Protocol for Low Energy Houses for Northern Canadian Regions

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ABSTRACT

Despite Northern Canada's unique environmental loads and challenges, homes are based on standards developed for the South. This thesis presents the development of a protocol for low energy homes (LEH) for northern Canada. The protocol integrated the building envelope system with passive solar design strategies for northern Canada. This research identified areas of interest and challenges for the region through literature review, interviews with occupants and builders, and data analysis of 1744 homes in the NWT from the EnerGuide energy rating service (ERS) database. A reference home was modelled to study design parameters such as thermal resistance values of building assemblies, window-wall ratios, thermal mass, BIPV/T system's capacity, night window shutters, shading schedules, and ventilation rates. Optimization of solar design strategies can achieve a 49% energy savings. This finding gives policy makers a methodology for displacing housing energy demand by promoting design strategies to builders such as better orientation and optimizing window-wall ratios for solar heat gains, and integrating thermal mass in floors and on interior walls. Based on the findings of this research, a protocol for low energy homes for the North is presented which includes key relevant standards, guidelines, criteria and verification methods that are to be met through the design, construction, and operational stages. The Protocol anticipates and addresses significant related challenges of the remote region to promote a delivery system that involves all stakeholders, reduces delays and cost overruns.

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Nomenclature

Symbols

A_i	Area of surfaces	m^2
A_w	Area of Windows	m^2
C_i	Thermal capacitance at node *i*	J/K
c_p	Specific heat	J/kg*°C
$\Delta t_{critical}$	Critical time step	seconds
G	Incident solar radiation hitting BIPV/T system	watts/m^2
h	Heat transfer coefficient	watts/m^{2*}K
I	Solar radiation rate per area incident to house	watts/m^2
k	Thermal Conductivity	watt/m*°C
R_a	Gas constant	J/Kg*K
$R_{(i,j)}$	Thermal resistance value between node *i* and *j*	m^2*°C/watts
q_i	Heat source at node i	watts
T_i^p	Temperature of node *i* at present time set	°C
t_s	Sunset time	hours
L	Latitude	°
ha_{it}	Hour angle	°
M	Airflow rate	m^3/s

Greek letters

α	Solar altitude	°
β	Tilt angles	°
δ	Declination angle	°
φ	Solar azimuth	°
ψ	Surface azimuth	°
ρ	Density	kg/m^3
ρ_g	Status of snow on ground, (1 = snow on ground, 0 = no snow on ground)	
θ	Angle of incidence	°
μ_{air}	Dynamic viscosity	Pa*s
υ	Viscosity	Kg/m*s
η_e	Efficiency of the photovoltaic panels	
σ	Stefan–Boltzmann constant	watts/$m^{2*}K^4$

Abbreviations and Acronyms

ACH	Air Change per Hour
ASTM	American Society for Testing and Materials
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BIPV/T	Building-Integrated Photovoltaic and Thermal

CFCs	Chlorofluorocarbons
CMHC	Canadian Mortgage and Housing Corporation
DHW	Domestic hot water
EGH	EnerGuide housing
ERS	Energy rating services
ERV	Energy Recovery Ventilators
EPS	expanded polystyrene
XPS	extruded polystyrene
HRV	Heat Recovery Ventilators
KWp	Kilowatt peak
MNECH	Model National Energy Code for Houses
NBCC	National Building Code of Canada
HCFCs	Hydrochloro-fluorocarbons
HDD	Heating degree days
NHC	Nunavut Housing Corporation
NHT	Nunavut Housing Trust
NSH	Northern Sustainable House
NWT	North West Territories
NWTHC	Northwest Territories Housing Corporation
OSB	Oriented strand board
PV	Photovoltaic
SHGC	Solar heat gain coefficient
SIPs	Structural insulated panels
WFR	Window to floor ratio
WWR	Window Wall Ratio

1. Introduction

1.1. Context and Motivation

Housing is central in shaping our lives, yet it remains inaccessible for some northern Canadians. The Canadian courts never examined the rights to housing; however, section 36 (1) of the Canadian Constitution (1982) commits Parliament to "(a) promoting equal opportunities for the well-being of Canadians; (b) furthering economic development to reduce disparity in opportunities; and (c) providing essential public services of reasonable quality to all Canadians" (Government of Canada, 1982). Also, article 11(1) of the International Covenant on Economic, Social, and Cultural Rights commits Canada to recognize "the right of everyone to an adequate standard of living for himself (herself) and his (her) family, including adequate food, clothing, and housing, and to the continuous improvement of living conditions" (UN General Assembly, 1966). Housing policies put forth by the federal government has fallen short of Canada's obligations to the people of the North (Tester, 2009; Pulla, 2012).

The North occupies 40% of Canada's landmass, yet holds only 0.2% of the country's population. The North is a diverse area with a culturally diverse population. Several unique geographical, climatic, social and economic factors create challenges to building homes in northern Canada. Despite these differences, the codes and standards adopted by southern regions are used to build homes in the North.

The physics of northern homes are straightforward, but its application is complex. Northern homes need to withstand extreme environmental loads. Temperatures drop to -50°C for extended periods of time, requiring homes to have high performing triple glazed windows and well insulated building envelope while minimizing thermal bridges and air leakages. Moisture flow through air leakage and vapour diffusion are of major concerns. Tiny gaps leaking air can lead to substantial moisture problems because the vapour drive remains high due to prolonged extreme temperature differences through the building envelope and higher indoor relative humidity. Northern homes should have continuous air and vapour barrier (Lstiburek, 2009; Nash & Seifert, 2011).

The North has permafrost - ground that remains frozen – if the permafrost melts, and the ground below consolidates, then the ground shifts, settles and moves the foundation. A solution has been to avoid heat from transferring into the ground by elevating the building, insulating the floor, and ventilating the space between the ground and floor.

Attics are ventilated to remove excess moisture. However, ventilated attics are problematic as fine windblown snow particles can accumulate in the attic, melt in the spring and cause moisture damage. Conversely, unventilated roofs do not have a mechanism to remove excess moisture (Kayello, & Fazio, 2013; Baril et al., 2013).

Air-to-air exchanges bring in the fresh air to airtight homes. However, with extreme temperatures, the exchanger core may freeze which reduces the efficiency and diminishes fresh air intake (Beattie et al., 2015).

The North's sparsely populated region has limited human and infrastructural capacity; there is little demand for private housing and small incentives for uniquely northern products. Communities are isolated from the rest of the country – the North imports it material through shipment from the south.

Many isolated communities lack skilled labour for building homes and maintaining them; labour imported from the South is expensive. Community leaders and governments encourage the use of local labour - consequently homes should be designed using straightforward and existing construction techniques.

Homes are costly to build, operate and maintain in Canada's North. The area relies on imported fossil fuels. Electricity per kilowatt-hour (kWh) can be up to 10x as much as in southern cities, for example, government subsidized rates for Yellowknife are 29.73 cents/kWh for the first 1000 kWh and 62 cents/kWh thereafter. Montreal residences pay 8.60 cents/kWh (Northwest Territories Power Corporation, 2015; Hydro-Québec, 2015). In short - housing is seen as a liability for many Northern communities. Homes deteriorates at a rate where the home are replaced before the period of amortization is over.

The North needs to build homes that are suitable for its environment. With growing concerns about climate change and the region's desire to become less dependent on fossil fuels, governments have identified new housing standards as urgent (Government of Nunavut, 2007a). Similarly, in 2009 when Canada Mortgage and Housing Corporation (CMHC) set out to conceptualize, design, build and monitor innovative housings for the North, they outlined the need for housing protocols (CMHC, 2007).

Designs of northern homes do not consider solar design strategies, such as thermal mass and window wall ratio. However, there is significant solar energy available in the North that may help displace energy consumption.

The primary objective of this research is to develop a methodology for achieving low energy homes (LEH) in northern regions of Canada. A protocol is developed that integrates the building envelope with other subsystems to optimize for energy efficiency, durability and efficient delivery of homes to the North. This protocol addresses thermal, moisture management, energy efficiency, optimization of solar design strategies, and the size and capacity of a building integrated photovoltaic/thermal systems. The protocol anticipates and addresses key challenges of remote regions throughout its lifecycle, and facilitates all stakeholders in meeting the challenges of the North and reducing delays and cost overruns.

The secondary objectives of this research are:

- To evaluate the effectiveness of an energy regulation introduced in Yellowknife, Northwest Territories by data-mining more than 1700 homes over 50 years.
- To optimize solar design strategies, including window-wall ratio, thermal mass, shading, and the size and capacity of building integrated photovoltaic/thermal systems (BIPV/T).

1.2. Methodology

Firstly, a state of the art literature review outlined current interests and challenges for the region. It identified new technologies, their limitations, existing codes and standards, and presented low energy housing examples built in northern regions.

Secondly, the research benchmarked the past and current housing trends. Author interviewed builders and occupants in Yellowknife, Northwest Territories between April 22 and May 19, 2015. These interviews established perspectives of northern housing, identified specific construction processes, and responses to identified challenges.

Thirdly, 1744 homes built since 1950 were data mined from the EnerGuide Energy Rating Service (ERS) database. The analysis showed the impact of Yellowknife's energy efficiency regulation for houses passed in 2008.

Fourthly, key design parameters were optimized through a parametric analysis. The explicit (forward) finite difference method is used to solve one-dimensional transient conduction equations that calculated hourly indoor air temperatures and hourly auxiliary heating requirements for a reference home using MATLAB. Parameters studied are window wall ratios, thermal resistance values, thermal mass, night window shutters and capacity of the BIPV/T systems.

Lastly, based on the steps above – a protocol for low energy homes for Canada's North was developed.

1.3. Research Scope

CMHC (2008) identifies the North as the three Canadian territories: Yukon, the Northwest Territories and Nunavut; the Inuit regions of Nunavik (located above the 55th parallel in Quebec); and the Inuit regions Nunatsiavut (Northern Labrador).

The protocol for low energy homes is a comprehensive guideline and should supplement existing standards for this region. It can be used for single-family, detached, semi-detached or row homes as well as multi-story apartment buildings. It may be used to evaluate both prefabricated and stick built homes. The protocol was developed for newly constructed homes, but may be utilized for retrofitted buildings as well. Owners, architects, builders and policy makers should use the protocol.

The protocol addressed the following parameters: (1) air leakage, (2) moisture management, (3) energy consumption, (4) energy performance, (5) indoor air quality, (6) HVAC selection, (7) schedule and cost, (8) and compatibility of materials.

Solar design strategies were studied for the region of Yellowknife, Northwest Territories. However, the recommendations of this thesis may be applied to any area of the North.

1.4. Thesis Overview

Below is a brief summary of the chapters presented:

1. Chapter 1 introduced background information, objectives, methodology, scope and limitations of the research.
2. Chapter 2 presented the state of the art literature review. It outlined the environment of the North, major challenges, new technologies with their limitations, existing standards and low energy housing built in the region.
3. Chapter 3 benchmarked the past and current housing trends through occupant and builder interviews, and data analyses of the EnerGuide energy rating service (ERS) database for NWT.
4. Chapter 4 presented a parametric analysis of key design strategies for northern homes. Parameters considered are window wall ratios, thermal resistance values, thermal mass, shading, night window shutters and size and capacity for the BIPV/T systems.
5. Chapter 5 presented the protocol for low energy homes for northern Canadian regions.
6. Chapter 6 concluded this research. It outlined the findings, contributions, limitations and future works for this thesis.

2. Literature Review

Several geographical, climatic, social and economic factors create challenges to the affordability of northern homes (Pulla, 2012; Said, 2006; CMHC, 2008; Deloitte & Touche LLP, 2010). The first part of this chapter outlined the main challenges of the North. The second part focuses on the existing codes and standards in northern Canada and other cold regions. The last part of this chapter presents existing exceptional homes in cold regions.

2.1. Challenges of the North

2.1.1. Environment

The average winter temperature is around -35°C, with extended periods of temperatures below -40°C. The building envelope has to cope with its large temperature gradients (Canada Mortgage and Housing Corporation, 2008). In the spring and autumn, there are daily cycles of melting and freezing of accumulated moisture in the building envelope due to insolation (Cornick et al., 2008). In the summer, gradual warming due to increased solar radiation that lasts all day leads to heat damages and premature aging of exposed materials.

Northern Canada tends to be windy throughout the year. High winds, at times up to 160km/hour, can cause huge snowdrifts (see Figure 2). The North has low outdoor relative humidity because temperatures are too cold throughout the year to hold a significant amount of atmospheric moisture. However, high indoor relative humidity is a problem is some communities due to overcrowded homes and cultural activities such as boiling meat for extended periods of time. Figure 1 shows climate data for selected Northern communities. Contrary to common perceptions, the North get much solar radiation.

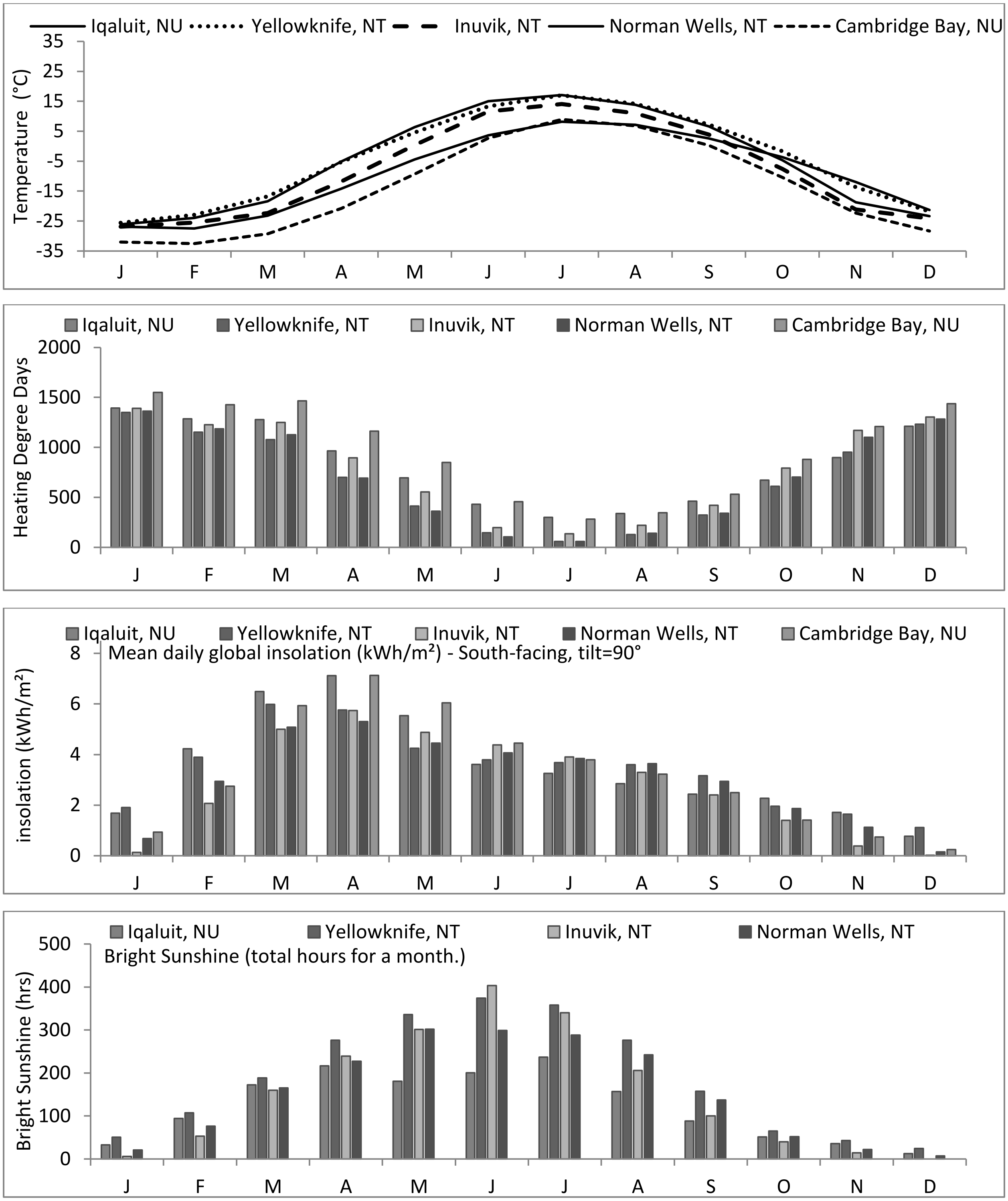

Figure 1: Weather profiles for northern communities: a) temperatures, b) total HHD per month, c) mean daily global insolation (kWh/m^2) and d) total monthly bright sunshine hours (Environment Canada, 2016).

The construction season is short. Shipment serves some communities once a year in late September, leaving a short window for workers to build the building envelope.

Figure 2: Snow drip at a home entrance, Arviat (Nunavut) (CMHC, 2014a).

2.1.2. Remoteness

The North is remote, with 0.2% of Canada's population spread across 40% of its landmass (Pulla, 2012). Its population density does not support important infrastructures such as piped water systems, sewage systems, and roads.

The North imports most of its energy fuels, with fuel prices about ten times higher than the Canadian average (National Energy Board of Canada, 2011). Materials to communities arrive through the seasonal ice roads, the shipments from Southern ports, or are flown in. Ice roads are temporary highways carved out of snow and ice (Pulla, 2012).

Missing materials from these shipments are flown in, which increase the project's cost. Replacements due to loss or damaged materials add about 10% to the project budget. Deloitte & Touche LLP (2010) studied 725 housing units built in 2009 in Nunavut, all of which had missing materials.

Few northern communities have the local skilled labour to built and maintain homes. Communities often import labour from the South, which is more expensive. However, Northern governments encourage the use of local labour as it provides local jobs and empowers community members. Therefore, the design of northern homes needs to be simple and use locally known construction techniques (Armstrong, 2014).

In 2006, the Canadian federal government made an investment of $200 million to the Nunavut Housing Corporation (NHC) to construct 725 new homes – this is known as the

Northern Housing Trust (NHT). In addition to the above mentioned challenges, Deloitte & Touche LLP (2010) found limited staff capacity and the NHC's decentralized organizational structure as challenges to deliver projects across the 25 communities. Also, NHC lacked the technological infrastructure to support the delivery of the NHT.

Finally, with the exceptions of the territorial capitals, there are no active rental markets. Most northern homes are either government staff housing or social housing. Social housing represents 73% of the rental stock in Nunavut (CMHC, 2008).

2.1.3. The Northern Family

Family plays central roles in Northern Canada. Housing design should reflect local values and lifestyles. In Inuit families, the extended family functions as a network of mutual support through which they can access food, equipment, labour, money and emotional support – socialising activities such as consumption of traditional food are critical moments for reaffirmation of family bonds (CMHC, 2004). In Inuit culture, activities are often performed together in a single, open and integrated space – this differs from Euro-Canadian values where individuality and privacy are central.

CMHC (2004) examined the spatial compatibility of northern homes to lifestyles and cultural values by comparing the domestic activities of families and the spatial distribution of rooms to the integration and visibility of these spaces. The most integrated and visible areas in a northern home are the corridors where little activities can be done. Communal spaces such as living room and kitchen vary in integration and are too small to accommodate large family gatherings (CMHC, 2004). CMHC (2014a; 2014b) made the following recommendations for northern homes:

- Open floor plans integrating the kitchen, living room and dining room and eliminate long central corridors.
- Kitchen design should accommodate cooking and cleaning of traditional foods. Provide a large stainless steel sink and energy efficient stoves with larger heating elements to boil meat.
- Better ventilation is needed to eliminate excess moisture produced by boiling meat for extended periods of time.

- A Single-floor dwelling will reduce summer overheating, and increase visual accessibility of the home.
- The construction of larger storage cupboards in the kitchen to accommodate larger cooking pots. Storage for winter and hunting equipment.

2.1.4. Roofs

International practices call for ventilated cold attics for cold climates. The Alaskan Residential Building Manual (Deer et al., 2007) recommends a cold ventilated roof design when snow accumulates on the roof.

Moisture can accumulate in the attic when moist air rises to it through air leakage paths, or water diffusion. This moist air condenses on colder surfaces, and frost builds up throughout the winter. When this frost melts in the spring, it can cause moisture problems (Seifert, 2013). Attics are ventilated to exhaust any excess moisture or water vapour. Also, ventilation helps cool the attic in the summer, prevents ice dams in the winter and extends the life of the roof (TenWolde & Rose, 1999).

In regions of the North, there have been noted cases of significant snow accumulation in the attic that melts in the spring and cause moisture damages (Baril et al., 2013; Kayello et al., 2013). For this reason, roofs are preferred to be sealed without a ventilated cavity. In theory, there is no need for ventilation if moisture is prevented from getting into the attic. A hot roof has no natural ventilation in the roof cavity. Conversely, the integrity of an unventilated roof depends on the reliability of an air and vapour barrier systems, which is very hard to achieve.

In Nunavik, Baril et al. (2013) documented ventilating the attic with filters to keep snow particles out. Filters were placed at the bottom and top of the ventilation channels located in the furring behind the envelope cladding. Still, there were concerns of snow penetration because there were reports of water leaks from the ceiling during the spring.

Hygrothermal performances of both vented and unvented attics were tested by Kayello and Fazio (2013). A structural insulated test hut was subjected to alternating periods of arctic winter and summer design conditions while exposed to different rates of air leakage from the interior space to the attic. This study showed unventilated attics can maintain lower relative humidity than a ventilated attic provided that the air leakage rate is under 5 litres per minute and the indoor relative humidity is moderated. Also, the capacity of the attic materials to buffer moisture from air leakage helped regulate the attic relative humidity. However, when there was excessive air leakage, it leads to higher humidity ratio and without adequate ventilation, moisture accumulation is unavoidable.

There are little literatures and standards relating to unvented attic design for cold climates. There exist few homes with unvented attic in the North and little-documented cases. The rule of thumb has been a ventilated cold roof below the tree line, and an unventilated hot roof above the tree line. Also, the design strategy of hot roofs relies on the wind to clear the roof of accumulated snow. The Alaska Residential Building Manual (Deer et al., 2007) suggests annual wind speed above 16km/h. If snow does accumulate, it needs to be removed (Seifert, 2013).

More research is needed for appropriate attic designs for northern climates. Seifert (2013) outlined the following recommendation for a hot roof:

- Carrying the air-vapor barrier over the top plates of partition walls.
- Minimizing electrical boxes in the ceiling.
- Avoid using recessed lighting in the ceiling.
- Providing flexible air and vapor tight seals around plumbing penetrations
- Providing sealing around chimney and fuel penetrations.

2.1.5. Heat Recovery Ventilators in Cold Climates

As homes are more airtight and better insulated, passive ventilations through the building envelope cannot remove excessive indoor humidity and airborne pollutants. Kovesi et al. (2009) studied increased risk of respiratory tract infection in Inuit children due to reduced levels of ventilation rates and overcrowding in northern homes. Natural ventilation is often discouraged in the North as it creates drafts and greatly increases heating energy requirement. Especially in the North, where heating fuel is expensive, it is important to use ventilators that reduce energy consumption.

Heat recovery ventilators (HRVs) supply fresh outdoor air to the house while expelling the stale indoor air. Within the HRV’s core, heat from the indoor air at room temperature is transferred to the incoming cold air from outside – the system typically recovers 70% to 90% of the heat from the exhaust air (Cold Climate Housing Research Center, 2015a). Kovesi et al.

(2009) showed health improvements when heat recovery ventilators were installed. Though HRVs reduce space heating requirements and provide fresh air from outside, there are some limitations in the North.

HRVs are not rated for extremely cold climates. When the warm, humid room air comes in contact with the cold surfaces of the exchanger, condensation and frost forms. Frost formation reduces the system's efficiency, reduces the flow rate supplied to the home, and can damage the system. Frost formation may start with supply air temperatures starting at -5°C, as reported by Kragh and Rose (2013). The typical strategy to eliminate frost formation uses heat coils to preheat the incoming air which reduces the efficiency of the HRVs. Another solution, tested by Beattie et al. (2015), uses a dual exchanger cores. When one of the cores form frost, the second exchanger core is used to supply the fresh air while the first core will defrost using the warm indoor air.

HRVs need to be correctly installed which is a challenge in the North as it is hard to find skilled tradespeople. Ventilation systems installed must be operated, maintained and repaired at the local level (CMHC, 2003). There are often misunderstandings about the HRVs in northern communities; occupants worry these devices make homes colder, noisier and increase electricity bills. Such concerns were not ill-found as homes surveyed in Nunavut by Kovesi et al. (2009) showed HRVs were sometimes not installed properly.

In some homes, the moist indoor air was exhausted while being replaced by dry outdoor air. This created a dry indoor climate causing occupant discomfort (Cold Climate Housing Research Center, 2014). An energy recovery ventilators (ERV) works similarly to a heat recovery ventilator, but it also recovers moisture from the indoor air. However, except for a few companies, this technology has not been rated for applications under -25 °C; and its suitability is not proven for Canadian climates (Eakes, 2013). ERV may potentially perform better, as the transfer of moisture from the relatively humid exhaust air to the cold, dry supply air could reduce the amount of vapour in exhaust airstream. Beattie (2016) showed this reduced the amount of moisture that could potentially condense and freeze. Cold Climate Housing Research Center (2014) tested 8 ERV systems in Fairbanks, Alaska – it showed that ERV systems could continue to operate in extremely cold temperature.

While HRVs may be a sure way to provide fresh air to homes, it is important to consider the local trades needed to install service and maintain the equipment. Homeowners need to have a better understanding of these systems. Specific guides or incentive programs could be adopted to help community members have a good knowledge of HRVs and their use. Also, standards for designing, installing and maintaining HRVs for the northern regions that take into consideration available skill sets should be developed.

2.1.6. Permafrost

Permafrost poses a significant challenge for construction in the North. Permafrost is ground that stayed frozen for more than two years (Government of Nunavut, 2013). Typically, the first few feet of the ground is called the active layer – as it thaws and freezes with the seasons. A second layer below the active layer is the permafrost (Permafrost Technology Foundation, 2000).

Permafrost can form in bedrock, gravel, sand, silt and clay soil. Silt and clay soil have higher ice and water content. When soil is below or at saturation and the permafrost melts, then the soil's volume does not consolidate, this is called 'thaw-stable." Building homes on thaw-stable soil are safe and does not require complex foundation systems. However, when the moisture content of the soil is greater than saturation, and the permafrost melts, the soil consolidates as it expels existing water. This soil is called "thaw-instable." Thaw-instable permafrost poses a challenge for builders and homeowners because if the ground melts, it shifts, settles and moves the foundation.

The permafrost should be preserved and prevented from thawing, or have the permafrost excavated, or thaw the permafrost before construction. The latter two options are not feasible in most parts of the North. So, homes are designed to prevent its heat from seeping into the ground which keeps the permafrost intact. However – with the onset of climate change, some communities are seeing the permafrost melt. In Sanikiluaq, Nunavut, the warmer temperatures destroyed the permafrost, damaging foundations and destabilizing homes (CMHC, 2008).

Typical homes in the North are often elevated a few feet above the ground, allowing for ventilation to cool the ground below and prevent heat from seeping into the ground. The protocol presented in this research addressed criteria to avoid heat transfer from homes to the ground.

2.1.7. Renewable Energy

At some point, the benefits of adding insulation and making homes more airtight diminish – northern communities are searching to find alternatives to lower energy consumption of homes. Electricity costs in the north are higher than the national averages because the North imports nearly all its fuel (National Energy Board of Canada, 2011). Fossil fuel consumption emits greenhouse gasses during operation, transportation, and use, and there are potentials for fuel leakage as they are in storage in communities for long-term use (Arriaga et al., 2013).

Reducing carbon emission is a priority for northern governments (Government of Nunavut, 2007b). There lies vast potential for renewable energy to offset these fuel usages. Proven systems, such as photovoltaic (PV) and solar hot water systems have faster payback periods in the North because of the higher cost of energy.

The North has an abundance of solar energy available. Northern Canada receives similar solar radiation as communities in the South (Figure 3).

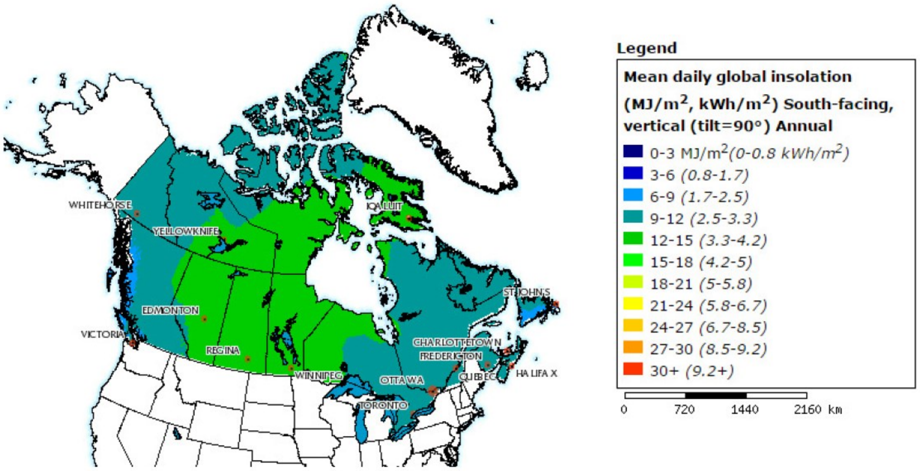

Figure 3: Mean annual global insolation (NRCAN, 2015)

Solar systems are used extensively in Nordic European countries to lower energy consumption of homes (Andresen et al., 2008). Natural Resources Canada, in collaboration with local partners installed and monitored a grid-connected 3.2 KWp (kilowatt peak) PV panels in Iqaluit, Nunavut in 1993 (Thevenard et al, 2000; Poissant et al., 2004). These systems have been in operation since 1995 and have been in successful operation for the first nine years, generating an average of 2.03MWh of electricity each year. The system was most optimal between March and May and produced very low electricity in December. Except December, the PV's efficiency was between 7 to 11.2% and the inverter's efficiency averaged at 81%.

One of the challenges in utilizing solar energy in the North is the mismatch between the abundance solar radiations available in the summer months and little to no solar energy available in the winter months when it is most needed. Other environmental factors that affect the performance of PV and solar systems in the North are: snow built up on systems – though, snow on the ground increases reflected solar radiation into the panels; and cold temperatures increase the PV's efficiency. However, colder temperatures reduce the effectiveness of the solar system.

Chen et al. (2012) studied the performance of conventional unglazed transpired collectors (UTC) and photovoltaic/thermal (PV/T) collectors in high latitude regions. The study found adding an exterior layer of transpired glazing improved the efficiency of the collectors.

Since Canada's North lack skilled labour, solar systems selected should be simple, off-the-shelf, with little to no moving parts, and require little maintenance (Arctic Energy Alliance, 2014). To further renewables' penetration in the North, the human factors, and social aspects should be understood and addressed.

Biofuel is an emerging fuel for the North. Wood pellets are small hard cylinders of highly compressed sawdust, a by-product of the lumber industry. Canadian wood is harvested sustainably, so wood pellets are considered carbon neutral. Using wood pellet can reduce the North's overall greenhouse gas emissions. Pellets can be stored in communities for winters; they are biodegradable and non-toxic. Burning pellets are cheaper than using heating oil. Canadian wood pellet industry mostly exports to more established markets in Europe (Arctic Energy Alliance, 2015). Wood pellets are gaining popularity in NWT in recent years because of the established supply of the wood pellets and availability of new heating appliances.

Wood pellet stoves provide heat by radiation and convection. The pellets are electrically fed to the stove. The stove indirectly heats indoor air. The stove also heats the room through radiant heating. Wood pellet boilers and furnaces may be used to heat a whole house and the domestic hot water. Though, appliances that use wood pellet are more expensive, and homeowners need regular maintenance (such as removal of ash).

2.1.8. Structural Insulated Panel (SIP) Homes for Northern Canada

Structural insulated panels (SIPs) are manufactured panels that offer both insulation and structure for a building; it can be used to build floors, wall or roof. SIPs consist of an insulating core, expanded polystyrene (EPS), extruded polystyrene (XPS), or a spray foam such as polyurethane, which are between two layers of sheathing. The sheathing may be plywood or oriented strand board (OSB) (Cold Climate Housing Research Center, 2015b).The faces of the panel resist most of the structural load, while the core transfers the shear loads (Allen & Neal, 1969).

SIPs use less timber thus have less thermal bridging. These panels are gaining traction in the North as it addresses two critical challenges. They require semi-skilled labour and the building envelope can be quickly assembled. Said (2006) outlined other advantages of SIPs:

- EPS has desirable hygrothermal properties such as the closed-cell structure that provides high resistance to moisture absorption and a stable R-values that does not decrease with the dissipation of the blowing agent. The EPS insulation is free of CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons), and formaldehyde and is environmentally friendly and non-toxic.
- Panels are lighter and easier to transport.

A field study of a SIP home, in the Repulse Bay, Nunavut, concluded that SIPs are suitable for Northern housing. It found the costs to build SIP homes were similar to that of stick built homes. Also, SIP homes required half the time than stick built houses to make them completely weather tight, so that construction work could proceed from the interior. SIP house needed semi-skilled labour, which was easily available within communities. A blower door test rated the home 0.49 ACH at 50 Pa compared to 1.5 ACH at 50 Pa for a standard R2000 home. After 13 months of monitoring, the SIP home used 25% less heating fuel than similarly constructed wood frame house (CMHC, 2001).

Though there is growing interests for SIPs, challenges remain to infiltrate into Northern markets which include unfavorable histories such as in Juneau, Alaska and there is little testing and performance evaluation of these panels in northern climate (Wyss et al., 2015).

Andrews (2001) outlined moisture issues in SIP roof assemblies in Juneau, Alaska. There were severe moisture issues concentrated along the panel joints. The notches for I-Beams in the foam board were too large. Another source of the problem was the moisture transport mechanism through air leakage and water vapour movement from the indoors to the panels. Researchers found poor installation and workmanship compromised the performance of the panels.

In Northwest Territories, in the 1970s, SIP homes failed due to excessive moisture problems. SIPs built in the Canadian South considerably shrunk when transported to the North. Misalignment of panels left huge gaps between them causing problems (Dunets & Smith, 1989).

Wyss (2011) investigated the hygrothermal performances of SIPs designed for northern Canada using an inverted test hut. The panels were made of OSB facings and an ESP core. The adhesive is a single-component urethane. Also, a 38mm of ESP separated the exterior surfaces from the I-joist within the panels; this separation was effective in minimizing thermal bridging (Wyss, 2011).

The joints between the panels present the weakest point for the SIP systems and it is the most likely failure mode for this system. Differential movement, material degradation, or shrinkage/expansion of panels may result in the creation of air leakage paths compromising the energy efficiency and durability of the system.

2.2. Codes and Standards for the North

2.2.1. Existing Codes and Standards in North America

The main requirement for buildings in the North is to meet the 2010 National Building Code of Canada (NBCC). The NBCC has four climate zones (Zone A, Zone, B, Zone C, and Zone D.) Most of the North falls within climate zone D with heating degree days (HDD) greater than 8000. However, some communities in the North have more than 12000 HDD.

The protocol presented in this research, the NBCC, ASTM standards and ASHRAE standards were consulted to identify minimum performance requirements.

2.2.1.1. Good Building Practice for Northern Facilities

The primary objective of the Good Building Practice for Northern Facilities is to “provide a technical reference handbook to help building developers produce the best value in northern buildings … and to incorporate proven methods and materials, while supporting improved building performance and new technology" (Government of the Northwest Territories, 2012). The guideline is prescriptive and supplements the NBCC. According to the document, focus was placed on, where more strict practices should be applied relative to that of the NBCC; where code requirement should be clarified; where experience has shown that a different approach than typical Canadian building industry practices is needed for northern communities and where there is a proven preference for specific products, systems or method to be employed.

2.2.1.2. R2000 Standard

The R2000 Standard, developed in Canada, is a voluntary building standard. The government and industry managed the program through consultations. They involved researchers, home builders, product manufacturers and other housing experts to meet and review new housing research and update the standard.

The R2000 standard is performance-based and addresses five areas: building envelope requirements, mechanical systems, energy performance targets, indoor air quality, and water conservation and environmental features. The building envelope requirements seek minimum insulation levels to meet or exceed provincial or local requirements. It has a maximum airtightness of 1.5 air change per hour at 50 Pa. R2000 specifies at least a double-glazed window with a low-emissivity coating, insert gas fill, and insulated spacers with wood, vinyl or fiberglass frames (Natural Resources Canada, 2016).

The next generation of R2000 standard plans to build on the existing standard to help recognize homes reaching net-zero energy performance in Canada. The new standard will focus on off the shelf technologies available today that meets industry standards and regulations with the intention of making net-zero energy homes more economical to Canadians (Natural Resources Canada, 2015).

2.2.2. Passive House Standards from Europe

Passive House (PH) refers to a voluntary standard put forth by the Passivhaus Institute in Germany (http://www.passiv.de) that pushed for homes with year round comfort and a healthy indoor environment without the significant use of active space heating or cooling. Generally, for central European climates, the Passive House has a maximum heating demand of 15KWh/m^2 per floor area and a combined primary energy demand of 120KWh/m^2 for space heating, DHW and all other electrical equipment (Strom et al., 2006).

Passive homes have highly insulated and airtight building envelopes, which are often tested with a blower door test. Passive homes use passive solar strategies for their useful heat gain. Other energy savings systems – such as HRV are also integrated. On-site renewable energy is often implemented to displace energy demands of the residence (Strom et al., 2006).

Slight tweaks to the original PH standard allowed for the successful implementation of the standard in the Nordic regions where heating design temperature is -43.4°C (Dokka & Andresen, 2006) - design temperature for Yellowknife is -41.3°C. By 2007, 28 passive houses were built in Norway. In Finland, single detached homes have been constructed with heating energy demands of 25 to 35KWh/m^2. By 2007, ten passive house homes were built in Finland (Elswijk & Kaan, 2008). Some of the challenges presented in the construction process include architect's poor knowledge on energy-related issues and breaking the industry's perception of the passive house as expensive.

Passive House principles have made great strides in North America. Canadian Passive House Institute (2015) trained over 500 Canadian builders, architects, engineers, tradespeople, designers, planners and homeowners in passive house design and construction since 2010. The Passive House Institute US launched certification programs in University and specific passive house building standards for North America (Passive House Alliance, 2016).

2.3. Exceptional Northern Houses

2.3.1. Northern Sustainable House

The Northern Sustainable Houses (NSH) was a series of homes built by the Canada Mortgage and Housing Corporation (CMHC) in partnership with local housing providers (CMHC, 2007; CMHC, 2014a; CMHC, 2014b; CMHC, 2014c; CMHC, 2014d). The aims were to design, build and monitor innovative energy-efficient houses that:

- Attain an energy performance level of 50% higher than that specified by the 1997 Model National Energy Code for Houses (MNECH).
- Are culturally appropriate.

- Help develop practical knowledge on energy-efficient, culturally appropriate houses in the North.

Designs were initiated through a charrette, which sought to incorporate perspectives of community members. Workshops were tailored to communities and dealt with issues relating to housing. These charrettes offered the following ideas:

- Families are large, with different generational needs, i.e.: the younger generation prefers warmer temperatures and more privacy.
- Open concept floor plans are preferred to accommodate large family gatherings.
- Provide cold rooms and storage spaces for activities.
- Foundation designs were of major concerns due to the melting of permafrost.
- Design two entrances; one for summer and the other for winter.
- Condensation on windows is a problem, and home should provide better ventilation.
- Lot size should be considered for sun exposure.
- Sun shading is needed to prevent overheating in the summer months.

