), based on a range of studies, have listed the embodied carbon value in mono-Si PV modules as 242 kgCO_2eq/m^2 (see Appendix: Table C.3.i), which can be translated as 303 kgCO_2eq/m^2 for PV/T module, considering the fact that the embodied energy for the PV module calculated earlier in section 7.2.2.1.2 was almost 75% of that of the total PV/T system. Therefore the embodied carbon value found in the current study for PV/T module as 294 kg CO_2eq/m^2 seems reasonable.

Emissions from transportation of PV/T modules from Germany to Montreal:

The total emissions value in terms of CO_2 eq due to the transportation of the PV/T panels from the manufacturing plant in Germany to Montreal is estimated as shown in Table 7.33.

Table 7.33 Total CO_2 Emissions from transportation of PV/T panels

Transportation route	Mode of transportation	Distance (km)	CO_2 emissions (g/kg/km)*	Total emissions (kg CO_2 eq)
Schuttorf, Germany - Amsterdam Netherlands	Truck	233	0.350	123.96
Amsterdam Netherlands - Montreal, Canada	Sea freighter	5978	0.001	9.09
Emissions from transportation of 16 PV/T panels				**133.04**
Total emissions from transportation of per m^2 PV/T area				**2.31**
*Frischknecht et al. (1996) cited in Krauter & Ruther (2004)				

Knowing the embodied emissions for PV/T and the transportation, the calculations for the total initial embodied emissions for the NZEH are performed as shown in Table 7.34. The embodied energy and emission values in the first row in this table are including the electrical and mechanical BOS but not including the PV/T modules, i.e. the entire PV/T system except the panels. This is because the entire PV/T system is locally purchased except for the PV/T modules manufactured in Germany. For the sake of comparison, the last column of Table 7.34 is a scenario with the assumption that the PV/T panels are also manufactured in Quebec. As expected, the emissions from the German manufactured versus Quebec manufactured PV/T are vastly different.

Table 7.34 Total embodied emissions for the NZEH with PV/T production assumed in Germany & Quebec

Items	Embodied energy ($kWh_{primary}$)	Emission (kg CO_2 eq) for scenarios with PV/T manufactured in	
		Germany	Quebec
Initial embodied values for NZEH with BOS & without the PV/T panels	233,338.32	4,042.00	4,042.00
PV/T panels	113,866.67	16,927.30	1972
Transportation of PV/T panels	947.61	133.04	0
Total	348,152.60	21,102.35	6,014.00
Total per unit area (/m^2)	**1,124.81**	**68.18**	**19.43**

As presented earlier in Table 7.30, the life cycle emissions value for the Base case over 30 year life span is 21,790 kgCO_2 eq. In case of the NZEH, the value just for the initial embodied emissions by using the PV/T panels manufactured in Germany is estimated at 21,102 kgCO_2 eq, and this value does not even include the emissions for replacement. Thus it is obvious that with the German made PV/T panels, total life cycle emissions of the NZEH will exceed those of the base case, since the PV/T panels need replacement after 25 years. Therefore it is assumed that by the time the PV/T modules need replacement, these will be produced locally in Quebec. Since the replacement is needed after 25 years, it is quite likely that the PV/T modules will be manufactured in Quebec by then. Hence further calculations are carried out assuming the initial PV/T panels from Germany but the replacement after 25 years by Quebec made modules, as presented in Table 7.35.

Table 7.35 Total life cycle emissions for the NZEH

Emissions of the NZEH (kg CO_2 eq)	Life span of the NZEH		
	30 years	40 years	50 years
Embodied			
*Initial embodied emissions	21,102	21,102	21,102
Maintenance			
Emissions due to replacement of components other than PV/T panels	415	794	1,173
**Emissions due to replacement of PV/T panels	1,972	1,972	1,972
Operation			
Emissions during Operation	0	0	0
Total Life Cycle Emissions	**23,489**	**23,868**	**24,247**
Specific emissions (kg CO2 eq/m^2 of floor area)	75.89	77.11	78.34
* German made PV/T for initial installation			
** Quebec made PV/T for replacement			

7.4 Discussion & Conclusion

LC Energy of R-2000 vs. traditionally built home:

The total life cycle energy per unit floor area of the 310 m^2 R-2000 base case house for the 40 year life span is estimated at 5007 kWh/m^2 as shown in Table 7.18. Compared to this, Leckner (2008) estimated the life cycle energy of a traditionally built house with the area of 208 m^2 in Montreal during the same life span as 1,381,822 kWh, i.e. 6643 kWh/m^2. Although the system boundaries and the data sources used in these two studies are not exactly the same, the comparison demonstrates that the traditionally built home in Leckner (2008) consumed almost 33% more energy compared to the R-2000 house in this study over the life span of 40 years. Since the goal of R-2000 homes is to build houses that are at least 30% more energy efficient than the traditionally built homes, the estimate for this base case house proves just that over its entire life span.

Employing LCA in the design process:

The three examples listed below are the samples of how LCA can be used in the design process:

1. Figure 7.2 demonstrates how LCA can be used by designers as a decision support tool. The decision of not adding any finishing materials on top of the concrete floors in the NZEH and only using the concrete sealer and stain, turned out to be beneficial in significantly saving cost, energy and emissions over the life span of the building.

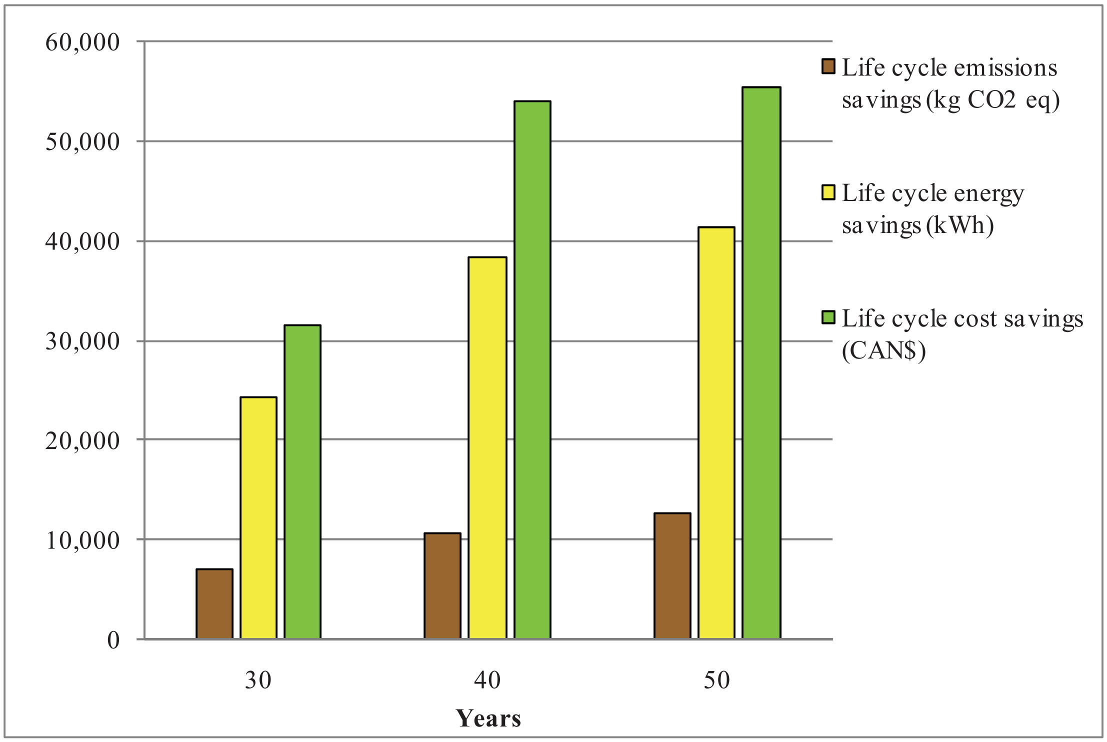


Figure 7.2 Life cycle cost, energy, and emissions savings by avoiding extra floor finishes

2. LCA can be used for emphasizing the importance of extra initial investment in order to benefit in the long run. Figure 7.3 shows the comparison of life cycle energy of the base case and the NZEH. Although the initial embodied energy of the NZEH is higher than the base case, over the life span of the building, this extra initial investment is found to be worthwhile since it drastically reduces the operating energy (including the maintenance).