Table 1: Summary of Northern Sustainable Houses (NSH)

	Arviat, Nunavut, NSH (2005)	**Dawson City, Yukon, E/2 Project (2006)**	**Inuvik, NWT, NSH (2009)**	**E/9 project, Dawson City, Yukon (2012)**	**Greenland Low Energy House (2005)**
Wall	Double Wall system, 2x6" and 2"x4" interior wall, with horizontal strapping (RSI 8 / R46)	Double Wall, 2x8" and a 2x4" wood stud (RSI 7.2 / R41)	Double wall, with staggered studs. (RSI 8.3 / R46)	SIPs envelope system, with horizontal strapping on interior (RSI 8.3 / R47.5)	RSI 6.5 / R37
Floor	RSI 9.1 / R52	RSI 7.8 / R44	RSI 9.3 / R53	RSI 7 / R40	RSI 7.14 / R40.6
Ceiling	RSI-11.6 / R66	RSI11 / R60	RSI 14 / R80	RSI 14 / R80	RSI 7.7 / R43.8
Windows	Triple Glazed, Argon filled, fibre glassed framed windows	Triple glazed windows, with overhangs		tripled glazed Low-E argon windows	tripled glazed windows
ACH Rate	1.4ACH at 50pa (Blower door tested)	1.7 ACH at 50a		0.75ACH @ 50pa	
HRVs	Yes, preheat air before reaching HRV core.	Yes, positioned above boiler, with hot water coil preheating incoming air	Yes, preheat air before reaching HRV core.	Yes	HRV, double core system with the defrosting mode.
Solar Systems	No solar systems.	No solar systems.	Hot water preheated by four glazed flat-plate solar collectors. Double wall, heat exchanger transfers heat to storage tank – which goes to DHW, which is heated as needed. 224W solar photovoltaic modules installed at 75° tilt with 1,792 watts per unit capacity.	The solar hot water system consists of 2 flat plate collectors mounted on the 60°, south-facing porch roof with a storage tank and circulation pump located in the utility room.	No solar systems.
Energy Performance	63% better than MNECH	25% better than MNECH	25% better than MNECH	68% better than MNECH	Half of Greenlandic Building Regulation (80KWh/m^2)

Figure 4: Northern Sustainable House in Arviat, Nunavut (CMHC, 2014a)

In 2005, CMHC, in partnership with Nunavut Housing Corporation (NHC,) started plans for an NSH in Arviat, Nunavut, a coastal community of about 2000 residents on the western shores of the Hudson Bay.

This project used a staggered double-wall system consisting of a 2in x 6in wood studs, 1/2in air gap, 2in x 4in interior wall, and 2in x 2in horizontal strapping with 1.5in of rigid insulation (RSI 8.0, R-46). Advanced framing details reduced timber used and minimized thermal bridging. A 6-mil polyethylene vapour barrier was on the interior side of the wall with a spun-bonded polyolefin for an exterior air barrier. Continuity of the air and vapour barrier was ensured by a pre-drywall blower door test. Lap joints were double sealed with acoustic caulking and duck tape. The home rated a1.4 ACH rate at 50 Pa.

The thermal resistance was RSI-9.1 (R-52) for the floor above-unheated crawlspace and RSI-11.6 (R-66) for the roof. The building had large triple triple glazed, argon filled, fibreglass framed windows on its south façade.

A heat recovery ventilator (HRV) unit used a pre-heat coil to avoid frost formation. The shed roof extended the south wall vertically for future installation of a photovoltaic or solar water heating system. Energy modelling showed the home uses 63% less energy than MNECH (CMHC, 2007).

Figure 5: E/2 House, Dawson City, Yukon (CMHC, 2014b).

CMHC with local housing organizations built the E/2 NSH in Dawson City. The city has a population of 2000 and is situated 550km north of Whitehorse, the capital of Yukon (CMHC, 2007). The charrette participants favoured the flex concept. The flex concept allowed homes to be modified as the family grows.This project used a double wall, 2in x 8in wood stud walls with an interior 2in x 4in wood stud wall. A 6mil polyethylene air/vapour barrier was installed between the two walls (CMHC, 2014b). The floors, built over an unheated crawl space, had a thermal resistance of RSI 7.8 and dwelling had raised heel roof trusses with a thermal resistance of RSI-11. Advanced framing techniques reduced materials and minimized thermal bridging.

The E/2 house project resulted in a single floor, 141 m^2 dwelling with three bedrooms and an open concept area for family gatherings (CMHC, 2014b).

The airtightness of the house was 1.7 ACH at 50 Pa (targeted airtightness was 0.7ACH.). Hot water coil connected to the boiler preheated the incoming air for the HRV.

The building was oriented to the south for passive solar heat gain with large triple-glazed windows on the south façade. Overhangs were used on the south façade to reduce overheating in the summer and provide protection from rain exposure.

After a year of monitoring, the house consumed about 25% less than the baseline house designed with the MNECH as opposed to the initial target of 50% reduction (CMHC, 2014b).

The hydronic heating system in the home was much more complex to supply, install, and commission because of the shortage of qualified contractors. Additionally, the system was oversized; it was not possible to find a boiler small enough for the home resulting in the boiler heating the space for a few minutes and then shutting down, which reduced the overall efficiency of the boiler (CMHC, 2014b). Smaller heating capacity appliances are needed for the lower space heating loads of highly insulated, low air leakage houses.

In February 2009, CMHC with the Northwest Territories Housing Corporation (NWTHC) built an NSH in Inuvik, NWT. The home was a 247m^2, one story and open concept duplex with a shared mechanical room.

The building used staggered double wood stud wall assembly. It had SIP flooring system and a custom ordered, raised heel roof trusses that accommodated more attic insulation. The roof had a tilt angle of angle of 75° for a solar system.

There is a high efficiency, condensing and modulating natural gas boiler met the space heating and the domestic hot water demands. Four flat-plate, glazed solar collectors supplemented the boiler. A heat exchanger transferred heat from the solar collector to a storage tank. Also, a 3.6 kW solar photovoltaic module, connected to the local power grid, was installed at 75° tilt. A hydronic pre-heat coil prevents core-freeze up in the HRV system.

Each unit of the duplex is expected to consume 7040 kWh of electricity and 46 GJ of natural gas per year. RETScreen estimated the eight-panel PV system for each unit would offset about 2,040 kWh of purchased electricity per year. The two-panel solar DHW system for each unit would yield an annual natural gas savings of approximately 12.6 GJ per unit, which represents a yearly saving of $1 380 for electricity and $540 for natural gas per year per unit in June 2013. This project aimed at a 50% reduction in energy consumption related to the 1997 Model National Energy Code for Houses (MNECH) (CMHC, 2014d).

The E/9 project was the other NSH in Dawson City. The E/9 was a duplex that targeted energy consumption of a fifth of a 1997 MNECH home (CMHC, 2014c). The E/9 duplex consists of a 139 m^2 *solar* unit and a 121 m^2 *flex* unit Figure 6. The duplex's longer façade had large triple glazed windows and was oriented towards the south. The building envelope used SIPs. The building had an airtightness target of 0.75ACH @ 50pa. The solar unit had a two flat plate solar collectors mounted on the south-facing porch roof, and a storage tank and circulation pump located in the utility room (Arctic Energy Alliance, 2014). The duplex achieved an estimated 68% reduction in net energy consumption.

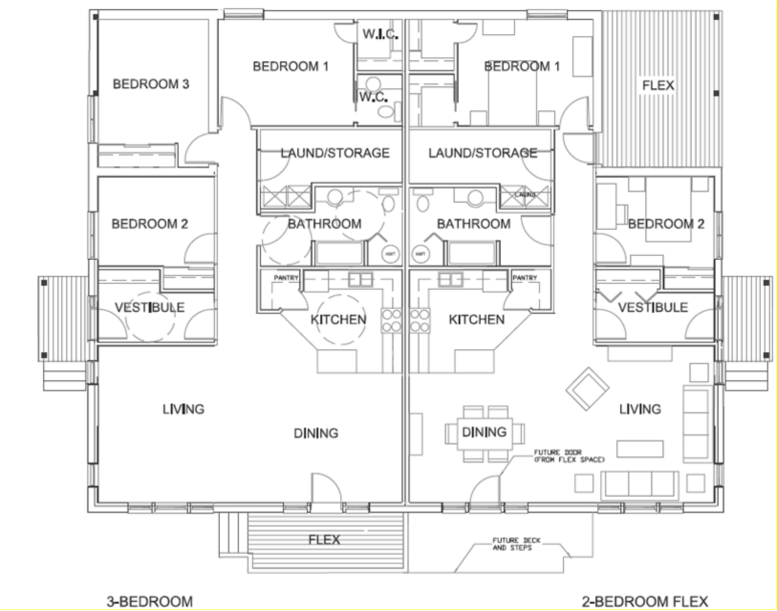

Figure 6: Duplex with solar unit (left) and flex unit (right)

2.3.2. Low-Energy Houses in Greenland

Greenland, located east of the Canadian Arctic Archipelago, shares similar environment and culture of northern Canada. Homes in Greenland are built using timber and mineral wool insulation. Bjarløv & Vladykova (2011) studied homes in Greenland built before 2006. Most homes were poorly insulated, with lots of thermal bridges and were not airtight – consequently, much energy was used to heat these homes - typical homes consume about 383 KWh/m^2 per year for heating and hot water.

To use new technologies and knowledge to improve the energy performances of Greenlandic homes, a model low energy house was built in Sisimiut, Greenland in 2005 with an energy target of 80kWh/m^2 for space heating needs only (Vladykova et al., 2012).

A semi-detached homes with a usable floor area of 186m^2 was built. The house was oriented for solar heat gains and thermal bridges were minimized. The walls had a thermal resistance of RSI 6.5, the floor had a thermal resistance of RSI 7.14; and the roof had a thermal resistance of RSI 7.7. Thermal resistance values used in the home was much higher than what was required of the Greenlandic Building Regulation. A double core HRV with a defrosting was used (Vladykova et al., 2012).

The project team identified a lack of commissioning processes that validates quality assurance of systems and components, and a lack of understanding of guiding energy efficiency principles by Greenlandic builders were challenges faced.

2.4. Wall Types for Northern Canada

Walls need to be suitable for the North's harsh climate. Since the North lacks skilled labour, designers should use known wall designs. Also, known quality assurance methods such as a blower door test should be performed before the interior gypsum boards are placed to ensure continuity of the air barrier. In 2008, several wall types appropriate for northern regions were selected to study for their hygrothermal, energy and environmental performances (Rousseau et al., 2008); outlined below are the six wall type selected.

Wall type 1: Reference wall: typical R2000 2X6 construction

- Painted wood lap siding.
- Dupont home wrap Tyvek membrane.
- OSB.
- 2 x 6 with R20 glass fiber batts.
- Polyethylene air and vapour barrier.
- Gypsum (painted).

Wall type 2: typical new NHC wall type

- Prefinished structural smart panel siding.
- Dupont home wrap Tyvek membrane.
- 2X6, 5.5 in. mineral fibre.
- Polyethylene air and vapour barrier.
- 2X3 strapping and 2.5 in. mineral fibre semi-rigid insulation.
- Gypsum (Painted).

Wall type 3: wall composition (Wall "B") for the CMHC E2 house in Dawson City Yukon.

- Hardboard siding.
- 1X3 strapping.
- Dupont home wrap Tyvek membrane.
- OSB.

- 2X8 with 7.5in batt insulation.
- Polyethylene air and vapour barrier
- 2X4 strapping with 3.5in mineral fibre insulation.
- Gypsum.

Wall type 4: SIPs System

- Hardboard siding.
- Dupont home wrap Tyvek membrane.
- Load-bearing 6.5 in. SIP (with EPS).
- Polyethylene air and vapour barrier.
- 2X2 strapping with 1.5in mineral fibre semi-rigid insulation.
- Gypsum (Painted).
- Wall type 5: I-Joist systems
- Hardboard lap siding.
- Dupont home wrap Tyvek membrane.
- OSB.
- 7.5 in. I-joist filled with mineral fiber insulation.
- Polyethyelene air and vapour barrier.
- 2X2 horizontal strapping filled with 1.5 in. mineral fibre insulation.
- Gypsum (painted).

Wall type 6:

- Prefinished structural smart panel siding.
- Dupont home wrap Tyvek membrane.
- 2X6 with 5.5 in. mineral fibre insulation.
- 2 in. gap filled with mineral fibre insulation.
- Polyethylene air and vapour barrier.
- 2X4 studs with 3.5 in. mineral fibre insulation.

2.5. Knowledge Gap

Northern homes are built to standards and codes developed for southern regions. There lack housing codes and standards suitable for the area. Such standards should consider local climate, environment, human and infrastructural limitations of the North.

Northern homes are light-frame wood structure. Building materials for light-frame wood structures are easier to transport, but difficult to incorporate thermal mass. The North has an abundance of solar resources available, yet existing literature, codes and standards remain mute on passive solar design principles. Though the NSH did consider the orientation of homes for solar heat gains, there were no specific recommendations for window sizes, and there was no mention of using thermal mass.

The North's low-density population offer little market support for products to be rated for its climate. Due to low availability of skilled labour, new technologies such as HRVs needs to be easy to install, use, maintain and operate. Northern specific guidelines and standards should be developed for HRVs and solar systems.

3. Benchmarking Current Trends

The following chapter benchmarked current building trends in Northern Canada and is presented in two sections: the field research and the analysis of the EnerGuide energy service rating (ERS) database.

The first section summarizes field research conducted from April 22 to May 19, 2015, in Yellowknife, Northwest Territories. The author evaluated four homes and interviewed their homeowners. The author also interviewed four builders. Appendices A and B contains the complete questionnaires and answers for occupant and builder surveys.

3.1. Summary of Interviews with Home Owners

This research evaluated four homes in Yellowknife through interviews with the owner and on-site inspections of their homes.

Of the homes evaluated, two had missing insulations in the roof. In two homes, floors above the unheated crawl space were not insulated. Moreover, in another house, a wall facing a semi-heated garage were uninsulated. These instances occurred at intersections where it was not clear one of the spaces in question were unheated – this showed a poor understanding by builders on which building assemblies to insulate or poor communication between the builders and the workers.

In house 4 (Figure 7), the HRV unit was located in an unheated crawlspace without any insulation. When builders do not install newer technologies such as the HRVs correctly, they become inefficient and costly for the owners. In turn, owners are not keen to pay for newer technologies. Part of the challenge for quicker adoptions of newer technologies in the North is the lack of skilled labour with experiences installing them.

Homeowners were concerned about frost formations around windows and doors. The frost forms during extremely cold temperatures in the winter. Also, two owners reported problems with their homes shifting and sinking due to the melting of the permafrost. In one house, the pipe froze and had to be steamed. Because the house sank, the slope of some pipes shifted. The water in the pipe stayed stagnant and froze.

Table 2: Summary of homes evaluated in Yellowknife

	House 1	**House 2**	**House 3**	**House 4**
Built Year & description	2012, row house, 2 storey	1983, single, detached, 1 storey	2008, mobile Home, 1 storey	2014, single, detached, 2 storey
Floor area (m^2)	194	167	108.5	449
Set point temperature (°C)	21.5	20	20	21
Night temperature (°C)	16	16	18	18
Thermal resistance levels of walls (RSI)	5.13	2.03	2.75	5.5
Thermal resistance levels of ceiling (RSI)	10.24	5.97	5.03	10.21
Windows	Triple Glazed, Low-E, argon-filled window	Double glazed, Low-E, air filled window	Double glazed, Low-E, argon-filled window	Triple Glazed, Low-E, argon-filled window
HRVs	Yes	no	no	Yes
Heating system	Boiler (Propane)	Furnace (propane)	Furnace (Oil)	Boiler (Propane)
ACH (@ 50 pa)	2.14	12.15	4.8	0.4
Total annual space heating and cooling (KWh/m^2)	88	336	243	70
EGH rating	81	55	71	83
Reported problems	1. Frost formation around windows and doors 2. Missing insulation in the roof and the between interior and the semi-heated garage space	1. Frost formation on windows 2. Moisture issues in bathroom (owner does not use exhaust fan.) 3. House sinking because of melting permafrost	1. Missing insulation in ceiling & moisture problems where insulation is missing 2. Frost formation. 3. House sinking, melting permafrost	1. Missing insulation in floor 2. Frost formation around doors in winter 3. Poorly installed HRV 4. Missing insulation in roof

Figure 7: a. (top left) house 1, b. (top right) house 2, c. (bottom left) house 3, d. (bottom right) house 4, (see Table 2).

3.2. Summary of Interviews with Builders

Builders trained their workers to construct a home in a single way. Introducing a new method would be costly as the workers need to be re-trained, new equipment may be necessary, and workers are more prone to making mistakes.

Most wall types were either single wood stud walls with interior or exterior strapping with semi-rigid insulations, double stud walls, or staggered stud walls.

Heat recovery ventilators got many call backs for noise or moisture issues – clients reported moisture issues when they turned the HRV off. Builders had difficulties finding skilled labour to install HRVs. Two of the builders interviewed felt HRVs were inappropriate for northern housing.

One contractor built unvented attic using spray foam to achieve the continuous vapour and air barrier in the ceiling. Another contractor used unvented attic but reported many moisture problems.

No builders interviewed were familiar with passive solar design strategies such as window wall ratio, or using thermal mass– though one contractor oriented homes for solar heat gains.

Table 3: Summary of builder’s interviews in Yellowknife

	Builder 1	Builder 2	Builder 3	Builder 4
Energy performance target	Client driven, and EGH 80	EGH 80 or 25% better than Model National Energy Code of Canada for Houses (2011)	N/A	Client driven and 1990 NBCC.
Solar design strategies	Oriented house towards the south. Window size is driven view	None	None	None
Wall construction	2x6 walls, 4in spray foam on the exterior	2x6 walls with batt insulation, and 1.5in of semi-rigid insulation on the interior	2x6 walls with Roxul insulation 2x2 horizontal strapping for wiring and retrofit	Double 2x4 walls with staggered studs
Thermal resistance levels of walls (RSI)	7 to 9	5.25	5.25	5
Thermal resistance levels of ceiling (RSI)	RSI 10.5 using 10in of spray foam	9	9 to 10.5	9.5 to 10.5
Thermal resistance levels of floors (RSI)	6	7	N/A	N/A
Attic construction	Non-vented attic – air/vapour barrier achieved using spray foam insulation.	Vented attics, and non-vented attics above tree lines; moisture issue in non-vented attics	Vented attics	Vented attics
Windows	Triple pane, argon, Low-E windows.	Triple pane, argon, Low-E windows	Triple pane, argon, Low-E windows	Triple pane, argon, Low-E windows
ACH targets	1.0	1.5 and verified using blower door test	N/A	N/A
HRVs	Occupants do not want to run them, but then there are moisture issues	Defrosting is a problem, we pre-heat the air	They are problematic (noisy, concerns regarding energy)	They are inappropriate. I think forced air system should allow adequate ventilation
Heating systems used	Boiler (better distribution of heat)	Forced-air Furnace	Forced-air furnace /boiler	Forced air furnace

3.3. Analysis on the EnerGuide Energy Rating Service (ERS) Database

This section presents data analysis of the EnerGuide energy rating service (ERS) database for Northwest Territories (NWT). The objective was to identify the past and current state of housing in NWT and determine the effect of the City of Yellowknife’s building EGH 80 by-law had on housing performance. This regulation, adopted in 2008, required a minimum EGH rating of 80 for all privately built residential buildings.

The EnerGuide ERS program is an energy assessment program for residential buildings. It was formerly known as the EnerGuide for Houses (EGH) program and developed by Natural Resources Canada (NRCan). NRCan conceived the ERS database as a comprehensive tool to track and manage residential energy evaluations (Blais et al., 2005). Certified energy auditors uploaded information on each home into a central database, the ERS database. 1744 homes from the NWT from this database were data mined as of July 15, 2015.

This database included five regions: Yellowknife, South Slave and Dehcho Region, North Slave, Sahtu Region, and Beaufort Delta (see Table 4.) In 2008, the city of Yellowknife made ERS energy audits mandatory for all private residential housing built in Yellowknife, this was part of a EGH 80 by-law (City of Yellowknife, 2008).

Homes were analyzed based on built year, albeit the actual energy evaluation date may be different. An energy audit in 2010 of a home constructed in 1960 would reflect any retrofits since then. The researcher considered using evaluation date. However, the evaluation dates do not indicate retrofit dates of homes. The trends identified through the EGH database, using built dates, are sufficient for benchmarking current performance levels of housing.

Table 4: Communities in each region

Regions	Communities in Region	# of Homes
Yellowknife	City of Yellowknife.	1002
South Slave and Dehcho	Fort Liard, Fort Providence, Fort Resolution, Fort Simpson, Fort Smith, Hay River, Kakis & Nahanni Butte.	327
North Slave	Behchoko, Dettah, Gameti, Lutsel Ke, Wekweti, Ndilo & Whati.	82
Sahtu Region	Deline, Fort Good Hope, Norman Wells & Tulita	120
Beaufort Delta	Aklavik, Fort McPherson, Inuvik, Paulatuk, Sachs Harbour, Tsiigehtchic & Tuktoyaktuk.	213

$$Normalizing\ Ratio = \frac{HDD_{Yellowknife}}{HDD_{Region}} \quad \text{(Eqn. 1)}$$

Table 5: Heating-degree days and normalizing ratios (Environment and Climate Change Canada, 2016)

	Heating-Degree Days	Normalizing Ratio
Yellowknife	7880	1
North Slave	6945	1.13
South Slave and Dehcho	7029	1.12
Sahtu Region	8083	0.97
Beaufort Delta	9160	0.86

Each region was evaluated based on local weather data. Performance indicators such as energy intensity (kWh/m^2) of homes corresponding to different weather data were normalized using (Eqn. 1, and

Table 5.)

Also, 819 single detached homes, 11 double/semi-detached homes, 101 mobiles homes and 71 row houses from Yellowknife were evaluated. A single detached home is defined as freestanding, single-family residential home. A double/semi-detached house has two homes that share a structural wall. Row houses are similar to semi-detached home, but more than two homes share structural walls. Mobile homes are pre-manufactured, built in factories and shipped to sites.

This chapter presented the results in graphs and tables. Graph plots the information on each home. The tables show the sample size, the mean and the standard deviation for different time periods: 1950 to 1969; 1970 to 1989; 1990 to 2009; and 2010 to 2015.

3.3.1. Energy Performances Across Different Regions in NWT

In this study, energy intensity included the energy needed to heat and cool the home. Across all areas evaluated, the energy intensity decreased over the years. In Figure 8, the energy intensity ranged from 100kWh/m^2 to 900kWh/m^2 compared to 25kWh/m^2 to 300kWh/m^2 after 2009. Homes built in Beaufort and Sahtu regions had higher energy intensity. For the years 2010 to 2015, Yellowknife had the highest energy intensity of 131kWh/m^2 compared to other areas but still showed a 45% decrease from the period of 1990 to 2009. For the same period, South Slave and Dehcho's mean energy intensity were 86kWh/m^2 (see Table 6).

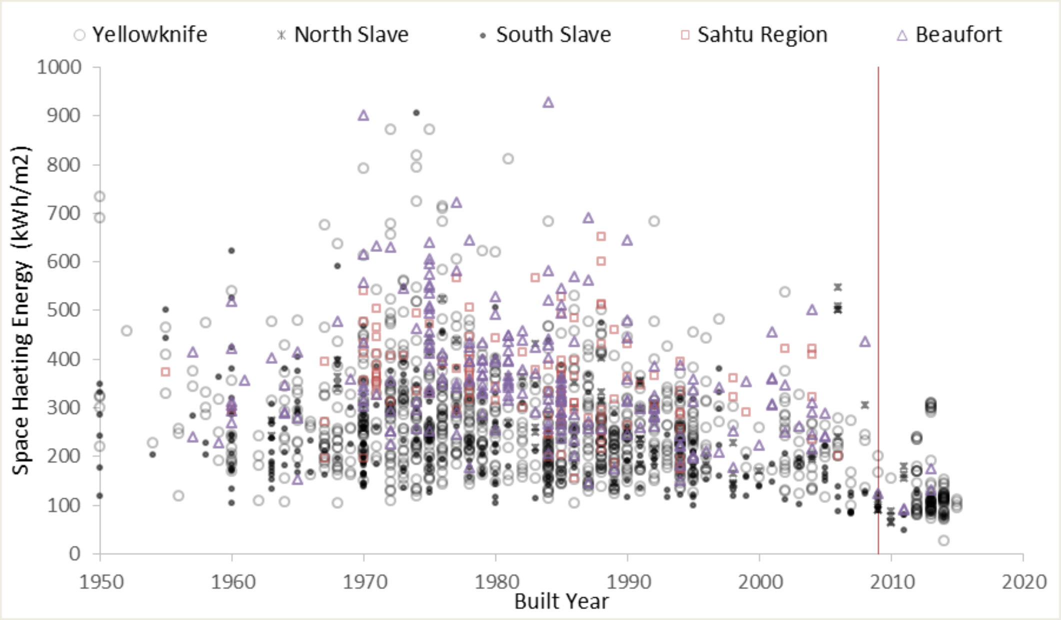

Figure 8: Energy intensity (kWh/m^2) by regions

Table 6: Mean energy intensity (kWh/m^2) by regions

	Year	Sample Size	Mean (kWh/m^2)	Standard Deviation
Yellowknife	1950-1969	110	282	118
	1970-1989	559	285	122
	1990-2009	225	241	81
	2010-2015	102	131	64
South Slave and Dehcho	1950-1969	66	266	111
	1970-1989	161	257	102
	1990-2009	86	176	63
	2010-2015	10	86	23
North Slave	1950-1969	6	327	58
	1970-1989	26	314	92
	1990-2009	34	249	122
	2010-2015	16	110	32
Sahtu Region	1950-1969	6	304	72
	1970-1989	89	370	97
	1990-2009	27	311	160
Beaufort Delta	1950-1969	19	335	91
	1970-1989	138	401	155
	1990-2009	52	299	95
	2010-2015	4	121	39

Until 2010, North Slave, South Slave and Dehcho, and Beaufort Delta regions had higher EGH rating than Yellowknife and Sahtu regions (see Table 7).

Regions outside of the Yellowknife had a tendency to outperform homes built in the city – however, the city's new building EGH80 by-law made it mandatory for all private homes built in Yellowknife to get an EGH energy audit. Homes in other regions were voluntarily evaluated; but, all private homes in Yellowknife were assessed. It is the author's belief that voluntarily evaluated homes may represent better homes.

Yellowknife had a mean EGH rating of 68 from 1990 to 2009. For 2010 to 2015, the EGH improved to EGH 79 (see Table 7). North Slave, South Slave, Dehcho, and Beaufort Delta regions had a mean EGH rating of 80 or above.

Table 7: Mean EGH rating and mean ACH rates by regions

			EGH Rating		**ACH Rate at 50 Pa**	
	Year	**Sample Size**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Yellowknife	1950-1969	110	65	8	5.6	4.4
	1970-1989	559	65	8	6.2	4.1
	1990-2009	225	68	6	4.8	2.4
	2010-2015	102	79	5	2.8	1.4
South Slave and Dehcho	1950-1969	66	66	9	6.0	3.3
	1970-1989	161	66	8	6.3	3.7
	1990-2009	86	74	5	4.1	2.5
	2010-2015	10	81	2	3.2	2.2
North Slave	1950-1969	6	70	4	9.8	1.5
	1970-1989	26	68	7	9.4	4.6
	1990-2009	34	72	5	6.2	5.0
	2010-2015	16	82	2	7.1	2.5
Sahtu Region	1950-1969	6	65	8	6.5	2.3
	1970-1989	89	63	8	8.8	3.8
	1990-2009	27	67	6	6.7	3.0
Beaufort Delta	1950-1969	19	65	6	6.5	2.1
	1970-1989	138	63	9	8.1	4.2
	1990-2009	52	69	6	5.5	3.3
	2010-2015	4	82	7	2.7	0.8

In Figure 9 and Figure 10, Yellowknife had some of the best EGH rated homes and most airtight homes built. Homes built in Beaufort and Sahtu regions had lower EGH rating, and higher ACH rating (see Table 7). Figure 11 and Figure 12 show insulation levels for walls and ceiling; after 2009, homes built in Yellowknife had higher thermal resistances in their building assemblies.

Between 2010 to 2015, Yellowknife, South Slave, Dehcho, and Beaufort Delta had an ACH rating of 2.8, 3.2, and 2.7 at 50 Pa respectively (see Table 7). There was a significant drop in ACH ratings in the previous decades.

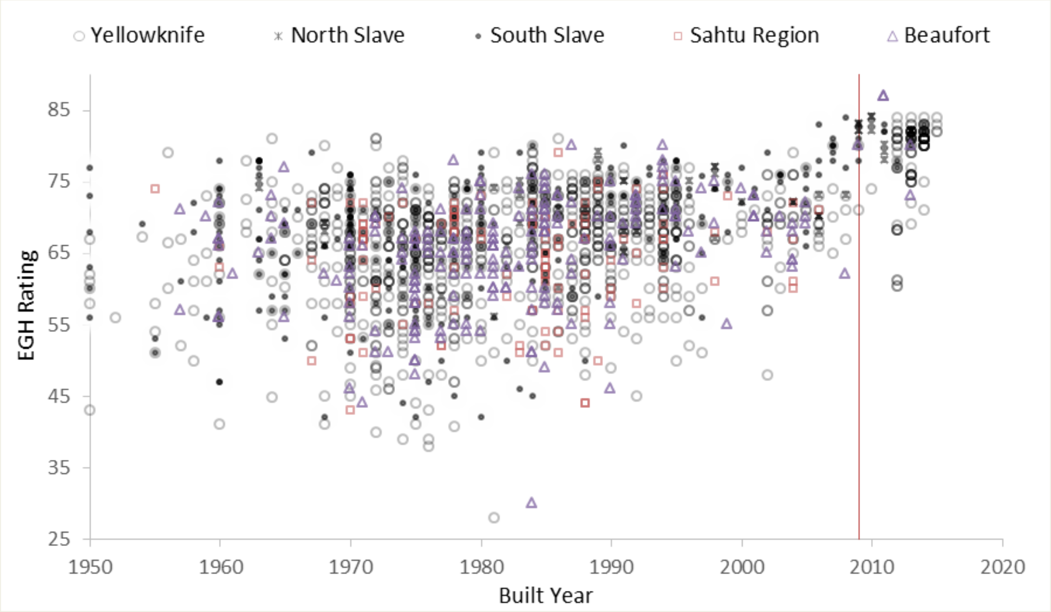

Figure 9: EGH rating by regions

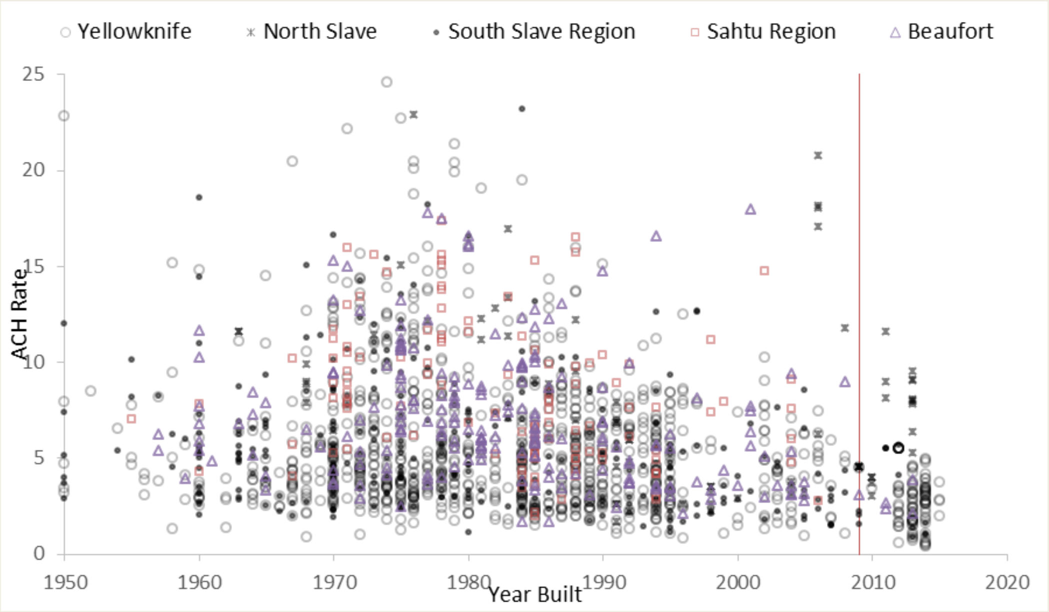

Figure 10: ACH rates at 50 Pa by regions

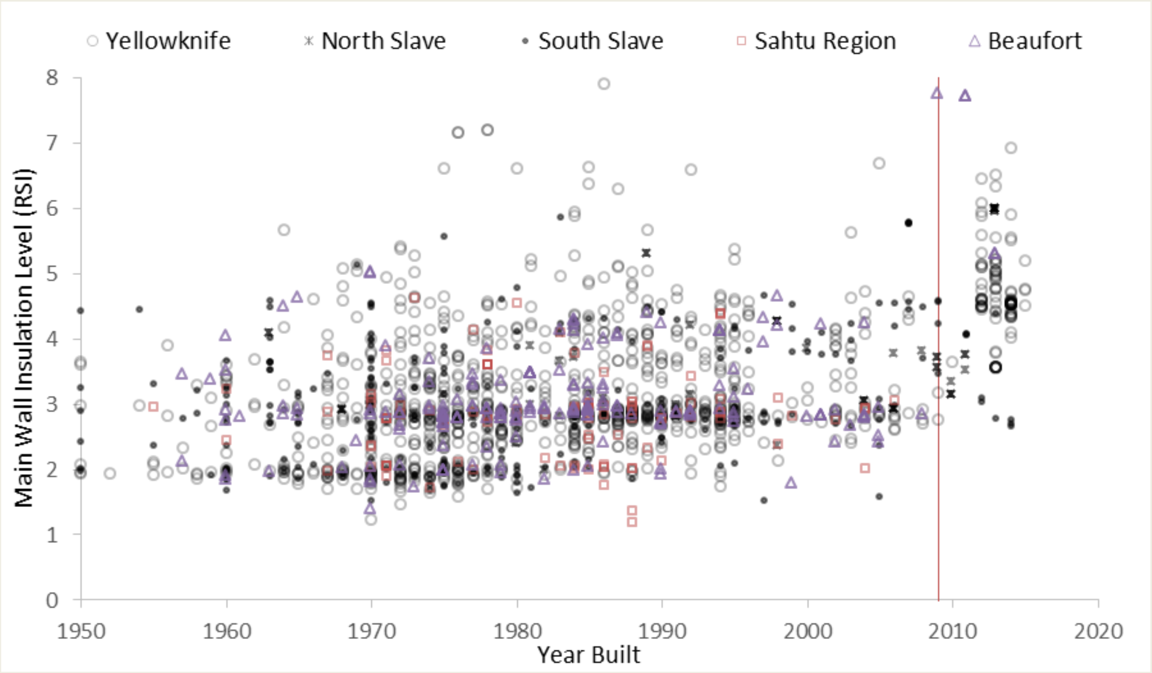

Figure 11: Thermal resistance (RSI) levels for main walls by regions

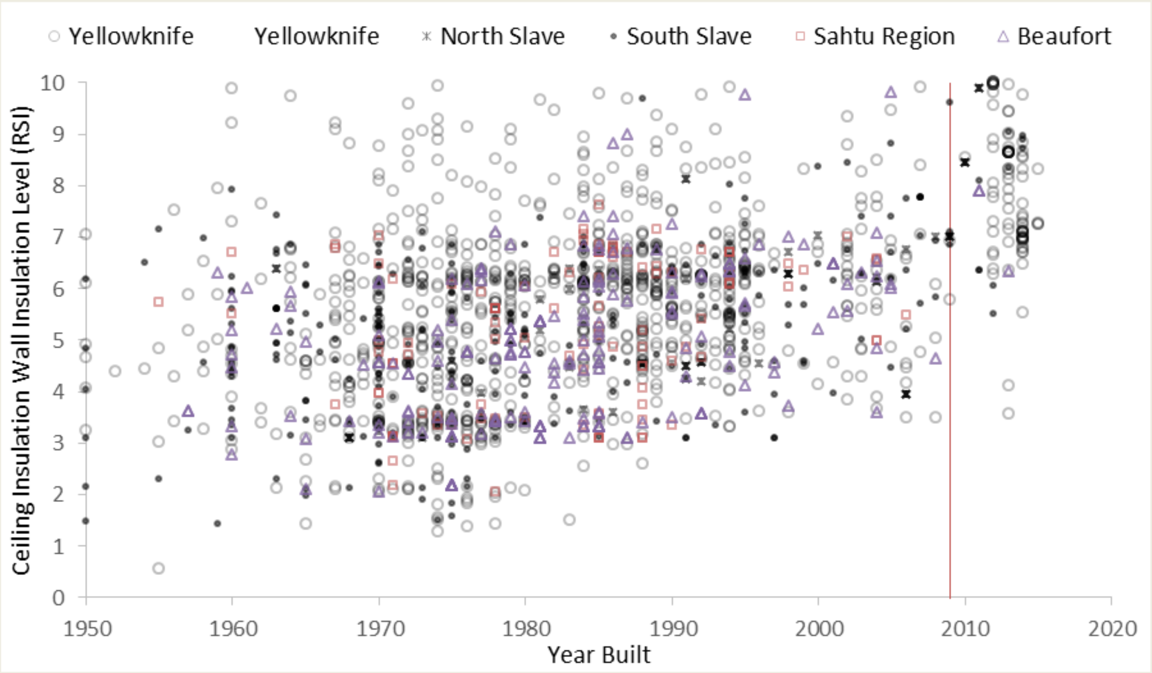

Figure 12: Thermal resistance (RSI) levels for ceiling by regions

Table 8: Mean thermal resistance levels (RSI) for main walls and ceiling by regions

			Wall RSI Levels		Ceiling RSI Levels	
	Year	Sample Size	Mean	Standard Deviation	Mean	Standard Deviation
Yellowknife	1950-1969	110	2.7	0.9	5.0	1.7
	1970-1989	559	3.1	1.0	5.5	1.8
	1990-2009	225	3.2	0.8	6.1	1.3
	2010-2015	102	4.7	0.7	8.3	1.6
South Slave and Dehcho	1950-1969	66	2.8	0.8	4.7	1.5
	1970-1989	161	2.8	0.8	4.9	1.6
	1990-2009	86	3.4	0.9	6.1	1.3
	2010-2015	10	3.4	0.7	7.6	1.4
North Slave	1950-1969	6	3.3	0.6	4.2	1.7
	1970-1989	26	3.2	0.8	5.1	1.1
	1990-2009	34	3.3	0.6	5.7	1.3
	2010-2015	16	4.9	1.3	9.9	0.9
Sahtu Region	1950-1969	6	2.9	0.6	5.9	1.2
	1970-1989	89	2.8	0.7	4.9	1.5
	1990-2009	27	3.0	0.6	5.9	0.9
Beaufort Delta	1950-1969	19	2.9	0.8	4.4	1.2
	1970-1989	138	3.0	0.6	4.5	1.4
	1990-2009	52	3.2	0.9	5.8	1.5
	2010-2015	4	6.5	1.4	8.1	1.6

Between 1990 and 2009, mean thermal resistance values for walls ranged from RSI 3.2 to RSI 3.4 and RSI 5.7 to 6.1 for ceilings for different regions in NWT. For years 2010 to 2015, these values ranged from RSI 3.4 to RSI 6.5 for walls and RSI 5.9 to RSI 9.9 for ceilings. For Yellowknife, mean thermal resistance values increased from RSI 3.2 to RSI 4.7 for walls from 1990 to 2009 to 2010 to 2015 and from RSI 6.1 to RSI 8.3 for ceilings for the same time periods (see Table 8.)

The mean primary heating equipment's efficiency was above 80% for all regions evaluated (Table 9); although, a home built in the 1950s may have had retrofitted its heating system. Homes assessed after 2009 had mean heating equipment's efficiency levels above 90%. In Figure 13, homes built in Yellowknife after the EGH80 by-laws had much better EGH rating, and improved primary heating equipment's efficiency. The city's by-law may be linked to the clustering effect of homes to the top right corner of the graph.

Table 9: Mean primary heating equipment's efficiencies

	Year	**Sample Size**	**Mean**	**Standard Deviation**
Yellowknife	1950-1969	110	82	5
	1970-1989	559	82	4
	1990-2009	225	83	4
	2010-2015	102	93	7
South Slave and Dehcho	1950-1969	66	84	6
	1970-1989	161	84	5
	1990-2009	86	84	5
	2010-2015	10	90	5
North Slave	1950-1969	6	83	1
	1970-1989	26	82	4
	1990-2009	34	83	2
	2010-2015	16	85	0
Sahtu Region	1950-1969	6	79	7
	1970-1989	89	81	4
	1990-2009	27	82	2
Beaufort Delta	1950-1969	19	83	6
	1970-1989	138	82	3
	1990-2009	52	83	2
	2010-2015	4	93	6

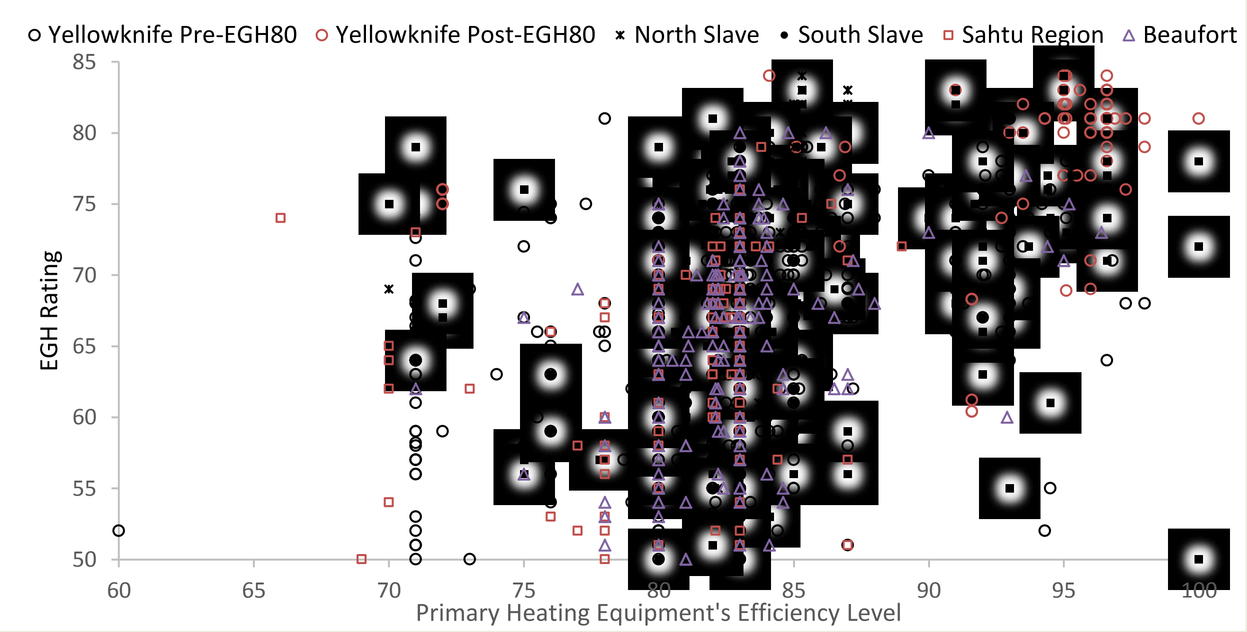

Figure 13: EGH rating for different primary heating equipment's efficiency levels by regions

The EGH database does not provide information regarding wall areas, total glazing areas, or ceiling areas. This information is found directly in the HOT2000 files, they were not accessible to the researchers. Heat loss through walls, ceiling, foundation, windows and air leakage were provided per total floor area of the home – this allowed researchers to identify patterns between different heat loss sources. Table 10 provides heat loss through building assemblies as a percent of total heat loss. Appendix C presents more detailed tables and graphs on heat. Air leakage accounted for about one-third of all heat loss for all regions except for North Slave, which saw unusually high ACH rates. Heat loss through walls and windows represented between a quarter to a fifth of the total heat loss each, and ceiling represents about a tenth of the heat loss.

Table 10: Percentage of heat loss over total heat loss

			% of Heat Loss to Total Heat Loss				
	Year	**Sample Size**	**Air Leakage**	**Foundations**	**Ceilings**	**Walls**	**Windows**
Yellowknife	1950-1969	110	29	23	9	20	19
	1970-1989	559	33	14	10	23	21
	1990-2009	225	31	14	9	24	21
	2010-2015	102	34	13	9	23	21
South Slave and Dehcho	1950-1969	66	32	21	9	19	19
	1970-1989	161	31	19	10	20	21
	1990-2009	86	29	17	10	21	24
	2010-2015	10	27	22	10	22	19
North Slave	1950-1969	6	40	9	13	23	16
	1970-1989	26	38	9	10	22	21
	1990-2009	34	37	15	10	21	16
	2010-2015	16	48	14	9	13	16
Sahtu Region	1950-1969	6	36	19	7	22	16
	1970-1989	89	39	10	10	24	17
	1990-2009	27	35	10	9	28	18
Beaufort Delta	1950-1969	19	35	11	11	26	18
	1970-1989	138	37	10	11	23	18
	1990-2009	52	34	10	10	26	20
	2010-2015	4	33	13	13	19	23

Table 11: Mean heat loss (kWh/m^2) and improvements (%) between pre and post EGH80 by-law

			Annual heat loss per total floor area (kWh/m^2)				
	Year	**Sample Size**	**Air Leakage**	**Foundations**	**Ceilings**	**Walls**	**Windows**
Yellowknife	1990-2009	225	82	38	25	64	57
	2010-2015	102	59	22	16	40	36
Percentage improvement between pre and post EGH80 by-law			28	42	36	38	36

3.3.2. Energy Performances Based on Types of Houses

There is a growing interest in the North for pre-manufactured, mobiles houses and multi-family homes. Pre-manufactured homes are easy and quick to build in the region's short construction season. Also, they are built in factory settings with better quality control. Multi-family homes have fewer walls exposed to the exterior, consequently they are less expensive and more energy efficient. Northern governments have made a push for more pre-fabricated and multi-family residences.

Mobile homes have the highest mean EGH rating of 81.1 and an average energy intensity of 115kWh/m^2 for the period of 2010 to 2015. During the same period, row houses had a mean energy intensity of 135kWh/m^2 and single-detached had the highest mean energy intensity of 151kWh/m^2. Single-detached homes are most airtight, with a mean ACH of 2.1 at 50 Pa between 2010 and 2015, but they have larger floor areas and higher volumes (

Table 12). Mobile homes, built under factory conditions, have a mean ACH of 3.2 (Table 13). Mobiles homes are sometimes damaged while being transported and have higher air leakage rates.

However, there does not seem to be very clear trends or differences among different types of houses given that many other factors influence the energy performance of the home - such as quality of workmanship. Though, based on the data – there is a definite shift towards mobile and multi-family dwellings. Of homes built between 1950 till 1999, single-detached homes represented 85 to 90% of the total shares of homes evaluated. This proportion dropped to 62% of homes built from 2000 to 2010, and 37% of all homes built from 2010 to 2015. Between 2010 and 2015, 31% of homes evaluated were mobile homes and 31% were multi-family houses.

Table 12: Mean energy intensity (kWh/m^2), EGH rating and total floor area (m^2) by home types

	Year	Sample Size	Energy Intensity (kWh/m^2)		EGH Rating		Total Floor Area (m^2)	
			Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Single Detached	1950-1969	102	277	112	65.2	8.2	170	45
	1970-1989	487	282	118	64.9	7.8	183	79
	1990-2009	184	237	85	68.0	6.1	200	92
	2010-2015	37	151	91	79.1	3.9	230	161
Semi-Detached	1970-1979	3	221	157	69.3	8.6	182	73
	2000-2009	1	167	N/A	80.0	N/A	44	N/A
	2010-2015	7	106	23	79.6	4.2	175	58
Mobile	1950-1969	4	400	222	66.3	10.9	67	8
	1970-1989	43	346	163	65.8	9.1	102	35
	1990-2009	23	264	57	68.7	3.7	124	32
	2010-2015	31	115	11	81.1	0.9	133	17
Row Houses	1950-1969	4	305	119	62.8	8.1	143	14
	1970-1989	26	248	89	67.9	9.2	139	36
	1990-2009	16	259	65	62.6	5.4	183	63
	2010-2015	24	135	56	74.6	8.0	224	49

Table 13: Mean thermal resistance (RSI) values for insulation in walls and ceilings by home types

	Year	Sample Size	Wall RSI Value		Ceiling RSI value	
			Mean	Standard Deviation	Mean	Standard Deviation
Single Detached	1950-1969	102	2.7	0.9	5.0	2
	1970-1989	487	3.0	1.0	5.5	1.7
	1990-2009	184	3.3	0.8	6.2	1.3
	2010-2015	37	4.7	1.0	8.6	1.9
Semi-Detached	1970-1979	3	3.8	0.5	7.2	3.4
	2000-2009	1	3.2	N/A	6.9	N/A
	2010-2015	7	5.0	0.8	7.7	0.9
Mobile	1950-1969	4	3.1	0.9	3.9	1.9
	1970-1989	43	3.1	0.8	4.6	2.1
	1990-2009	23	2.8	0.2	5.3	1.2
	2010-2015	31	4.6	0.2	7.2	0.5
Row Houses	1950-1969	4	2.5	0.8	5.8	1.3
	1970-1989	26	3.4	1.7	5.4	1.1
	1990-2009	16	3.4	0.7	5.4	1.1

	2010-2015	24	4.8	0.3	9.3	1.3

Table 14: Mean ACH rating and mean primary heating equipment’s efficiency (%) by home types

	Year	Sample Size	ACH @ 50 Pa		Primary heating equipment’s efficiency (%)	
			Mean	**Standard Deviation**	**Mean**	**Standard Deviation**
Single Detached	1950-1969	102	5.3	4.2	82	5
	1970-1989	487	5.8	3.8	82	4
	1990-2009	184	4.4	2.3	84	4
	2010-2015	37	2.1	1.3	89	10
Semi-Detached	1970-1979	3	6.4	6.0	82	2
	2000-2009	1	4.6	N/A	93	N/A
	2010-2015	7	2.7	1.1	94	5
Mobile	1950-1969	4	12.1	6.7	81	1
	1970-1989	43	10.8	5.6	83	6
	1990-2009	23	6.4	1.8	83	4
	2010-2015	31	3.2	0.7	97	0
Row Houses	1950-1969	4	6.5	1.3	83	2
	1970-1989	26	6.0	1.7	84	4
	1990-2009	16	6.7	2.2	80	3
	2010-2015	24	3.6	1.7	94	2

3.3.3. Energy Performance Based on Window Types

Based on the evaluated data, triple glazed, Low-E, argon, and air filled windows were the best-performing windows (Figure 14). In Table 15, homes that used triple glazed, Low-E, argon-filled windows had a mean energy intensity of 197kWh/m^2 from 2010 to 2015. While, evaluation of 14 homes with double glazed, Low-E argon window for the same period had a mean energy intensity of 499kWh/m^2. On average, houses with double glazed windows had 2.5 times the energy intensity of homes with triple glazed windows. Performances indicators of homes with triple glazed, Low-E, argon-filled windows outperformed homes with other windows; they had lowest energy intensity, highest EGH ratings, and lowest ACH rates. Homes built between 1990 to 2007 that installed Low-E, argon-filled triple-glazed windows had lower energy intensity than homes built between 2010 to 2015 with double glazed windows.

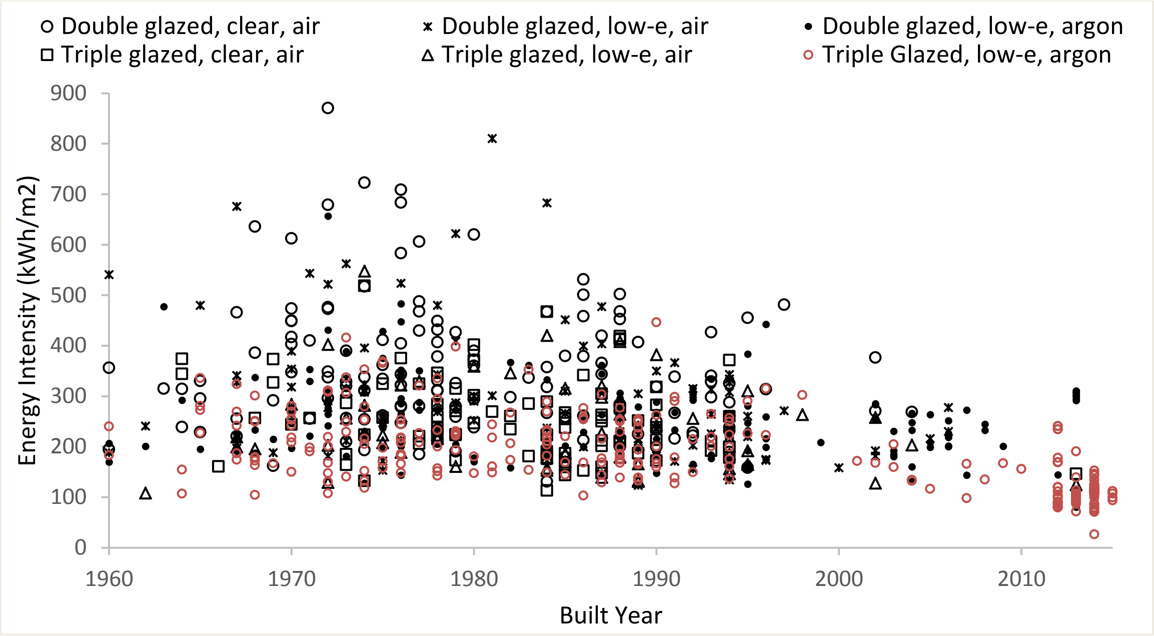

Figure 14: Energy intensity (kWh/m^2) for different window types

Table 15: Energy intensity (kWh/m^2), EGH rating and ACH rate @ 50 Pa of homes

			Energy Intensity (kWh/m^2)		EGH Rating		ACH Rate @ 50pa	
	Year	**Sample Size**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Double Glazed, Clear, Air	1950-1969	25	400	123	62	8	5.6	2.7
	1970-1979	63	485	165	60	8	8.2	4.8
	2000-2009	3	397	103	64	6	5.5	2.3
	2010-2015	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Double Glazed, Low-E, Air	1950-1969	11	522	229	61	11	10.7	9.5
	1970-1979	32	440	174	64	9	7.6	5.2
	2000-2009	6	339	95	68	5	5.1	2.4
	2010-2015	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Double Glazed, Low-E, Argon	1950-1969	19	369	117	66	7	5.6	3.5
	1970-1979	50	393	109	66	6	6.2	2.9
	2000-2009	25	336	82	69	5	5.0	2.2
	2010-2015	14	499	239	77	3	3.1	1.1
Triple Glazed, Clear, Air	1950-1969	6	418	92	63	8	6.1	2.1
	1970-1979	24	348	106	66	6	5.4	3.2
	2000-2009	N/A	328	81	66	6	4.1	1.7
	2010-2015	1	216	N/A	72	N/A	4.4	N/A
Triple Glazed, Low-E, Air	1950-1969	4	265	53	73	4	2.7	1.2
	1970-1979	16	345	124	67	6	5.2	3.2
	2000-2009	3	321	95	69	6	4.1	2.2
	2010-2015	1	200	N/A	76	N/A	4.6	N/A
Triple Glazed, Low-E, Argon	1950-1969	24	304	78	70	6	4.0	2.0
	1970-1979	62	309	89	70	5	4.7	2.8
	2000-2009	11	290	105	70	6	4.1	2.6
	2010-2015	86	197	47	79	6	2.8	1.4

For the years 2010 to 2015, 84% of homes evaluated in the EGH database used a triple glazed, Low-E, argon-filled windows. This data shows an improvement from 1990 to 2007 as only 22% of homes evaluated used triple glazed, argon filled windows. In Figure 15, most homes evaluated between 2010 and 2015 used triple glazed, Low-E, argon-filled windows –between 1990 to 2007 (and the previous decades) there is more diversity in the types of windows installed. After the EGH80 by-law, installation of more energy efficient windows added to the overall improved energy efficiency of homes.

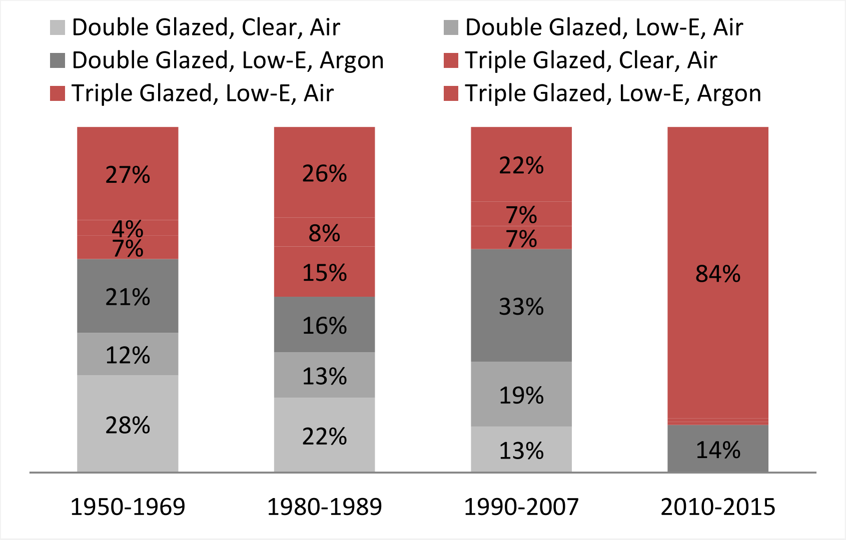

Figure 15: Distribution of windows type in homes evaluated in Yellowknife

3.4. Discussions

1744 homes from the NWT where data mined from the EGH database. Performance indicators such as energy intensity (kWh/m^2), total floor area (m^2), ACH rates, EGH ratings, thermal resistance values, and primary heating equipment’s efficiencies were assessed based on different regions in NWT; different housing types; and types of window installed in homes.

In 2008, the City of Yellowknife adopted the EHG80 by-law, which introduced a mandatory minimum EGH rating of 80 for new private homes built. The ordinance went into effect after in 2010. One of the objectives of this section was to assess the impact of the EGH80 by-law on home’s energy performance.

Researchers compared 220 homes built in Yellowknife between 1990 and 2007 to 102 homes constructed in 2010 and 2015. In all eight performance indicators, homes built after 2010 were remarkably better (see Table 16); they had 42% more insulations in walls, 34% more insulations in ceilings and were 36% more airtight. Homes built after 2010 used 12% less electricity and reduced total energy consumption by 30% compared to homes constructed in the previous decade.

Energy performances of the homes in Northwest Territories improved gradually over the years. However, the author believes the adoption of EGH80 by-law gave a momentum to introduce a new wave of energy efficient buildings. Contractors adopted known strategies to achieve much higher energy efficiency. For instances, for the year 2010 to 2015, 84% of homes evaluated in the EGH database used a Low-E, argon-filled triple-glazed windows, in contrast to only 22% of homes evaluated between 1990 to 2007.

Table 16: Performance parameters before and after the by-law

	1990 to 2009 (Sample Size = 225)		**2010 to 2015 (Sample Size = 102)**		**Percentage Improvements pre/post EGH80 By-law**
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	
Energy intensity (kWh/m^2)	241	81	131	64	22
EGH rating	68	6	79	5	13
ACH rating (@ 50 Pa)	5	2	2.8	1.4	36
RSI levels (main wall)	3.2	0.8	4.7	0.7	42
RSI Levels (ceiling)	6	1	8.3	1.6	34
Primary heating equipment's efficiency (%)	83	4	93.1	7.1	11
Total electricity used (kWh)	3460	775	30375	2218	12
Total energy used (kWh)	66145	15843	40291	24276	30

Finally, there is a shift towards mobile and multi-family housing in the North. Until about 1999, they represented about 85 to 90% of the market shares of homes evaluated. After 2010, there was a definite shift towards mobile and multi-family dwellings. Between 2010 and 2015, 31% of homes built in Yellowknife were mobile homes and 24% were row houses.

The analysis presented in this section showed the EGH80 by-law passed in Yellowknife was successful and builders adopted the new energy efficiency requirements.

4. Parametric Study of Solar Parameters

4.1. Objective

Builders can achieve significant energy savings for little-added cost by building high performing envelope systems and by integrating solar design strategies. The aim of this parametric study is to optimize selected key design parameters to minimize energy consumption for a typical home in Yellowknife. One-dimensional transient conduction equations were solved to obtain hourly indoor air temperatures, hourly heating demands, and annual energy consumption. The following parameters were studied: thermal resistance values in walls, ceiling and floors, window-wall ratios, thermal mass, BIPV/T capacity and area, summer ventilation rates, and night window shutters.

In northern Canada, there is little literature on solar design strategies. The NSHs used larger windows on its south façade for solar heat gains, but there were no specific recommendations on the sizing and placement of the windows. The field surveys showed that builders did not consider solar designs strategies in their design process.

Relevant standards and guidelines only specify minimum thermal resistance values for building assemblies. This parametric study should give optimal thermal resistance ranges for walls, floors, and ceilings.

There is a strong push from northern governments to built energy efficient homes. The findings presented in this chapter should help builders reduce energy consumption of northern homes. As such, the findings should be relevant for policies makers in the north.

4.2. Methodology

The finite difference method provides accurate estimation on heat flows and temperatures while allowing for the integration of non-linear effects such as radiation and convection (Helou, 2003). MATLAB is used to write the program and obtain hourly temperature and auxiliary heating required by the house. Appendix E presents the MATLAB.

Construction assemblies such as walls, floors, and roofs are represented as a purely resistive exterior layer and a resistive and capacitive layer on the interior. Each sub-layer is symbolized by a node (*i*), with each node having an associated thermal capacitance (C_i) and thermal resistances (R_{ij}) connected to an adjacent node (*j*). To identify the number of control volumes needed for the model's accuracy, the floor is modelled wth one thermal capacitance, two thermal capacitances, and four thermal capacitances.

4.2.1. The Explicit (forward) Finite Difference Method

The explicit (forward) finite difference method gives the future temperature of a node based on the temperatures of its connecting nodes from the previous time step (Helou, 2003). The basic one-dimensional transient conduction equation is as follows:

$$k \cdot \frac{d^2T}{dx^2} = \rho \cdot c_p \cdot \frac{dT}{dt} \tag{Eqn. 2}$$

Where T is the temperature, k is the thermal conductivity, c_p is the specific heat, and ρ, the density. The explicit (forward) finite difference of the above equation is:

$$T_i^{p+1} = \frac{\Delta \mathrm{t}}{C_i} \cdot \left(q_i + \sum_j \frac{T_j^p - T_i^p}{R_{(i,j)}} \right) + T_i^p \tag{Eqn. 3}$$

Where j represents all nodes connected to node i, q_i represents all heat sources on node i, T_i^{p+1} is the temperature at next time step, T_i^p is the temperature at the current time step, Δt is the time step in seconds, C_i the thermal capacitance for node *i*, and $R_{(i,j)}$ is the conductive, radiative or convective thermal resistance between node *i* and j. To reduce calculation errors, the critical time step is calculated as:

$$\Delta \mathrm{t}_{critical} = \min \left(\frac{C_i}{\sum_j \frac{1}{R_{(i,j)}}} \right) \tag{Eqn. 4}$$

4.3. Solar Radiation

Despite the abundant of solar radiation available in the North, there is a mismatch between the energy available in the summer and when it is most needed in the winter. Athienitis (2015) describes a methodology for calculating the total solar radiation incident to the house. This model computed three solar radiation components: the direct beam radiation, diffused sky radiation, and reflected radiation.

Researchers obtained hourly data on outdoor temperature, site direct solar radiation rate per area (W/m^2), site diffused solar radiation rate per area (W/m^2) for Yellowknife, Northwest Territories from the EnergyPlus software (U.S. Department of Energy, 2015). These data were historical average for 25 years. They were used to determine the solar radiation incident on exterior walls and transmitted through windows.

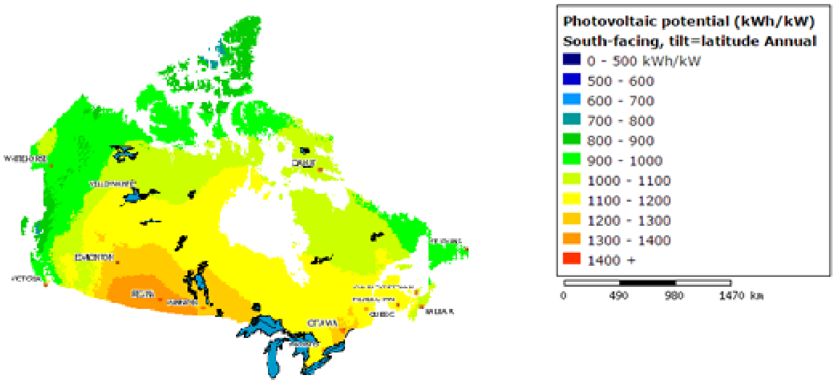

Figure 16: Annual PV potential for Canada for south-facing wall (NRCAN, 2015)

4.3.1. Solar Geometric Calculations

Solar geometric calculations identify the relationship between the sun’s rays and planes of interest. Athienitis (2000) outlines the calculation methods:

(1) Declination angle (δ or Dec) represents the angle between the equator and the sun at solar noon; it is calculated as:

$$\delta = 23.45° \cdot \sin\left(360 \cdot \frac{284+n}{365}\right) \qquad \text{(Eqn. 5)}$$

Where n is the number of days since January 1st.

(2) The Sunset time (t_s) calculates sunset and sunrise hours relative to solar noon.

$$t_s = \cos^{-1}(\tan(L) \cdot \tan(\delta)) \cdot \frac{hr}{15 \cdot deg} \qquad \text{(Eqn. 6)}$$

(3) The latitude (L) is a geographical reference in relationship to the north-south position of a point on the earth's surface. Yellowknife is located 62.4° north of the equator (Environment Canada, 2015).

(4) Hour angle (ha_{it}) converts the local solar time (LST) into degrees, ha_{it}=0° at solar noon.

$$ha_{it} = 15 \cdot \frac{deg}{hr} \cdot t_{it} \qquad \text{(Eqn. 7)}$$

(5) Solar altitude (α) is equal to the angle the sun's rays make with the horizontal plane. If $t_{it} < t_s$, $\alpha = 0$, else:

$$\alpha = \sin^{-1}(\cos(L) \cdot \cos(\delta) \cdot \cos(ha_{it}) + \sin(L) \cdot \sin(\delta)) \qquad \text{(Eqn. 8)}$$

(6) Solar azimuth (φ or az) is equal to the sun's rays relative to the south.

$$\varphi = \cos^{-1}\left(\frac{\sin(\alpha) \cdot \sin(L) - \sin(\delta)}{\cos(\alpha) \cdot \cos(L)}\right) \cdot \frac{ha_{it}}{|ha_{it}|} \qquad \text{(Eqn. 9)}$$

(7) The angle of incidence (θ or I) represents the angle of the rays of the sun to the normal plane of the surface:

$$\cos(\theta) = \cos(\alpha) \cdot \cos(|\varphi - \psi|) \cdot \sin(\beta) + \sin(\alpha) \cdot \cos(\beta) \qquad \text{(Eqn. 10)}$$

$$\theta = \cos^{-1}\left(\frac{\cos(\theta) + |\cos(\theta)|}{2}\right) \qquad \text{(Eqn. 11)}$$

Where ψ are the surface azimuths and β are the tilt angles between the surface and the horizon.

(8) Given the site's direct solar radiation rate per area (W/m^2) per hour (I_{direct}), the incident beam radiation at a given surface is calculated as:

$$I_{beam} = I_{direct} \cdot (\cos(\theta)) \qquad \text{(Eqn. 12)}$$

(9) The instantaneous incident sky diffused radiation (I_{ds}), and instantaneous ground reflected radiation per hour (I_{dg}) is calculated using site diffuse solar radiation rate per area (W/m^2) ($I_{diffused}$).

$$I_{ds} = I_{diffused} \cdot \left(\frac{1 - \cos(\beta)}{2}\right) \qquad \text{(Eqn. 13)}$$

$$I_{dg} = I_{diffused} \cdot \rho_g \cdot \left(\frac{1 - \cos(\beta)}{2}\right) \qquad \text{(Eqn. 14)}$$

Where ρ_g is 0.8 when the status of snow on ground is 1, meaning there is snow on ground.

4.3.2. Modelling of Windows

The window can impact the indoor temperature of the home in three ways: the U-factor, the solar heat gain coefficient (SHGC), and the air leakage (U.S. Department of Energy, 2015). Three window types were evaluated (Table 17). The U-value and SHGC were obtained using WINDOWS 7.3 (U.S. Department of Energy, 2015). WINDOWS 7.3 gave the SHGC of the beam component as a function of its incident angle (θ). Equation (Eqn. 15) calculates the total energy transmitted through the window. It was assumed 30% of the solar gains are absorbed by the interior walls, and 70% are absorbed in the floors.

$$q_{window} = \left(SHGC_b \cdot I_{beam} + SHGC_{ds+dg} \cdot (I_{ds} + I_{dg})\right) \cdot Area_{window} \tag{Eqn. 15}$$

Table 17: U-Values and SGHCs for windows

Window Description	**U-Value (W/m^2*K)**	**SHGC (diffusion component)**	**SGHC (direct) where θ = incidence angle**
Low-E .6, argon filled, triple glazed window	0.894	0.439	(-1E-07 θ^2 + 0.0053 θ + 484)/1000
Low-E .6, argon filled, double glazed window	1.689	0.451	(-1E-07 θ^2 + 0.0068 θ + 554)/1000
Low-E .6, argon filled, double glazed window with suspended film	0.855	0.422	(-1E-07 θ^2 + 0.0052 θ + 458)/1000

4.4. Simple Model for Building Integrated Photovoltaic/Thermal Systems

Charron and Athienitis (2006) present a simple BIPV/T model for a roof to determine the capacity of the system. The author assumed the solar panels have 15% efficiency. The BIPV/T system is divided into five separate sections. The area of each section is $15m^2$ of which $9m^2$ are PV panels. This BIPV/T model calculated the inlet and outlet temperature of each section. The inlet temperature of the first section was assumed to be equal to the outdoor temperature, and the inlet temperature of the following section is equal to the outlet temperature of the previous section.

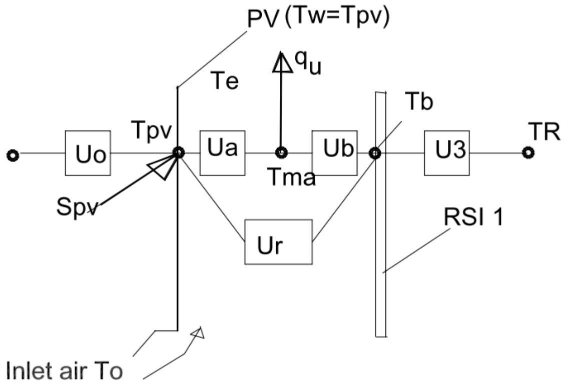

Figure 17: Thermal network model for a simple BIPV/T system (Charron & Athienitis, 2006)

Input data for air properties and the BIPV/T model are:

- Atmospheric pressure, p = 1 atm (101 325 pascal)
- Gas Constant, R_a= 287.08 J/Kg*K
- Density, $\rho = \frac{p}{R_a+(T_O+273.1)*K}$ (kg/m^3)
- Specific heat, c=1000 J/kg*°C
- Viscosity, $\upsilon = 17.6 * 10^{-6}$ (Kg/m*s)
- Conductivity, k=0.0247 watt/m*°C
- Dynamic viscosity, $\mu_{air} = 1.8 * 10^{-5}$ (Pa*s)

Below are the associated properties for the calculation of airflow rates:

- Thickness of channel, L_{pv}=0.04 m
- Width of channel, W_{pv}=15m
- Flow length of channel, H_{pv}=1m
- Surface area of first section (m^2), A_{pv}=15m^2
- Airspeed, V=0.5m/s
- Airflow rate, (M) = V*L*M (m$^{3/}$s)
- Efficiency of the panel (η_e), $\eta_e = 15 - 0.0002 * (T_{pv} - 25°C)$, (Eqn. 16)

To calculate temperatures of the panel (T_{pv}), the length of the air stream is divided into 10 points. The inlet temperature is point 1, and outlet temperature being the point 10. Outlet temperature from the previous section is the inlet temperature of the next section.

- $T_i = (T_1, T_2, T_3 \ldots T_{10})$ (°C)
- $T_{inlet\ air} = T_{10}\ from\ previous\ section$ (°C)

G is the incident solar radiation. The convective heat transfer coefficients (U_a, U_b, U_r) are calculated:

- Stefan–Boltzmann constant, $\sigma = 5.67 * 10^{-8}\ \frac{watts}{m^2 * K^4}$
- Mean temperature, $T_m = \frac{T_{PV}+T_O}{2} + 273$ (K)
- Radiative heat coefficient, $h_r = 4 * \sigma * T_m^3 * K^4\ (\frac{watts}{m^2 * C})$
- Convective coefficient at one side of the air cavity, assumed, $h = 7.094\ \frac{watts}{m^2 * C}$
- Exterior heat coefficient, $h_O = 7.094\ \frac{watts}{m^2 * C}$
- $U_r = A_{pv} * h_r$ (kgm^2 s^{-3})
- $U_a = A_{pv} * h = U_b$(kgm^2 s^{-3})

- $U_o = \mathrm{A}_{pv} * h_o$ (kgm^2 s^{-3})
- $a = \frac{M * C_a * \rho_a}{W * h}$ (m)

Charron and Athienitis (2006) used the following equations to calculate the mean flow air temperature (T_{ma}).

$$T_i = \frac{T_{PV}+T_b}{2} + \left[T_O - (\frac{T_{PV}+T_b}{2})\right] * e^{\frac{-X_i*2}{a}}\ (°C) \quad \text{(Eqn. 17)}$$

$$T_{ma} = \frac{\sum_i T_i}{11}\ (°C) \quad \text{(Eqn. 18)}$$

Values for T_b and T_{pv} are assumed ($T_b = 50°C$ and $T_{pv} = 64°C$) and the equations are solved until their solutions converge:

$$T_b = \frac{T_{ma}*U_b+T_R*U_3+T_{pv}*U_r}{U_b+U_3+U_r}\ (°C) \quad \text{(Eqn. 19)}$$

$$T_{PV} = \frac{T_o*U_o+T_{ma}*U_a+T_b*U_r+S_{pv}}{U_b+U_3+U_{br}}\ (°C) \quad \text{(Eqn. 20)}$$

The useful heat captured (q_u), total solar radiation absorbed (S_{total}), solar radiation converted to electricity ($E_{electric}$), and solar radiation converted to heat (S_{pv}) are calculated as outlined by Charron and Athienitis (2006):

$$q_u = M * C_a * \rho_a * (T_{10} - T_o)\ \text{(watts)} \quad \text{(Eqn. 21)}$$

$$S_{total} = a_w * A_{section} * G\ \text{(watts)} \quad \text{(Eqn. 22)}$$

$$E_{electric} = \eta_e * A_{pv} * G\ \text{(watts)} \quad \text{(Eqn. 23)}$$

$$S_{pv} = S_{total} - E_{electric}\ \text{(watts)} \quad \text{(Eqn. 24)}$$

4.5. Case Study

The reference home is single story with no basement, detached and rectangular. The dwelling has four occupants with a total floor area of 130m^2. The floor to ceiling height is 2.5m. The north and south facades measure 15m long, and the east and west facades measure 8.6m wide. The slope of the roof, window to floor ratio, and insulation levels are to vary (see Figure 18).