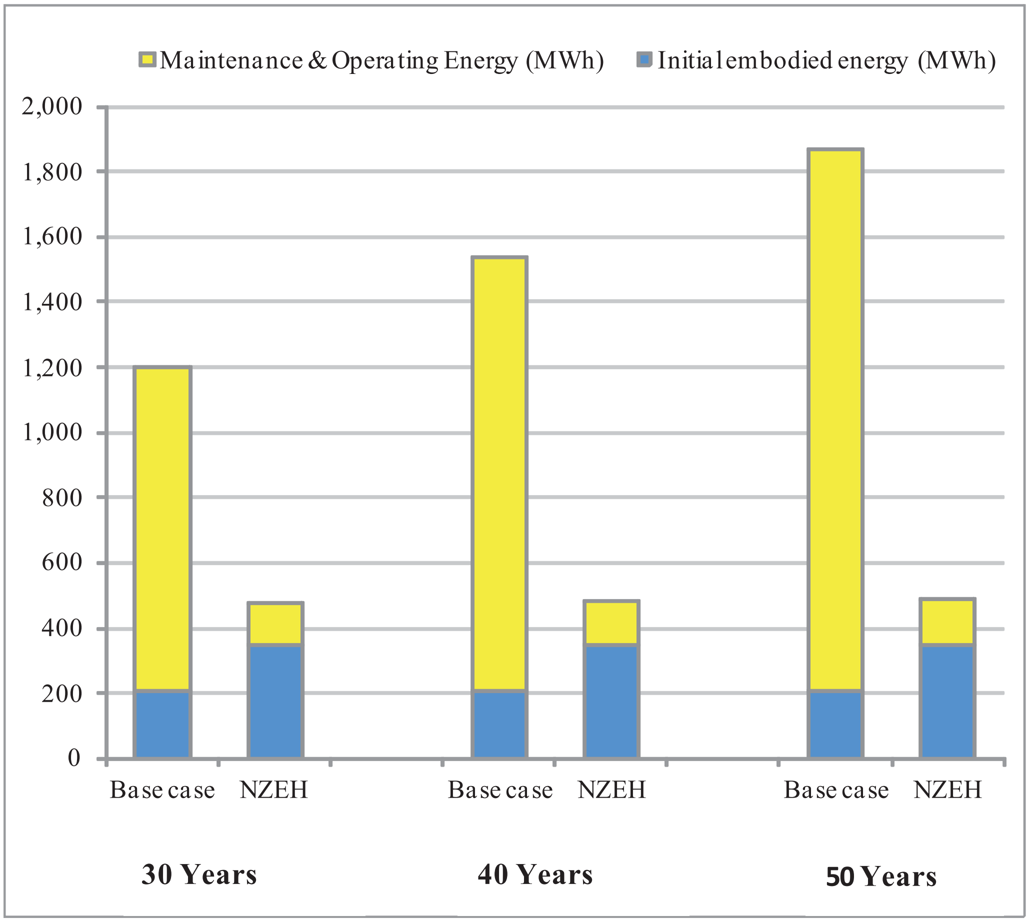


Figure 7.3 Comparison of life cycle energy of the Base case and the NZEH

3. LCA provides a complete picture of the design alternatives to examine their shortfalls and strengths and it can be used in order to make revisions. Table 7.36 shows all aspects of the LCA, i.e. cost, energy, and emissions for the Base case and the NZEH and Table 7.37 shows these LCA values per unit area of the house. Although LCA is useful for making alterations to the design, in this study it is conducted merely as an exercise since proposing revisions based on it is out of scope of this thesis.

Table 7.36 LCA: Comparison between the Base case & the NZEH

LCA component	Life Span of the building		
	30 years	40 years	50 years
Total life cycle cost ($)			
Base case	330,070	377,864	408,219
*NZEH	376,245	388,444	402,638
Total life cycle energy (kWh)			
Base case	1,208,613	1,549,724	1,886,474
NZEH	473,798	482,565	491,332
Total life cycle emissions (kg CO2 eq)			
Base case	21,790	27,961	34,058
** NZEH	23,489	23,868	24,247

*PV/T module cost at the time of replacement after 25 years is assumed 50% of the currant price

**Quebec made PV/T assumed for replacement after 25 years

Table 7.37 LCA: Comparison per unit area of the Base case & the NZEH

LCA component	Life Span of the building		
	30 years	40 years	50 years
Life cycle cost ($/m^2)			
Base case	1,066	1,221	1,319
NZEH	1,216	1,255	1,301
Life cycle energy (kWh/m^2)			
Base case	3,905	5,007	6,095
NZEH	1,531	1,559	1,587
Life cycle emissions (kg CO_2 eq/m^2)			
Base case	70	90	110
NZEH	76	77	78

The life cycle cost analysis may work out better in favor of PV in other places in Canada where the electricity prices are higher than in Quebec, e.g. as of 2007, electricity prices were highest in PEI with 14.18 ¢/kWh, followed by over 12 ¢/kWh in Saskatoon, New Brunswick, Nova Scotia, Alberta, and Ontario. The residential electricity prices in Quebec are the third lowest in Canada at 7.62 ¢/kWh, British Columbia being the lowest at 7.25 ¢/kWh, followed by Manitoba at 7.44 ¢/kWh (Government of Canada, 2008).

7.5 Challenges Encountered in Performing LCA

Although Athena Impact Estimator is a useful tool for calculating embodied energy and emissions, it only covers structural and envelope components. To conduct the LCA of other items, detailed information from the manufacturers is essential and many a times, the manufacturers are reluctant to provide proprietary information. Therefore for most of the components in NZEH, data from the previously done studies in the literature is used for embodied energy. Although this is useful in obtaining an estimate of embodied energy, it is recognized that it has significant limitations. Normally the embodied energy values reported in the literature are only in terms of primary energy. The actual electricity values differ depending on the location, e.g. 1996 MJ of primary energy is required to produce an ERV in Finland, where the electricity production efficiency is 0.46 (Nyman & Simonson, 2005). To manufacture the same component in, say, Quebec, primary energy required will not be the same. This introduces approximations in the embodied energy estimate based on literature.

The same problem affects the emissions estimate. While estimating the emissions based on embodied energy, data are not available that separately list the percentage and type of energy constituting the total primary energy. As an example, the primary energy in ceramic tiles is 9 MJ/kg. The manufacturing process of ceramic tiles might be using heat directly from natural gas, besides the electricity. Not knowing the heat and electricity in the primary energy separating, it is assumed that the entire embodied primary energy is from electricity, and then the emissions are calculated.

Since performing detailed LCA for each component of the systems under consideration is out of scope of this thesis, the only way to conduct the complete LCA is with the help of literature review. If the electricity and other forms of energy that make up the total embodied energy are reported separately, this problem can be avoided.

8. Conclusions

8.1 Summary and Conclusions of the Thesis

The research done in this thesis and its main contributions are divided in the following three areas:

1. Converting the R-2000 home to a NZEH using hybrid PV/T
2. Impact of climate change on the R-2000 home and the NZEH
3. Life Cycle Analysis of the R-2000 home and the NZEH

8.1.1. Converting the R-2000 home to a NZEH using hybrid PV/T

In the entire thesis, the term ‘Base case’ refers to the R-2000 home described earlier in Chapter 4. To calibrate the Base case TRNSYS model, the simulation results obtained are compared with the energy consumption from the actual utility bills. The annual results are in agreement with the total energy consumption from the bills by less than 2% difference. The R-2000 homes, in general, are designed to consume 30% less energy than the regular code-built homes. The simulation results for Ray Vision house in this thesis using TMY2 file for Montreal, show that this particular R-2000 house, built in the year 2000, achieves its expected performance by consuming 72 $kWh/yr \cdot m^2$, which is 33% less than the consumption of 108 $kWh/yr \cdot m^2$, for the houses built in Montreal after 1999 (Zmeureanu et al., 1999).

This Base case model is then converted to a NZEH by using hybrid PV/T as the renewable system. Before sizing the PV/T system, various measures are undertaken to reduce all the existing loads of the Base case. The appliance load is reduced by 52%, by using Energy Star qualified appliances, from 5,228 kWh in the Base case to 2,490 kWh in the NZEH. The lighting load is reduced by 75% by using CFL bulbs, from 2,546 kWh in the Base case to 637 kWh in the NZEH. The MEL is reduced by minimizing stand-by losses and using Energy Star qualified small appliances. The MEL of 2,764 kWh in the Base case is reduced to 1,128 kWh in the NZEH, a reduction of 59%. A significant reduction of 68% is achieved in the DHW load, from 4,955 kWh in the Base case to 1,559 kWh in the NZEH. This is achieved by proposing ultra-low flow faucets, a GWHR unit, a TMV, additional tank insulation and water efficient appliances. The NZEH has mechanical ventilation system with a HRV unit.

A radiant floor system is used for heating the house. The hydronic PV/T system is designed to supply for the thermal loads from heating and DHW as well as the rest of the electrical loads of the house. Sensitivity analyses are conducted on various parameters of the PV/T combi-system, including tank volume, PV/T area, number of glass covers on the PV/T modules, collector slope, and the flow rate of the propylene glycol mix through the PV/T closed loop. Based on this, the final system includes single glazed PV/T panels manufactured by a German company, Holtkamp SES, with 57.6 m^2 of aperture area and a 1,041 L of solar tank. The PV/T produces 6,627 kWh of thermal energy and 10, 456 kWh of electrical energy annually with a surplus of 465 kWh of electricity. On a monthly basis, the house produces surplus electricity during every month of the year except the winter months, November through January. The net metering option allows the house to buy back from the grid during these three months and the surplus is sold to the grid during the rest of the year, thus achieving the net zero goal on an annual basis.