The following sets of assumptions were made for the simulation:

- Set point temperature is 21°C for heating and 27°C for cooling
- Night temperature is 18°C between 10 pm and 8 am when active heating is needed

- Radiations transmitting through windows are absorbed by the floor (70%) and interior walls (30%)

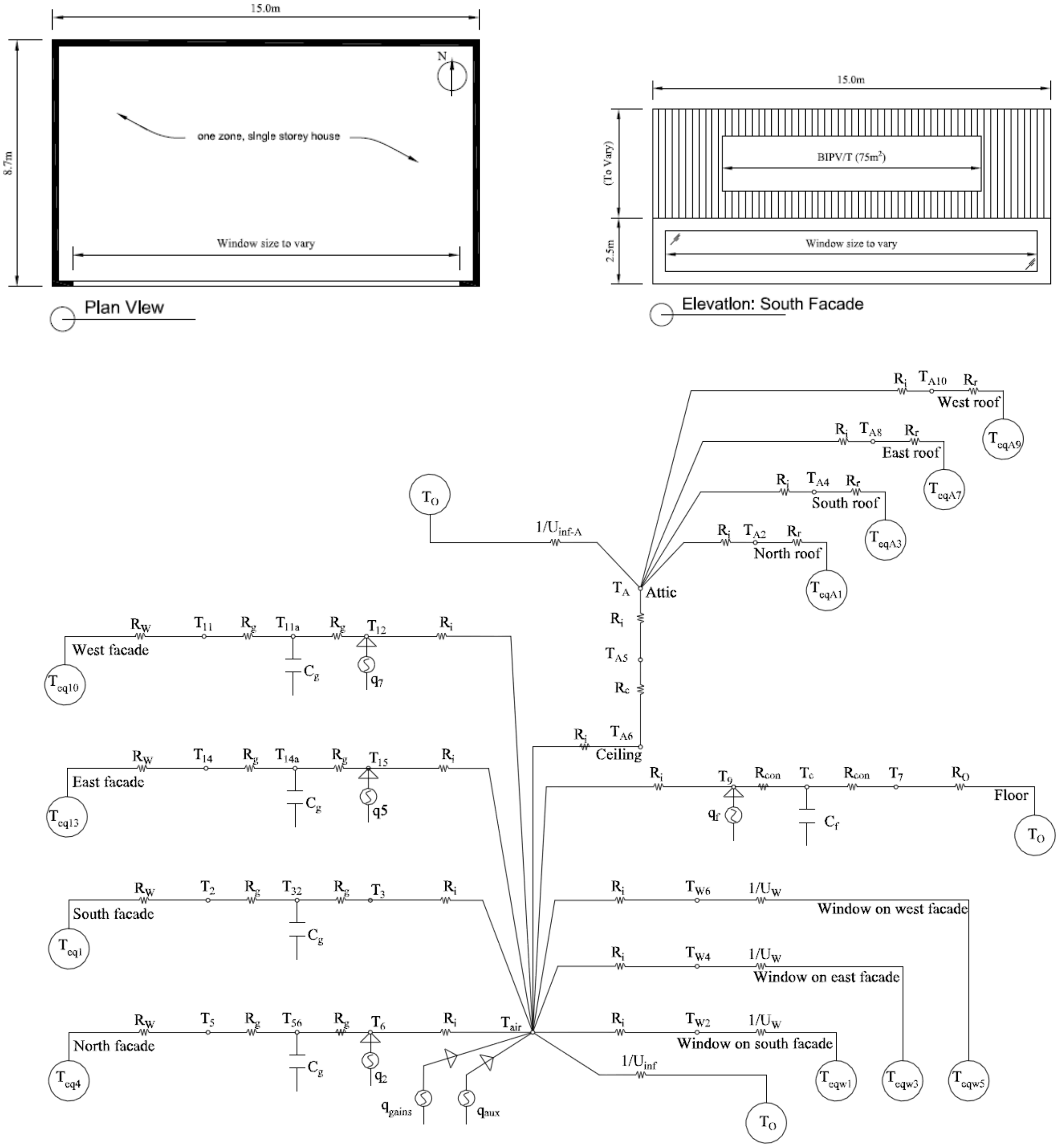

Figure 18: Plan view, elevation and thermal network model with a single control volume for the reference home

The simulation model used the following variables and constants:

- R_g, thermal resistance value (RSI) of half a gypsum board, 0.395m^2*C/watts

- R_{con}: thermal resistance value (RSI) of 5cm of concrete, 0.074m^2*C/watts
- R_w: thermal resistance value (RSI) of wall to vary, (m^2*C/watts)
- R_c: thermal resistance value (RSI) of ceiling to vary, (m^2*C/watts)
- R_r: thermal resistance value (RSI) of roof, 1.0 m^2*C/watts
- R_f: thermal resistance value (RSI) of floor to vary, (m^2*C/watts)
- U_w: U-value of the window (see Table 17)
- h_i: Interior convection transfer coefficient, 8.29 W/m^2K
- h_o: Interior convection transfer coefficient, 22 W/m^2K
- c_c: Specific heat of concrete, 800 Joules/Kg*C
- c_g: Specific heat of interior gypsum, 750 Joules/Kg*C
- c_f: Specific heat of engineered floor tiles 2492 Joules/Kg*C
- p_c: Density of concrete 2200 kg/m^3
- p_g: Density of gypsum 800 kg/m^3
- U_{inf}: Indoor air change U-value = $ACH*\rho_{air}*cp_{air}*V_{air}/3600$
- $U_{inf\text{-}a}$: Attic air change U-value = $ACH*\rho_{air}*cp_{air}*V_{atticair}/3600$
- ρ_f: Density of engineered floor tiles 571 kg/m^3
- C_s: Thermal capacitance of south wall to vary, (J/K)
- C_e: Thermal capacitance of east wall to vary, (J/K)
- C_f: Thermal capacitance of floor to vary, (J/K)
- C_w: Thermal capacitance of west wall to vary, (J/K)
- C_w: Thermal capacitance of west wall to vary, (J/K)

The following is a list of variables used in energy balance equations (see Figure 18):

- T_O: Outdoor air temperature ($°C$)
- T_R: Room air temperature ($°C$)
- Teq_x: Equivalent temperatures at the exterior surfaces of the home ($°C$)
- T_2 to T_{15}: Temperature at the the surface or interface of building assembly ($°C$)
- T_A: Attic air temperature ($°C$)
- T_{A2} to T_{A8}: Temperature of surface or interface of building assembly in attic ($°C$)
- T_{w1} to T_{w6}: Equivalent temperature of surface of window ($°C$)
- Q_{w1}, Q_{w5} and Q_{w5}: Solar radiation on gain through windows (watts/m^2)
- q_{gains}: Internal heat gains, 200-450 watts

- q_f: Heat gains on the floor, from solar radiation (watts)
- q_{aux}: Heating loads or cooling loads require to maintain set point temperature (watts)

4.6. Energy Balance Equation

The energy balance equation for room air is;

$$T_R^{p+1} = \frac{A}{B} \tag{Eqn. 25}$$

Where

$$\begin{aligned} A = \{ & Q_{gains} + Q_{aux} + h_i \\ & \cdot \left(T_3 \cdot A_{sw} + T_6 \cdot A_{nw} + T_9 \cdot A_f + T_{15} \cdot A_{ew} + T_{12} \cdot A_{ww} + T_{w2} \cdot A_{w1} \right. \\ & \left. + T_{w4} \cdot A_{w3} + T_{w6} \cdot A_{w5} + T_{A6} \cdot A_c\right) + T_o \cdot U_{inf} \} \end{aligned} \tag{Eqn. 26}$$

$$B = \left\{h_i \cdot \left(A_{sw} + A_{nw} + A_f + A_{ew} + A_{ww} + A_{w1} + A_{w3} + A_{w5} + A_c\right) + U_{inf}\right\} \tag{Eqn. 27}$$

$$Q_{aux} = K(21 - T_{R,unheated}^{p+1}) \qquad \& \qquad K = q_{max}/2 \tag{Eqn. 28}$$

K is a proportional constant (Athienitis, 2000) and q_{max} was calculated. The energy balance equations through the south facade are:

$$T_2^{P+1} = \frac{\left(T_{eq1} \cdot \frac{A_{sw}}{R_w} + T_{32} \cdot \frac{A_{sw}}{R_g}\right)}{\frac{A_{sw}}{R_w} + \frac{A_{sw}}{R_g}} \tag{Eqn. 29}$$

$$T_{32}^{p+1} = \frac{\Delta t}{C_s}\left((T_2 - T_{32}) \cdot \frac{A_{sw}}{R_g} + (T_3 - T_{32}) \cdot \frac{A_{sw}}{R_g}\right) + T_{32}^p \tag{Eqn. 30}$$

$$T_3^{P+1} = \frac{\left(T_{32} \cdot \frac{A_{sw}}{R_g} + T_R \cdot h_i \cdot A_{sw}\right)}{\frac{A_{sw}}{R_g} + h_i \cdot A_{sw}} \tag{Eqn. 31}$$

Energy balance equations through the north facade are:

$$T_5^{P+1} = \frac{\left(T_{eq4} \cdot \frac{A_{nw}}{R_w} + T_{32} \cdot \frac{A_{nw}}{R_g}\right)}{ar\frac{A_{nw}}{R_w} + \frac{A_{nw}}{R_g}} \tag{Eqn. 32}$$

$$T_{56}^{p+1} = \frac{\Delta t}{C_n}\left((T_5 - T_{56}) \cdot \frac{A_{nw}}{R_g} + (T_6 - T_{56}) \cdot \frac{A_{nw}}{R_g}\right) + T_{56}^p \tag{Eqn. 33}$$

$$T_6^{P+1} = \frac{\left(T_{56} \cdot \frac{A_{nw}}{R_g} + T_R \cdot h_i \cdot A_{nw}\right)}{\frac{A_{nw}}{R_g} + h_i \cdot A_{nw}} \tag{Eqn. 34}$$

Energy balance equations through the east facade are:

$$T_{14}^{P+1} = \frac{\left(T_{eq15} \cdot \frac{A_{ew}}{R_w} + T_{14a} \cdot \frac{A_{ew}}{R_g}\right)}{\frac{A_{ew}}{R_w} + \frac{A_{ew}}{R_g}} \tag{Eqn. 35}$$

$$T_{14a}^{p+1} = \frac{\Delta \mathrm{t}}{C_e}\left((T_{14} - T_{14a}) \cdot \frac{A_{ew}}{R_g} + (T_{15} - T_{14a}) \cdot \frac{A_{ew}}{R_g}\right) + T_{14a}^{p} \tag{Eqn. 36}$$

$$T_{15}^{P+1} = \frac{\left(T_{14a} \cdot \frac{A_{ew}}{R_g} + T_R \cdot h_i \cdot A_{ew}\right)}{\frac{A_{ew}}{R_g} + h_i \cdot A_{ew}} \tag{Eqn. 37}$$

Energy balance equations through the west facade are:

$$T_{11}^{P+1} = \frac{\left(T_{eq10} \cdot \frac{A_{ww}}{R_w} + T_{11a} \cdot \frac{A_{ww}}{R_g}\right)}{\frac{A_{ww}}{R_w} + \frac{A_{ww}}{R_g}} \tag{Eqn. 38}$$

$$T_{11a}^{p+1} = \frac{\Delta \mathrm{t}}{C_w}\left((T_{11} - T_{11a}) \cdot \frac{A_{ww}}{R_g} + (T_{12} - T_{11a}) \cdot \frac{A_{ww}}{R_g}\right) + T_{11a}^{p} \tag{Eqn. 39}$$

$$T_{12}^{P+1} = \frac{\left(T_{11a} \cdot \frac{A_{ww}}{R_g} + T_R \cdot h_i \cdot A_{ww}\right)}{\frac{A_{ww}}{R_g} + h_i \cdot A_{ww}} \tag{Eqn. 40}$$

Energy balance equations through the floor are:

$$T_7^{P+1} = \frac{\left(T_8 \cdot \frac{A_f}{R_f} + T_o \cdot h_o \cdot A_f\right)}{\frac{A_f}{R_f} + h_o \cdot A_f} \tag{Eqn. 41}$$

$$T_8^{P+1} = \frac{\left(T_7 \cdot \frac{A_f}{R_f} + T_{89} \cdot \frac{A_f}{R_{con}}\right)}{\frac{A_f}{R_f} + \frac{A_f}{R_{con}}} \tag{Eqn. 42}$$

$$T_{89}^{p+1} = \frac{\Delta \mathrm{t}}{C_{con}}\left((T_8 - T_{89}) \cdot \frac{A_f}{R_{con}} + (T_9 - T_{89}) \cdot \frac{A_f}{R_{con}}\right) + T_{89}^{p} \tag{Eqn. 43}$$

$$T_9^{P+1} = \frac{\left(T_{89} \cdot \frac{A_f}{R_{con}} + T_R \cdot h_i \cdot A_{ww}\right)}{\frac{A_{ww}}{R_{con}} + h_i \cdot A_{ww}} \tag{Eqn. 44}$$

Energy balance equations through the attic are:

$$T_{A4}^{P+1} = \frac{\left(T_{eqA3} \cdot \frac{A_{sr}}{R_r} + T_A \cdot h_i \cdot A_{sr}\right)}{\frac{A_{sr}}{R_r} + h_i \cdot A_{sr}} \tag{Eqn. 45}$$

$$T_{A2}^{P+1} = \frac{\left(T_{eqA1} \cdot \frac{A_{nr}}{R_r} + T_A \cdot h_i \cdot A_{nr}\right)}{\frac{A_{nr}}{R_r} + h_i \cdot A_{nr}} \tag{Eqn. 46}$$

$$T_{A10}^{P+1} = \frac{\left(T_{eqA9} \cdot \frac{A_{wr}}{R_r} + T_A \cdot h_i \cdot A_{wr}\right)}{\frac{A_{wr}}{R_r} + h_i \cdot A_{wr}} \tag{Eqn. 47}$$

$$T_{A8}^{P+1} = \frac{\left(T_{eqA7} \cdot \frac{A_{er}}{R_r} + T_A \cdot h_i \cdot A_{er}\right)}{\frac{A_{er}}{R_r} + h_i \cdot A_{er}} \tag{Eqn. 48}$$

$$T_{A5}^{P+1} = \frac{\left(T_{A6} \cdot \frac{A_c}{R_c} + T_A \cdot h_i \cdot A_c\right)}{\frac{A_c}{R_c} + h_i \cdot A_c} \tag{Eqn. 49}$$

$$T_{A6}^{P+1} = \frac{\left(T_{A5} \cdot \frac{A_c}{R_c} + T_R \cdot h_i \cdot A_c\right)}{\frac{A_c}{R_c} + h_i \cdot A_c} \tag{Eqn. 50}$$

$$T_A^{P+1} = \frac{h_i \cdot (A_{nr} \cdot T_{A2} + A_{sr} \cdot T_{A4} + A_{wr} \cdot T_{A10} + A_{er} \cdot T_{A18} + T_{A5} \cdot A_c) + T_o \cdot U_{infA}}{A_{sr} \cdot h_i + A_{nr} \cdot h_i + A_{er} \cdot h_i + A_{wr} \cdot h_i + A_c \cdot h_i + U_{infA}} \tag{Eqn. 51}$$

Energy balance equations through the windows are:

$$T_{w2}^{P+1} = \frac{(T_{w1} \cdot U_w \cdot A_{w1} + T_R \cdot h_i \cdot A_{w1})}{U_w \cdot A_{w1} + h_i \cdot A_{w1}} \tag{Eqn. 52}$$

$$T_{w4}^{P+1} = \frac{(T_{w3} \cdot U_w \cdot A_{w3} + T_R \cdot h_i \cdot A_{w3})}{U_w \cdot A_{w3} + h_i \cdot A_{w3}} \tag{Eqn. 53}$$

$$T_{w6}^{P+1} = \frac{(T_{w5} \cdot U_w \cdot A_{w5} + T_R \cdot h_i \cdot A_{w5})}{U_w \cdot A_{w5} + h_i \cdot A_{w5}} \tag{Eqn. 54}$$

4.6.1. Number of Control Volumes

The author determined needed accurancy of model by studying the number of control volumes placed in the floor. The model was simulated with a single thermal capacitance, two thermal capacitances, and four thermal capacitances in the floor. Energy balance equations for two control volumes for the floor's equation are as follows:

$$T_7^{P+1} = \frac{\left(T_8 \cdot \frac{A_f}{R_f} + T_o \cdot h_o \cdot A_f\right)}{\frac{A_f}{R_f} + h_o \cdot A_f} \qquad \text{(Eqn. 55)}$$

$$T_8^{P+1} = \frac{\left(T_7 \cdot \frac{A_f}{R_f} + T_{89A} \cdot \frac{A_f}{R_{con}}\right)}{\frac{A_f}{R_f} + \frac{A_f}{R_{con}}} \qquad \text{(Eqn. 56)}$$

$$T_{89A}^{p+1} = \frac{\Delta \mathrm{t}}{(C_{con})}\left((T_8 - T_{89A}) \cdot \frac{A_f}{R_{con}} + (T_9 - T_{89A}) \cdot \frac{A_f}{R_{con}}\right) + T_{89A}^{p} \qquad \text{(Eqn. 57)}$$

$$T_{89B}^{p+1} = \frac{\Delta \mathrm{t}}{(C_{con})}\left((T_{89A} - T_{89B}) \cdot \frac{A_f}{R_{con}} + (T_{89A} - T_{89B}) \cdot \frac{A_f}{R_{con}}\right) + T_{89B}^{p} \qquad \text{(Eqn. 58)}$$

$$T_9^{P+1} = \frac{\left(T_{89B} \cdot \frac{A_f}{R_{con}} + T_R \cdot h_i \cdot A_{ww}\right)}{\frac{A_{ww}}{R_{con}} + h_i \cdot A_{ww}} \qquad \text{(Eqn. 59)}$$

Energy balance equations for four control volumes are as follows:

$$T_7^{P+1} = \frac{\left(T_8 \cdot \frac{A_f}{R_f} + T_o \cdot h_o \cdot A_f\right)}{\frac{A_f}{R_f} + h_o \cdot A_f} \qquad \text{(Eqn. 60)}$$

$$T_8^{P+1} = \frac{\left(T_7 \cdot \frac{A_f}{R_f} + T_{89A} \cdot \frac{A_f}{R_{con}}\right)}{\frac{A_f}{R_f} + \frac{A_f}{R_{con}}} \qquad \text{(Eqn. 61)}$$

$$T_{89A}^{p+1} = \frac{\Delta \mathrm{t}}{(C_{con})}\left((T_8 - T_{89A}) \cdot \frac{A_f}{R_{con}} + (T_9 - T_{89A}) \cdot \frac{A_f}{R_{con}}\right) + T_{89A}^{p} \qquad \text{(Eqn. 62)}$$

$$T_{89B}^{p+1} = \frac{\Delta \mathrm{t}}{(C_{con})}\left((T_{89A} - T_{89B}) \cdot \frac{A_f}{R_{con}} + (T_{89A} - T_{89B}) \cdot \frac{A_f}{R_{con}}\right) + T_{89B}^{p} \qquad \text{(Eqn. 63)}$$

$$T_{89C}^{p+1} = \frac{\Delta \mathrm{t}}{(C_{con})}\left((T_{89B} - T_{89C}) \cdot \frac{A_f}{R_{con}} + (T_{89B} - T_{89C}) \cdot \frac{A_f}{R_{con}}\right) + T_{89C}^{p} \qquad \text{(Eqn. 64)}$$

$$T_{89D}^{p+1} = \frac{\Delta t}{(C_{con})}\left((T_{89C} - T_{89D}) \cdot \frac{A_f}{R_{con}} + (T_{89C} - T_{89D}) \cdot \frac{A_f}{R_{con}}\right) + T_{89D}^{p} \qquad \text{(Eqn. 65)}$$

$$T_9^{P+1} = \frac{\left(T_{89D} \cdot \frac{A_f}{R_{con}} + T_R \cdot h_i \cdot A_{ww}\right)}{\frac{A_{ww}}{R_{con}} + h_i \cdot A_{ww}} \qquad \text{(Eqn. 66)}$$

4.7. Limitations of the Study

The aim of this study is to optimize selected key solar and design parameters and show that the consideration of these parameters can have a significant effect on energy consumption. The reference home was modelled based on historical weather data of Yellowknife, Northwest Territories. However, as the North shares similar weather, the conclusions of this study should hold true for the region.

Variables such as the floor area, number of floors, type of housing, number of occupants, and orientation of the building were based on a standard new home in Yellowknife. A single profile was assumed for occupant behavior such as temperature settings for the day and night. However, the behavioral habits of many northerners may differ from the assumptions made for this study.

Also, the building surroundings such as trees and other structures that may obstruct the solar radiation are not considering in our model. Moreover, the lot size and location can restrict orientation of the home due south.

Finally, the explicit (forward) finite difference method of the basic one-dimensional transient conduction equation is a simplified model, though the model is accurate enough for the purpose of this study.

The conclusion of this research shows that solar strategies and optimization of design parameter can significantly reduce energy consumption in northern homes. Moreover, this thesis recommends specific values and ranges for solar strategies and design parameter; however, builders should keep in mind the limitation of this study. The builder should consider the solar strategies outlined in this research, but also do energy modelling for their home to benchmark optimal values for each solar strategy and design parameter.

4.8. Results and Discussions

The author investigated the reference home's indoor air temperatures with different control volumes. The number of control volumes made the most impact on days with higher solar radiation. As shown in Figure 19a, on June 18th, the maximum difference between 4 thermal capacitances and 1 thermal capacitance is 3°C.

With 4 thermal capacitances, the total annual cooling load was reduced by 21.8% compared to the home simulated with only a single thermal capacitance and the total energy consumption for the year was reduced by 1.8%. Because of the effect of 4 control volumes on the accuracy of the model, simulations were done with 4 control volumes. The researcher felt this accuracy level was sufficient for the purpose of this parametric study.

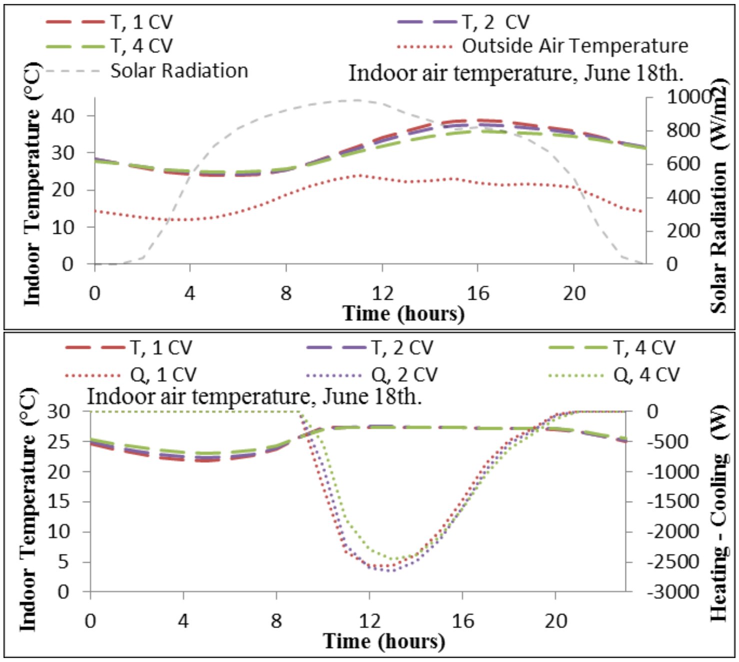

Figure 19: Passive response (top) and active response (bottom) for different control volumes for June 18th

Table 18: Total daily and annual cooling consumption for different control volumes

	Total cooling loads for June 18th (kWh) (Walls)	Total annual cooling (kWh/m^2) / brackets show % reduction from the reference case (1 CV.)	Total annual heating load (kWh/m^2) / brackets show % reduction from the reference case (1 CV.)
1 CV	16	-6.4 (0 %)	130.2 (0 %)
2 CV	17	-5.8 (9.3%)	129.4 (0.6%)
4 CV	15	-5.0 (21.8%)	127.9 (1.8%)

Table 19 presents the parameters studied, values for reference house and parameter ranges studied. Analyses were done on four different days (Figure 20) with different temperature and solar radiation conditions for Yellowknife.

The graphs presented in this section show the passive response of the home (without active heating or cooling), and the active response of the home (with active heating and cooling). The passive response graphs show indoor air temperature (°C), total solar radiation (watts/m^2) incident to the home and outdoor temperatures (°C). The active response graphs show indoor air temperature (°C), along with the heating or cooling profile (watts.)

For each parameter studied, the graph shows the performance of the reference home to that of one or two different cases to show how the parameter values affect air temperatures and energy consumption.

Table 19: Parameters studied, values for reference house and parameter ranges studied

Parameters	Reference House	Parameter Ranges Studied
Thermal resistance values: for walls	RSI 4.26	RSI 1 to RSI 10, increments of RSI 1.
for ceilings	RSI 5.57	
for floors	RSI 6	
Thermal mass	6mm wood tiles on floor, and 1 layer of gypsum on walls.	Case 1: 6mm wood floor, 1 layer of gypsum. Case 2: 6mm wood floor, 2 layers of gypsum. Case 3: 12mm wood floor, 2 layers of gypsum Case 4: 5cm concrete, 1 layer of gypsum Case 5: 10cm concrete, 1 layer of gypsum Case 6: 10cm concrete, 2 layers of gypsum
Windows	Triple glazed. Low-E, argon-filled	Triple glazed. Low-e, argon filled Double glazed, Low-e, argon filled Double glazed, suspended film, Low-e, argon filled
Window-wall ratio (WWR, south façade)	20%	0% to 80%.
Night shutters	No night shutters	Night shutters with RSI 1 to RSI 4, with increments of RSI 1.
Shading schedule	None	Blocks 90% of solar radiation when indoor air temperature > 26.5°C.
Ventilation rates	0.3 ACH rate	0.3 ACH and ACH 1.0 when indoor air temperature > 26.5°C.
BIPV/T systems	None	BIPV/T system with efficiency of PV panels are15% on roof with slope of roof ranging from 5°to 90°.

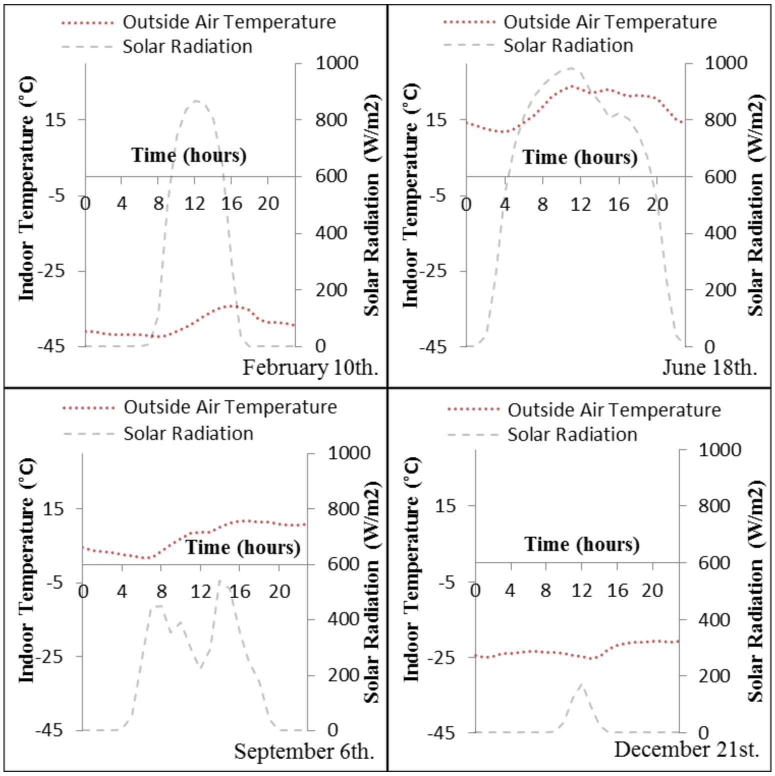

Figure 20: Yellowknife's outdoor air temperature and solar radiation (U.S. Department of Energy, 2015)

4.8.1. Thermal Resistance values

The higher the thermal resistance values of a building assembly, the higher the indoor air temperatures. However, these temperature differences minimize with increased solar radiation as the home receives equal amounts of solar heat gains. Also, the rate of temperature increases reduces as the thermal resistance values increase Figure 21. Simulation results show that increasing the floor's thermal resistance value had the biggest impact. On February 10th, the need for heating decreases as thermal resistance of the walls increases (Figure 22).

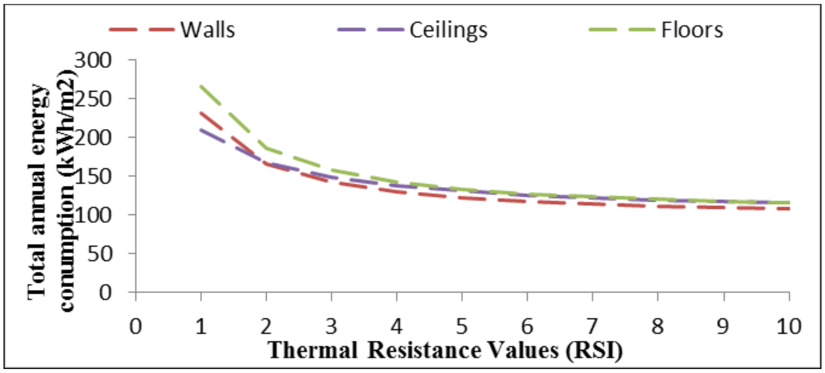

Figure 21: Total annual energy consumption as a function of thermal resistance values

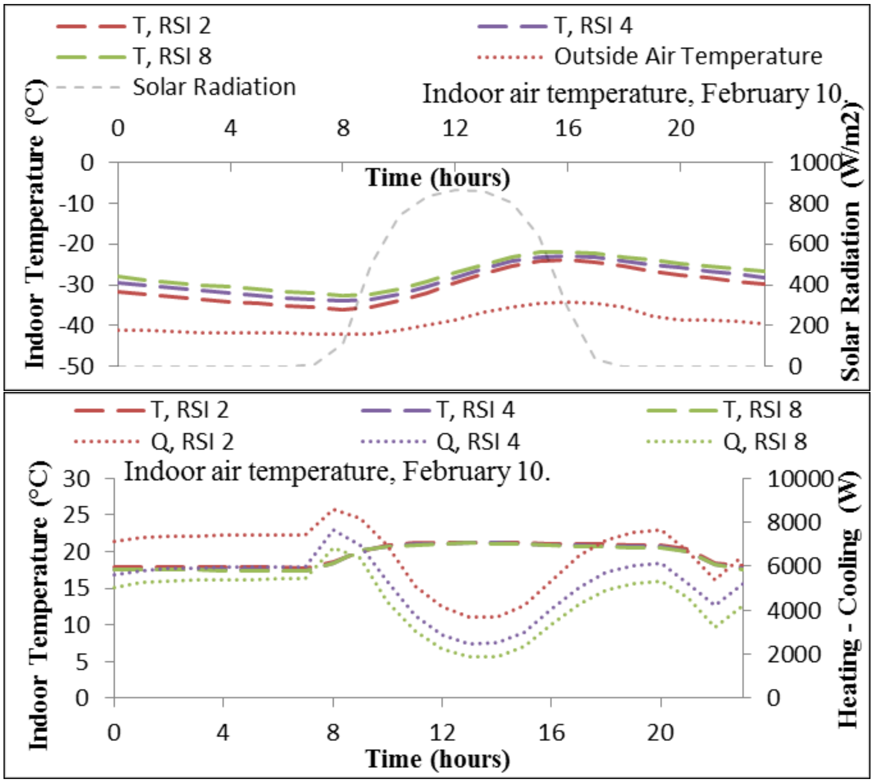

Figure 22: Passive response (top) and active response (bottom) for different thermal resistance values

4.8.2. Thermal Mass

The author considered six different case studies to investigate the effect of thermal mass on indoor air temperatures (see Table 19). As the model increased the thermal mass in the floor, the indoor air temperatures fluctuated less. For a cold day with some solar radiation, like for February 10th and September 6th, indoor air temperatures at its peak is 6°C higher for case 5 (10cm concrete on floor) compared to the reference case (6mm wood floor, 1 layer of gypsum). During the day, more heating was needed for case 5 as some of the solar heat gains are stored in the thermal mass. However, less heating was required for the day as this stored heat was available to heat the home at night (see Figure 23 and Figure 25).

In the summer, thermal mass reduced overheating. For June 18th, indoor air temperatures for the reference case reach 36°C. By adding 10cm concrete, the peak temperature drops to 27°C. There is no need for active cooling with 10cm concrete, while 15.3kWh was required for cooling the day for the reference case (see Table 20).

Table 20: Total daily heating or cooling consumption

	Total heating for February 10th (kWh) / In brackets, energy reduction compared to reference house (%)	Total cooling for June 18th (kWh) / In brackets, energy reduction compared to reference house (%)	Total heating for September 6th (kWh) / In brackets, energy reduction compared to reference house (%)	Total heating for December 21st (kWh) / In brackets, energy reduction compared to reference house (%)
Case 1: Reference house: 6mm wood floor, 1 layer of gypsum.	120.9	15.3	11.7 (0)	99 (0)
Case 2: 6mm wood floor, 2 layer of gypsum.	120.1 (0.7)	15.6 (-2.0)	11.7 (0)	98 (1.3)
Case 3: 12mm wood floor, 2 layer of gypsum	119.4 (1.2)	14.6 (4.5)	10.4 (11.1)	97 (1.4)
Case 4: 5cm concrete, 1 layer of gypsum	120.8 (0.1)	0.7 (95.5)	9.3 (20.5)	101 (-1.5)
Case 5: 10cm concrete, 1 layer of gypsum	118.1 (2.3)	0 (100)	9.5 (18.8)	99 (-.04)
Case 6: 10cm concrete, 2 layer of gypsum	117.7 (2.6)	0 (100)	9.5 (18.8)	101 (-1.7)

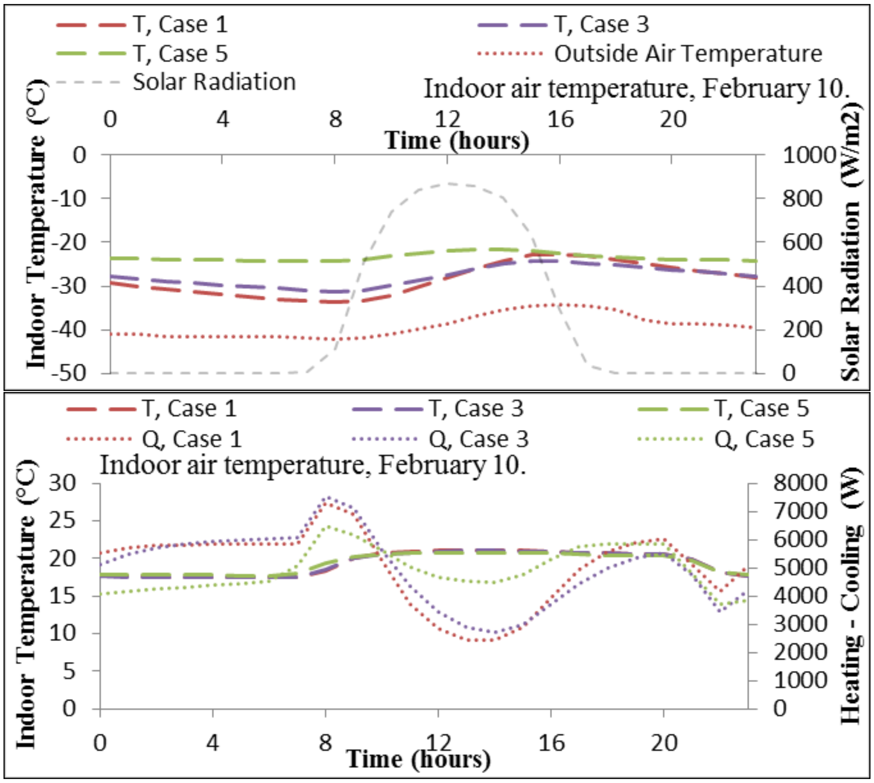

Figure 23: Passive response (top) and active response (bottom) for different thermal mass cases for February 10th

Table 21: Total annual heating and cooling consumptions

	Total annual heating (kWh/m^2)	Total annual cooling (kWh/m^2)	Total annual energy use (kWh/m^2)	Annual energy reduction from reference house (%)
Case 1: Reference house: 6mm wood floor, 1 layer of gypsum.	122.9	-5.0	127.9	
Case 2: 6mm wood floor, 2 layer of gypsum.	122.0	-4.6	126.7	1.0
Case 3: 12mm wood floor, 2 layer of gypsum	121.0	-3.7	124.7	2.5
Case 4: 5cm concrete, 1 layer of gypsum	121.9	-2.1	124.0	3.1
Case 5: 10cm concrete, 1 layer of gypsum	122.4	-1.8	124.2	2.9
Case 6: 10cm concrete, 2 layer of gypsum	121.5	-1.8	123.3	3.6

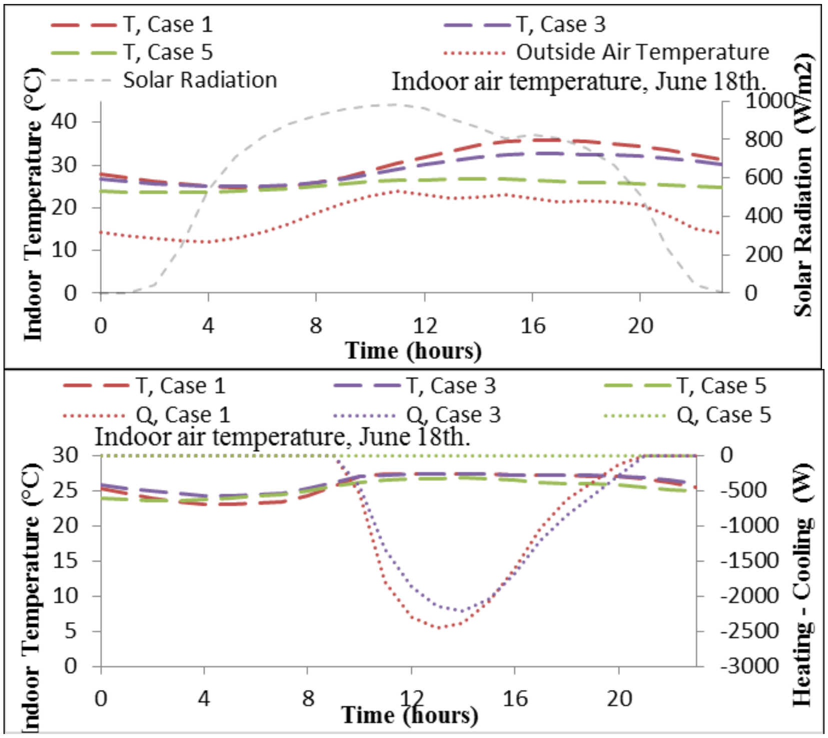

Figure 24: Passive response (top) and active response (bottom) for different thermal mass cases for June 18th

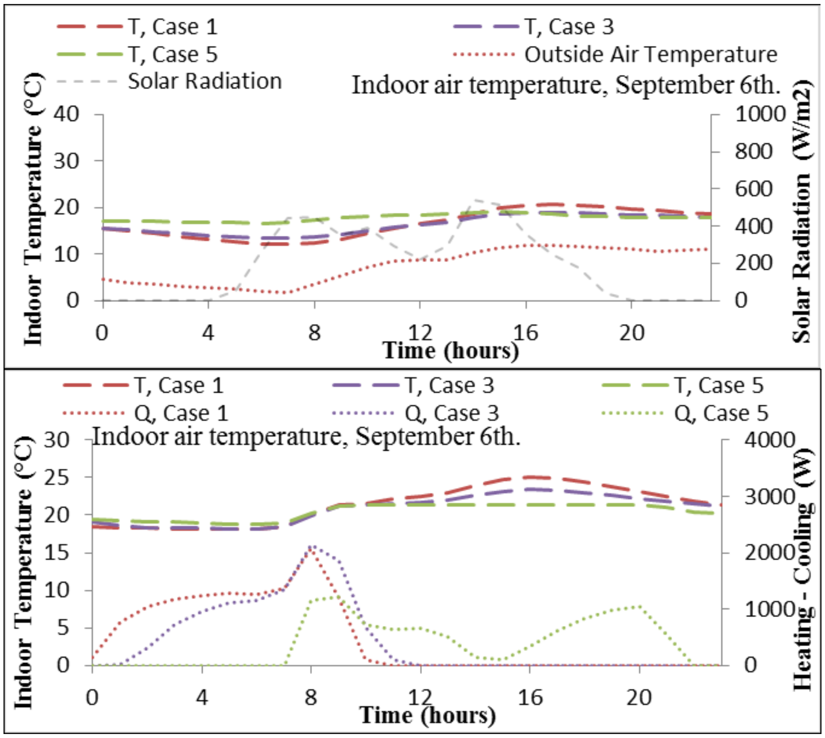

Figure 25: Passive response (top) and active response (bottom) for different thermal mass cases for September 6th

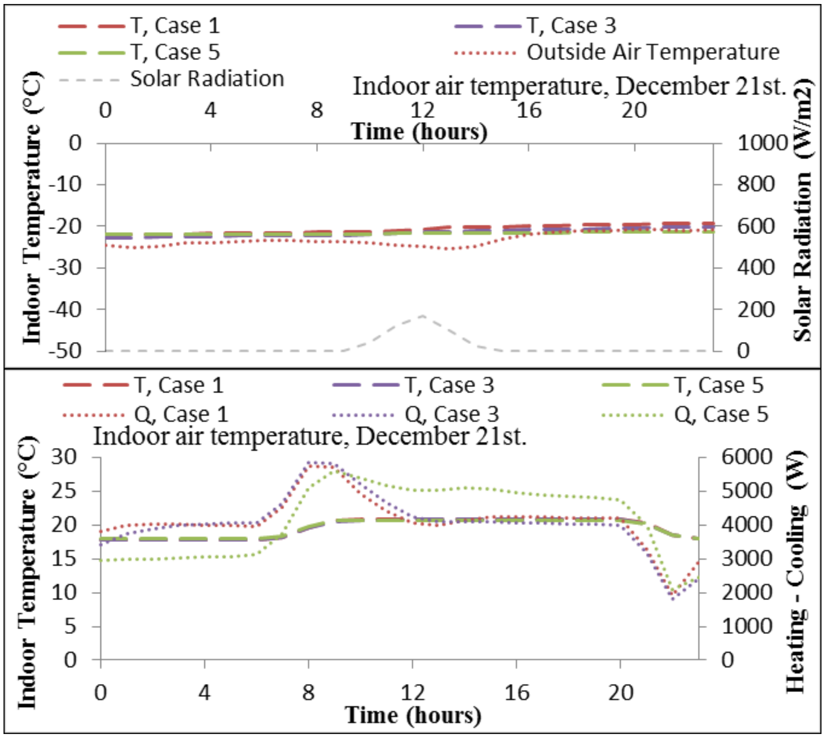

Figure 26: Passive response (top) and active response (bottom) for different thermal mass cases for December 21st

Thermal mass had a positive effect during the shoulder seasons (September) and the summer months (see Table 20). It significantly reduced cooling loads in the North and decreased the heating loads for February and September when there was some solar radiation. Increased thermal mass did not have an effect on the heating loads for December 21st (see Table 20 and Figure 26).

From Table 21, by adding 5cm concrete to the floor (case 4,) the annual energy consumption was reduced by 3.1%. Most of these savings came from the reduced cooling loads, which was reduced by 60% for the year. Also, overheating is an issue for northern homes. Thermal mass can make homes more comfortable in the summer months and help to make homes more energy efficient.

4.8.3. Night Window Shutters

Windows have low R-values. Night shutters can add a layer of insulation to windows when daylighting is not required. However, night window shutters are rarely considered in the North as the shutters need to work without freezing in the winter. This simulation studied night window shutters rated RSI 2 to see their impact on the energy consumption of the reference house.

The window shutter's schedule followed the sunshine hours for Yellowknife (Figure 1.) In January, the night window shutter is active for all but 2 hours. In March, the night window shutter is on for all but 6 hours.

In February, with outdoor temperatures at -42°C, using the night window shutters raised indoor temperatures without active heating by 0.5°C. Overall, the heating systems needed 150 watts hour more to heat a home without the window shutters (Figure 27). Window night shutters reduced daily energy consumption for February 10th by 3.3% and decreased the yearly energy use by 3.5% (Table 22).

Table 22: Heating consumption for the day with and without night shutters

	Total heating required for February 10th (kWh)	Total energy reduction compared to reference house for February 10th (%)	Total annual energy consumption (kWh/m^2)	Annual energy reduction compared to reference house (%)
Reference house (Without Night Shutters)	120.9	0	127.9	0
With Night Shutters (+ 2 RSI)	116.9	3.3%	123.5	3.5

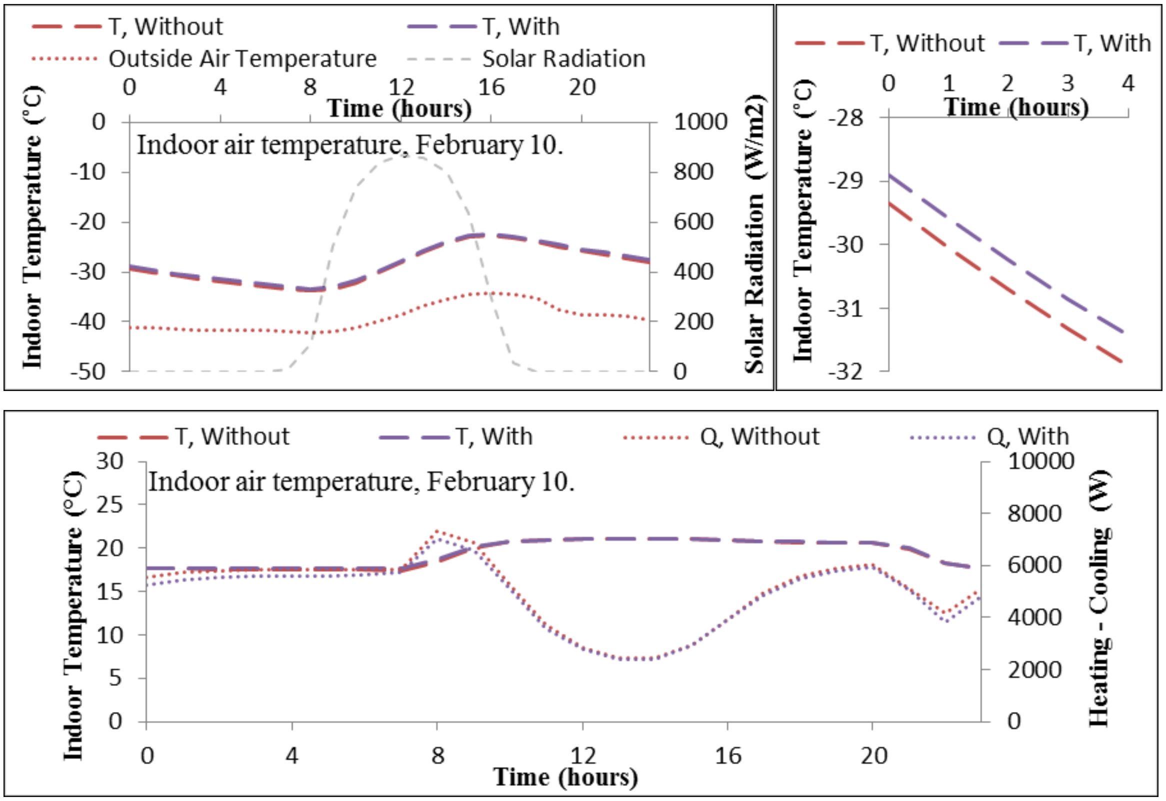

Figure 27: Passive response (top) and active response (bottom) with and without night shutters for February 10th

4.8.4. Strategies to avoid overheating

Cooling represents about 4% of total space conditioning's energy consumption – to further reduce consumption, the author implemented a shading schedule, and increased the ventilation rates.

When indoor temperatures were higher than 26.5°C, an interior window shade reduced 90% of solar radiation transmitted into the house. Most of the overheating happen during the summer month due to heat gain from solar radiation.

Similarly, when the indoor air temperature was higher than 26.5°C, the ventilation was increased to 2.0 ACH from 0.3 ACH to simulate occupants opening the windows. Table 23 shows the total cooling loads for these strategies. By implementing both strategies, annual cooling loads can be reduced by 70%.

Table 23: Daily and annual cooling loads for different strategies to reduce overheating

	Cooling requirement for June 18th (kWh)	Annual cooling requirement (kWh/m^2)	Annual cooling load reduced compared to reference house (%)
Reference House	-15.3	-5.0	0
Shading Schedule	-9.6	-2.8	43.7
Increase ventilation to 2.0 ACH (with no shading)	-10.6	-2.9	42.5
Shading with increased ventilation	-4.5	-1.5	70%

4.8.5. Window Wall Ratio

Glazing in the building envelope lowers the overall thermal resistance of the wall but allow for views, daylighting and heat gains from solar radiation. A walkthrough survey of Yellowknife and the builders' interview showed that the view and the cost governed window sizes and their placements. The author studied different WWR while including the strategies to reduce overheating outlined in section 4.8.4.

For cold days, higher window wall ratio on the south façade decreases the heating loads when there is some solar radiation (Figure 28). For February 10th, indoor air temperatures without active heating were increased by 20°C when the WWR was increased from 10% to 70% and no heating was required with 70% WWR between 1 pm to 3 pm (Figure 28b). Using a window blind and increasing the ventilation rate show that WWR can be increased without overheating (Figure 29).

In December, as there is little to no solar radiation, there is greater heat loss through the window than heat gained from solar radiation. In Figure 30, more heating is needed with higher WWR. However, annually, higher WWR decreased the energy consumption of homes. The reference house had a 20% WWR. Increasing the ratio to 70% reduced the total annual energy consumption by 19% (Table 26).

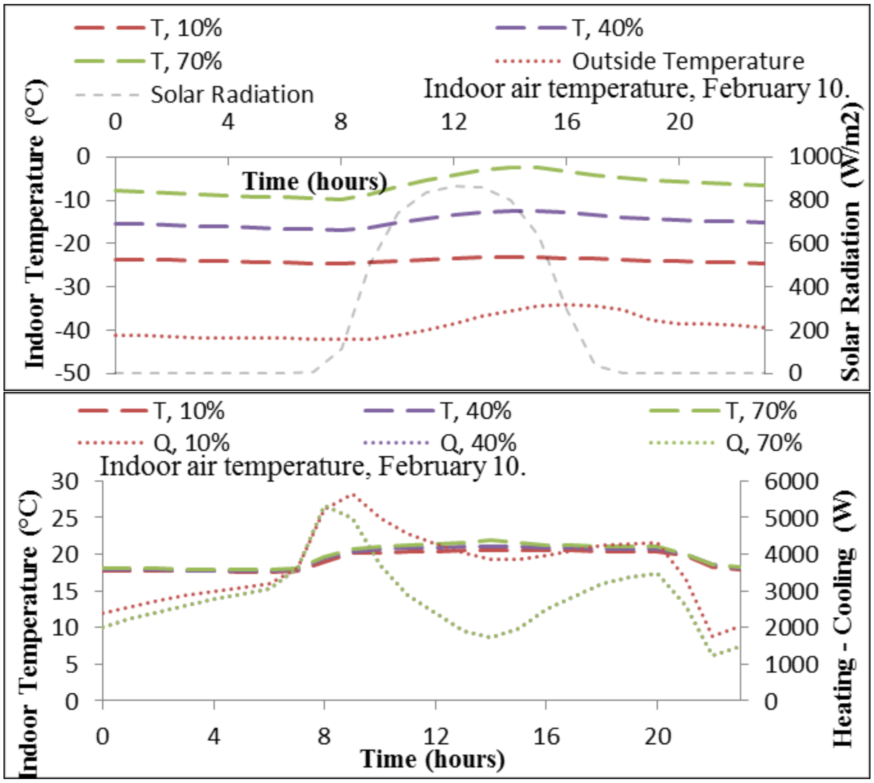

Figure 28: Passive response (top) and active response (bottom) for different WWR for February 10th

Table 24: Total daily heating loads for different window-wall ratios for February 10th

WWR on South Façade (%)	Total Qheating for February 10th (kWh)	WWR on South Façade (%)	Total Qheating for February 10th (kWh)
5%	92	50%	62
10%	88	60%	57
20%	81	70%	50
30%	74	75%	47
40%	67	80%	46

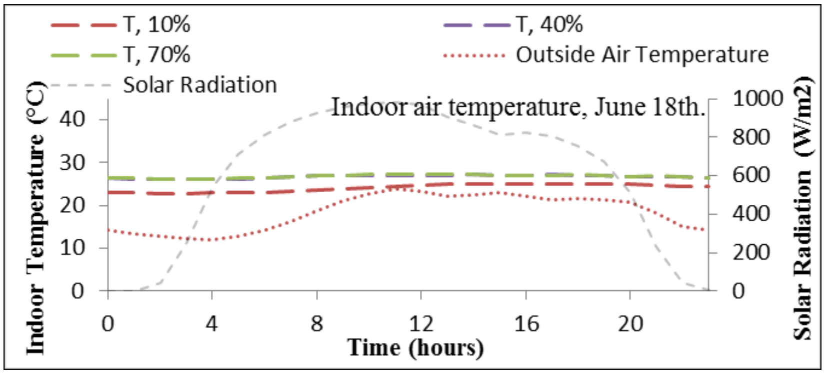

Figure 29: Passive response for different window-wall ratios for June 18th

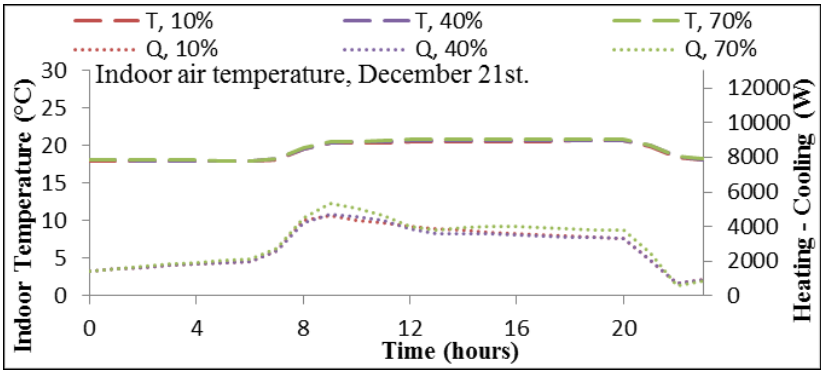

Figure 30: Active response for different window-wall ratios for Decembr 21st

Table 25: Total heating loads for different window-wall ratios for December 21st

WWR on South Façade (%)	Total Qheating for December 21st (kWh)	WWR on South Façade (%)	Total Qheating for December 21st (kWh)
5%	69	50%	70
10%	69	60%	71
20%	69	70%	74
30.0%	69	75%	71
40%	68	80%	72

Table 26: Annual heating, cooling, and total energy consumption for different window-wall ratios

WWR on South Façade (%)	Total annual Qheating (kWh/m^2)	Total annual Qcooling (kWh/m^2)	Total heating and cooling, Qtotal (kWh/m^2)	% difference from 20% WWR (reference)
5%	92.3	0.0	92.3	-15.1%
10%	87.8	-0.1	87.9	-9.6%
20%	79.71	-0.47	80.18	0.0%
30.0%	72.6	-1.1	73.70	8.1%
40%	66.7	-2.1	68.8	14.1%
50%	63.8	-3.6	67.4	15.9%
60%	60.5	-5.3	65.9	17.9%
70%	57.8	-7.4	65.2	18.7%
75%	56.7	-8.6	65.2	18.6%
80%	55.8	-9.8	65.6	18.2%

4.8.1. Window Types

The properties of a window, such as the U-value, solar heat gain coefficient (SHGC) and air leakage rate have an effect on the energy consumption of the home. Three window types with different U-values and SHGCs were studied for northern homes.

The triple glazed window and the double glazed window with suspended film performed better on colder days like February 10th – these windows had lower U-value. Double glazed windows had highest SGHC and required higher cooling for a hot day like June 18th (see Table 27). Overall, triple glazed window had the lowest annual energy consumption, but double glazed windows with suspended film performed similarly.

Table 27: Window types, window properties and total daily and annual energy consumptions

	U-value (W/m^2*K)	Average SHGC (direct component)	Total heating load for 70% WWR for February 10th (kWh/m^2)	Total cooling load for 70% WWR for June 18th (kWh/m^2)	Annual energy consumption for 70% WWR (kWh/m^2)
TG	0.894	0.433	50	19	65.2
DG	1.689	0.515	83	22	76.5
DG +SF	0.855	0.417	53	17	65.3

Note: TG is triple glazed, Low-E, argon-filled windows, DG is double glazed, Low-E, argon-filled windows, and DG +SF is double glazed, Low-E, argon-filled window with suspended film

4.8.2. BIPV/T System

Northern governments are pushing for renewable energy to displace fossil fuel use in response to the higher cost of fuel and climate change (Government of Nunavut, 2007a). Researcher modelled a $75m^2$ BIPV/T system placed on the south-facing roof. The PV panels in this system had an efficiency of 15% and occupied 60% of the BIPV/T surface area. The researcher calculated the total annual thermal and electricity energy generated (see Table 28). If the roof was sloped 55° towards the South, the BIPV/T system can produce 304.4 kWh/m^2 of thermal energy and 80.4kWh/m^2 of electric energy for the year.

Table 28: Thermal and electric energy generated (kWh/m^2) for different slopes for BIPV/T system

Slope of Roof (BIPV/T)	Total annual thermal energy generated (kWh/m^2)	Total annual electric energy generated (kWh/m^2)
10°	268.8	68.2
20°	281.3	73.3
30°	291.7	77.1
40°	299.7	79.6
50°	304.0	80.5
55°	304.4	80.4
60°	303.5	79.9
70°	303.5	79.9
70°	299	77.9
90°	276	69.7

4.8.3. Optimized Northern House

The reference home used 127.9kWh/m^2 for space heating and cooling– a similar house modelled in HOT2000 used 132.8kWh/m^2 –the author obtained this data from the ERS database. The optimized home, using the recommended values outlined in

Table 29 for the key design parameters, needed 65.2kWh/m^2 of energy, 49% more energy efficient compared to the reference home.

By adopting the recommended values for design parameters, indoor air temperature, without auxiliary heating, increased by at least 25°C for February 10th (Figure 31) and by at least 6°C for September 6th (Figure 32).

The home used only 3.3kWh/m^2 of the useful heat generated from the BIPV/T system to heat the home because most of the energy generated were from the summer months when heating was not needed. However, generated thermal and electric energy can go towards other systems such as the DHW system and electrical appliances. The BIPV/T system modelled produced 304.4 kWh/m^2 of thermal energy and 80.4kWh/m^2 of electric energy for the year.

Table 29: Key design parameters studied, their values for the reference house and recommended/optimized values

Key design parameters	Reference house	Optimized/recommended valued
Thermal resistance values for walls	RSI 4.26	RSI 8
Thermal resistance values for ceilings	RSI 5.57	RSI 9
Thermal resistance values for floors	RSI 6	RSI 9
Thermal mass	6mm wood tiles on floor, and 1 layer of gypsum on walls	5cm Concrete, 1 layer of gypsum
Windows	Triple glazed. Low-E, argon-filled	Triple glazed. Low-E, argon-filled
Window wall ratio (WWR, south façade)	20% (This value is assumed.)	70%
Window night shutters	No night shutters	Night shutters with RSI 2
BIPV/T systems	None	BIPV/T system with an efficiency of 15% for the PV panels.
Shading schedules	None	Blocks 90% of solar radiation when indoor air temperature > 26.5°C.
Ventilation rates	0.3 ACH rate	0.3 ACH and 1.0 when indoor air temperature > 26.5°C.

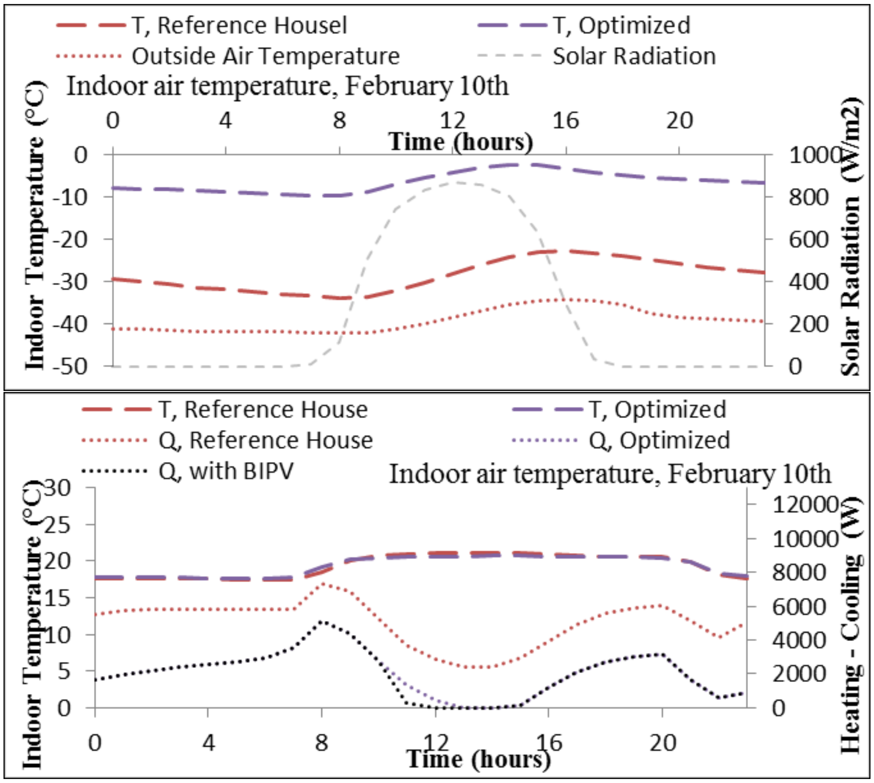

Figure 31: Passive response (top) and active response (bottom) comparing reference house to optimized house for February 10th

Table 30: Total daily energy consumption for reference house and optimized house

	Qheating (kWh) for February 10th	Qheating (kWh) for September 6th
Reference home (typical Yellowknife Home)	120.9	11.7
Optimized House without Thermal Energy from BIPV/T System	49.6	0.0
Optimized House with Thermal Energy from BIPV/T System	48.0	0.0

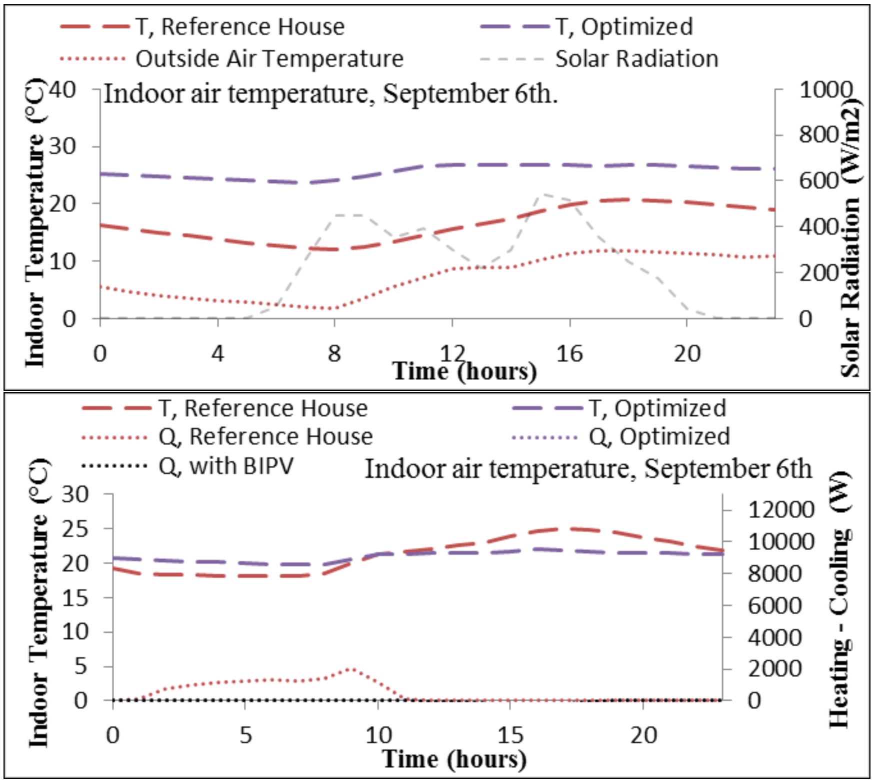

Figure 32: Passive response (top) and active response (bottom) comparing reference house to optimized house for September 6th

Table 31: Total annual heating, cooling and total energy consumption for the reference house and the optimized house

	Qheating (kWh/m^2)	Qcooling (kWh/m^2)	Qtotal (kWh/m^2)	Energy Reduction from Typical (%)
Reference home	122.9	-5.0	127.9	0
Optimized House without Thermal Energy from BIPV/T System	57.8	-7.4	65.2	49.0
Optimized House with Thermal Energy from BIPV/T System	54.3	-7.4	61.9	51.6

5. Protocol for Low Energy Homes in Northern Canada

5.1. Objectives

The aim of this thesis was to develop a guideline that integrates the building envelope with other subsystems to optimize for energy efficiency, durability, and delivery of Northern Houses. This thesis presented the development of a protocol for low energy home (LEH) for northern Canada. This protocol considered all relevant standards, guidelines and criteria that should be met and addressed regarding energy consumption, moisture management and energy performance, as well as optimization of site generated energy, schedule, and cost. The set of criteria presented anticipate and address key relevant challenges of the North, and promote a delivery system involving all stakeholders to reduce delays and cost overruns.

5.2. Overview

The protocol for low energy home in northern Canada is based on the development of the main set of parameters needed for the successful delivery of energy efficient and durable homes for Canada's North. These parameters were based on the previous research, Horvat (2005) developed a protocol for performance evaluation of a light-frame building envelope for residential building for Canadian climates.

The scope of this research considered eight parameters that were important for energy efficient northern homes. They are: (1) air leakage, (2) moisture management, (3) energy consumption, (4) energy performance, (5) indoor air quality, (6) HVAC selection, (7) schedule and cost, (8) and compatibility of materials.

For each parameter, their functional requirements, criterion, and verification methods are developed – and presented using the Nordic Five Level System Table 32.

Table 32: Nordic Five Level System (Oleszkiewicz, 1997)

Level 1: Main goal(s)/objective(s)	Level 2: Functional requirements	Level 3: Corresponding Criterion/Criteria	Level 4: Verification/ evaluation method(s)	Level 5: Supplementary Information
Energy consumption	Thermal resistance of opaque parts of the envelope	RSI value of 7.0 for suspended floors, RSI 5.6 for walls and RSI 8.75 for roofs	Parallel-path and/or isothermal planes (Ch. 26, Eq. 15, ASHRAE Handbook – Fundamentals, 2009).	To take effective RSI Value.

The author studied several local, North American, and Northern European standard to identify existing requirements for parameter required. The protocol was further benchmarked based on the finding in this thesis. The following subsections of this chapter present the protocol for low energy homes for Northern Canada. The protocol should be used to complement existing codes and standards.

5.3. Airtightness

Airtightness

Operative (Performance Requirement)	Criterion		Evaluation (Verification Methods)
Air permeance of principal membrane	≤ 0.02 L/s* m^2 @ 75 Pa for material intended to provide the principal resistance to air leakage.		Selection of Materials. Inspection if installed by design specifications Sources: 1. Good Building Practice for Northern Facilities, (Article 3.1.5.3) (Government of the Northwest Territories, 2012) 2. NBCC, Table A-5.4.1.2.(1) and (2.) (Canadian Commission on Building and Fire Codes, 2010) 3. ASTM E1677-05 Standard Specification for an Air Retarder (AR) Material or System for Low-Rise Framed Building Walls (ASTM, 2005)
Air permeance of the opaque panel assemblies system (floors, roof & walls)	R.H of the warm side of the insulation @ 21^{o}C	Maximum Air Leakage Rate @ 75pa	
	< 27%	≤ 0.15 L/s*m^2	
	27 to 55%	≤ 0.10 L/s*m^2	
	> 55% $^{\text{(See note 1)}}$	≤ 0.05 L/s*m^2	
	Note 1: This will typically apply to residential occupancies including group homes, student residences or long term care facilities, and to humidified portions of hospitals, indoor pools and spa rooms.		

Air change rates	0.6 air changes per hour @ 50 Pa	Select of Material and Pre-gypsum blower door should be performed according to CAN/CGSB-149.10-M86 (Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method). _________________ Sources: Passivhaus Standards
Dual air / vapour barrier	A vapour barrier can perform as an air barrier if its air leakage requirements are met, and can withstand wind and sustain min. pressure. Location of air / vapour barrier to be on warm side of insulation.	Selection of Materials.
Air leakage of windows	≤ 0.2 L/s*m^2 @ 75 Pa for fixed windows and skylights ≤ 0.5 L/s*m^2 @ 75 Pa for operable windows and skylight.	Selection of Windows, tested in accordance with AAMA/WDMA/CSA 101/I.S.2/A440 NAFS – North American Fenestration Standard/ Specification for Windows, Doors, and Skylights. Fenestration that is not site built is listed and labeled as meeting AAMA /WDMA/CSA 101/I.S.2/A440 Inspection at junctions of window components, gaps, breaks, and opening/penetration in window assembly. _______________ Source: National Energy Code of Canada for Building (2011) 3.2.4.3.
Operable window: sash	Operable sash recommended being casement or awning type with rugged hinges, simple rugged push bar handles and rugged camlocks, with metal rather than plastic. Camlocks are found to provide good compression when closed. Sliding or by-passing operable sash tends to jam with frost or ice in the northern climate.	Selection of Materials, Control of design (drawings and specifications.) _______________ Source: Good Building Practice for Northern Facilities, 2011 (A.4.4.4)
Exterior doors	Requires weather seals – weather seals are to be selected and design so they remain flexible in extreme cold, structural movement and contraction/expansion due to temperature change. See Moisture Management.	Control of Design (Drawings and Specifications) _______________ Source: Good building practice for northern facilities, 2011 (A.4.1)

Air leakage of doors - sliding doors and non-weather stripped doors	≤ 0.5 L/s*m^2 @ 75 Pa	Selection of door, which should have been tested in Accordance with ASTM E283 Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Source: National Energy Code of Canada for Building (2011) 3.2.4.4. Inspection at junctions of door components, gaps, breaks, and opening/penetration in door assembly.
Air leakage of doors - all other doors that separate heated space from unheated space or the outside air:	≤ 17 L/s*m door of door crack[1] & be weather-stripped on all edges.	Control of Design (drawings and specification) & Selection of Materials. Inspection at junctions of door components, gaps, breaks, and opening/penetration in door assembly.
Continuity of air barrier	Air barrier must be continuous across construction, control and expansion joints, across junctions between different building assemblies, and around penetration through the building assembly – including the floors. AB manufacturers to provide field application instructions.	Control of Design (drawings and specifications). Inspection at junctions of building components, gaps, breaks, and opening/penetration in building envelope. Blower door test before putting up gypsum board. Source: National Building Code of Canada, (Article 5.4.1.2.3)
	Breaks/gaps within barrier shall be sealed.	Control of Design (drawings and specifications) Source: ICC IECC (2012): International Energy Conservation Code, Table R402.4.1.1 Inspection and control of installation at the plant or site
	Duct, shafts, or penetration of utility of building envelope shall be sealed around perimeter.	Control of design (Drawings and specifications) Source: ICC IECC (2012): International Energy Conservation Code, Table R402.4.1.1 Inspection and control of installation at the plant or site

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[1] Quebec Regulation respecting energy conservation in new buildings (Div 5 S.70)

Selection of sealants	Sealants used as part of a building envelope assembly must be: - Selected for its substrate, and chemically compatible with adjacent materials - Installed under recommended moisture and temperature range - Serviceable to -50ºC in their fully cured state. - Strong enough to resist loads and elastic and compressible enough to withstand movements of joints without deforming, breaking or moving out of position. - Place in primed joints of proper dimensions and proportion with backing rod or bond breakers. Silicone based or one-component elastomeric sealant types that meet the performance criteria are recommended. Acrylic and solvent curing types not recommended for very cold climates.	Selection of Materials, Control of Drawings, inspection on site. Source: Good Building Practice for Northern Facilities, 2011 (Article, 3.1.7.4)
Selection for prefabricated construction	• Maximize panels width to limit number of panel connections (keeping in mind practical, such as transportation restriction) - thereby minimizing the weak points in the system. • Design SIPs to minimize incorrect assembly on site in order to ensure panels perform as expected	Selection of Materials. Source: (Wyss, 2011)
Building envelope floor assemblies	In permafrost areas, elevated floors help minimize heat flow from building to ground. They provide opportunities for heat loss, air leakage, snow infiltration and water vapour diffusion. Thus, the above requirements should be applied for the floor assemblies.	Control of Design (Drawings and Specifications.) Source: Good Building Practice for Northern Facilities, 2011.
Roofs	Recommendation: protected, fully adhered coincident air/vapour (AV) barrier membranes located above the structural deck for all buildings located in areas of continuous airborne snow drifting. Careful care must be taken to make air/vapour barrier continuous.	Control of Design (Drawing and Specifications.) Source: Good Building Practice for Northern Facilities, 2011. (A.3.6.3.)
Heated or semi-heated enclosed crawl spaces	Interior walls with semi-heated or semi-enclosed spaces, such as semi-heated garages, or crawl spaces should be insulated.	
Recessed lighting	All recessed luminaires in building envelope shall be *IC-rated* and labeled as having an air leakage rate not more than 2.0cfm (0.944 L/S) + sealed to limit air leakage. Careful care must be taken to ensure continuity of air/vapour barrier.	Control of Design (Drawings and Specifications.) Source: ICC IECC (2012): International Energy Conservation Code, R402.4.4

5.4. Moisture Management Performance

Moisture Management Performance

Operative (Performance Requirement)	Criterion	Evaluation (Verification Methods)
Water vapor permeability of the assembly	General requirement of vapor retarder/barrier system on the inside (warm side) of insulation – though, in Northern Canada, it is recommended to use a continuous vapour barrier than vapour retarder. Recommended permeance of vapour retarder in relation to permeance of insulation. (1) When insulation has permeance less than 17.16 ng/(Pa-s-m^2), where the joints and seams have a permeance equal to or less than that of insulation, no separate applied vapor retarder is normally needed. (2) When insulation has permeance between 17.16 to 228.8 ng/(Pa-s-m^2), vapor retarder for (a) walls < 57.2 ng/(Pa-s-m^2) (b) underslab: < 57.2 ng/(Pa-s-m^2). (3) When insulation has permeance above 228.8 ng/(Pa-s-m^2), vapor retarder for (a) walls < 57.2 ng/(Pa-s-m^2) (b) underslab: < 22.9 ng/(Pa-s-m^2).	Selection of Materials. Source: ASTM C755-03 Standard practice for selection of Water Vapor Retarders for Thermal Insulation (Article 7.4.5, and Table 2).
Location of vapour barrier for floors, walls, and roofs.	Provide only one plane of high water vapour resistance on the warm side of thermal insulation, preferably in the same plane as the required continuous air barrier. Trapped vapour in envelope shall be allowed to migrate to the exterior or to the naturally ventilated cavity.	Control of Design (Drawings and Specifications.) Source: Good Building Practice for Northern Facilities, 2011 (A.3.1.3).
Continuity of vapour barrier	Continuity of vapour barrier is important to prevent moisture damage in walls in Northern Climates.	Control of Design (Drawings and Specifications) Source: Alaskan Housing Manual 7e (2008)
Location of vapour barrier in roofing assembly.	Vapour barrier on the warm side of the thermal insulation, preferably in the same plane as the required continuous air barrier.	Control of Design (Drawings and Specifications) Source: Good Building Practice for Northern Facilities, 2011 (A.3.1.3)
Building envelope floor assemblies	In permafrost areas, elevated floors help minimize heat flow from building to ground. They provide opportunities for heat loss, air leakage, snow infiltration and water vapour diffusion. Thus, the above vapour barrier requirements should be applied for the floor assemblies.	Control of Design (Drawings and Specifications)
Building envelope: elevated floor assemblies	Recommended soffit materials should be durable, lightweight, easily installed, and easy to maintain with minimal number of joints preventing entry of snow, dust and insect & positioned to allow for enough air movement to ventilate.	Control of Design (Drawings and Specifications) Source: Good Building Practice for Northern Facilities, 2011 (A.3.3.3).

Exterior doors	Requires weather protection at the head with extended eaves or canopies to deflect falling snow, ice and water.	Control of Design (Drawings and Specifications) ________________ Source: Good building practice for northern facilities, 2011 (A.4.1.)
Appropriate use of a hot roof designs, (unventilated roof)	- Requires an average annual wind speed > 6km/h to effectively clear the roof of accumulated snow. - When large snow accumulation does occur, the snow must be removed. - The roof must be tightly constructed with a perfect air and vapour barrier.	Coordination, Control of Design (Drawings and Specifications) ________________ Source: CMHC – Attics and Roofs for Northern Residential Community
	Protected, fully adhered coincident air/vapour (AV) barrier membranes located above the structural (naturally ventilated or un-ventilated) recommended for areas of continuous airborne snow drifting.	Control of Design (Drawings and Specifications) ________________ Source: Good Building Practice for Northern Facilities, 2011. (A.3.6.3.)
Prevention of moisture in roof	Install a continuous air and vapor barrier on warm side of insulation in roof/ceiling.	Control of Design (Drawings and Specifications) ________________ Source: Attics and Roofs for Northern Residential Construction (Seifert, 2013)
Low slope roofs	All low-slope roofs are recommended to be constructed with a minimum drainage slope of 4% (1:25) leading to drains positioned at the low points of the roof.	Control of Design (Drawings and Specifications) ________________ Source: Good Building Practice for Northern Facilities, 2011. (A.3.6.4.)
	Roof valleys sloped away from the building	Control of design (Drawings and Specifications)
Eaves / canopies	Recommended: eaves or canopies designed to divert falling snow, ice and water originating on roofs away from exterior doors.	Control of Design (Drawings and Specifications), Selection of Materials. ________________ Source: Good Building Practice for Northern Facilities, 2011. (A.3.6.6.)
Eaves/canopy: integrity of AV barriers.	Eaves and canopy projections beyond the line of the AV barrier must not weaken the air tightness of the building envelope.	Control of Design (Drawings and Specifications) ________________ Source: Good Building Practice for Northern Facilities, 2011. (A.3.6.6.)
Eaves projections	Minimal eaves projections ranging from 100 to 200 mm are preferred in colder and drier regions of the North. Larger eaves projecting 300 to 600 mm are necessary in wetter regions and in specific communities where the rainy season concentrates annual rainfall into a short period of the year, and wind driven rain increases the rate of periodic wetting of building walls. Care to be taken to not weaken air vapour tightness of building envelope.	Control of Design (Drawings and Specifications) ________________ Source: Good Building Practice for Northern Facilities, 2011. (A.3.6.6.)
Roof: flashing and sealing @ intersections	Flashing shall be installed at junctions between roofs and: a) Walls that rise above the roof. b) Guards that are connected to the roof by more than pickets or posts. c) Masonry walls / chimneys	Control of design (Drawings and Specifications) ________________ Source: NBCC 2010 9.26.4.1. . (See NBCC 2010, 9.26.4.4.)

Surface condensation	To be minimized - interior surface temperature must not fall below the dew point of the interior air (depends on indoor RH levels) – thus, enough insulation needs to be provided.	Computation: Dew-Point Method- ASHRAE Fundamentals, 2013 – 25 OR COPNDENSE/WUFI software ________________ Source: National Building Code of Canada, 2011 (Article 5.3.1.2.(1))
Strategies to prevent or control moisture accumulation: (1) limit moisture sources		Control of Design (Drawings and Specifications) ________________ Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 5.1.2.1)
(2) Minimize moisture entry into the building or building envelope		Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 5.1.2.1)
(3) Remove moisture from the building envelope[2]	Wood frame walls constructed with wet building materials, or under wet conditions, should be allowed to dry by evaporation before they are enclosed.	Control of Design (Specifications) ________________ Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 5.1.2.1)
	Initial moisture content of lumber shall not be > 19% at the time of installation.	Selection of Materials & Control of Design (Specifications) ________________ Source: ASTM D4442-07 Standard Test methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials
Rain water penetration management: rain screen principles[3]	Building envelopes are to be designed in accordance with the 'rain screen cladding technique' (pressure equalization practice.) The rain screen principle has two complimentary defense systems. The first line of defense minimizes water passage into wall. The second line of defense to intercept this water and dissipate it effectively back to the exterior.	Control of Design (Drawings and specifications.) ________________ Source: Good building practice for northern facilities, 2011 (A.3.1.6)
	Water intercepted by the second line of defense must be dissipated to the exterior by means of drainage or evaporation, or both. (e.g.: weep holes)	Control of Design (Drawings and specifications.) CAN/CGSB-51.32-M, “Sheathing, Membrane, Breather Type.” ________________ Source: Moisture Control Handbook (Lstiburek et John Carmody, 1991); ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Buildings; and NBCC 2010 9.27.32.1. & NBCC 2010 9.27.32.2.
	Weep paths/weep holes to drain liquid water where condensation or water leaks can occur.	Control of Design (Drawings, and Specifications) ________________ Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 5.5.1)

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[2] Moisture Control Strategies that combine these approaches are usually most effective.

[3] Joseph Lstiburek and John Carmody, Moisture Control Handbook: New, Low-rise, Residential Construction, U.S. Department of Energy Conservation and Renewable Energy, 1991.

	- 25-mm-deep air cavity (free from mortar dropping) for masonry veneer.	Control of Design (Drawings, and Specifications).
	- Boundary layer to have higher water resistance	Control of Design (Drawings, and Specifications).
Rain water penetration management: flashing	Flashing shall be installed at every: - Horizontal surfaces that intercept the drainage cavity must be flashed - Horizontal junctions between cladding elements - Horizontal offset in the cladding, Horizontal line where the cladding substrates changes, and where the substrates different deficiency for stress to be concentrated along that line, or the installation of the cladding on the lower substrate may compromise the drainage of moisture from the behind cladding above.	Control of design (drawings) & Selection of Materials Flashing materials shall consist of not less than a) 1.73mm thick sheet lead or, b) 0.33 mm thick galvanized steel or, c) 0.46 mm thick copper or zinc or d) 0.48 mm thick aluminum, or e) 1.02 mm thick vinyl. ________________ Source: National Building Code of Canada, 2010, (Articles 9.27.3.1, 9.27.3.7, & 9.27.3.8.)
Flashing configuration	Minimum of 6% slope needed for effective drainage, the drip edge to extend at least 10 mm beyond the face of the wall (preferably 25 mm) to accommodate typical construction practices. Flashing to incorporate dimensional changes in materials.	Control of designs (drawings and specifications.) ________________ Source: NBCC Appendix Article (A.9.27.3.8)
Operation of mechanical equipment	Design to incorporate moisture from mechanical equipment - air-handling equipment, which can induce a moisture transfer mechanism that can move large amount of moisture.	Control of Design (Specifications) and Selection of Equipment. ________________ Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 5.4.3)
Drainage of precipitation and surface runoff	Surface grading, ground slope away from walls	Control of design (Drawings and Specifications) ________________ Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 8.1.1)
	Building external drains	Control of design (Drawings and Specifications) ________________ Source: ASTM E241-09 Standard Guide for Limiting Water-Induced Damage to Building (Article 8.1.2)
	Balconies, terraces & decks sloped away from exterior walls	Control of design (Drawings and Specifications)
	Window sills sloped away from the window	Control of design (Drawings and Specifications)
Limiting intrusion of precipitation: reducing deposition on exterior walls	Drip on window sills or coping	Control of design (drawings),
Expected wood shrinkage	A positive 6% slope should remain on roofs and similar construction after expected shrinkage of the building frame.	Control of Design (Drawings and Specification) & Calculations: Shrinkage = (total horizontal member height) x (initial MC – equilibrium MC) x (0.002) MC = Moisture content, equilibrium moisture content for wood in the North = 7 (source: CWC 2000, 'Wood Reference Handbook.'