The distribution of the total energy consumption of this NZEH on an annual basis includes 41% for heating, 15% for appliances, 14% for HRV and pumps, 9% for DHW, 7% for MEL, 4% each for lighting and cooling and the rest 6% for thermal losses. Compared to the traditionally built houses, the percentage of heating energy use is much lower in the NZEH due to tighter envelope with higher R-values.

8.1.2. Impact of climate change on the R-2000 home and the NZEH

To study the impact of climate change on the R-2000 house and the NZEH, climate data for the four parameters, ambient temperature, solar radiation, relative humidity, and wind speed for 2050s is used for Montreal location. As per the IPCC recommendation to use multiple climate models in the impact studies, in order to obtain the possible range of impact future climate data is obtained from three climate models with two IPCC scenarios each. The climate models used are CGCM2, ECHAM4, and HadCM3; while the scenarios used are A2 and B2. The results based on these six climate data sets suggest that the heating loads decrease while the cooling loads increase in Montreal in the 2050 climate.

The Base Case in 2050s

For the Base case, the reduction in heating load is in the range of 11 to 22%, while the cooling load increases by 25 to 93% in 2050s compared to the Base case. Similarly, the peak heating load decreases by 2 to 10%, while the peak cooling load increases by 26 to 57%.

All these results are for the Base case house that uses shading and natural ventilation in conjunction with the air conditioning. Therefore, further analysis is done to evaluate the contribution of these two passive cooling strategies. It is found that without the free night cooling, the cooling load further increases in 2050s by e.g. 35% under the CGCM2 A2 scenario. Thus under this scenario, the cooling load for this house incorporating shading and natural ventilation strategies changes from 909 kWh in the current climate to 1,191 kWh in 2050s, and without the free night cooling, it further increases to 1,612 kWh in 2050s. In addition, if neither the night cooling nor the shading is used, this cooling load increases from 909 kWh in the current climate to 2,523 kWh in 2050, which is a significant 177% increase.

Thus designing the houses that facilitate the passive cooling techniques is even more important, anticipating the future increased energy need for cooling. Some of the examples of such design strategies include providing operable windows, allocating the windows in a way to improve cross ventilation and natural air flow, taking advantage of natural stratification of air to get rid of warmer air from the windows at higher heights in the house, external and internal shading, planting deciduous trees on the South side to further improve shading in summer. In addition to the envelope with higher thermal mass, these strategies are certainly significant in lowering the cooling loads for the future climate. Incorporating and evaluating these solutions at the preliminary design stage is certainly advisable before designing the cooling system sizes.

The only energy source in the Base case house is electrical, for all the loads. The absolute decrease in the heating load is found higher than the absolute increase in the in the cooling loads. This is because the house is located in cold climate, where heating use dominates the total energy use in the residential sector. The total energy use of the Base case is expected to decrease by 8 to 20% in the 2050s compared to the baseline climate (1961-1990).

Most of the Canadian residential buildings use electricity for cooling. In Canada, coal is still used for almost 17% of the electricity generation (Government of Canada, 2008). If the electricity generation mix remains unchanged, the increased electricity demand in the future due to climate change will further increase the country's GHG emissions. Therefore, to cope up with the higher cooling demand resulting due to climate change, renewable energy options for residential sector need to be explored.

The NZEH in 2050s

The impact of climate change is observed in the NZEH as well. The heating energy use, which is mostly thermal, and partially electrical in case of the NZEH, overall, reduces by 10 to 20% and the electricity requirement for the cooling increase by 26 to 123% in 2050s compared to the current climate. The electricity needed for other miscellaneous uses, such as HRV, pumps, is also found to decrease by 9 to 20% in the future climate.

The impact results related to PV/T are not as consistent; some GCMs show decrease, while others show increase in the electrical and thermal energy production. Depending on the GCM, the electrical production changes by -1 to 4%, while thermal production changes by -10 to 1%. In hindsight, independent analysis of the energy production of the PV/T panels should have been done, without linking it to the heating or DHW system. The PV/T system directly responds to the loads and shuts on/off based on the loads, i.e. if the heating loads are reduced, the pumps operate less, and less energy is produced. Therefore, the impact of climate change only on the PV/T cannot be isolated. In any case, under CGCM2 and HadCM3 A2 as well as B2 scenarios, the house achieves its net zero goal even in 2050s. The results indicate that the total energy need from all the loads of the NZEH decreases due to climate change, while the PV/T energy production gets relatively less affected, and the system is still able to meet the energy needs of the house and produce surplus electricity. This makes the hybrid PV/T technology a viable renewable energy option even in the future climate.

Compared to B2 scenario, the extent of impact due to climate change is higher with the A2 scenario. This goes hand in hand with the IPCC scenario description. The A2 scenario, which is a pessimistic scenario, assumes the world with higher population growth and more focus on economy. In contrast, the B2 scenario, described as an optimistic scenario, assumes moderate population growth and more focus on the environment. Therefore the impact of the higher GHG emission levels resulting with A2 compared to B2 scenario, reflect in this study.

Given the uncertainties associated with the socio-economic scenarios and the climate change predictions, this study is an attempt to quantify the impact of climate change on the energy use of a house in Montreal; it only serves in providing the range of possible impact and not exact values.

8.1.3. Life Cycle Analysis of the R-2000 Home and the NZEH

The LCA of these two houses include all three components of analysis - cost, energy, and emissions, over the life spans of 30, 40, ad 50 years. The LCA is a very time consuming process and the reliable information required for the analysis is not always readily available. The LCA tools and the databases, although improved considerably over the past few years, do not provide complete information. Having said that, after completing the entire LCA in this thesis, it is realized how it can be a powerful supporting tool in design related decision-making process for buildings.

Life Cycle Cost

The professionals working in the building industry today, that are trying to promote sustainable development through the measures such as energy efficiency and renewable technologies, face the biggest challenge of justifying the higher initial cost of these measures. Therefore an attempt has been made in this thesis to demonstrate how life cycle analysis over entire life span of the building can be used to avoid short-sighted decisions. Although the energy efficiency measures such as CFL, HRV, GWHR unit, need the upfront extra cost, within a period of few months to up to 10 years, this extra cost is shown to pay off due to reduction in energy consumption.

The total life cycle cost of the NZEH is higher than the Base case house by 14% over the life span of 30 years. This is mostly due to the lower electricity cost of electricity in Quebec. In other provinces such as Saskatchewan and PEI, where the electricity prices are almost twice as compared to Quebec, this life cycle cost scenario will be much more favorable to NZEHs.

Over the longer life spans, the gap between life cycle cost of the Base case and the NZEH starts reducing. Over the 40 year life span, the NZEH cost is higher than the Base case by only 2.8%. Over the 50 year life span, however, the NZEH costs relatively less, i.e. $1,301/m^2 versus $1,319/m^2 for the Base case.

Life Cycle Energy

On the energy side, e.g. the NZEH has an embodied energy of 1,123 kWh/m^2 compared to 669 kWh/m^2 for the Base case. However, over the entire life span, the NZEH needs very minimum operating and maintenance energy. Therefore, although the embodied energy of the NZEH is 40% higher compared to the Base case, over the life span of 30 to 50 years, the Base case needs 1.5 to almost three times more energy than the NZEH.

The LC Energy need of the R-2000 house over 40 year life span is estimated at 5,007 kWh/m^2. Compared to traditionally built home, also in Montreal (Leckner, 2008), this R-2000 home consumes 33% less energy over the same life span.

Life Cycle Emissions

Similar to the life cycle cost, over 30 year life span, the life cycle emissions are higher for the NZEH, 76 kg CO_2 eq/m^2 compared to 70 kg CO_2 eq/m^2 for the Base case. The discussion about the life cycle emissions is largely dependent on the energy. Over 30 years, the NZEH actually needs less, i.e. 405 kWh/m^2 of operating and maintenance (O&M) energy compared to 3,230 kWh/m^2 needed for Base case house. Thus, although the O&M energy for the NZEH is lower than the Base case, that difference is not reflected in the emissions due to several factors:

i. The electricity produced in Quebec is cleaner, with over 96% of it being hydroelectricity. A similar comparison of emissions analysis will be a lot more in favor of NZEH in other parts of Canada, where energy generation mix is not as clean.

ii. The PV/T modules have higher embodied energy and emissions compared to the rest of the building components.

iii. The PV/T modules used in the study are made in Germany, where almost 40% of the electricity is still made from coal.

In spite of this, in longer run, the emissions due to the NZEH are found to be lower than the Base case, with 77 versus 90 kg CO_2 eq/m^2 respectively over 40 year life span, and 78 versus 110 CO_2 eq/m^2 respectively, over 50 year life span.

The life cycle analysis of the PV/T system

The total embodied energy of the PV/T system is calculated as 2,239 kWh/m2 of the PV/T area; 75% of which is due to the PV modules. Based on this, the EPR i.e. energy payback ratio and the EPBT, i.e. energy payback time of the PV/T used, are calculated.

EPR of the PV/T system

EPR, is the ratio of the energy output from and the energy input into the system. The energy input for this system includes the embodied energy as well as the energy for transportation, mechanical and electrical BOS, as well as the component replacements throughout the life span of the system. The energy output includes the electrical and mechanical energy produced by the system over the same life span. The EPR for the entire PV/T system is found to be 2.1, 2.8, and 3.6 years, over the 30, 40, and 50 years life span of the NZEH respectively. Thus the system produces two to three and a half times more energy than invested in it.

EPBT of the PV/T system

The energy payback time is the ratio of the total energy consumed by the system over the annual energy production of the system. The EPBT is found to be 9.2 years for just the PV portion of the system and seven years for the combined PV/T system. Thus, the thermal component helps to reduce the EPBT of the hybrid PV/T systems by almost 24%. This is an encouraging finding to support further promotion of this system for the residential application.

Modeling with TRNSYS

Finally, a minor, but still noteworthy contribution of this thesis is for the TRNSYS users. The methodology used to make the TRNSYS models is presented in detail in this thesis. Various modeling components, i.e. Types, their upstream or downstream arrangement in the respective system, linking of inputs and outputs between these Types, etc. can serve as guideline in the future studies using TRNSYS. The methodology to model natural ventilation presented in Chapter 5, the use of some components such as Type 701, Type 93, etc., are just some examples that can be instrumental for someone learning to use this software, as a supplement to the TRNSYS documentation. One of the challenges encountered during the simulation was for the radiant floor heating system in the multi-zone NZEH model. Although, designing a detailed and accurate model was finally achieved, the simulation model became somewhat complex since there were in all 10 zones, and more than one zone per floor.

8.2 Recommendations for future work

1. Impact of climate change on the current housing stock

The impact study in this thesis is not for an average Canadian house but for an energy efficient R-2000 house as well as a NZEH. Passive cooling strategies such as night cooling and shading have been used in both of these cases, resulting in a conservative estimate of impact on cooling load. The average, code-built house with no such measures and lower R-values with higher infiltration rate will be affected differently than the current examples modeled here; such an evaluation is recommended for future study.

2. Impact of climate change on house in other parts of Canada

Based on the current study, it can be anticipated that the decrease in heating load will probably be higher than the increase in cooling load for any Canadian location; but the extent of the change in the total energy use will be different in each of these zones. Analyzing the impact on houses from representative Canadian locations in other climatic zones, e.g. Vancouver, BC, Edmonton, AB, Winnipeg, MB, Halifax, NS is recommended for future work.

3. Impact study with the RCM data

A similar impact study using the TRNSYS models in this thesis is recommended to estimate the impact on both, the R-2000 and the NZEH, with the RCM data already derived in the thesis (Chapter 3) in order to compare the results with the results obtained using the GCM data.

4. Envelope modifications

Although the envelope design was not part of the scope for this thesis, in hindsight, sensitivity analysis on some of the factors such as SHGC should have been done for the NZEH. Many a times, all the windows in houses have same properties, however, keeping the U-value the same, SHGC can be varied, e.g. higher value up to 0.7 on south windows and lower value such as 0.25 on the other sides with same U-value.

5. Impact of climate change on an isolated PV/T system

Since the PV/T system in the NZEH model is connected to the DHW and heating system, its performance is based on these two loads. The pumps for the thermal component only work if there is need for that energy. Therefore, to estimate the real impact of climate change on only the PV/T production, it should be isolated from other systems and the annual performance should be analyzed under the current and 2050 climates. This can be very easily done using the current setup of the TRNSYS models.

6. Comparison between the hybrid PV/T for the NZEH versus separate solar collectors and PV panels

Combined PV/T is a good option to supply for both heat and electricity. But in case of NZEH with PV/T, the sizing of this system becomes critical, since all of the energy needs of the house have to be met by this single system in which the areas of both the thermal and the electrical sides are tied-up. It will be interesting to see the area requirement for side by side PV and solar thermal system for the same house and compare the performance.

7. Geothermal heat pump

Using geothermal heat pump in conjunction with the PV/T system can be a good option for NZEHs and should be explored in future studies.

8.3 Take-home message

Climate Change:

The overall annual energy demand seems to reduce due to climate change in the cold climate. However, any research that concludes even remotely that there is any advantage associated to climate change, is unreasonable. Aside from global warming, climate change is causing adverse effects on overall quality of life because of increased pollution, irregular weather patterns, climate related disasters, extreme weather patterns, increasing sea levels forcing migration of populations and so on. In spite of any future efforts to reduce GHG emissions in order to minimize climate change, adaptation efforts will still be needed. Because the harm done to the environment over the past century or two is irreversible and since elimination of CO_2 producing practices is impossible, mitigation and adaptation strategies need to be planned.

Some parts in the developing world will be getting affected tremendously as an effect of climate change causing ever limiting water supply, droughts, heat waves, food shortage etc. And the recent economic downturn has proved that the rippling effects of any event in any part of the globe are felt much faster and wider all over the world now due to globalization more than ever before. Climate change is a global challenge; the political and scientific communities in all parts of the world need to act together to combat it for the common betterment.

Building Design:

While working on this thesis, the significance of holistic approach to design is realized frequently. The systems - heating, cooling, ventilation, lighting, along with the renewable energy systems - all affect each other, and should be analyzed together. At a macro level, another key issue recognized, is the interdependence of architectural and engineering design processes of this house, or any building, for that matter. Each of these, have an impact on the other, making the Integrated Design Process (IDP), significant for a final efficient design.

Finally, the most important take-home message of this thesis is that the buildings and its external environment are extremely closely related. The buildings make an impact on the environment through their energy use and emissions, albeit not always measureable; similarly, the environment affects the buildings and their energy use. Realizing this relationship and trying to make it more symbiotic is the only way to achieve sustainable development.

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Appendix A. Climate Models, IPCC Scenarios and Climate Data

Appendix A Climate Models and Scenarios

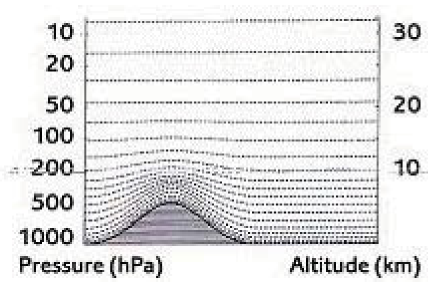


Figure A.1.i Vertical resolution - Levels (Climateprediction.net, 2010)

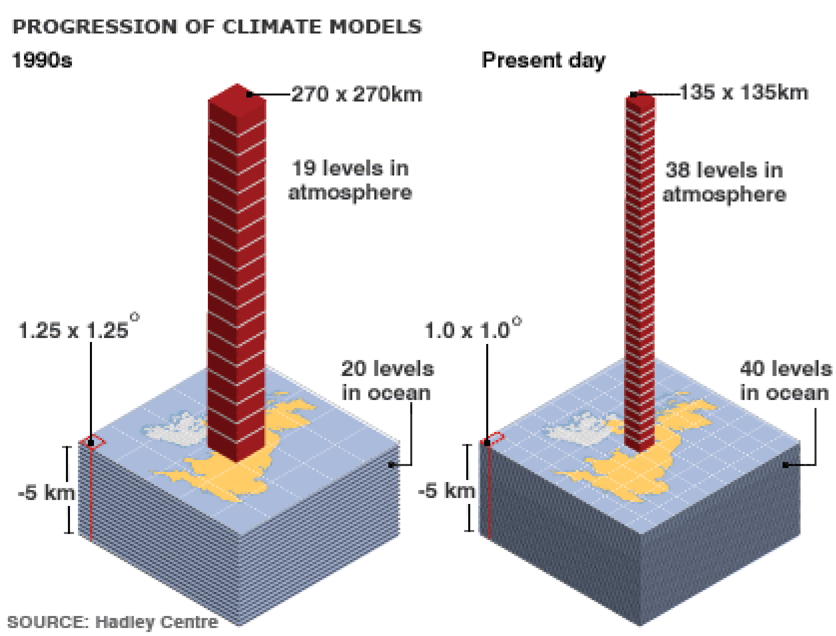


Figure A.1.ii Improvement in resolution of climate models (Pope, 2007)