Protection of cladding from moisture: ground	A clearance of ≥ 200mm must be provided between finished grounds and cladding that is adversely affected by moisture (such as untreated wood, plywood, OSB, waferboard and hardboard.).	Control of Design (Drawings), Source: NBCC 9.27.2.4.
Protection of cladding moisture: roof	A clearance of ≥ 50mm must be provided between roof surfaces and cladding that is adversely affected by moisture.	Control of Design (Drawings), Source: NBCC 9.27.2.4.
Capillary suction - control below grade	3/4 in layer of crushed stone below basement slab where applicable.	Control of design (drawings),
	Capillary break over the top of the footing, placed prior to construction of perimeter foundation walls where applicable.	Control of design (drawings)
	When the number of degree days > 3400, and moisture index > 1.00, exterior walls exposed to precipitation shall be protected against precipitation ingress by an exterior cladding assembly consisting of a first plane of protection and a second plane of protection incorporating a capillary break (See Rain Screen Principle). Unless the first and second planes of protection need not incorporate a capillary break, where a) It can be shown that omitting the capillary break will not adversely affect the performance of the building assemblies, b) The building is an accessory building, c) The wall is constructed of non-moisture-sensitive materials, and intersecting or supported floors are also constructed of non-moisture-sensitive materials or is constructed as a mass wall of sufficient thickness to minimize the transfer of moisture to the interior.	Control of Design (Drawings and Specifications) Source: NBCC 9.27.2.2.(5) & (6)

	Unless the exterior wall is interrupted for penetration for windows, doors and services, flashing, or furring (provided, the furring does not make up more than 20% of the furred area,) a cladding assembly should have a capillary break between the cladding and the backing assembly, where a) There is a drained and vented air space ≥ 10mm deep behind the cladding, over the full height and width of the wall, b) An open drainage material, ≥ 10mm thick and with a cross sectional area that is not less than 80% open, is installed between the cladding and the backing, over the full height and width of the wall, c) The cladding is loosely fastened to the backing and behind each cladding component there is a clear air space that is continuous for the full width of the component, ≥ 10mm deep at the bottom of the component, and ≥ 6mm deep over ≥ 90mm for every 230mm of exposed height of the component, d) The wall is masonry cavity wall or the cladding is masonry veneer.	Control of Design (Drawings and Specifications) Source: NBCC 9.27.2.2.(1) & (2).
	A durable continuous moisture barrier > 6mil thick shall be placed over exposed soils in crawlspaces and extend 1ft (305mm) up the crawlspace walls. Joints in the moisture shall overlap a min of 1ft (305mm)	Control of Design (Drawings and Specifications) Source: ASHRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Building (Article 5.11.1)
Capillary suction - control below grade	Capillary break between the sill plate and the top of foundation wall. Capillary break to be provided between foundation and floor when homes are elevated.	Control of Design (Drawings and Specifications)
Capillary suction - control above grade	Capillary break in porous cladding materials (e.g. horizontal wood siding)	Control of Design (Drawings and Specifications)
Moisture by tracking in snow and water.	An enclosed porch at the house entrance helps minimize this factor[4].	Control of design (drawings)

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[4] Said, M.N.A "PERD-079 - Engineered Building Envelope Systems to Accommodate High Performance Insulation with Outdoor/Indoor Climate Extremes. Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates." Institute for Research in Construction, National Research Council Canada, Ottawa, 2006, (Page 15/120)

5.5. Energy Consumption

Energy Consumption		
Operative (Performance Requirement)	Criterion	Evaluation (Verification Methods)
Thermal resistance of opaque parts of the envelope (as built values)	Suspended Floors: RSI 7.0 Walls: RSI 7 Roofs: RSI 9 Floors above Thermosyphon Grids or Thaw Susceptible Soils: Custom Design Value Floors on grade on non-frost susceptible soils: RSI 6.69* or Custom Design Value Unvented Crawlspace: 5.28*	Calculation: ASHRAE Handbook – Fundamentals, 2009 – chapter 25, parallel-path and/or isothermal planes – equations 15; Note: Custom Design Value may be used if an energy modeling study is performed on the building Source: 1. Good building practice for northern facilities, 2011 & 2. ASHRAE Standard 90.2 2007 Energy-Efficient Design of Low-Rise Residential Buildings (For Climate Zone 8)
Continuity of insulation	Where an interior wall, ornament, or building envelope assembly breaks the continuity of the building envelope, it shall be insulated on both of its sides from the building envelope for a distance equal to 4 times the non-insulated thickness of the penetrating wall with an R-value of the superior wall. Joints between components of the building envelopes shall be insulated in a manner that provides continuity across such joints.	Control of Design (Drawings and Specifications) Source: National Energy Code of Canada for Building (2011) 3.2.1.1.
Thermal resistance of installed windows	Recommended: Wood, vinyl or fiberglass framed, triple-glazed, low-e, argon filled windows sealed units with thermal break with an insulated spacer. RSI = 0.625 m^2 K/W	Selection of Materials. Source: 1. Good Building Practice for Northern Facilities, 2011 (A.4.4.5.) & 2. National Energy Code of Canada for Building (2011) Table 3.2.2.3
Placement of window	Windows shall be located in the wall assembly such that the interior of the frame is located on the warm side of the insulation.	Control of Design (Drawings) Source: Good Building Practice for Northern Facilities, 2011 (A.4.4.3)
Thermal resistance of exterior doors	RSI = 0.70 m^2 K/W All exterior doors are recommended to be insulated 16 Ga. steel construction, (14 Ga. in areas of known high traffic or forced entry), minimum RSI 1.3 and rated for climate zone "D" for durability, energy conservation and frost prevention. Solid core or hollow wood doors are not recommended.	Selection of Material, Control of Design (Drawings and Specifications.) Source: Good building practice for Northern facilities, 2011 (A.4.1.1.)
Vestibules	The use of vestibule is highly encouraged, as it keeps warm air within the house – it can be designed to be used as a cold storage for animal skin.	Control of Design (Drawings and Specifications.) Source: Good building practice for Northern facilities, 2011 (A.4.1.1.)

Floors assembly	Northern buildings can be placed on the ground when rock or similar durable soil conditions are available. Floors should be elevated above the ground surface to eliminate heat flow when there are thaw susceptible soils. Elevated buildings require careful design of air, vapour and thermal barriers.	Selection of Material, Control of Design (Drawings and Specifications.) Source: Good building practice for Northern facilities, 2011 (A.3.3.)
Foundation: heat flow from building to soil interrupted and carried away from soil.	- Building raised a minimum of 2ft (0.6m) above the ground surface and allows free circulation of air. - Raised Space not to be used as storage, nor blocked. - Thermal breakage should be provided where there is a possibility of building to foundation piles.	Control of Design (Drawings and Specifications) Source: Design Manual for New Foundation on Permafrost, (2000,) Permafrost Technology Foundation.
Selection of insulation in contact with soil	Insulation that is to be in contact with soil should not deteriorate nor loss thermal property and its physical shape in present of soil moisture, chemicals and physical loading.	Selection of Materials Source: Design Manual for New Foundation on Permafrost, (2000,) Permafrost Technology Foundation.
Minimizing thermal bridges	Thermal bridging – such as through structural members – should be designed and minimized. Where insulation is installed within structural framing, a layer of insulating sheathing should be provided on the exterior of the framing or the exterior structural sheathing.	Control of Design (Drawings and Specifications) Source: Good building practice for Northern facilities, 2011 (3.2.3)
Prefabricated homes: minimizing thermal bridges	Minimize thermal bridges at connections (i.e.: thermal break).	Control of Design (Drawings and Specifications) Source: (Wyss, 2011)
Ratio of glazing vs. floor	Total glazing area to floor ratio should be around 10% (Optimized for city of Yellowknife)	Control of Design (Drawings and Specifications) Source: Optimization, See 4.

5.6. Energy Performance

Energy performance

Operative (Performance Requirement)	Criterion	Evaluation (Verification Methods)
Orientation of solar systems	Should be oriented due south or less than 15degree off south.	Control of Design (Drawings and Specifications) Source: (Arctic Energy Alliance, 2014)
Tilt angle for solar systems	Tilt should be latitude -15 degrees, or integrated vertically on façade.	Control of Design (Drawings and Specifications) Source: (Arctic Energy Alliance, 2014)**,**
Passive solar design: window wall ratio	Window to wall ratio of south facing wall should be approximately 70%.	Control of Design (Drawings and Specifications)

passive solar design: integration of thermal mass	When appropriate, 5 to 10 cm of concrete may be used as thermal mass to help reduce energy consumptions. Doubling of gypsum boards is also an appropriate strategy.	Control of Design (Drawings and Specifications)
Photovoltaic (PV) systems	The addition of glazing to PV system would improve its efficiency.	Control of Design (Drawings and Specifications) Source: (Chen et al., 2012)

5.7. Indoor Air Quality

<table>
<tr><th colspan="3">Indoor Air Quality</th></tr>
<tr><th>Operative (Performance Requirement)</th><th>Criterion</th><th>Evaluation (Verification Methods)</th></tr>
<tr><td>Required ventilation rates</td><td>$Q_{fan} = Q_{tot} - Q_{inf}$
Where:
Q_{fan} = Required mechanical ventilation rate, cfm
Q_{tot} = Total Require ventilation rate, cfm
Q_{inf} = Infiltration rate, may not be greater than $2/3*Q_{tot}$</td><td>Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings</td></tr>
<tr><td>Required mechanical ventilation rate to supplement summer infiltration, cfm</td><td>Minimum requirement when summer design infiltration rate is less than 0.35 ach, Mechanical ventilation = 50cfm
Mechanical Ventilation = ((0.35 – S)*V)/60
Where Mechanical Ventilation = required mechanical ventilation rate to supplement summer infiltration (Cfm,)
S = summer design infiltration rate (ach.)
V = Volume of conditioned space (ft^2)</td><td>Source: ASRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Buildings (Article 6.6)</td></tr>
<tr><td>Local mechanical exhaust</td><td>Local mechanical exhaust system shall be installed in each kitchen and bathroom. They shall be either a) a Demand-Controlled Mechanical (DCM) system or a Continuous Mechanical (CM) exhaust system.
Required Airflow Rates:
<table>
<tr><th></th><th>DCM</th><th>CM</th></tr>
<tr><td>Kitchen</td><td>100cfm[5]</td><td>5 ach[6]</td></tr>
<tr><td>Bathroom</td><td>50cfm</td><td>20cfm</td></tr>
</table></td><td>Selection of Materials. Demand-controlled exhaust system to meet requirements of section 5.2, and a continuous mechanical exhaust system meeting the requirement of section 5.3 of ASHRAE Standard 62.2-2013.
Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings</td></tr>
<tr><td>Cloth dryers</td><td>Clothes Dryers shall be exhausted directly to the outdoors.</td><td>ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings</td></tr>
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[5] Vented Range Hood (including Appliance-range hood combinations) required if exhaust fan flow rate is less than 5 kitchen air changes per hour.

[6] Based on Kitchen Volume

5.8. HVAC selection

HVAC Selection

Operative (Performance Requirement)	Criterion	Evaluation (Verification Methods)
Selection of HVAC system	The HVAC systems must be easily maintained by locals and reliable, because transportation is expensive and sometimes not available due to bad weather.	Source: Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates (Said, 2006)
Ventilation openings	Habitual spaces shall be provided each with ventilation opening, openable area not less than 4% of the room area nor less than 5ft^2. Toilets & Utility rooms shall be provided with ventilation openings, openable area not less than 4% of the room floor area or less than 1.5ft^2. (Exceptions: Utility rooms with dryers exhaust duct and toilet compartments in bathrooms.)	Control of Design (Drawings and Specifications.) Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings
Filtration	Systems that supply air to an occupied space through ductwork exceeding 10ft in length and through a thermal conditioning component (except evaporative coolers) shall be provided with a filter having a minimum efficiency designation of MERV 6 or better before air passing through the thermal conditioning components.	Selection of Material, Control of Design (Drawings and Specifications.) Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings
Air inlets	Air inlets in ventilation design shall be located a minimum of 10ft from sources of contamination, and be placed so that air entering is not obstructed by snow, plants or other materials and should be provided with rodent/insect screens (mesh not larger than 1/2in.) Exceptions: a) Ventilation opening in the way may be as close as 3ft from sources of contamination exiting through the roof or dryer exhaust. b) No minimum separation distance required between windows and local exhaust outlets in kitchens and bathrooms c) Vent terminations covered by and meeting the requirement of National Fuel Gas Code (NFPA 54/ANSI Z223.1) or equivalent.	Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings
Carbon monoxide alarms	A carbon monoxide alarm shall be installed in each dwelling unit.	Conform to NFPA 720, Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment. Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings
Air intakes and exhaust: keeping snow out	Construction details of air intakes and exhausts require particular attention to keep out driving snow. In some regions air intakes and exhausts need to be protected from hoarfrost or snow.	Source: Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates (Said, 2006)

Location of air intakes	Air intakes and outlets should be located high but not through the roof. Roof-mounted inlets and outlets are not desirable, except in areas with little snowfall. Avoid locating inlets on the windward side.	Source: Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates (Said, 2006)
Pre-heating of intake air	Ventilation air should not be introduced directly into occupied spaces. With hot-air heating systems, ventilation air is either preheated by a heating coil or supplied to the return air plenum.	Source: Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates (Said, 2006)
Corridors and common areas in multifamily buildings	Corridors and other common areas within the conditioned space shall be provided with ventilation at a rate of 0.06cfm per ft^2	Source: ASHRAE Standard 62.2-2013, Ventilation and Acceptable Indoor Air in Low-Rise Residential Buildings
Hygrothermal requirements for ducts outside conditioned space	All portions of the air distribution system installed in or on building for heating and cooling shall be R-8, with vapour retarders having permeance not greater than 0.5 perm	Source: ASHRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Buildings (Article 6.2)
Temperature control	Each systems or each zone within a system shall be provided with at least one thermostat capable of being set from 13^{O}C to 29^{O}C and capable of operating the system's heating/cooling. The thermostat or control system, or both, shall have an adjustable deadband, the range of which includes a setting of 5.6 ^{O}C between heating and cooling when automatic changeover is provided.	Control of Design (drawings,) For wall-mounted temperature controls shall be mounted on an inside wall. Source: ASHRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Buildings (Article 6.10)
Ventilation control	Each mechanical ventilation system (Supply, exhaust or both,) shall be equipped with a readily accessible switch or other means for tight shutoff.	Source: ASHRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Buildings (Article 6.10)
Humidity control	Heating: If additional energy-consuming equipment is provided for adding moisture to maintain specific selected relative humidity in spaces or zone, a humidistat shall be provided. This device shall be capable of being set to prevent energy from being used to produce relative humidity within the space above 30% Cooling: If additional energy-consuming equipment is provided for reducing humidity, it shall be equipped with controls capable of being set to prevent energy from being used to produce a relative humidity within the space below 50% during periods of human occupancy and below 60% during unoccupied periods.	Source: ASHRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Buildings (Article 6.10)
Pump operations	Circulating hot water systems shall be arranged so that circulating pump(s) can be turned off (automatically or manually) when hot water system is not in operation.	Source: ASHRAE Standard 90.2 (2007) Energy-Efficient Design of Low-Rise Residential Buildings (Article 7.2)
Comparing different HRV efficiency	The Sensible Recovery Efficiency (SRE) quantifies the amount of heat recovered from the exhaust air at a given air flow and temperature.	Source: (Cold Climate Housing Research Center, 2015a)
Continuous operation of ventilation systems	Cooling and ventilating systems must be designed for continuous operation without reducing loads during the night, because solar gains do not subside during the night. Designers should ensure that computerized load analysis programs account for continuous solar gain conditions.	Source: Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates (Said, 2006)

Suitability of radiant floor system in extreme cold climate	Radiant floor or wall panel heating systems may not be suitable when outdoor temperatures fall below -54ºC (-65ºF), because corresponding design floor temperatures may exceed the ASHRAE comfort guidelines of 30ºC (85ºF) or above for light footwear.	Source: Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates (Said, 2006)

5.9. Schedule and Cost

Schedule & Cost

Operative (Performance Requirement)	Criterion	Evaluation (Verification Methods)
Materials: waste and complexity of design	Designer to choose size and type of structural elements used in a building so to be standardized.	Selection of Materials Source: Good building practice for northern facilities, 2011 (S.2.3.)
Material: transportation	Pressure treated wood or steel is preferred. Concrete is not recommended unless quality assurance can be guaranteed.	Selection of Materials Source: Good building practice for northern facilities, 2011 (S.2.3.)
Material: Transportation	The size of the glazing units selected should accommodate transportation limitations for communities off the road system.	Selection of Materials Source: Good building practice for northern facilities, 2011 (A.4.4.)
Details	Designer to simplify detailed design and minimize the number of operations required installing components.	Control of Design (Drawings and Specifications) Source: Good building practice for northern facilities, 2011 (S.2.3.)
Advance framing techniques or optimum value engineering: wood frame	Design based on common material dimensions (i.e., 24-inch grid) as a basis for design to maximize material use and minimize waste	Control of Planning. Source: Alaskan Housing Manual 7e (2008)
	Where municipal regulations allow, increase joist spacing to 24”.	Limit State Design & Control of Design (Drawings and Specification) Source: Alaskan Housing Manual 7e (2008)
	Structural headers are needed only for load bearing walls; headers should be sized appropriately for its load and if possible, use single header. Only use double headers when required.	Limit State Design Source: Alaskan Housing Manual 7e (2008)
	Use stud corners, it provides the number of framing members necessary for structural support for most residential.	

Transportation and handling of material	All components should be sized small enough and light enough so they can be moved to the site and erected with available equipment.	Coordination with community and available equipment. Source: Good building practice for northern facilities, 2011 (S.2.1.)
Overhead doors	All overhead doors, i.e., for garage, should be metal with replaceable panels. Damaged panels can be easily replaced in sections rather than having to replace the whole door.	Selection of Materials. Source: Good building practice for northern facilities, 2011 (A.4.1.2.)
Hardware	Selection of locksets should be coordinated with maintenance staff so that operational and maintenance preferences and standard keying systems are accommodated.	Coordination with local community. Source: Good building practice for northern facilities, 2011 (A.4.3.1.)
Service spaces/trenches below building	Sufficient space is required for maintenance personnel to access so to conduct maintenance tasks on equipment and services installed in basements, crawl spaces and service trenches. Service spaces will be a minimum of 1.5 m. tall and 1.0 m wide.	Control of Design (Drawings and Specifications) Source: Good building practice for northern facilities, 2011 (A.3.3.5.5)

5.10. Compatibility of Materials

Compatibility of Materials

Operative (Performance Requirement)	Criterion	Evaluation (Verification Methods)
Metal: galvanized corrosion	Design to take into consideration that galvanized corrosion (dissimilar metal corrosion) happens when two dissimilar metals come together creating potential due to different electric conductivity of the metal. Methods of protection includes but limiting to (a) Hot-dip galvanizing (b) Electroplating (c) coating	Control of Design (Drawings and Specifications) Source: Good building practice for northern facilities, 2011 (A.3.3.5.5)
Metal: copper flashing	Copper flashing with metal fasteners can cause corrosion.	Control of Design, use copper nails and screws to faster copper flashing. Source: CMHC Research Report: Incompatible Building Materials (2003)
Metal: strapping of hot water tank	For hot water tank strapping use either similar metal as casing for the strapping, or a layer of sheathing materials should separate metals.	Control of Design. Source: CMHC Research Report: Incompatible Building Materials (2003)
Metal: wood treated with copper-based preservatives.	Unprotected fasteners made out of metals that are susceptible to corrosion should not be used with wood treated with copper-based preservatives in wet locations - the copper will accelerate the oxidizing effect of water on the metal. Also, types of wood that have natural resistance to decay, such as redwood and the cedars, contain natural chemicals that can also cause premature failure of nails and screws.	Control of Design, recommended to use hot-dipped galvanized and coated fasteners. Code recommends these hot-dipped galvanized fasteners conform to CSA B11. Source: CMHC Research Report: Incompatible Building Materials (2003)

Metals: differential thermal movements	Cladding damage because metals of different thermal coefficients connected to produce stresses. Design to allow for movement, choice of materials	Control of Design. Source: CSA S478-95 (2007) Durability in Buildings
Wood: swelling and shrinkage of soil	To prevent settlement, damage to building fabric, floor and building envelope, preserve permafrost or design for thaw susceptible soil.	Control of Design, see thermal performance. Source: CSA S478-95 (2007) Durability in Buildings
Wood: fungal decay	Avoid sustained moisture and oxygen with temperature from 5 – 40^{o}C through drainage, ventilations.	Control of Design, See moisture, air and thermal management. Source: CSA S478-95 (2007) Durability in Buildings
Wood: thermal degradation	Selection of stable fire-retardants. Roof ventilation may prevent high temperature and moisture in roof, which may contribute to thermal degradation of wood.	Selection of material Source: CSA S478-95 (2007) Durability in Buildings
Wood: UV exposure	Prevent surface degradation, coating breakdown by using protective coating and stains.	Selection of material Source: CSA S478-95 (2007) Durability in Buildings
Wood: drying shrinkage perpendicular to grain	Use dry wood, protective coating and improved design to allow for movement.	Selection of Material, Control of Design. Source: CSA S478-95 (2007) Durability in Buildings
Wood: differential movements due to changes in moisture content.	Use dry wood of good grade, design to allow movements	Selection of Material, Control of Design. Source: CSA S478-95 (2007) Durability in Buildings
Housewraps and surfactants	Surfactants may damage spundbonded polyolefins. Surfactants may original from certain wood species with high tannin content.	Control of Design; install the cladding over strapping so that the cladding is not in direct contact with the housewrap. Source: CMHC Research Report: Incompatible Building Materials (2003)
Housewraps and UV exposure	Building paper and housewrap are not design to withstand long exposure to UV. Design should allow for quick covering of housewrap by exterior cladding.	Control of design. Source: CMHC Research Report: Incompatible Building Materials (2003)
Vinyl windows/doors and peel-and-stick membranes	Certain peel-and-stick membranes react with vinyl windows and doors. It causes color leaching and may damage the performance of the door. Recommendation: Use new generation of peel-and-stick membranes or rubber products. Check with manufacturer for compatibility of membrane with vinyl doors/windows.	Control of design. Source: CMHC Research Report: Incompatible Building Materials (2003)

EPS/XPS insulation and vinyl siding	Vinyl siding directly installed on rigid insulation (EPS or XPS) is a plastic-on-plastic configuration, which has different coefficient of thermal expansion Differential expansion can cause a squeaky noise that is audible through exterior walls. Housewrap / membrane should be install between the vinyl sliding and rigid insulation.	Control of design. Source: CMHC Research Report: Incompatible Building Materials (2003)
Hot-applied bituminous membranes on polyisocyanurate	Hot-applied bituminous membranes on polyisocyanurate can cause damage to roof. The association recommends a cover board of minimum thickness of ½" using any of the following materials: glass-faced siliconized gypsum board, perlite board, wood-fibre board, glass-fibre board, mineral-fibre board.	Control of design. Source: CMHC Research Report: Incompatible Building Materials (2003)
Bitumen and polystyrene foam insulation	Bitumen can cause polystyrene foam insulation to disintegrate. An approved cover board is recommended between the two.	Control of design. Source: CMHC Research Report: Incompatible Building Materials (2003)
EPDM with bituminous-based membranes/flashing	EPDM (ethylene propylene diene monomer) membrane is prone to becoming brittle and cracking where it contacts bituminous-based membranes and flashings. A galvanized metal flashing should be installed to help transition between the two membranes.	Control of design. Source: CMHC Research Report: Incompatible Building Materials (2003)
Durability of sealant	The durability of a sealant depends on the application conditions, the conditions in which the sealant will serve (temperature, UV radiation, wind, rain and atmospheric pollutants) and the suitability of the sealant for the materials to be sealed and the expected range of movement. A sealant should be selected that best suits the service conditions.	Selection of Materials Source: CMHC Research Report: Incompatible Building Materials (2003)
Solvent-based sealants (or adhesives) and polyethylene or polystyrene foam insulation	Solvent-based sealants (or adhesives) cause the degradation of polyethylene or polystyrene foam insulation. Manufacturers of sealant do not control its formulation. Recommendation: for residential construction, use latex (acrylic) butyl, silicone sealants or adhesives with polystyrene rigid insulation.	Selection of Materials Source: CMHC Research Report: Incompatible Building Materials (2003)
General requirements for Silicone Sealants:	- Silicone sealants do not hold paint well and thus should not be used in areas where painting is required. - When re-sealing, other types of sealants do not bond well to silicone sealant, so use silicon sealant. - Where ponding is expected, a primer should be used, especially when used with concrete.	Control of Design. Source: CMHC Research Report: Incompatible Building Materials (2003).
(Poly)urethane sealants and polyethylene sheet.	There is normally very poor adhesion between (poly)urethane sealants and polyethylene sheet. Selection of sealant should be selected for long life.	Selection of Materials Source: CMHC Research Report: Incompatible Building Materials (2003)
Asphalt materials and sealant	Asphalt roofing materials contain solvents that can damage (poly)urethane sealants. Only use sealant recommended by manufacturers of asphalt materials.	Selection of Materials Source: CMHC Research Report: Incompatible Building Materials (2003)

Paint	Paint to be applied at temperatures above the recommended minimum application temperature. For instance, latex paint must have a min. temperature of at least 10^{o}C for it to be effective.	Control of Design (Specficiation) Source: CMHC Research Report: Incompatible Building Materials (2003)
Wood subfloors and resilient floors	Certain wood subfloors emit surfactants that can damage (cause discoloration) of resilient floors. Verify with the resilient flooring manufacturer the types of wood panel sub-flooring that will be compatible with their warranties. Note: In many cases, warranties will be voided if unapproved products are used.	Control of Design Source: CMHC Research Report: Incompatible Building Materials (2003)

6. Conclusion

Housing is central in the shaping of any cultures. In the North of Canada, several unique geographical, climatic, social and economic factors create multiple challenges to building homes. The region's low population density does not support the needed human, transport and energy infrastructural to deliver homes. Despite these differences and more severe weather conditions, housing is based on codes, regulations, and standards developed for southern regions.

With growing concerns about climate change and the North's desire to become less dependent on fossil fuels, governments identified lack of housing standards as an urgent problem for the North (Nunavut, 2007; CMHC, 2007).

This thesis presents the development of a protocol for low energy homes (LEH) for northern Canada. It identified areas of interest and challenges for the region through literature review, interviews with occupants and builders, and data analysis of 1744 homes in the NWT from the EnerGuide energy rating service (ERS) database. Next, a reference home was modelled to study key design parameters and solar strategies such as thermal resistance values of the building assemblies, thermal mass, window-wall ratios, BIPV/T system's size and capacity, night window shutters, shading schedules, and ventilation rates. A protocol for low energy homes for the North is presented that integrates the Canadian, North American and Europeans housing standards.

The city of Yellowknife introduced the EGH80 by-law, an energy efficiency regulation for homes. The EGH80 by-law was successful in pushing builders to construct better homes. This research compared 225 homes built between 1990 and 2009 to 102 homes built between 2010 and 2015 to show the impact of this regulation. In all eight performance indicators studied, homes built after 2010 were remarkably better; they had 42% more insulations in walls, 34% more insulations in ceilings and were 36% more airtight. Homes built after 2010 used 12% less electricity and reduced total energy consumption by 30% compared to homes constructed in the previous decade. Of the 102 homes evaluated since 2010 in Yellowknife; the mean EGH rating for homes was 79.

A reference home was modelled in MATLAB using the explicit (forward) finite difference method. This research showed by using recommended values from the parametric study for key design parameters and solar strategies, the reference home's energy consumption for space heating and cooling can be reduced by 49%. This study showed the window-wall ratios to have a significant impact on energy consumption. By increasing the WWR ratio of the reference home from 20% to 70%, its total annual energy use for heating and cooling is reduced by 20%.

This research recommends using triple glazed, Low-E, argon-filled windows with a WWR of 70% on the south façade and have high thermal resistance values for the building envelope. The optimized house used the follow thermal resistance values which may be utilized by northern builders: RSI 8 for walls and RSI 9 for floors and ceilings. This research also recommends the use of night window shutters as they showed to reduce heating loads.

Although the North is a heating dominated climate, overheating in the summer was cited as a problem in the literature review. Integrating more thermal mass in the floor reduced overheating in the summer months. Thermal mass also reduced heating loads in the shoulder seasons. This research recommends the use of 5cm concrete on the floor for thermal mass. In communities that lack access to concrete, the doubling the gypsum layers on the interior walls should yield similar benefits.

The modelled BIPV/T system generated 80.5 kWh/m^2 of electricity, and 301.1 kWh/m^2 of additional thermal energy – but, most of this energy could not be used for heating as the energy was mostly generated in the summer.

Northern Canada imports almost all of its heating fuel and the cost of their energy is very high. The recommended design strategies and values for design parameters in this research can offset energy bills for families, and make housing much more affordable.

The main contributions of this research are:

1. Optimization of solar design strategies and key parameters can achieve a 49% energy savings. This findings gives policy makers a methodology for displacing housing energy demand by promoting the results of this research to builders such as better orientation and optimizing the window-wall ratios for solar heat gains, and integrating thermal mass in floors and on interior walls.
2. This thesis presented the development of a protocol for low energy homes (LEH) for northern Canadian regions. The protocol integrated the building envelope system with solar design strategies. Local standards and codes have not addressed solar design parameters.

3. Analysis of the EnerGuide’s ERS database showed builders adopted the City of Yellowknife's energy efficiency by-law for homes. Arctic Energy Alliance presented this finding to the City Council of Yellowknife. This finding has important implications for policy makers – as it is a stepping stone for similar by-laws to be introduced in other Canadian municipalities.

Recommendation for future studies should include:

1. The North’s population is young and rapidly growing. Communities would need to build more houses. Future studies on community planning should integrate solar strategies. Currently, lot layouts for homes do not consider southern sun exposure.
2. The HVAC systems should be integrated with the heat recovery ventilators and solar collectors – better control algorithms should be designed for northern climates based on the outlet temperature of supply air. These systems should be easy to operate requiring minimum maintenance.
3. Future studies are needed on night window shutters for the northern regions. Night window shutters showed to offset heating energy requirement in the north. The primary concern with night shutters is using them during the winter without it freezing.
4. A demonstration home should be design, built, and monitored that integrates recommended strategies to reduce energy consumption of a northern home.

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Appendix A: Occupants' Interviews

Between April 22nd to May 19th, 2015, the author surveyed four occupants and their homes were evaluated through a walkthrough survey. This section presents questions asked in the interview and their answers.

Background Information:

- What year was your home built?
- What year did you move into your home?
- How many occupants live in the house, and when are they usually in the house?

Occupant 1: The house was built in 2012, we moved in 2013. We are two adults and 3 children in this home. We go away in the summer for a week or two. Typically, our home remains empty between 8 am to 6 pm.	**Occupant 2:** Our house was built in 1984, and we moved in 2004. There are 2 occupants. I work 9 to 5, but otherwise I am home. My partner is home every 2 weeks for 1 week.
Occupant 3: This home was built in 2008, and we moved in thereafter. We are 2 occupants, and we both have a 9 to 5 job. We usually go on vacation for 1 month every year.	**Occupant 4:** This house was built in 2013, and we moved in the same year. We are 2 adults, and 2 kids. We are out of the house between 7:30 am and 5pm. We are usually at home in the summer as well.

Indoor Comfort:

- What are the indoor temperature settings for each room? Are you able to control the indoor temperatures? Do you find the space too cold, or too hot? In which rooms and around what time of the year does this happen?
- Do different occupants have different indoor temperature preferences and if so, what are their preferences? Do you have different temperature setbacks for the night? Are there different temperature setbacks for different seasons? What are they?
- Does it get too hot in the summer months? What do you do when there is overheating? (For instance, do you use heavy drapes to block out the sun, air conditioning, or open the windows?) How about the winter times? Does it get too hot inside? What do you do to improve such situations?
- Do you use space heaters in the winters? If so, how long do you use the heaters for?
- Do you notice any visible moisture issues, or mold on your walls/windows/doors? Which rooms have these problems and what steps had you taken to improve these situations?
- Do you feel the air is too stuffy in the winter? Is there enough fresh air in the house? What actions have you taken to improve these situations?

Occupant 1: Our home is a single zone. I grew up in Africa, so I like it pretty warm but not my wife. 21.5°C is the happy medium for us. Our upstairs end up being a little warmer. We use a forced air systems, so heat rises to top. Pellet stove down here – we try to use that to heat the house as much as possible. During the day, we have a smart thermostat that automatically keeps the home at 16C when we are away. We keep the garage at 10C – but we only have a 2in and a half wall between the garage and interior, so that can be a problem. The upstairs can get quite hot in the summer. We pull the blinds down to help; we have a fan in the master bedroom. We have a pellet stove. Before the stove, the propane sometimes gelled when it gets really cold. We turn off pellet stove when we go to bed, and the forced air system kicks in and keeps it at 18 to 19 degree. We had moisture problems when we lived here; it was due to the fact that the house was brand new. We had a dehumidistat that kicks in at 40% relative humidity. We also use a timer on our HVAC to bring in more fresh air, and that has helps. We also had issues with frost in the garage, but we used a dehumidifier to bring the R.H from about 50% to 30% and that helped.	**Occupant 2:** We keep our home at 20°C and 16°C when I am out of the house but we have no night setbacks. I feel comfortable in the house, in the winter time when it gets very cold, I use our wood stove to heat the home. In the summer, it feels very comfortable. I don't even own a fan. There is a little bit of moisture problem in the bathroom. However, I do not use the bathroom exhaust fan because it makes too much noise. In the winter time, the air gets very dry. I had my windows replaced – there is some condensation and in the winter, it gets frost. I also get drafts from my windows. Most of my new windows are double or triple pane. The older were double pane windows. The permafrost is melting, and I had two different parts of my house leveled by 5 to 10 inches. I know friends who live a few houses down with the same problem – there is an old river bed that runs through here.
Occupant 3: We set the temperature at 20°C and have a night temperature of 18°C. If it gets too hot in the summer, we open the windows and use fan. There are some moisture issues we see in the house, especially in the corners, we have condensation and frost. There is also some moisture on the ceiling. We can see it was damaged, but we found out there was batt insulation that was missing.	**Occupant 4:** Downstairs about 20°C to 21°C, 18°C in the night. We have a forced air furnace. We thought it would be really hot in the summer, because we have a lot of south-facing windows, but it was actually nice. Downstairs is cooler. We use shades, which make a lot of differences.

Windows and Doors:

- Are there visible condensations around the window? Do you notice a lot of air coming out of a window? Which windows and when do they occur? Do you notice anything interesting about these occurrences? For instance, does it happen around spring? Or after somebody has been in the shower?
- Houses can have insulated night shutters that will automatically close during the night. The motorized shutters would use some electricity, but there would also be potential energy savings. Would you consider these night shutters on your house if they cost $1000 per window unit? Do you feel it is suitable for Yellowknife? Why or why not?
- In the winter, do you have problems shutting or opening your doors or windows? Are there any steps you take to improve this situation?

Occupant 1: When it is really cold – we do see some frost on doors, but as soon as we lift up the blind in the morning and the sun comes in, the frost goes away in an hour or so. For night shutters, it depends if there is a good payback period. I would definitely consider it. When it gets to minus 40C, and you had opened the door, the weather stripping won't come to its place – so we don't try to open the door in the winter. This door opens to the outside. Our front door opens to the inside, and we do not have the same problems. We use the garage door to go out. Generally, the floor area in front of our front door is very cold – it is hard wood. We are considering putting in floor heating in the front area, so we can use this space.	**Occupant 2:** I would not consider a night shutter; I rather prefer spending money on better windows. Also, I would not want to wake up to the noise of shutter opening and closing. I need to keep one of my doors closed in the winter. I do have some issues with the doors, there is frost and it gets stuck and won't close, but I put in better doors with more weather proofing.
Occupant 3: We see frost showing up on walls, corners (where the insulation may be away from joist). There is poor detailing in this house. For instance, a chunk of batt insulation was missing from the ceiling – there was condensation and moisture problem in that area.	**Occupant 4:** We get frost on the windows when it gets really cold. We would consider shutters, especially if it reduces our energy consumption. We really put in a lot of money into our house to reduce its energy consumption.

HVAC systems:

- Do you have thermostats, humidistats, (heat recovery ventilator) HRV, and ventilations controls in your home? Which ones? Are there any challenges you face with these controls? For example, do you have trouble heating your house to a desired temperature?
- Is there a CO detector in your house, in which rooms?
- Do you know what a heat recovery ventilator is? A HRV brings in fresh air from the outside and exhausts stale air from inside. The heat recovery core of the HRV transfers a portion of heat from the indoor air to outdoor air. HRV take out excess indoor moisture, while bringing pre-heated fresh air.
- Can you tell me a little bit more about the HRV? Are you satisfied with it? Have you encounter any problems with it? Do you feel such a system is suitable for Northern climates? Why or why not?
- What type of heating appliance do you have? Have you heard about wood pellets that can be burned in pellet stoves, boilers and/or furnaces? Do you have any of these systems in your house, what is your opinion regarding them?

Occupant 1: We have a CO_2 detector our mechanical room, garage, and on both floors. We have a temperature sensor too, so it will alert us and the security company if it gets too hot (like a fire) or the house drops below 7 C. When we first got our HRV system, I was considered because it was not rated for the North but it works well. It is not too loud, and we have a single unit, with our HRV and furnace – it is ideal for our small mechanical room. Though, I would like to be able to recirculate air from the house, but they require us to have a separate HVAC system for that. The upstairs is warmer, so that could have helped cool the upstairs and warm the downstairs. Our HRV works more on colder nights, and so far we have not noticed frost in it. When we first got our pellet stove, there were some problems because there was not enough insulation in our outdoor air duct. But, we got that fixed now.	**Occupant 2:** I have 1 thermostat, but no humidistat. My log house is quite drafty, so there is a fair amount of air coming through. So, I do not have an HRV – there was a lot of air leakage also from the windows and doors. I remember this from my energy audit. Propane furnace and I also use a wood stove using chopped wood. I think wood pellets are nice, they are probably less expensive – and what I do not like is that when the power goes out, they stop working and we have had quite a few power outages when it was very cold outside.
Occupant 3: We do not have an HRV here. Our house is quite drafty and not tight enough. They have a purpose if you have an airtight house. But you need airtight house for them to beneficial. We have an electrical hot water system; it is a lot less expensive than using diesel fuel. We have a furnace for heating.	**Occupant 4:** We have 1 thermostat, and 1 humidistat. Our bathroom exhaust and kitchen exhausts are hooked into our HRV (so, each time we use these devices, the HRV turns on for 20 or 40 minutes.) We have a modular home, but the HRV manufactures were different. I am not too comfortable with the HRV and how it was set up but not a lot of contractors here know much about the system. I don't like to have it on constantly, so I like the fact we only use it when we are using the bathroom. So far, we have not had frost problems. We have a high velocity forced air boiler, and radiant heaters that use propane. It works fine for us.

Challenges in the Winter:

- What are the challenges you face with your house in the winter? For instance, do you encounter freezing of the pipes? Do you remember what may have caused it? Did something leak, or was it related to a mechanical issue?
- How long would you leave your house without running waters? When you go on vacations, do you take any precautionary steps? May you explain these steps? For instance, do you have somebody to run the pipe every 24 hours so the pipes will not freeze?
- Do you winter proof your house? What do you do to winter proof your house?

Occupant 1: If we are going away, that is not a problem with us – our new alarm system works well, we will find out if our house drops below 7 C. The alarm could call a friend for you. If I leave my house for more than two weeks, I would definitely have someone come in and run the pipes and flush the toilets. We do winter proof our house, we try to put plastic wrap on windows, but the kids just destroy it.	**Occupant 2**: In the winter, there has been occasional freezing of the pipes – what I have been told; the house shifted a little bit. So, the gradient to the sewer tank is not proper, so it slows down the flow so the water sometimes sits there and freezes. There is a private contractor that steams the pipes to unfreeze it (about $140 each time.) I would not leave my house unattended in the winter for long time. I usually stay in Yellowknife. I do winter prove my home. Replace weather stripping, put plastic over windows.
Occupant 3: Pipe froze when the valves were shut by the city, so we had to get someone to come fix that. We had to replace our hot water once, because it started to leak.	**Occupant 4**: Icing around the door noob. The vent stacks for the plumping systems freezes up, causes a little bit of smell from the sewage tank. We winter proof the doors we don't use. So, two doors in the house.

Retrofitting:

- Has there been any retrofit that has happened since you brought your house? Are there any parts of the house that you would like to retrofit in the future? What are they, and why?
- What do you like most about your house, and what do you dislike about it? Is there anything you would like to change in your house? What would they be? Have you noticed anything particularly different about your house (compared to that of your friends, and neighbors) – for instance, you feel that your house uses too much energy or is very efficient?

Occupant 1: We added a pellet stove; the heat is much nicer with it. One of the things I am looking at doing is putting in some pot lights around the living area here, and maybe some in floor heating in the front door area to make it useable. I dislike the orientation of the house, it is not south facing – and I would like more light coming in. A tiny long horizontal window would be helpful to save on daylight savings. It would be useful to maximize natural light coming in. With the pellet stove, the home is much more comfortable around here. I like that my home is quite energy efficiency, I noticed our consumption of the house has remained the same as our condo for the most part (despite the house being much bigger).	**Occupant 2:** I do not like how much energy the house uses. I have gotten a new furnace, new windows, and wood stove – it helps. I do not like the fact that my house is sinking – repairs are extraordinary expensive here. Overall, I love this house, it is a beautiful house, it feels homely and it is welcoming.
Occupant 3: I really like the location of the house.	**Occupant 4:** I would like to maybe put some solar or wind turbine for the house – power sometimes here is unreliable. Also, spray foaming the floor –the crawl space below is not insulated. We like our house, it is perfect for us. We really do not have much complains – perhaps it may be a bit too big for us, but that is not really a problem for us.