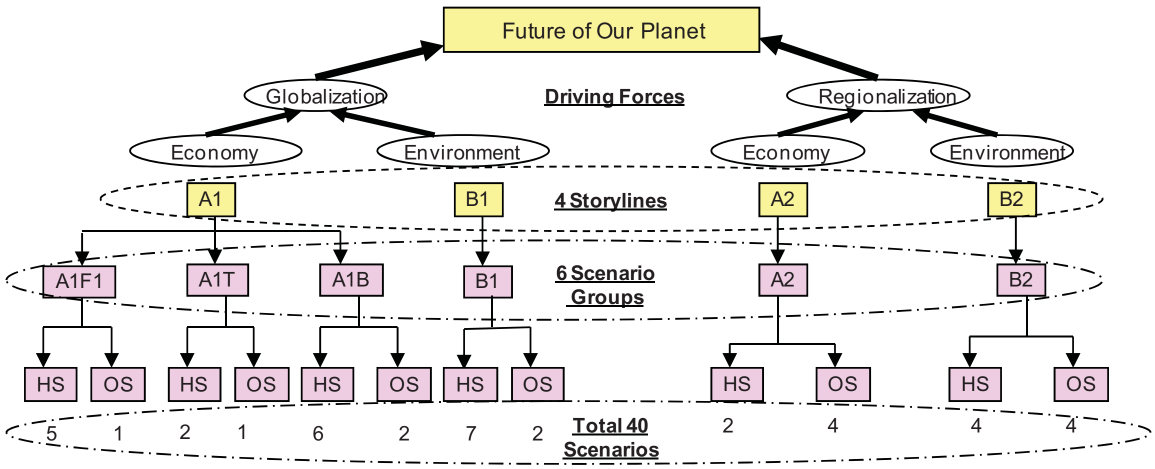
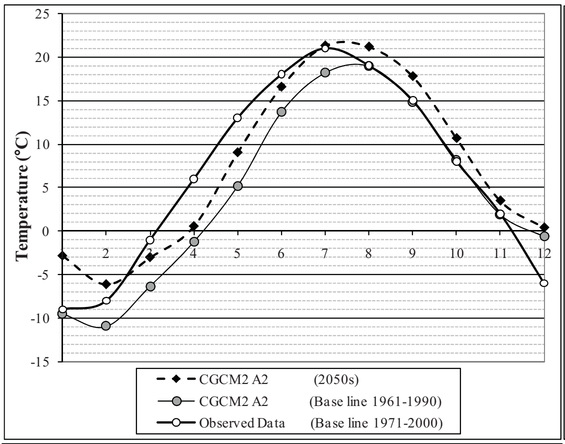
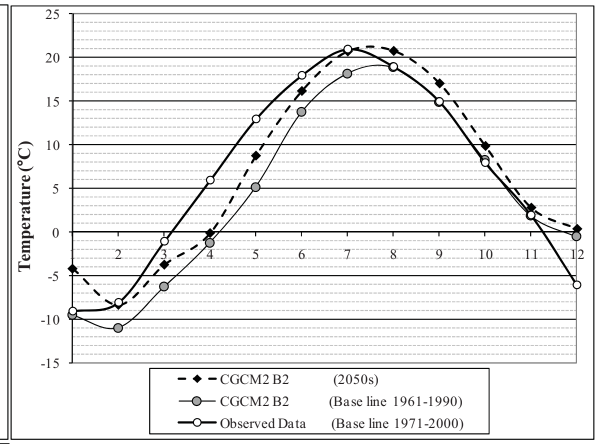
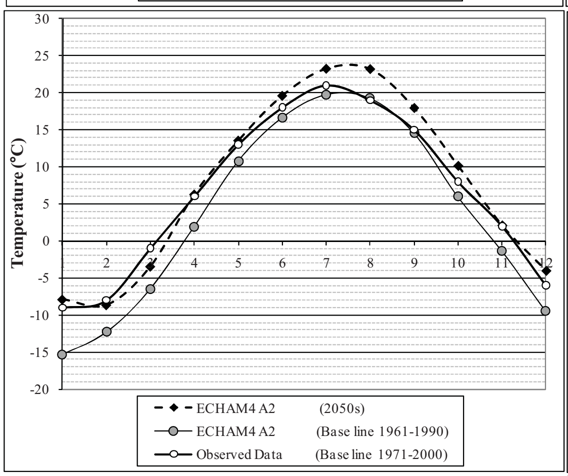


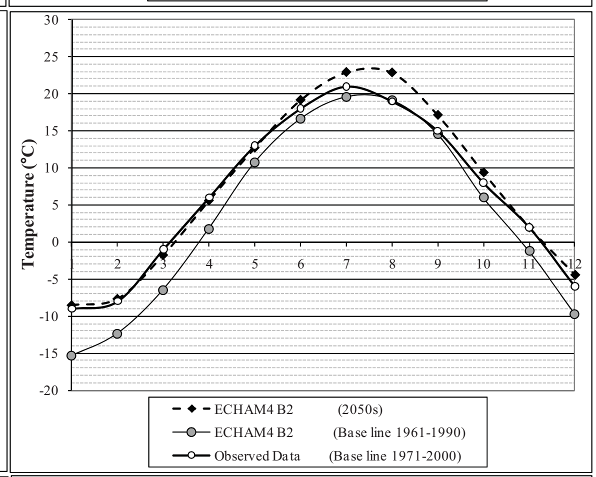
Figure A.1.iii Summary of the driving forces, storylines, scenario groups and the scenarios derived in IPCC SRES (2001)

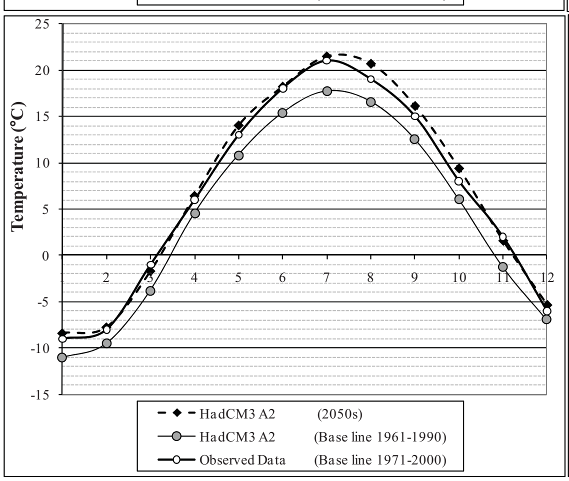
Appendix A.2 Comparison of Monthly Observed Temperature Data versus the GCM Data

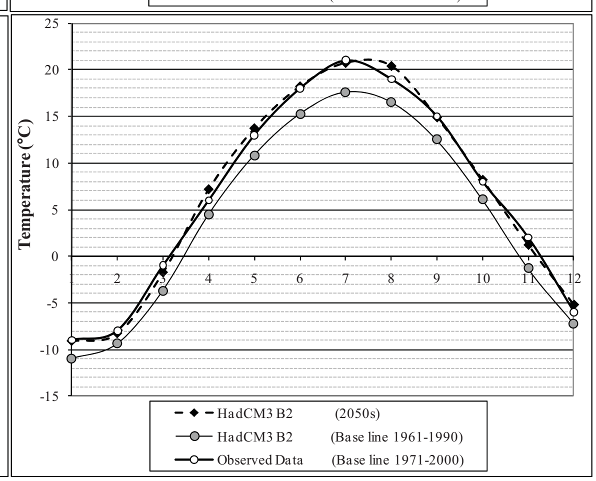












Appendix B. Thermo-Physical Properties of Materials Used in the Envelope

Note: mass-less layers not included

Zone	Wall	Layers	Thickness	Conductivity		Capacity	Density
			m	W/m.K	kJ/h.m.K	kJ/kg. K	kg/m^3
Basement							
	EXT_BASEMENT_WALL	GYP_BRD	0.013	0.163	0.585	1.09	800
		STUD_CELLUL_INSUL	0.089	0.040	0.144	1.38	45
		POLYURETHANE_INSUL	0.050	0.024	0.085	1.00	40
		CONCRETE_USER	0.250	0.781	2.813	0.90	1600
	EXT_BASEMENT_FLOOR	CERAMIC	0.020	2.000	7.200	0.80	590
		CONCRETE_USER	0.080	0.800	2.880	0.90	1600
		POLYSTYRENE_INSUL	0.050	0.028	0.102	1.21	40
		Condeck	0.150	0.900	3.240	0.90	1600
Ground Floor							
	EXT_WALL_ABOVE_GR	GYP_BRD	0.013	0.163	0.585	1.09	800
		STUD_CELLUL_INSUL	0.140	0.040	0.144	1.38	45
		STUD_POLYURETHANE_INSUL	0.038	0.022	0.078	1.21	40
		FIBRE_BOARD	0.013	0.054	0.196	1.30	290
		BK_VENEER	0.090	1.125	4.050	0.79	2080
	INT_WALL_USER	GYP_BRD	0.013	0.163	0.585	1.09	800
		GYP_BRD	0.013	0.163	0.585	1.09	800
	FLOOR_GF	FLOOR_HDWOOD	0.015	0.187	0.673	2.30	720
		FLOOR_WOOD	0.015	0.130	0.468	1.38	600
		GYP_BRD	0.013	0.163	0.585	1.09	800
Second Floor							
	FLOOR_SF	CARPET	0.015	0.043	0.155	0.71	800
		FLOOR_WOOD	0.015	0.130	0.468	1.38	600
		STUD_CELLUL_INSUL	0.100	0.040	0.144	1.38	45
		SHEATHING	0.013	0.241	0.867	1.30	290
		GYP_BRD	0.013	0.163	0.585	1.09	800
		GYP_BRD	0.013	0.163	0.585	1.09	800
	ATTIC_FLOOR	ROOF_INSUL	0.424	0.040	0.144	1.38	45
		SHEATHING	0.013	0.231	0.833	1.30	290
		GYP_BRD	0.013	0.163	0.585	1.09	800
	ROOF	Wood_joist	0.040	0.044	0.160	1.63	700
		PLYBOARD	0.013	0.110	0.396	1.21	540
		ASPHALT_SHINGLE	0.005	0.065	0.234	1.26	1100

Appendix C. Life Cycle Analysis

Appendix C.1 Life Cycle Cost Analysis

The costs from RS Means (2009) in Tables C.1.i - vii are adjusted for Montreal location.

Table C.1.i Cost breakdown for items related to floor construction: Base Case & NZEH

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
1. Structure						
Concrete*					1	p.62
	4" regular concrete slab	1.66	0.70	2.63		
	2 1/2" lightweight concrete floor fill	1.42	0.71	2.44		
Floor Finish						
	Acid stain: Concrete slab floor finish in NZEH					
	Stain, one coat	0.13	0.40	0.54	1	p.319
	Stain, two coats	0.27	0.46	0.73	1	p.319
	Acrylic sealer, one coat	0.18	0.10	0.29	1	p.319
	Acrylic sealer, one coat	0.37	0.19	0.55	1	p.319
	Ferrous sulphate stain for concrete floors: including the acid stain, concrete sealer, organic degreaser, and neutralizer	23.89	_	_	2	1 gallon covers 200 sq ft. Total 17 gallons (64 L) required. Cost US $84 per gallon
	Plywood					
	Plywood underlayment, 1/2"	1.22	0.34	1.55	1	p. 170
	Wooden Floors: Ground floor in Base Case					
	Parquetry, standard, 5/16" thk, not including finish, min. available rates:				1	p. 298-299
	Oak	5.37	1.88	7.24		
	Teak	5.83	1.88	7.71		
	Walnut	6.51	1.88	8.39		
	Flooring, wood, bamboo	5.40	1.17	6.58		
	Flooring, wood, bamboo	5.95	1.17	7.12		
	Sanding and finishing, 2 coats polyurethane	0.95	0.81	1.76		
	Carpet: Second floor in Base Case					
	carpet, nylon, light to medium traffic	31.64	3.81	35.45	1	p.304
	Ceramic tiles: Basement in Base Case					
	12" x 12" floor tiles in basement	5.62	1.58	7.20	1	p.294

* The total cost includes equipment cost besides material and labor

Table C.1.ii Radiant floor cost breakdown: NZEH

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
2. Components of heating system: Radiant floors						
Tubing	Tubing, PEX (cross-linked Polyethylene)					
	Oxygen barrier type for systems with ferrous material, 1/2"	1.14	0.83	1.98	1	p. 507-508
	Non barrier type for ferrous free systems, 1/2"	0.62	0.83	1.46	1	p. 507-508
	Tubing: Uponor Wirsbo hePEX 12.7mm (1/2")	0.66	_	_	3	Tubing length estimate: 80'/100sq ft; Cost: US $599.95/1000'
Manifolds						
	Brass				1	p. 507-508
	Valved 1", 3 circuit	77.28	60.50	137.78		
	Valved 1", 4 circuit	106.49	74.10	180.59		
	Valveless 1", 3 circuit	38.94	55.34	94.29		
	Valveless 1", 4 circuit	50.51	66.60	117.10		
	Copper (to be used with non barrier type tubing)				1	p. 507-508
	3 circuit, 1" x 1/2" x 2"	14.66	45.96	60.63		
	4 circuit, 1" x 1/2" x 2"	16.73	54.40	71.14		
	Plastic					
	Wirsbo EP (Engineered Plastic)					Manifolds are offered with various number of loops from 2 to 8. Number of zones on a floor = no of loops needed in the manifold on that floor.
	3-loop manifold each in basement and on first floor	267.45	_	_	3	
	4-loop manifold on second floor	315.60	_	_	3	

Table C.1.iii Radiant floor cost breakdown: NZEH (continued)

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Connectors, adapters, couplings						
	Manifold connector kit including mounting brackets, couplings, end cap, air vent, valve, plug, 1"	98.58	83.48	182.06	1	p. 507-508
	Manifold connector kit including mounting brackets, couplings, end cap, air vent, valve, plug, 1-1/4"	116.22	95.68	211.90	1	p. 507-508
	Adapters: 3/4" to 1/2" PEX	7.44	_	_	3	4 adapters per zone (2 each for supply and return
	Couplings	7.95	_	_	3	2 couplings per zone
Valves						
	Thermostatic Mixing Valve (TMV)					
	TMV 1/2"	107.70	24.86	132.56	1	p. 507-508
	TMV 3/4"	130.22	26.73	156.95	1	p. 507-508
	TMV 1"	139.96	30.95	170.91	1	p. 507-508
	Honeywell RC-AM101C	79.99			6	
	Motorized zone valve operator	59.63	22.04	81.68	1	p. 507-508
	3-way mixing / diverting valve, brass				1	p. 507-508
	1/2"	142.39	31.42	173.81		
	3/4"	146.04	33.30	179.34		
	1"	169.16	37.52	206.68		
	4-way mixing / diverting valve, brass				1	p. 507-508
	1/2"	148.47	41.74	190.22		
	3/4"	165.51	44.56	210.07		
	1"	184.98	50.18	235.17		
	Motor control for 3 or 4 way valves, for valves up to 1-1/2"	205.67	22.04	227.72	1	p. 507-508
	Mixing valves	353.05	_	_	3	
	Diverter	39.75	_	_	4	

Table C.1.iv Radiant floor cost breakdown: NZEH (continued)

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Controls						
	for zone valves	192.29	41.74	234.03	1	p. 507-508
	for circulators	273.83	41.74	315.57	1	p. 507-508
	Thermostats: Wirsbo programmable set point controller, without floor sensor	176.50	_	_	4	
	Floor sensors: Wirsbo A3040079	47.03	_	_	4	10' long, can be used with concrete slab
Pumps	Taco Variable Speed Delta T008-VDTF6	463.00	_	_	5	Phone conversation
Piping	**Copper**					
	1/2" dia.	4.66	4.52	9.18	1	p.448
	1/2" dia.	16.00	_	_	6	available in 12' length
	3/4" dia.	7.30	4.83	12.13	1	p.448
	3/4" dia.	27.00	_	_	6	available in 12' length
	1" dia.	11.01	5.39	16.41	1	p.448
	1" dia.	34.00	_	_	6	available in 12' length
	Piping: 1” Wirsbo AquaPEX	1.05	_	_	3	Tank to each floor: supply and return, red for supply and blue for return. Price: US$ 104.95/100'
Pipe Insulation						
	Rubber tubing, flexible closed cell foam				1	p.447
	1" wall, for 1/2" pipe	2.08	3.85	5.93		
	1" wall, for 3/4" pipe	2.52	3.94	6.46		
	1" wall, for 1" pipe	2.93	3.94	6.87		
	Pipe insulation AM Conserv 071FS11834	0.66	_	_	7	Only supply pipes are insulated, no need to insulate the return pipes. Price: US$ 74.08/120'

Table C.1.v Cost breakdown for insulation materials

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Board Insulation						
1	Extruded polystyrene (XPS), 25 PSI compressive strength				1	p.194
	1", R5	0.62	0.38	1.00		
	2", R10	1.27	0.41	1.68		
	3", R15	1.70	0.41	2.12		
	Extruded polystyrene: 25 mm (1 inch), CodeBord, Model # 270457, size 1"x48"x96"	0.65	_	_	6	$20.57/1"x48"x96" (32sqft). i.e. $0.65/sq ft, $6.92/sq m
2	Expanded Polystyrene (EPS)				1	p.194
	1", R3.85	0.29	0.38	0.67		
	2", R7.69	0.74	0.41	1.16		
	3", R11.49	0.95	0.41	1.36		
3	Isocyanurate, 4' x 8' sheet, foil faced both sides				1	p.194
	1/2" thk, R3.9	0.37	0.38	0.74		
	1" thk, R7.2	0.67	0.38	1.04		
	2" thk, R14.4	0.99	0.41	1.40		
	3" thk, R21.6	2.31	0.41	2.73		
	4" thk, R28.8	2.60	0.41	3.02		
Sprayed-on Insulation					1	p.197
	** Polyurethane spray foam, closed cell, 2 pounds per cubic feet density					
	1" thk	0.85	0.11	0.96		
	2" thk	1.70	0.23	1.93		
	3" thk	2.57	0.34	2.91		
	4" thk	3.41	0.46	3.87		
	5" thk	4.26	0.57	4.83		
** The total cost includes equipment cost besides material and labor						

Table C.1.vi Cost breakdown for heating and DHW components: Base Case

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Baseboard heaters					1	p. 508
	Baseboard units including controls, not including conduits or feed wiring	112.57	80.20	192.77		
	Thermostats	24.95	22.04	46.99		
DHW tank						
	DHW: Residential, electric heater, double element					
	52 gal	681.52	182.91	864.43	1	p.459
	80 gal	924.92	361.13	1286.05	1	p.363
	120 gal	1429.98	261.70	1691.68	1	p.459

Table C.1.vii Cost breakdown for solar storage tank components: NZEH

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Solar storage tank						
	SunMaxx Solar, 1000L	1631.75	_	_	8	Phone conversation
	Polypropylene Solar Hot Water Storage tank, 265 gal	780.00	_	_	9	email communication. can withstand temperatures up to 93 °C(200 °F)
Tank insulation						
	100 mm (4") polyurethane insulation: INFLEX, R16	1123.50	_	_	10	email quotation for 1000L tank, plus $389.56 shipping cost
	Boiler insulation, 2" fiberglass	4.27	7.46	11.73	1	p.477
Expansion tank						
	EPK-3/4", includes expansion tank, air eliminator, fill and drain valves, pressure gauge, and pressure relief valve, and mounting hardware	341.33	_	_	4	

Table C.1.viii Cost breakdown for miscellaneous energy efficiency items: NZEH

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Heat Recovery Ventilator						
	HRV: Fantech VHR 1405R	710.69	_	_	11	Price US$ 664.20
Ducts					1	p.485
	Flexible air ducts, Insulated, 1" thk, PE jacket					
	3"dia	2.54	1.68	4.22		
	6"dia	2.81	2.45	5.26		
	10"dia	4.15	4.56	8.71		
	12"dia	5.16	6.38	11.54		
Grey Water Heat Recovery unit						
	Power-Pipe R3-60, 3" dia., 60" long,	680.00	_	_	6	
Artificial Lighting						
	CFL bulbs: GE 13W, 6 pack	16.96	_		12	
	Incandescent lighting: 60W, 4 pack	3.73	_		12	

Table C.1.ix Cost breakdown for major appliances

Category	Product	2009 Bare Costs (CAN$)			Reference	Comments
		Material	Labor	Total		
Cooking range					1	p.362-363
	30" wide, free standing, 1 oven					
	Min	389.44	47.37	436.81		
	Max	1977.63	47.37	2024.99		
	21" wide, free standing, 1 oven	383.36	47.37	430.72		
	Frigidaire CFEF 272DS, 24", free standing, 1 oven	849.00	0.00		18	Energuide rating 397 kWh/yr
Refrigerator, 18 to 20 cu-ft					1	p.362-363
	Min	699.78	59.09	758.87		
	Max	1217.00	118.19	1335.19		
	Energy Star, 18 to 20 cu-ft					
	Min	638.93	150.08	789.01		
	Max	1277.85	300.16	1578.01		
	Energy Star, 21.7 cu-ft	1064.88	150.08	1214.96		
Dishwasher: built-in, 2 cycles					1	p.362-363
	Min	250.70	180.10	430.80		
	Max	377.27	361.13	738.40		
	Energy Star					
	Min	383.36	180.10	563.45		
	Max	1217.00	361.13	1578.13		
Clothes Washer: automatic					1	p.362-363
	Min	383.36	121.94	505.30		
	Max	1338.70	365.82	1704.52		
	Residential, 4 cycle, average	973.60	121.94	1095.54		
	Energy Star, front loading	620.67	121.94	742.61		
	Energy Star, top loading:					
	Min	590.25	121.94	712.19		
	Max	1204.83	121.94	1326.77		
Dryer					1	p.362-363
	Gas fired residential, 16 lb capacity	760.63	121.94	882.57		
	Electric, GE PBXR473EH	369.00	_	_	18	EnerGuide rating 900 kWh/yr
	Energy star, electric, front loading					
	Min	310.34	175.41	485.74		
	Max	1734.23	263.58	1997.80		

Table C.1.x Cost breakdown for PV/T panels, electrical & mechanical BOS: NZEH

Category	Product	Unit	2009 Bare Costs (CAN$)			Reference	Comments
			Material	Labor	Total		
PV/T panels							
	SES PVT 540/2300	each	3152.00	_	_	13	€ 2,000
	SES PVT 360/1550	each	2364.00	_	_	13	€ 1,500
	SES PVT 180/765	each	1418.40	_	_	13	€ 900
Balance Of System							
	Controller: WSE618C-6, 5 temperature sensor	each	341.55	_	_	14	Phone conversation on September 4, 2009
	Differencial controller with two sensors					1	p. 498
	Thermostat, hard wired	each	96.75	45.96	142.71		
	Five station with digital read-out	each	265.31	121.94	387.25		
	Pump: Taco solar thermal circulator 006-VTF4	each	630.00	_	_	5	email received on September 4, 2009
	Pump package: WSE SOL-0100 (includes controller, 3-way valve, air-vent, BTU meter, flow meter, and Grundfos variable speed pump)	each	995.00	_	_	13	Phone conversation on September 4, 2009
	Heat exchanger: fluid to fluid, package includes two circulating pumps, expansion tank, check valve, relief valve controller, high temperature cut-off and sensors	each	845.82	263.58	1109.39	1	p. 498
	Inverter						
	Xantrex GT Grid-tie 4kW	each	3130.90	_	_	15	Total 9W needed
	Xantrex GT Grid-tie 5kW	each	3950.50	_	_	15	
	Fronius Ig4500-Lv 4500W Grid-tie	each	3179.00	_	_	16	

Table C.1.x (continued)

Category	Product	Unit	2009 Bare Costs (CAN$)			Reference	Comments
			Material	Labor	Total		
Heat transfer fluid							
	Propylene glycol, inhibited anti-freeze	L	4.45	3.46	7.91	1	p. 498, prices converted from per gal to per L
	Propylene glycol mix ProSol L-HT	L	6.75	_	_	17	Phone conversation, $135 per 20L container
Other accessories						1	p. 498
	Roof clamps	Set	2.86	9.43	12.29		
	Roof strap, teflon	L.F.	24.28	1.78	26.06		
	Collector panel mounting	each	264.09	93.80	357.89		for flat roof or ground rack
Roofing materials							
	Plywood sheathing on roof: 1/2" thk, pneumatic nailed	sq ft	0.56	0.35	0.91	1	p. 170
	Asphalt roof shingles					1	p. 199
	Inorganic, pneumatic nailed	100 sq ft	60.85	46.90	107.75		
	Organic, pneumatic nailed	100 sq ft	62.07	41.27	103.34		

1	RS Means (2009)
2	Direct Color Inc. (2009)
3	PexSupply.com (2009)
4	Radiant Floor Company (20
5	Jacques Desjardins Agence (2009)
6	Home Depot (2009)
7	AM Conservation Group Inc. (2008)
8	SunMaxx Solar - Silicon Solar Inc. (2009)
9	Plastic-Mart (2009)
10	INFLEX (n.d.)
11	Midlight Electric (2005)
12	Walmart (2009)
13	Holtkamp SES
14	WSE Technologies
15	GreenerEnergy.ca
16	Alternative Energy store
17	solarnetix

Appendix C.2 Life Cycle Energy Analysis

Table C.2.i Embodied energy values for various envelope and structural materials

Item	Specific embodied energy [MJ/kg]	Specific embodied energy [MJ/unit]	Specific emissions [kgCO_2 /kg]	Reference
Structure & Envelope				
Concrete	_	*1930/ m^3	_	Athena (2003)
"	1.00	_	0.065	Asif et al. (2007)
"	0.69	1663/m^3		Dimoudi & Tompa (2008)
"	1.60	_	0.2	Blanchard and Reppe (1998)
Concrete (17.5 Mpa)	0.90	2019/ m^3	0.114	Alcorn (2003), p.27
Concrete slab floor		266.31/m^2	–	Edmonds & Lippke (2005)
Concrete (Cement-sand-aggregate ratio 1:2:4, typical in construction of buildings under 3 storeys)	0.95	_	0.129	Hammond & Jones (2008), p.28
Concrete with fly ash (25% cement replaced by fly ash)	0.80	–	0.102	Hammond & Jones (2008), p.39
Wood joist floor	_	106.85/m^2	–	Edmonds & Lippke (2005)
Brick: common	3.00	_	0.52	GreenSpec (2008)
Asphalt shingles	_	*280/m^2	/m^2	Athena (2003)
"	14.60	_	0.3	Blanchard and Reppe
"	12.01	123.2/m^2	–	Friedman and Cammalleri (1995)
Plywood	15.00		0.81	GreenSpec (2008)
"	8.30		0.1	Blanchard and Reppe (1998)
15.9 mm thk plywood sheathing	14.62	119.95/m^2		Friedman and Cammalleri (1995)
12.5 mm (1/2") thk plywood		*64.3/m^2	/m^2	Athena (2003)
* Values used in the current study				

Table C.2.ii Embodied energy values for floor finish materials

Item	Specific embodied energy [MJ/kg]	Specific embodied energy [MJ/unit]	Specific emissions [$kgCO_2/kg$]	Reference
Floor finish				
Wooden floors (15 mm thk)	_	8330/m^3	_	Athena (2003)
Parquetry flooring	7.38	*46.95/m^2	_	Friedman and Cammalleri (1995)
Ceramic tiles	_	161.67/m^2	_	Nicoletti et al., 2002
"	_	147/m^2	_	Fay et al., 2000
"	9.00	_	0.59	GreenSpec (2008)
"	2.14	33.42/m^2		Friedman and Cammalleri (1995)
"	8.00	_	0.571	Asif et al. (2007)
Ceramic tiles (14.3 kg/m2, Pullen, 2000)	9.00	_	0.52	Hammond & Jones (2008), p. 26
Average value for ceramic tiles	_	*114.03/m^2	_	_
Carpet	_	*186.7/m^2	9.76/m^2	Hammond & Jones (2008), p. 24
"	74.42	186.65/m^2	_	Friedman and Cammalleri (1995)
"	67.9-149	_	3.55-7.31	GreenSpec (2008)
Carpet (2.4 kg/m2; Pullen, 2000)	135.68	_	_	Hammond & Jones (2008), p. 39
* Values used in the current study				

Table C.2.iii Embodied energy values for insulation materials

Item	Specific embodied energy [MJ/kg]	Specific embodied energy [MJ/unit]	Specific emissions [$kgCO_2/kg$]	Reference
Insulation				
Cellulose	0.94 - 3.3			Hammond & Jones (2008), p.43
Mineral wool	16.60		1.2	Hammond & Jones (2008), p.43
Polystyrene insulation	92.90	–	–	Hammond & Jones (2008), p.43
"	88.60	_	2.5	GreenSpec (2008)
"	100.30	_	2.1	Blanchard and Reppe
"	117.00			Athena (2003)
Extruded Polystyrene (XPS)		*85/m^2	2	Athena (2003)
"	188.59	1144.94/m^2	–	Friedman and Cammalleri (1995)
"	58.40	1868/m^3	2.495	Alcorn (2003), p.28
"	–	–	1.79	Papadopoulos & Giama (2007)
"	58.40	1401/m^3	2.495	Alcorn (2003), p.28
Polyurethane: 100 mm thk	*80.1	–	–	Hammond & Jones (2008), p.43
Polyurethane insulation	72.10	_	3	GreenSpec (2008)
Polyisocyanurate	70.60	–	–	Blanchard and Reppe (1998)
* Values used in the current study				

Table C.2.iv Comparison of energy requirement for poly-Si (p-Si) & mono-Si (m-Si) module production (Alsema, 2000)

Process	Poly-crystalline modules		Mono-crystalline modules	
	Primary energy [MJ/m^2]	Percent of the total for p-Si	Primary energy [MJ/m^2]	Percent of the total for m-Si
Mg silicon production	450	9.78	450	7.38
Silicon purification	1,800	39.13	1,800	29.51
Crystallization & contouring	750	16.30	2,300	37.70
Wafering	250	5.43	250	4.10
Cell processing	600	13.04	550	9.02
Module assembly	350	7.61	350	5.74
Frame	400	8.70	400	6.56
Total	**4,600**	**100.00**	**6,100**	**100.00**

Table C.2.v Breakdown of material use in the PV/T system Tripanagnostopoulos et al. (2005)

System Component	Sub-component & material	Mass* (kg/m^2)
Electrical BOS	Steel	0.33
	Copper	0.20
	Plastic (Poly Vinyl Chloride)	0.13
Solar thermal panel	Copper sheet	1.50
	Copper pipe	3.50
	**Mineral wool insulation: 90 mm	0.90
	**Polystyrene insulation: 30 mm	1.20
	Collector frame: aluminum	2.00
	Collector back cover: aluminum	1.00
	Glazed covering: low-e glass	12.50
	Additional collector frame for glazed covering	1.50
Mechanical BOS	Support structure for tilted roof: Galvanized iron rods	3.00
	Support structure for tilted roof: Aluminum	1.00
	**Pipes for water circulation: Wirsbo AquaPEX	0.05
	**Water storage tank: 1000 L, stainless steel	1.49
	Heat exchanger coils in the tank: copper	0.83

* Based on mass (kg) values for 30 m^2 PV/T in Tripanagnostopoulos (2005)
** Materials from the current study; differ from Tripanagnostopoulos (2005)

Appendix C.3 Life Cycle Emissions Analysis

Table C.3.i Embodied energy and emissions values for different types of PV modules

Item	Specific embodied energy [MJ/m^2]	Specific emissions [$kgCO_2$ eq/unit]	Reference
Mono-crystalline Silicon modules (m-Si)			
m-Si modules	4750 (2590 - 8640)	242 (132 - 440)/m^2	Hammond & Jones (2008), p. 6
"	1380.00	_	Nawaz & Tiwari (2006)
"	6900.00	_	Knapp & Jester (2001)
"	_	5.020/kWp	Schaefer & Hagedorn (1992) cited in Sherwani et al. (2010)
"	_	0.091/kWh	Kato et al. (1997) cited in Sherwani et al. (2010)
"	_	0.165/kWh	Kannan et al. (2006) cited in Sherwani et al. (2010)
"	_	0.044/kWh	Muneer et al. (2006) cited in Sherwani et al. (2010)
m-Si, frameless	5700 (6100 for framed)	_	Alsema (2000)
Poly-crystalline silicon modules (p-Si)			
p-Si modules	4070 (1945 - 5660)	208 (99 - 289)/m^2	Hammond & Jones (2008), p. 6
"	4435 or 34 MJ/Wp		Pacca et al. (2006)
p-Si, 10.7% efficient, aluminum framing, module	5150.00	463/m^2	Battisti and Corrado (2005)
p-Si, including single glazing, and framing	3043.33	396.33/m^2	Tripanagnostopoulos et al. (2005)
p-Si, frameless	4200 (4600 for framed)	_	Alsema & Nieuwlaar (2000)
Thin film amorphous silicon modules (a-Si)			
Thin film modules	1305 (775 - 1805)	67 (40 - 92)/m^2	Hammond & Jones (2008), p. 6
"	14 MJ/Wp		Pacca et al. (2006)
a-Si thin film, frameless	1200 (1600 for framed)	0.05 - 0.06/kWh	Alsema & Nieuwlaar (2000),
"	17 MJ/Wp		Alsema (2000)
* m^2 refers to the PV area and kWh refers to the electricity produced by PV			

Table C.3.ii Embodied energy and emissions values for various PV/T system components

Item	Specific embodied energy [MJ/m^2]	Specific emissions [kgCO_2 eq/unit]	Reference
Electrical BOS			
Inverter	118.80	–	Nawaz & Tiwari (2006)
BOS	700.00	–	or 1 MJ/Wp, Alsema & Nieuwlaar (2000)
O & M, waste, electronic components, cables	450.00	–	Nawaz & Tiwari (2006)
Electrical BOS	31	–	Tripanagnostopoulos et al. (2005)
Complete electrical BOS, boundary includes material production to end of life	526-542	29-31 /m^2	Mason et al. (2005) cited in Sherwani et al. (2010)
Solar thermal flat plate collector			
Glazed collector	1495.00	–	Kalogirou (2004)
Collectors matching the ones in the currant study; distribution and disposal not	1016.67	84.33/m^2	Tripanagnostopoulos et al. (2005)
Collector and storage tank connected together in a thermo siphon (passive)	1649.06	127.23/m^2	Ardente et al. (2005) a., p. 1045
Hybrid PV/T			
Glazed PV/T with poly-Si PV	4612.33	396.33/m^2	Tripanagnostopoulos et al. (2005)
* m^2 refers to the PV (or PV/T) area			

Table C.3.iii Electricity generation split by resource

Region	Hydro	Nuclear	Coal	Natural gas	Petroleum and other	Renewables	Total	Reference
Quebec	96.2	2.5	0	0.2	0.5	0.6	100	Government of Canada (2008)
Canada	59.3	14.4	16.7	5.6	2.6	1.4	100	Government of Canada (2008)
USA	5.8	19.4	48.5	21.6	2.2	2.5	100	eia (2007)

Table C.3.iv Typical values of GHG emissions for various energy generation options in North America (Gagnon et al., 2002)

Electricity generation option	GHG emissions (kt CO_2 eq/TWh)
Base and peak load options	
Hydro with reservoir	15
Diesel	778
Heavy oil	778
Base load options with limited flexibility	
Hydro run-off river	2
Coal (without SO_2 scrubbing)	1050
Coal (with SO_2 scrubbing)	960
Nuclear	15
Natural gas	443
Fuel cell	664
Biomass plantation	118
Intermittent options that need backup generation	
Wind power	9
Solar PV	13