Perception of future northern housing:

- There is currently an idea of net-zero energy housing. The gist of it is to have low energy consuming homes that is also capable of generating power using renewable resources such as solar power. When the power generated on an annual basis can match the power consumed, we call that a net-zero energy home.
- Do you feel such housings would be appropriate for Yellowknife? Why or why not?
- If you were building a house, how much more are you willing to pay for such a house (20%, 30% more?) What do you think is a comfortable payback period?
- How do you envision the future of housing in Yellowknife? What do you see as the future of energy efficient house? Are there any other issues regarding your house that I may have missed that you would like to share?

Occupant 1: Net-zero housing would be great for Yellowknife since power is so expensive. Especially if we can sell back to the grid at the rate they charge, that would be really great! I am not sure how it would actually be implemented – during the winter, the sun is not really there. Though, in the summer we got 24/7 sunlight.	**Occupant 2:** I would be interested in solar panels if it can cut my energy bills. I am certainly willing to look at different approaches to making homes energy efficient, but it has to be within my budget. I would like to see better energy efficient homes, especially in the North because energy is so expensive here.
Occupant 3: I would pay about 20% more for a net-zero home, but in Yellowknife, you don't get any benefits for overproducing any energy. To me, that would remove the incentive. $15 000 to $20 000 for solar panels would be good if the payback was something like under 10 years. In Yellowknife, not everybody wants to stay around for 10 years.	**Occupant 4**: We put in as much any we can to make this home as energy efficient as we can. If there is a good payback period, we would consider investing more money to make the home energy efficient. We are very interested in solar and wind.

Appendix B: Builders' Interviews

The following presents questions and answer from four builders, and two architects. They were surveyed in Yellowknife from April 22 to May 19.

<table>
<tr><th colspan="3">**Question:** What are your energy performance targets for new buildings? How do you come up with these targets (for instance, do you aim to meet the new Yellowknife bylaws (EGH 80?) Or are your energy performance levels of houses driven by client's wants, or are there other factors?</th></tr>
<tr><td>**Builder 1:** We meet the city's by-law of EGH 80. Though, our energy targets are very client driven, some clients are happy with cheaper energy bills and they are willing to pay more.</td><td>**Architect 1**: We aim for EGH 80.</td><td>**Builder 2:** We built social housing; all new construction should meet EGH 80 or be 25% better than 2011's Model National Energy Code of Canada for houses.
Since we design for the whole territory, we generally take worst case scenario (coldest regions) and built across NWT based on that region.</td></tr>
<tr><td>**Architect 2:** The aim should really be net-zero energy homes.
One of the challenges is that people from the South come to work here for a few years, so when they buy their homes, they don't care about energy efficiency because the payback period is no good for them.
Builders should meet minimum code requirements. When we have new regulations with strict energy efficiency requirements, everybody complains that homes become expensive – so, the issue becomes political.
Home should be built with high R values, like R50 for walls and R80 for ceiling – and we should not be using central heating systems.</td><td>**Builder 3:** I do not consider energy performance targets, because I mostly do interior works and retrofits.</td><td>**Builder 4:** The energy performance targets of buildings should be client driven – we usually try to give homeowners the '*best bang for their buck*.'
I feel EGH regulation is not appropriate... it is unnecessarily expensive, and blower door test does nothing to help us.
We have to comply with energy requirements from the city by-laws. If not, we also used the 1990 National Building Code of Canada.</td></tr>
</table>

Questions: Passive and Active Solar Design

- Have you ever considered passive design strategies in your homes? For example, do you consider south-facing window sizes in relationship to the sun? What are the governing factors that contribute to your window selections and sizing (energy efficiency, view, or cost)? What are the considerations towards designing energy efficient houses? In your opinion, how do you feel we should approach energy efficient homes in Northwest Territories?
- How do you feel about active solar energy systems, such as PV panels, or integration of solar thermal systems in buildings? Do you feel the construction industry is moving towards integration such systems in the North? Have your clients shown interest or asked about these systems to be installed in their homes?
- Do you think solar hot water system is economical feasible? Have you implemented a PV or solar hot water systems in any homes? What is your experience with it? What were the challenges?
- Do you know about BIPV systems? Unlike a PV system, BIPV systems are integrated within the building facades. Do you feel such systems are suitable for northern regions? Why or why not?
- Are houses solar ready? That is, are houses built to allow for future addition of larger windows, or BIPV or PV systems?

Builder 1: We try to consider window size in relationship to the sun. The challenge is how the streets are laid by the city. There is very little consideration for passive solar design. For us, windows are driven by customer needs, such as southern exposure, views, and bedroom windows.	**Architect 1**: Homes should be solar ready for PV panels. Homes should be oriented along south façade. Window to wall ratio should be around 15%.	**Builder 2:** We don't pay too much attention to passive solar heat gains, or orientating the home for the sun. Though, we do orientate the home facing south but that is because we want to install active solar systems.
Architect 2: Passive solar strategies make sense for the North. We should be trying to use some of the solar heat gains. Yellowknife's energy comes from hydro, so we need to question if it makes sense to add PV panels here. In communities that depend on fossil fuel, PV panels are a straight forward yes.	**Builder 3:** I do not consider energy performance targets.	**Builder 4:** Yes, I try to orient buildings towards the south.

Questions:

- What type of construction assemblies do you use for your homes? Do you work with stick-built, prefabricated (trailer,) or modular construction? Which ones of these approach do you prefer and why?
- What are the R-values for walls, ceilings, floors and foundation? What types of windows do you use in your houses (triple pane, low-e coated glazing?) What R-values and windows would you recommend?
- What type of attic construction do you use, vented or unvented attic? What are the reasons for your selection?
- What is the air change per hour (ACH) that you aim for when building houses? Where you able to achieve that ACH for recently built projects? If not, what are the challenges in reaching the desired ACH?

Builder 1: We built non-vented attics. We use spray foam, which provides a perfect air and vapour barrier. We don't get moisture issues with our type of roof. We use 2x6in wood stud walls, with 2.5 in of spray foam on the inside, and plywood sheathing on the outside with 4in metal z-bars @ every 36in horizontally and sprayed with an additional 3.5-4in of foam on the outside. This gives us a R40-50 wall. Our spray foam method also eliminates a lot of thermal bridges. We use 10in of spray foam in the ceiling to get R60. The floors are R35 with 7in of spray foam. We only do 3in of spray foam (R15) if underneath slab. We use triple pane, argon filled window, with low-e coating – and we place the window in the middle of the assembly. We aim for an ACH of less than 1.	**Architect 1**: We design vented attic, but non-vented can be done with spray foam. We use a double wall system, two 2x4in wood stud wall with 5in of space in between them - this gives us a total of 13in space to fill with Roxul insulation (R50). The roof is R60, filled with cellulose insulation. We use triple Pane, low E, and argon window with high solar gains (R4). We looked at potential use of night shutters with manual exterior louvers. We aimed for an ACH of less than 1. We use two systems for our air barrier, first a typar air barrier on the outside, and then a polyethylene film vapour barrier on the inside.	**Builder 2:** For the last 20 years, we used typical conventional stick frame houses. That is a 2x6in wood stud wall with batt insulation, and a 1.5in of semi rigid insulation on the inside (R30). Floors are R40, and ceilings are R50. We sandwich a 6m poly between two sheets of drywall with vapour barrier paint – this gives us a Structural vapour barrier. Below the tree line, we built vented attic. Above the tree line, we built non-vented hot roof – though there are moisture problems with these roofs. We use triple pane, 9 to 13mm space, non-metallic spacer, low-e film, with argon fill. (Zone D rated, with minimal air leakage of A3 rating, water leakage of B3 rating, and wind resistance C4 rating.) And our homes are ACH 1.5, verified using blower door test.
Architect 2: You need 15in thick walls with regular insulation to get R50, which is great for Yellowknife. You can use foam and get thinner walls. But, some communities don't have the facilities or equipment to use spray foam so it can be panelized, but they are difficult to transport. Should use vented attics for Yellowknife – this would be more of an issue in Inuvik. Non-vented attics will work with foam insulation system, since it is not difficult to get 100% vapour barrier in the ceiling. Otherwise, it is problematic as there are moisture issues. We should use triple glazed, solar gain windows - since it is easy to accommodate for the overheating.	**Builder 3:** Typically, we use a 2x6in wood stud wall with Roxul fill, a vapour barrier, and then a 2x2in horizontal strapping with rigid insulation (R30.) We aim for R50 to R60 for our ceilings. Prefer to use vented attics. There were a lot of unvented flat roof done in Yellowknife in the 80s, but there were moisture problems.	**Builder 4:** We use an R28 wall by using a double wood stud wall (2x4in) with staggered studs and filled with Roxul insulation. Then, we have interior strapping with 2x2in. When there is a crawl space, we aim to get an R28 floor and R55 to R60 for our ceilings. We use regular trusses, with vented soffit. We prefer vented roof because it is the standard way we have done it, and we do not have any problems with it.

Question:

- What is your perspective on prefabricated systems? Do you approve of such a system for Yellowknife (and NWT)? Is it a more economical approach to bring pre-fabricated systems from the South?
- How about in terms of energy efficiency? Do you feel prefabricated homes are energy efficient? What are the current energy efficiency levels of prefabricated systems? What do you think the future targets of these systems will be? What are the advantage/disadvantage of prefabricated homes? Do you feel there is a future for prefabricated homes in the North?
- Have you ever considered structural insulated panels system? Do you feel it this is something that you may consider working with in the near future, why or why not?

Builder 1: We used SIPs but it had a double vapour barrier and rotted out. In NWT, they do not have good reputations since they were used a few decades ago and there were lots of problems with them. SIPs also have limitations – they are difficult to customize. I like to consider myself a true builder, and I like to actually build homes. Modular homes tend to be built to the minimum building codes and standards – they do not last very long.	**Architect 1:** The big challenge with modular homes and SIPs are that in more isolated communities, cranes and other equipment to build such homes are not available. Personally, I do not like SIPs, the ESP gives off gas.	**Builder 2:** We considered prefabricated systems years ago. But, they did not meet our standards. They are getting better. We deliver modular housing for market rental housing (for full waged workers such as RCMP, teachers. etc.) We can capture 100% of rental fee for those homes. We like to provide as much northern input as possible in terms of material and labour; there isn't much material/labour component available with modular houses. We use SIPs in floors and ceilings assemblies - they go together quickly and they have good integrity since they have good drainage. They often have fewer mistakes and fewer thermal bridges. They are a bit finicky in walls and they need to fit just right For public projects, local contractors are given 15% headway on projects – thus, we have two competing mandates when we try to import prefabricated homes from the South.
Architect 2: Prefabricated homes make sense to me. I guess it really depends on local labour cost. If labour cost is high, prefabricated homes are good for that. It is difficult for smaller communities due to transportation limitation. There are some environmental concerns with foam used in SIPs.	**Builder 3:** I think prefabricated homes are a great idea since we have very short building seasons, and not a lot of skilled labour. I feel it will fit really well in the North.	**Builder 4:** No problem with prefabricated homes. Transportation is difficult; a lot of them come here damaged. Though, if you get the right design, it might be a good deal if you transport it here.

Question:

- What is the most common type of heating appliance you use, and why? Do you prefer force air system or hot water system, and why?
- Have you installed wood pellets stoves, boilers and/or furnaces? How suitable do you feel these systems are for NWT? What are the attitudes of your clients for these products?
- Have you installed a HRV systems homes? If not, why? Have you had any calls back on these systems, what did your clients tell you about them? What is your take on HRV systems? What are the challenges with the HRV systems?

Builder 1: Almost exclusively boilers – they distribute heat better (radiant heating), and there is more control for occupant. Propane can gel-up when it gets too cold. HRV are great, as long as you make sure they are installed properly. There tends to be call backs for HRV when clients don't want to run them, but when homes do not use HRVs, owners find a lot of humidity in the home.	**Architect 1**: We built a home with single point of heat source (wood pellet stove). But, the city of Yellowknife requires a back-up central system. HRVs are not needed if toxic gas emissions were carefully controlled.	**Builder 2:** We typically use forced air systems for single detached homes. For larger homes, like duplexes – hydronic boiler systems is better. We mostly use diesel, but biofuel is becoming more popular. We try to integrate the HRVs and solar systems for much larger applications. Since homes are super airtight, we need ventilation. But, HRVs on the markets are not rated for northern climates. They often go into defrost cycles. So, we have to provide pre-heated air to the HRV even if it brings down its efficiency. Also, the North does not have the technical expertise to maintain HRVs, so there are a lot of issues. We need simple systems; the jury is still out on HRVs.
Architect 2: We install forced air systems. They are great; they take care of ventilations as well. I am not in favour of automated HRVs. HRV should not be legislated. People should control it. If the air change is too high, then there is wasted energy. People in house should be responsible for their own air quality. When the outdoor temperature goes below minus 40C, there is frost. I think passive ventilation systems are better.	**Builder 3:** Propane forced air system also acts as a fresh air intake for the house. We also use boiler systems. I leave HRVs to my mechanics, but there tends to be a lot of problem with them – I get call backs to turn it off. There are complains that they are too noisy.	**Builder 4:** We use forced air systems - but they are hard to heat garages. Pellet stoves are good, and customers tend to be happy with them. With pellet boilers, it was much more complex and difficult to install. I don't feel HRVs are appropriate. We use high efficiency furnaces, and you just get forced fresh air. Plus, when you run bathroom fans, you also bring in fresh air. Clients have HRVs on when they are out of the house and that wastes energy.

Question:

- What are the challenges of building homes in the North? Are materials/equipment easily accessible in Yellowknife (and NWT)? What kinds of equipment are difficult to access in Yellowknife (and NWT)?
- Are you able to find needed skill-labour for your projects? Are you able to find people who can do the work required with the quality you want? Do you have any issues with quality of workmanships? If you are working in the winter, how do you ensure integrity of the building systems, such as the building envelope?
- Does your ability to access materials, equipment & labour presents a major roadblock to housing projects? If so, can you tell me of some of the challenges you have faced?
- Have you ever built homes in remote communities, how do you bring in materials/skill-labour/equipments? Can you share some of the challenges you face in remote communities? What do you could be done to improve these situations?
- What is the window of construction in the year? How early do you start construction and how late do you end it? What is the latest month you were still building? Do you run into challenges when you are building in the winter?

Builder 1: I train my own labour. We have been quite successful in training our own labour for 12 years – we had at least 13 guys go through the "*red seal*" program through us. Spray foam is temperature dependent, so we have to work very hard in the summer to close the building with spray foam, if not – we have to use auxiliary heating to get the temperature right for the foam.	**Architect 1:** The cost of labour here is very high. We consider modular construction – but the challenge with that is finding appropriate cranes for them.	**Builder 2:** Labour is a problem; there is a lack of human capacity in the North. Often, we have to bring labour from the South and that is very costly. Some communities have access only by barge or winter roads – which are seasonal, so materials at times arrive at the end of the construction season. Some equipment (such as tools used by an electrician) may be brought in by air as they can come with the labour. Other stuff, we typically won't fly it in – because it is too costly, and we wait another year. We have two different kind of wall assembly depending on the temperature. Peel and stick membrane on exterior insulation for summer construction. If you know you are going into winter construction, you try to use the traditional wall assembly with the poly on the inside.
Architect 1: In northern communities, there is little source of wood and little source of solar energy.	**Builder 3:** Material is typically not an issue, but finding good skilled labour can be tricky in Yellowknife. Typically, we do a lot of interior works, so that goes around all year around. For the building envelope, we like to get it done by October or it gets too costly.	**Builder 4:** Labour was huge issue 2014. There was a job boom in Alberta, and less people came up North. When we don't have the right people, we (the contractor) need to be more on site to ensure quality. Trusses are difficult to build, because they are large and prefabricated. We worked through winter a lot. We try to finish up by Christmas time – but it is definitely not where you want to be. For example, in cold temperature shingles don't seal properly. The issue is really about time and money – and going into winter makes it more expensive.

Question:

- Have you ever considered passive design strategies in your homes? For example, do you consider south-facing window sizes in relationship to the sun? What are the governing factors that contribute to your window selections and sizing (energy efficiency, view, cost)?
- What are the considerations towards designing energy efficient houses? In your opinion, how do you feel we should approach energy efficient homes in Northwest Territories?
- How do you feel about active solar energy systems, such as PV panels, or integration of solar thermal systems in buildings? Do you feel the construction industry is moving towards integration such systems in the North? Have your clients shown interest or asked about these systems to be installed in their homes?
- Do you think solar hot water system is economical feasible? Have you implemented a PV or solar hot water systems in any homes? What is your experience with it? What were the challenges?
- Do you know about BIPV systems? Unlike a PV system, BIPV systems are integrated within the building façade. Do you feel such systems are suitable for northern regions? Why or why not?
- Are houses solar ready? That is, are houses built to allow for future addition of larger windows, or BIPV or PV systems?

Builder 1: Clients do not ask for PV panels yet – but they do sometimes ask for house to be ready in case they want to install PV panels.	**Architect 1:** We need to look at where the electricity comes from and then decide if it is worth putting up the PV panels. In some communities in NWT – such as Yellowknife – we have hydro-electricity. So, it may not be completely suitable for Yellowknife, we are not offsetting the carbon. But, it gets complicated; we need to further study the payback for PVs in places like Yellowknife.	**Builder 2:** More and more projects now implement PV systems, partially because there is a mandate within the NWT government. We are showing good results as well within our projects – we have a simple payback period of 7 to 12 years, which is good for us. We also built multiplex houses which gives us more opportunity use solar systems. We find PV much more cost effective than solar hot water systems. Also, we noted that solar hot water systems need maintenance while PV can be a plug and play system.
Architect 2: South facing wall should be optimized for windows– I think it is 6%. Though windows-wall ratio should be optimized for shoulder season because the overheating in the summer can be taken care of by cross ventilation. Also, the overheating season is not too long. Regarding PV, there is also the question of how much the utilities are willing to pay to buy your excess electricity.	**Builder 3:** I work with designers and architects. I typically don't participate in the process of how to select windows or how big they should be in relationship to sun.	**Builder 4:** We try chose lots accordingly - for instance, if we have a lot with a lot of southern sun exposure, we put more windows on the south side. We have no clients who went with a PV systems so far.

Appendix C: EGH DATABASE

Energy Performances Based on Type of House

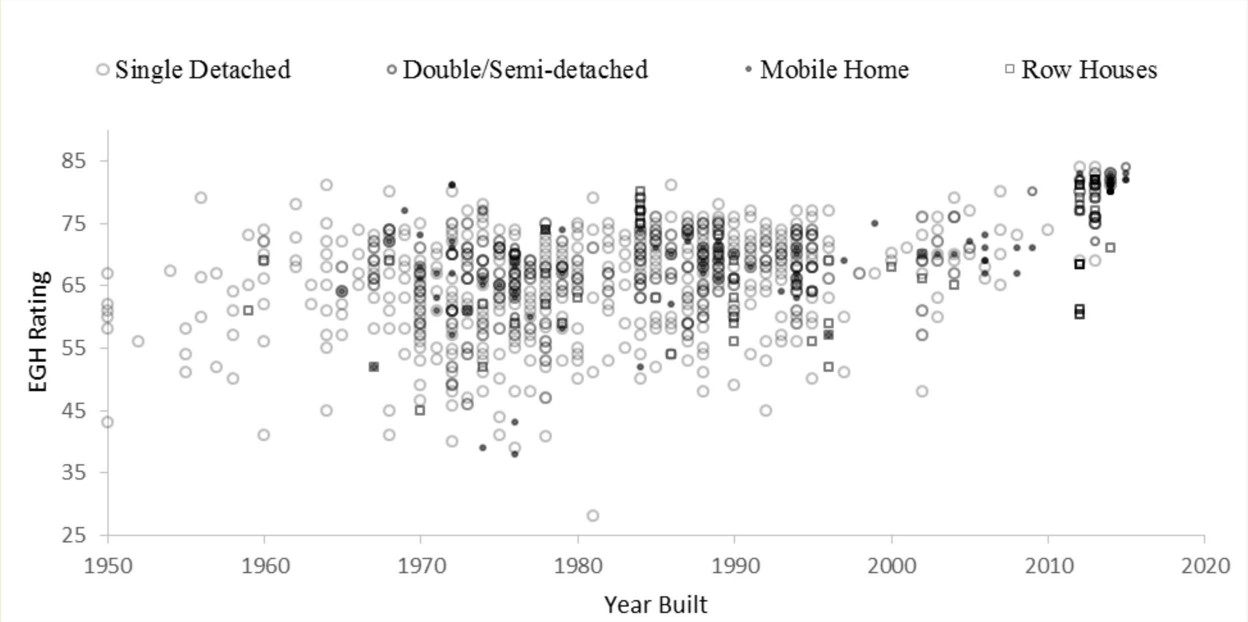

Figure 33: EGH ratings for different home types in Yellowknife since 1950

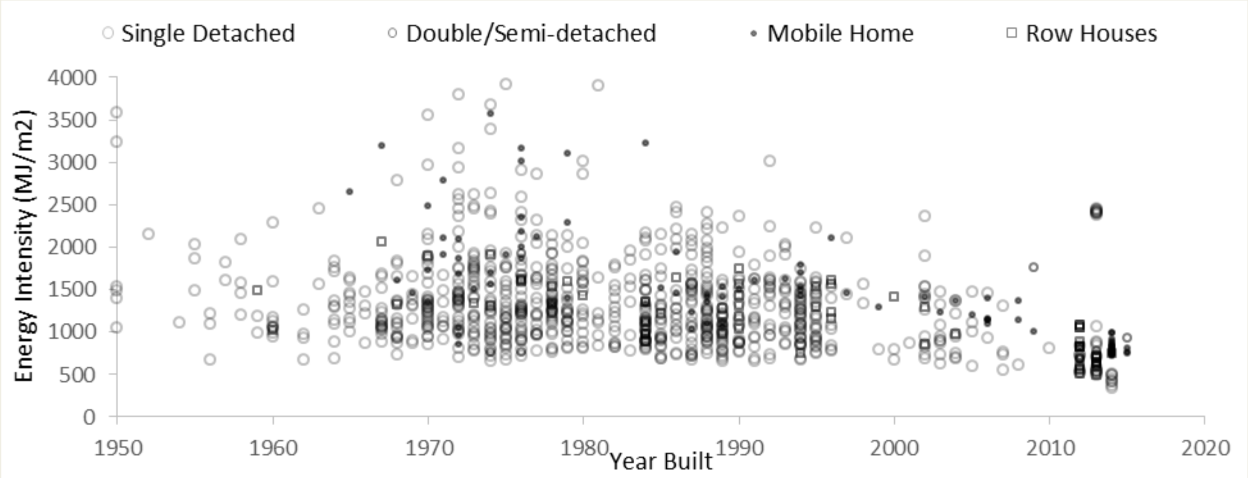

Figure 34: Energy intensity levels for different home types in Yellowknife since 1950

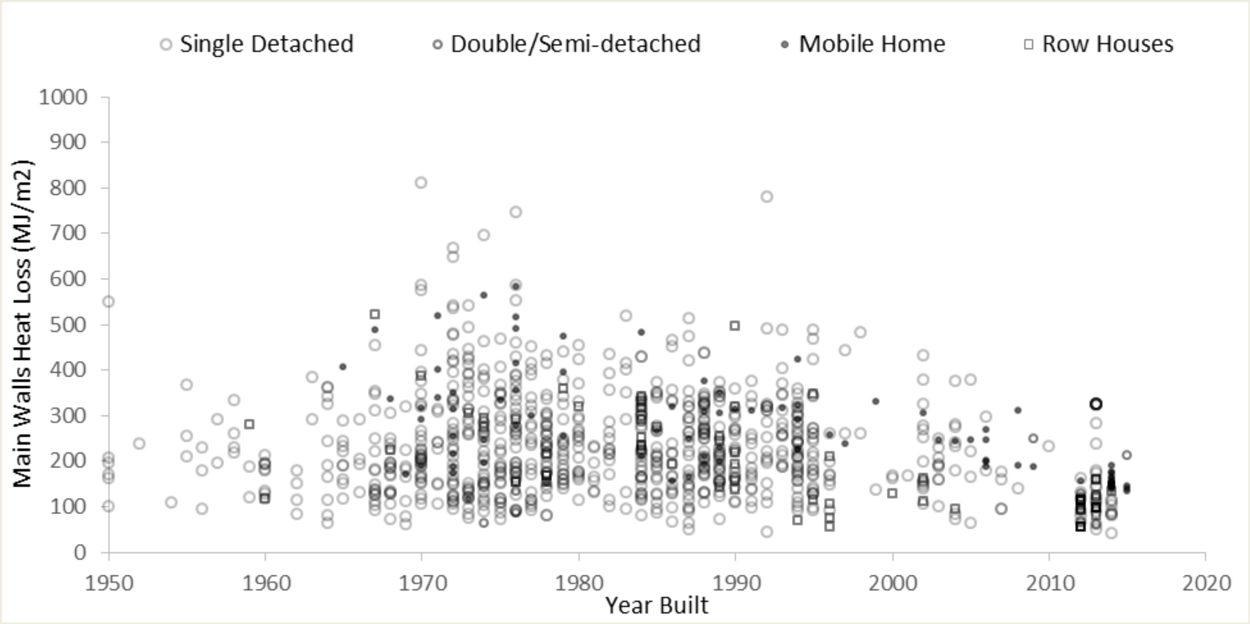

Figure 35: Main walls heat loss per total floor areas for different home types in Yellowknife

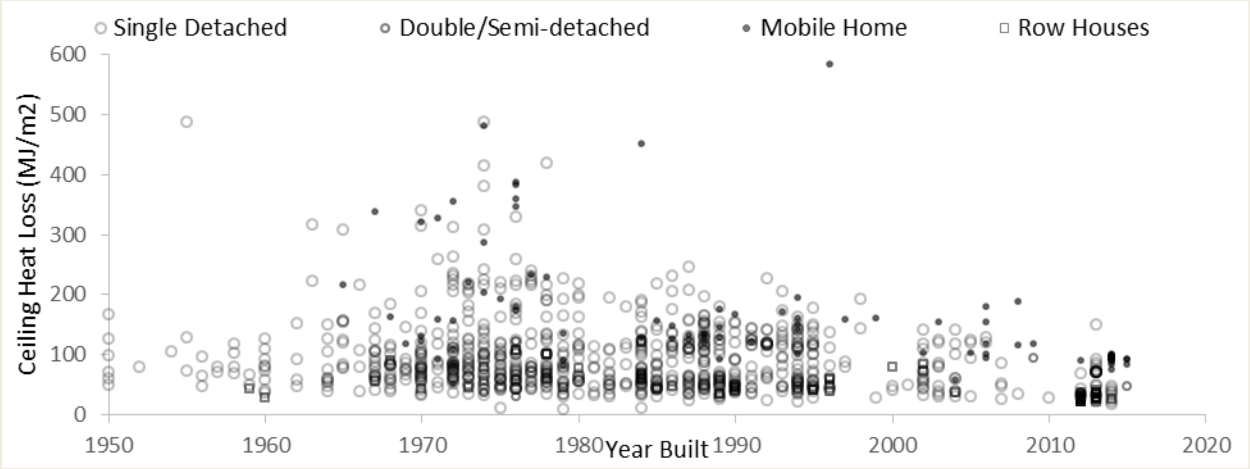

Figure 36: Ceiling heat loss per total floor areas for different home types in Yellowknife

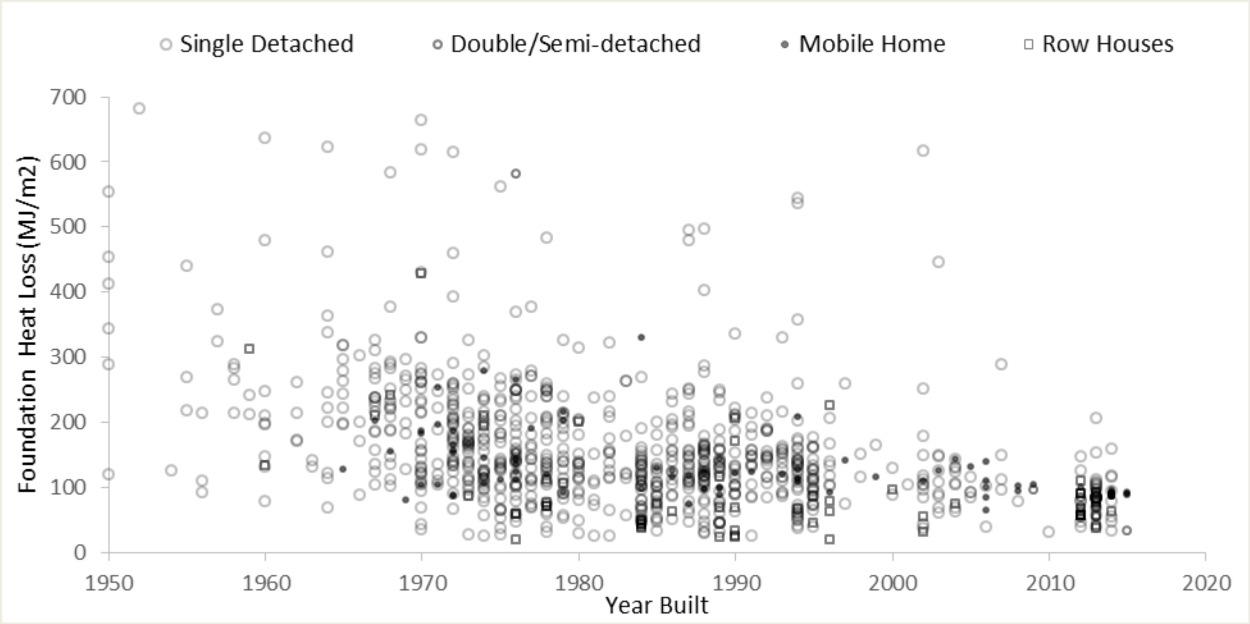

Figure 37: Foundation walls heat loss per total floor areas for different home types in Yellowknife

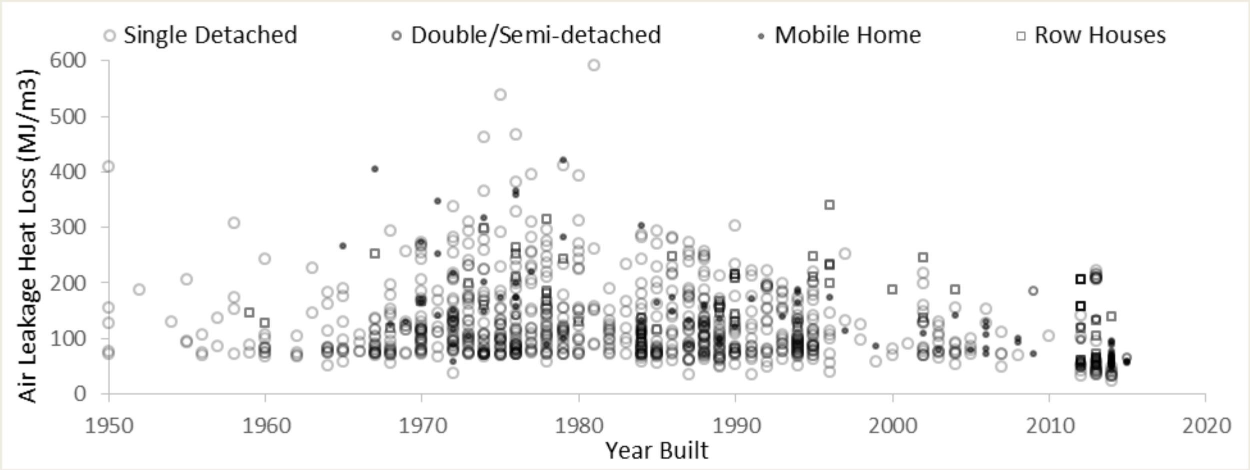

Figure 38: Air leakage walls heat loss per total floor areas for different home types in Yellowknife

			Main wall heat loss		**ceiling heat loss**	
	Year	**Sample Size**	**Mean (MJ/m^2)**	**Standard Deviation**	**Mean (MJ/m^2)**	**Standard Deviation**
Single Detached	1950-1969	102	198	88	97	63
	1970-1979	271	256	129	107	74
	1980-1989	216	237	97	89	48
	1990-1999	140	239	103	89	43
	2000-2009	44	202	87	72	36
	2010-2015	37	172	101	53	27
Semi-Detached / Duplex	1950-1969	N/A	N/A	N/A	N/A	N/A
	1970-1979	3	95	36	63	52
	1980-1989	N/A	N/A	N/A	N/A	N/A
	1990-1999	N/A	N/A	N/A	N/A	N/A
	2000-2009	1	250	N/A	94	N/A
	2010-2015	7	110	51	32	8
Mobile	1950-1969	4	350	136	208	95
	1970-1979	28	329	130	213	117
	1980-1989	15	268	89	154	84
	1990-1999	11	296	58	191	132
	2000-2009	12	236	44	123	38
	2010-2015	31	151	12	93	5
Row Houses	1950-1969	4	285	172	54	26
	1970-1979	12	243	85	72	26
	1980-1989	14	261	56	64	27
	1990-1999	13	192	129	45	7
	2000-2009	13	124	29	68	22
	2010-2015	24	102	28	28	6

Table 33: Mean heat loss per total floor area through walls and ceilings for different home types in Yellowknife

			Foundation Heat Loss		Air Leakage Heat Loss	
	Year	**Sample Size**	**Mean (MJ/m^2)**	**Standard Deviation**	**Mean (MJ/m^2)**	**Standard Deviation**
Single Detached	1950-1969	102	249	120	293	192
	1970-1979	271	176	102	363	210
	1980-1989	216	134	74	326	177
	1990-1999	140	144	93	288	124
	2000-2009	44	153	184	246	93
	2010-2015	37	90	37	226	183
Semi-Detached / Duplex	1950-1969	N/A	N/A	N/A	N/A	N/A
	1970-1979	3	283	260	241	96
	1980-1989	N/A	N/A	N/A	N/A	N/A
	1990-1999	N/A	N/A	N/A	N/A	N/A
	2000-2009	1	96	N/A	461	N/A
	2010-2015	7	60	16	204	89
Mobile	1950-1969	4	141	51	579	332
	1970-1979	28	157	53	499	237
	1980-1989	15	124	60	344	138
	1990-1999	11	125	30	355	90
	2000-2009	12	109	23	247	58
	2010-2015	31	89	3	154	31
Row Houses	1950-1969	4	224	74	402	154
	1970-1979	12	123	111	550	132
	1980-1989	14	69	46	322	106
	1990-1999	13	85	70	496	167
	2000-2009	13	64	28	472	110
	2010-2015	24	70	19	277	145

Table 34: Mean heat loss per total floor area through foundation walls, and through air leakage for different home types in Yellowknife

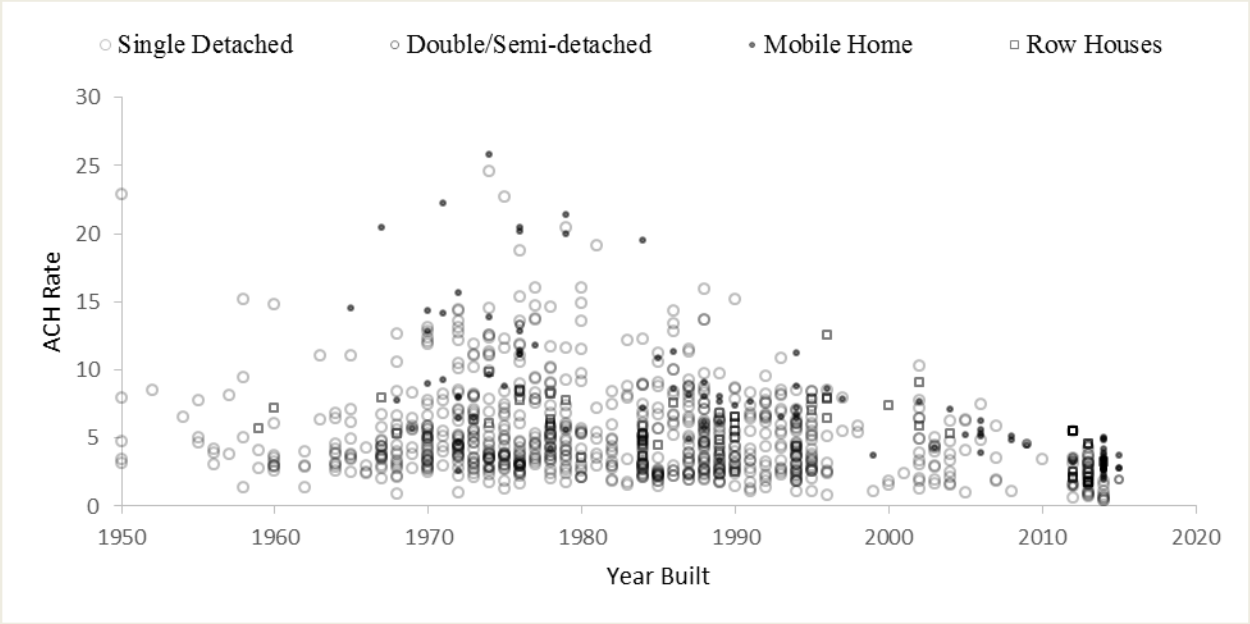

Figure 39: ACH rates at 50 Pa for different home types in Yellowknife

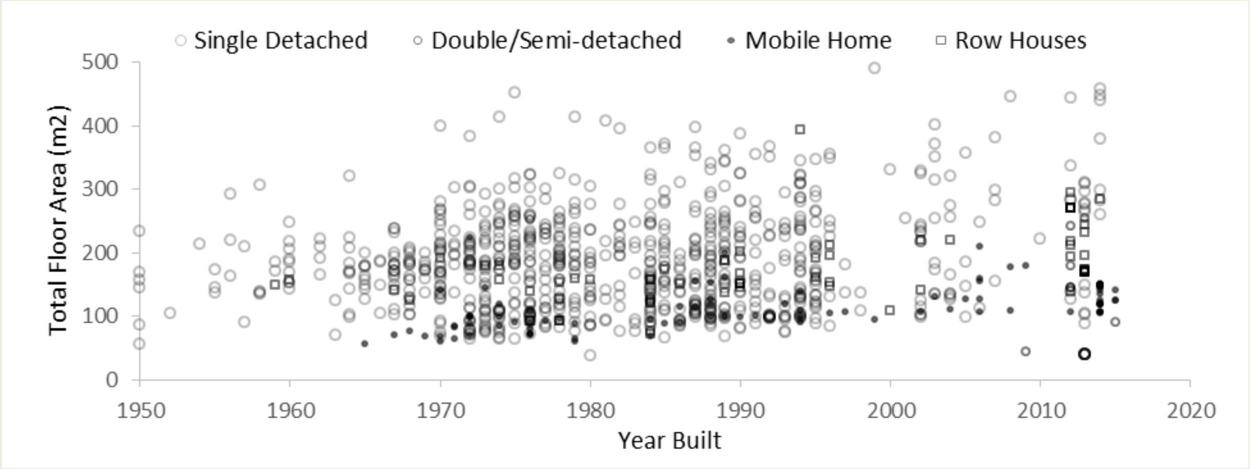

Figure 40: Total floor area for different homes types in Yellowknife

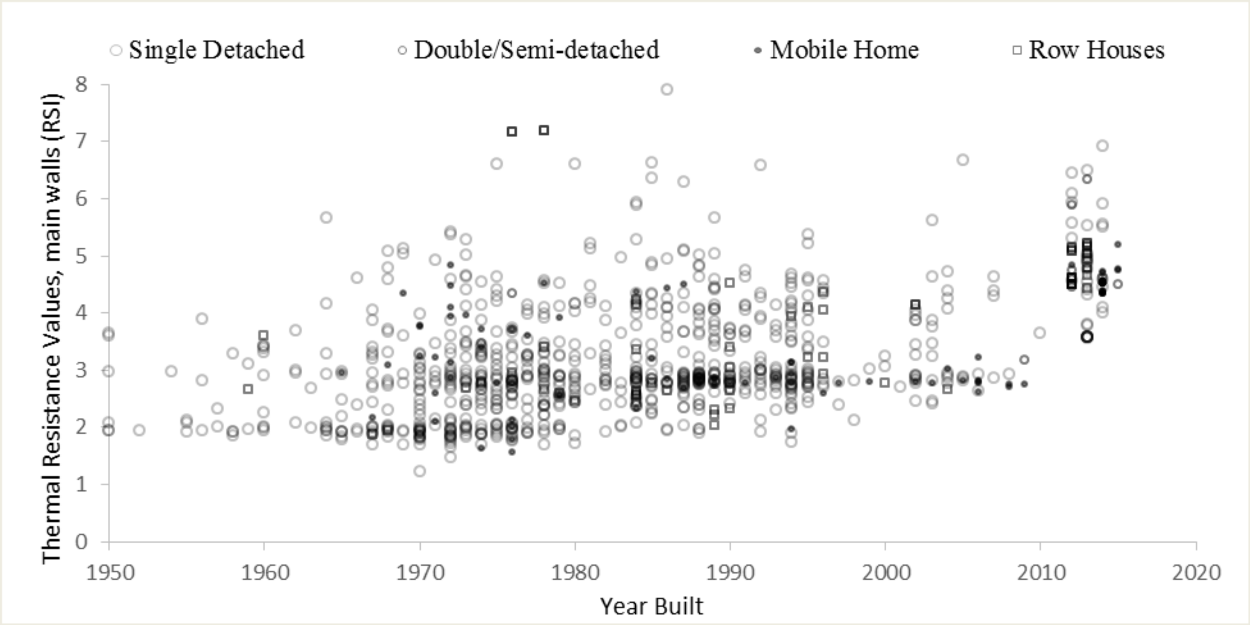

Figure 41: Main wall insulation level and year built for different house types

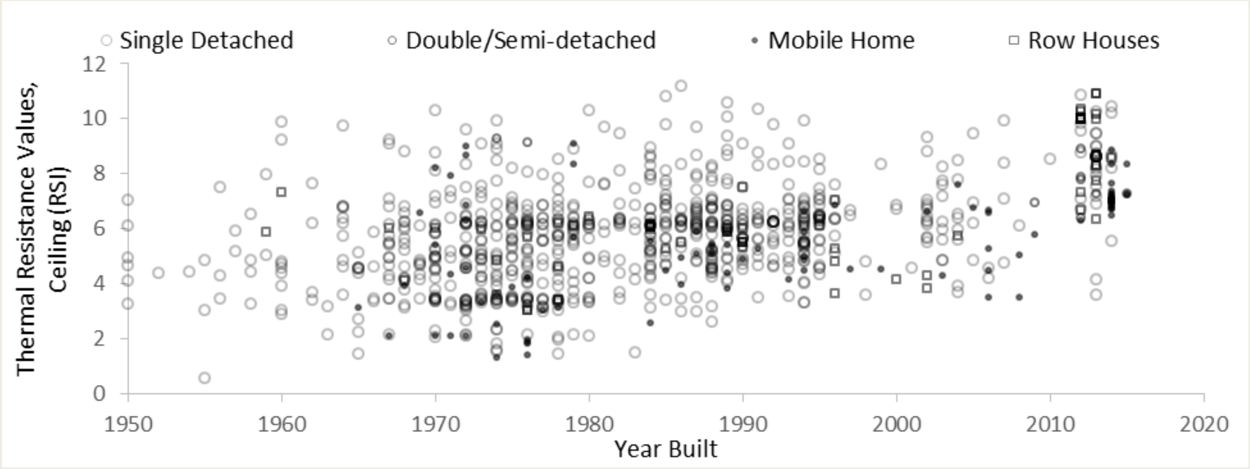

Figure 42: Ceiling insulation level and year built for different house types

Appendix D: Parametric Study of Solar Parameters

Thermal resistance values for walls:

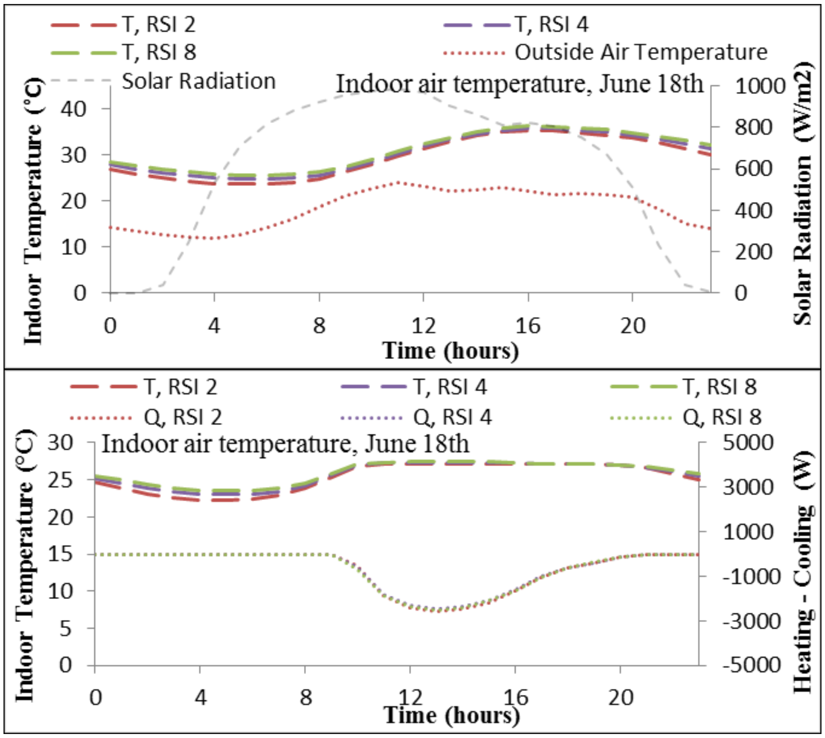

Figure 43: Passive response (top) and active response (bottom) for different thermal resistance values for wall for June 18th

Table 35: total heating for design dates for different thermal resistance values in walls

RSI Levels in Walls	Total heating for February 10th (kWh)	Total cooling for June 18th (kWh)	Total heating for September 6th (kWh)	Total heating for December 21st (kWh)
1.00	214	17	24	171
2.00	156	16	16	125
3.00	134	16	14	109
4.00	123	15	12	100
5.00	116	15	11	95
6.00	111	16	10	91
7.00	108	16	10	88
8.00	107	16	9	89
9.00	105	16	9	87
10.00	103	16	9	83

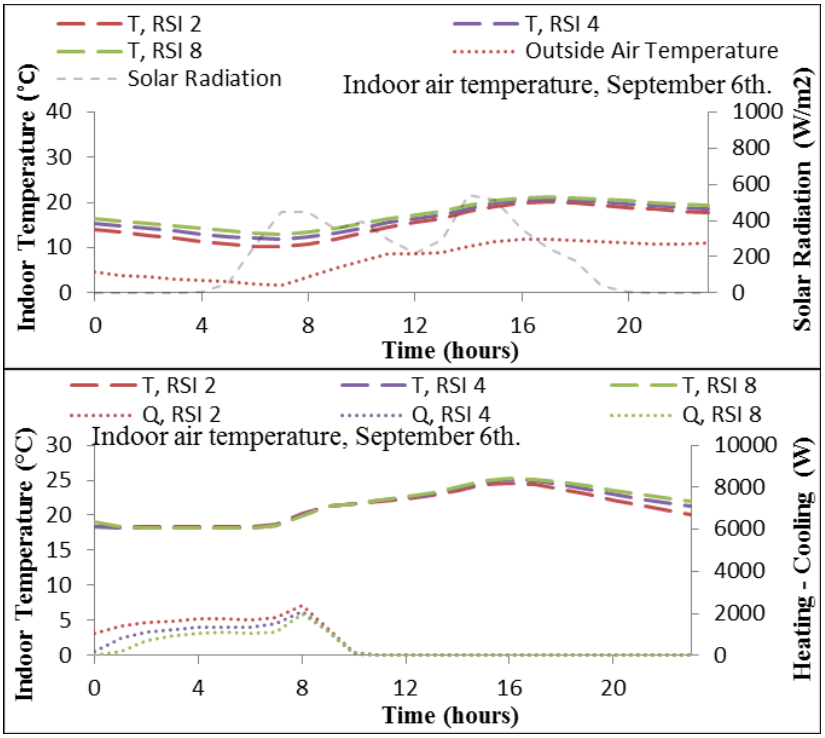

Figure 44: Passive response (top) and active response (bottom) for different thermal resistance values for wall for September 6th

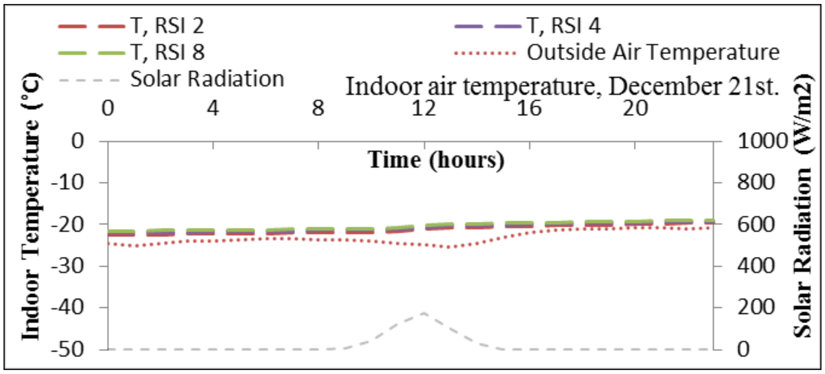

Figure 45: Passive response for different thermal resistance values for wall for December 21st

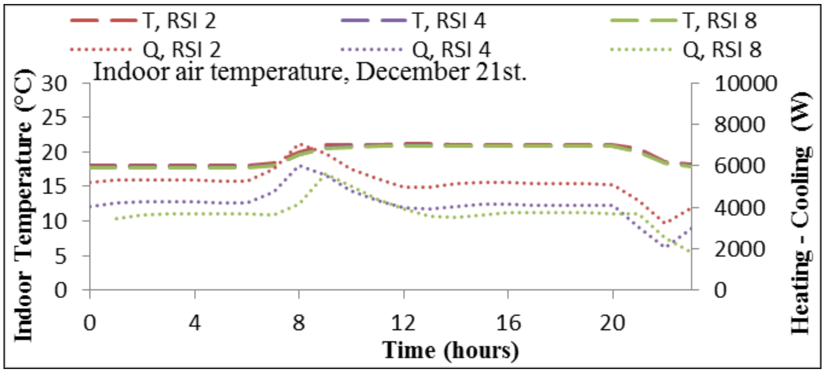

Figure 46: Active response for different thermal resistance values for wall for December 21st

Thermal resistance values for ceiling:

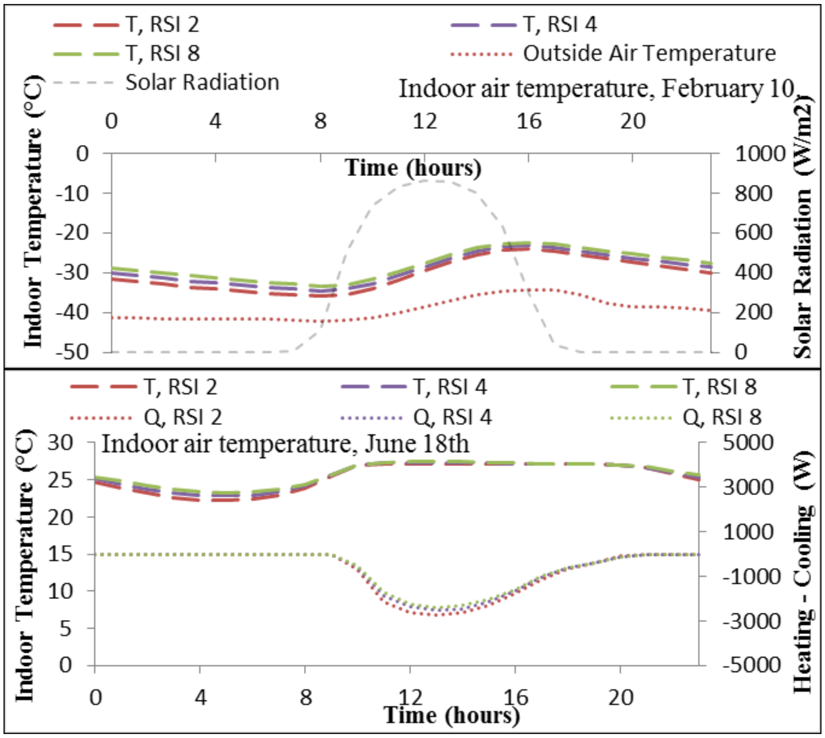

Figure 47: Passive response (top) and active response (bottom) for different thermal resistance values for ceiling for February 10th

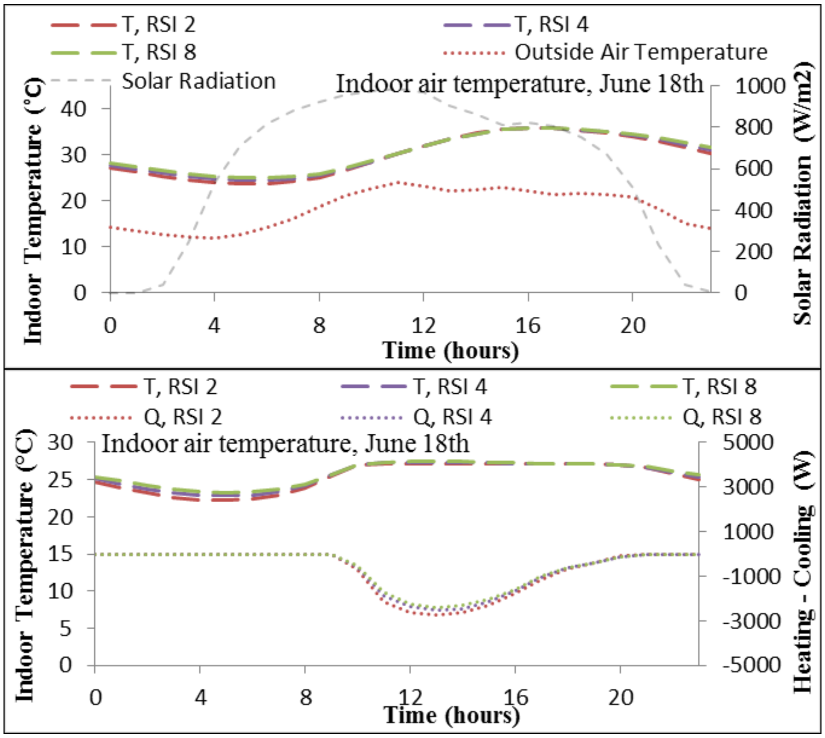

Figure 48: Passive response (top) and active response (bottom) for different thermal resistance values for ceiling for July 18^{th}

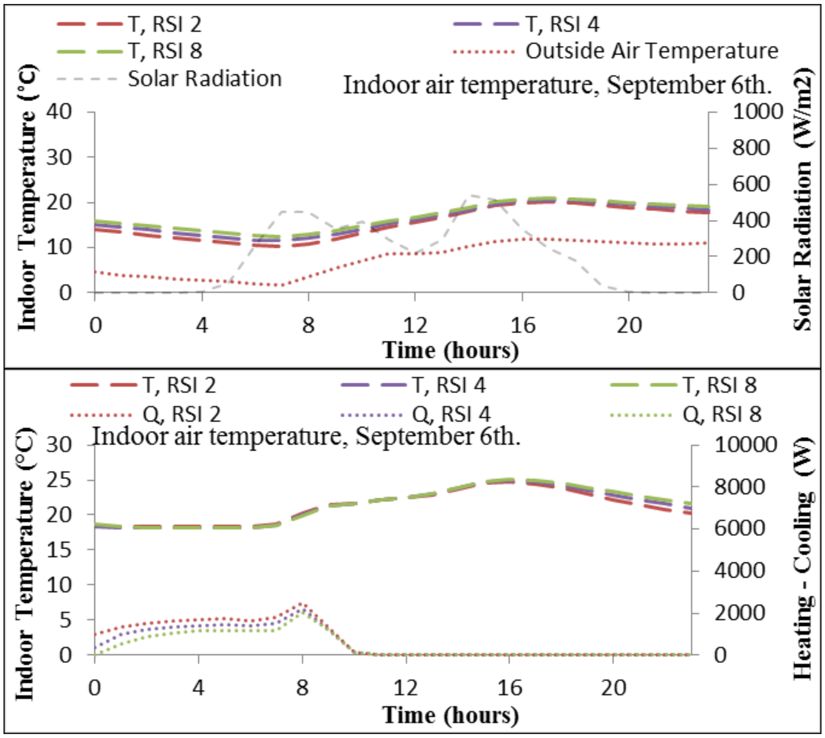

Figure 49: Passive response (top) and active response (bottom) for different thermal resistance values for ceiling for September 6^{th}

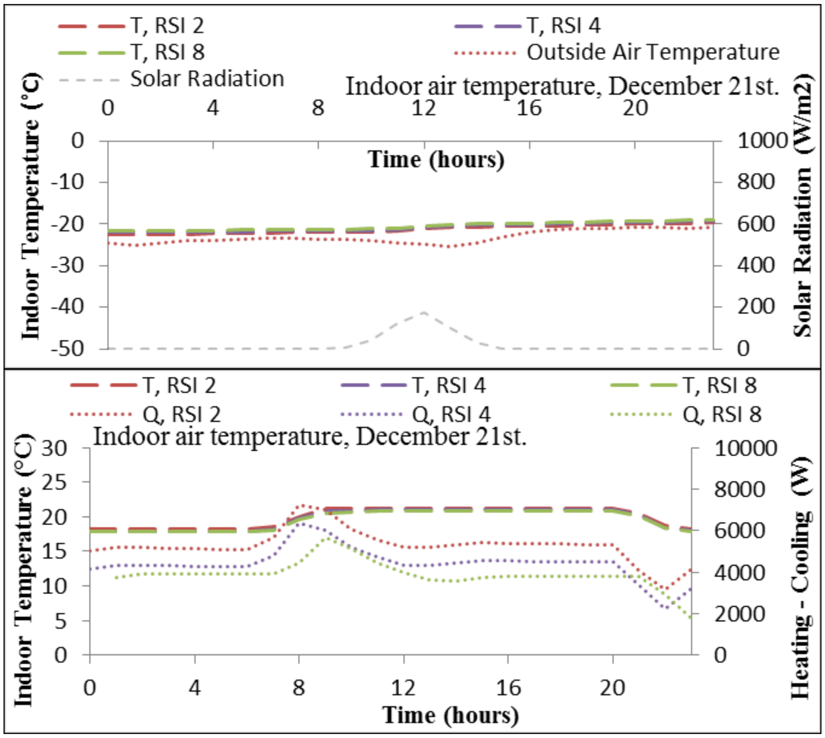

Figure 50: Passive response (top) and active response (bottom) for different thermal resistance values for ceiling for December 21st

Table 36: total heating for design dates for different thermal resistance values in iling

RSI Levels in Walls	Total heating for February 10th (kWh)	Total cooling for June 18th (kWh)	Total heating for September 6th (kWh)	Total heating for December 21st (kWh)
1.00	195	20	21	156
2.00	161	17	16	127
3.00	140	16	14	111
4.00	130	16	13	106
5.00	124	15	12	101
6.00	119	15	11	97
7.00	116	15	11	95
8.00	113	15	11	92
9.00	109	15	10	91
10.00	107	15	10	89

Thermal resistance values for ceiling:

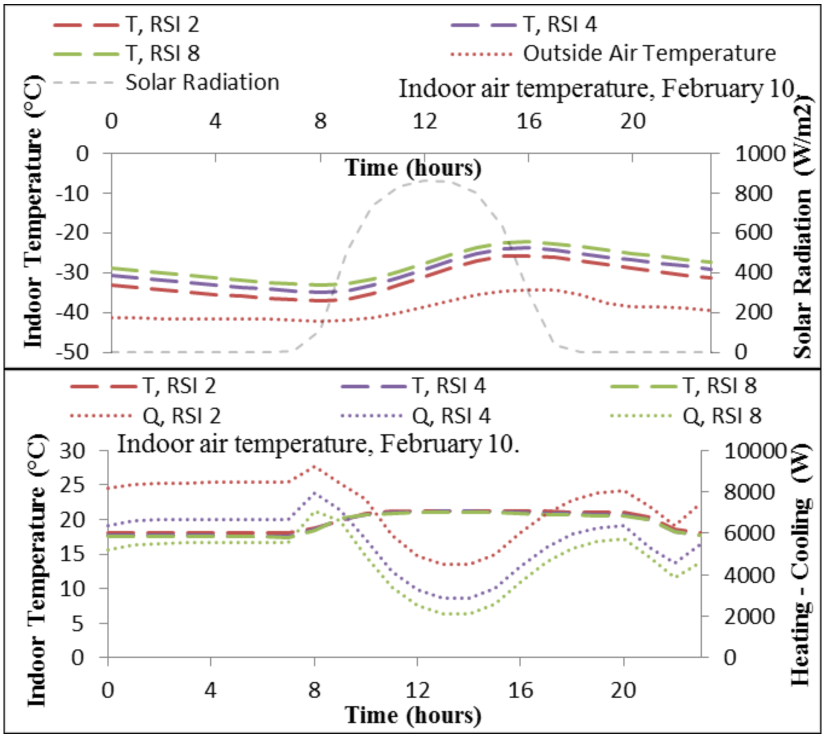

Figure 51: Passive response (top) and active response (bottom) for different thermal resistance values for floor for February 10th

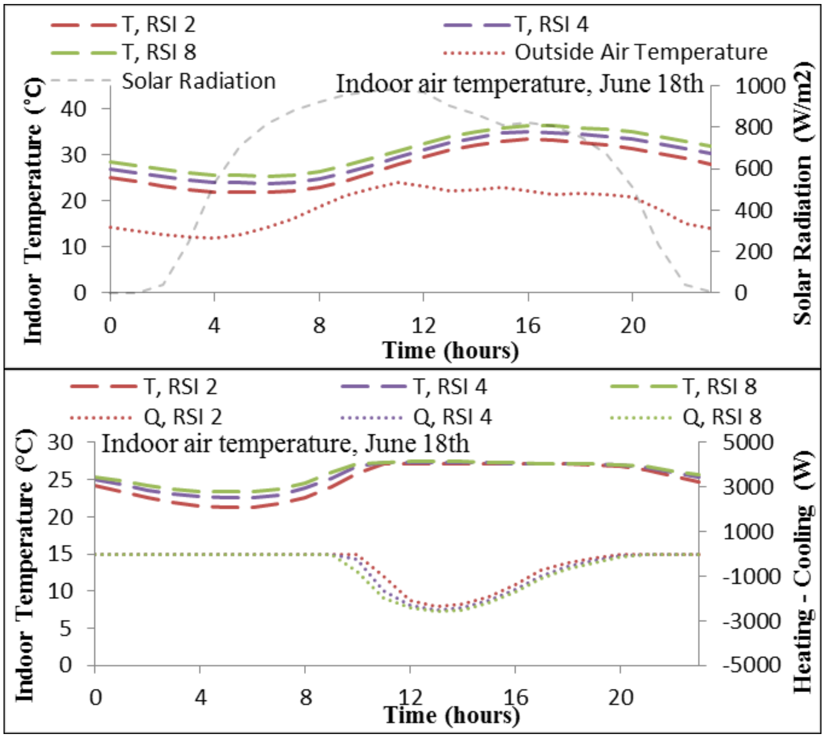

Figure 52: Passive response (top) and active response (bottom) for different thermal resistance values for floor for July 18th

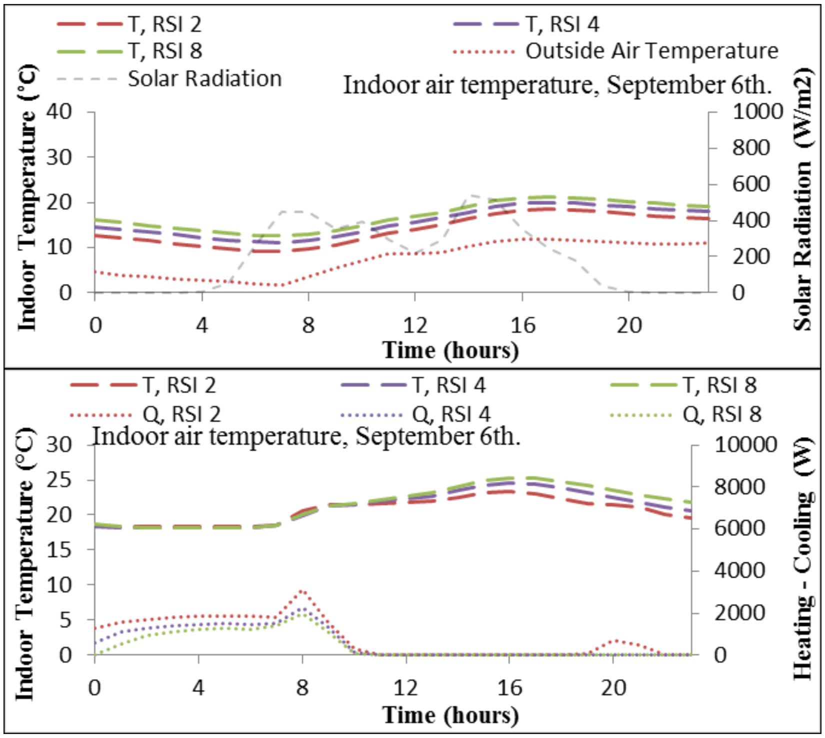

Figure 53: Passive response (top) and active response (bottom) for different thermal resistance values for floor for September 6th

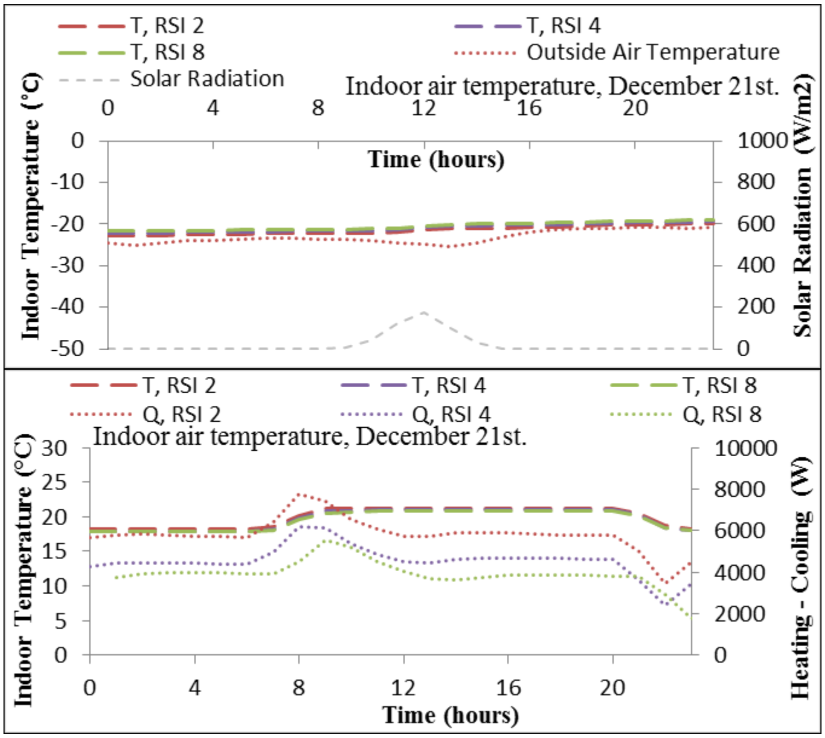

Figure 54: Passive response (top) and active response (bottom) for different thermal resistance values for floor for December 21st

Table 37: total heating for design dates for different thermal resistance values in Different thermal resistance values for floor:

RSI Levels in Walls	Total heating for February 10th (kWh)	Total cooling for June 18th (kWh)	Total heating for September 6th (kWh)	Total heating for December 21st (kWh)
1.00	243	9	33	188
2.00	175	12	20	140
3.00	148	14	16	119
4.00	134	15	14	109
5.00	126	15	13	103
6.00	121	15	12	99
7.00	116	16	11	96
8.00	113	16	11	93
9.00	111	17	10	91
10.00	109	17	10	90

Window Night Shutters

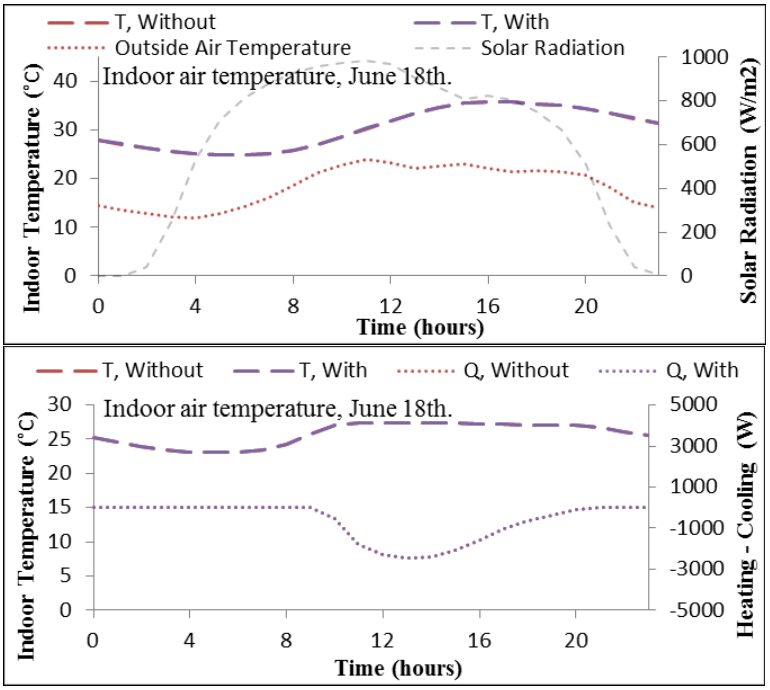

Figure 55: Passive response (top) and active response (bottom) for house with and without night shutters for June 18th

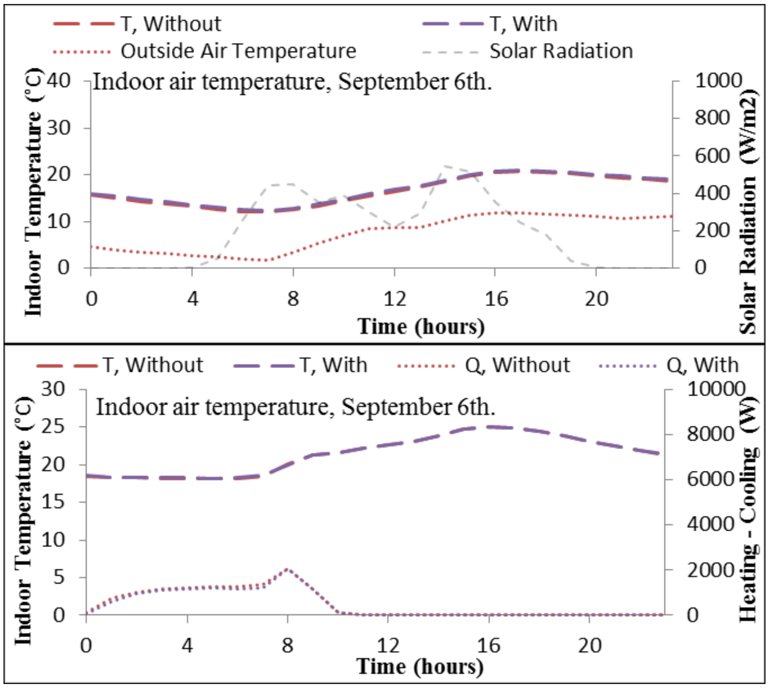

Figure 56: Passive response (top) and active response (bottom) for house with and without night shutters for September 6th

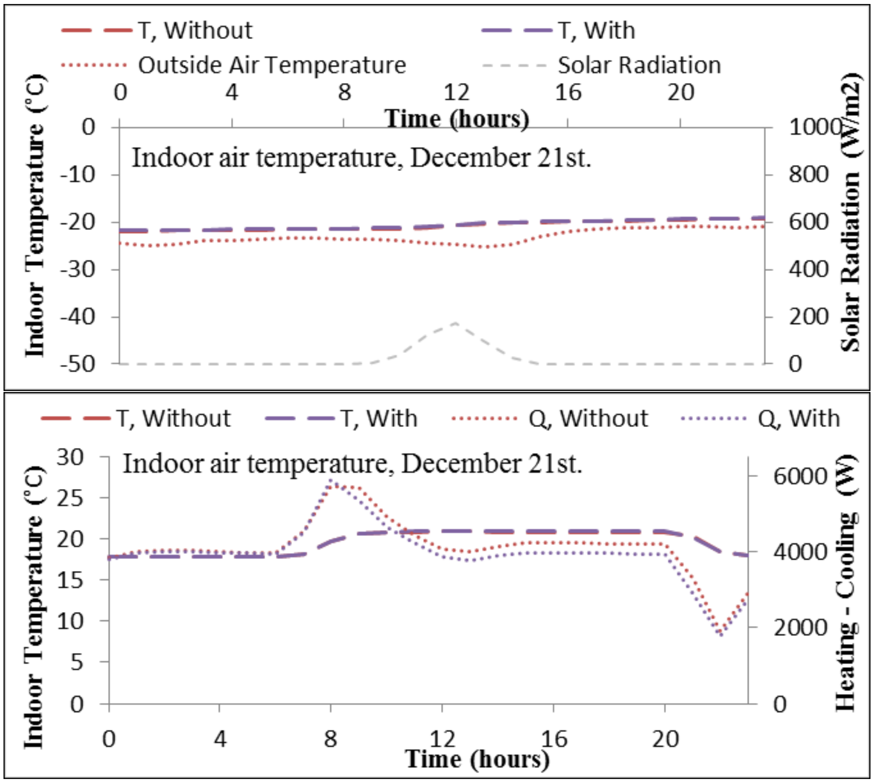

Figure 57: Passive response (top) and active response (bottom) for house with and without night shutters for December 21st

Table 38: Heating consumption for different days with and without night shutters

	Total Q cooling for June 18th (kWh)	Total Q heating for September 6th (kWh)	Total Q heating for December 21st (kWh)
Reference house (Without Night Shutters)	15.3	11.7	98.8
With Night Shutters (+ 2 RSI)	15.3	10.9	95.0

Window Wall Ratio (triple glazed window.)

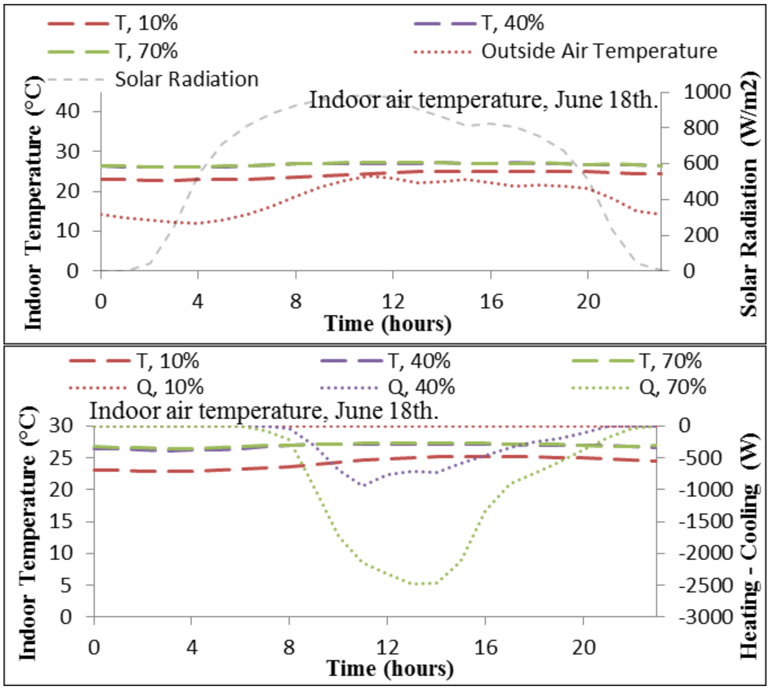

Figure 58: Passive response (top) and active response (bottom) for different window-wall ratios for June 18th

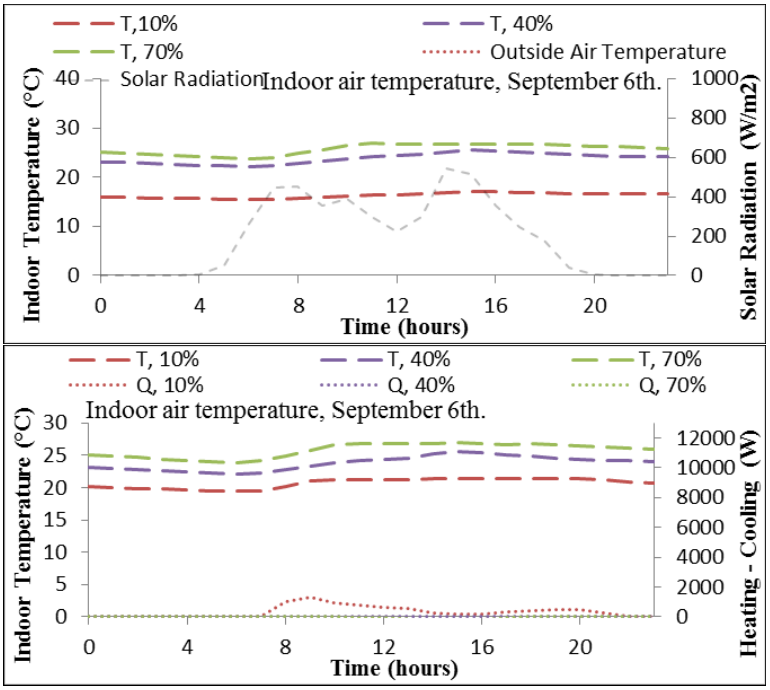

Figure 59 Passive response (top) and active response (bottom) for different window-wall ratios for September 6th

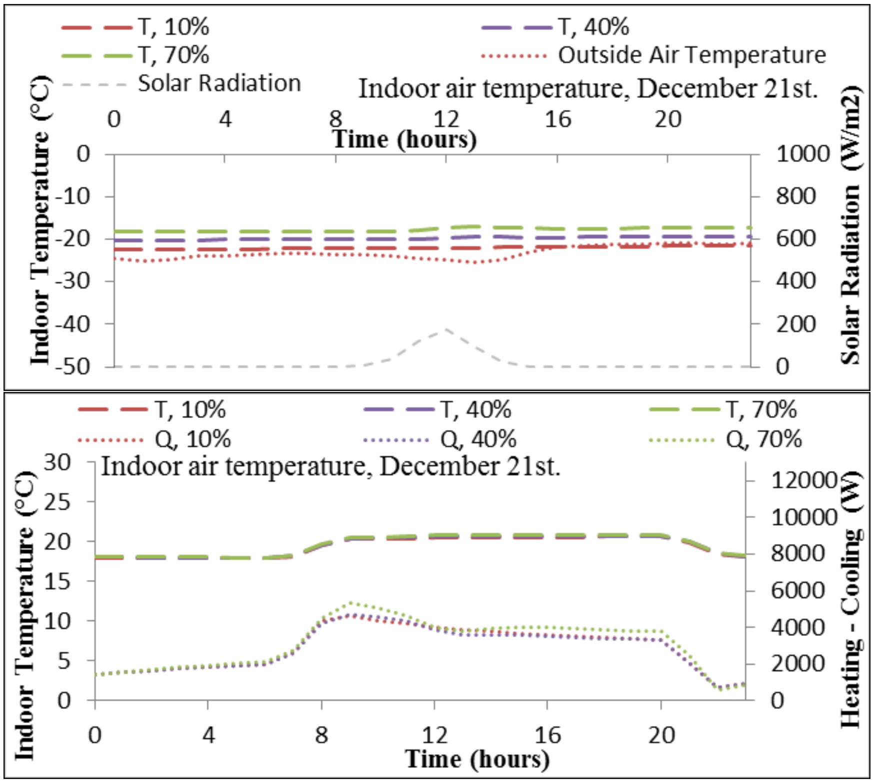

Figure 60: Passive response (top) and active response (bottom) for different window-wall ratios for December 21st

Table 39: Total daily Q heating or cooling for different window-wall ratios

WWR on South Façade (%)	Total Qcooling for June 18th (kWh)	Total Qheating for September 6th (kWh)	Total Qheating for December 21st (kWh)
5%	0	11	69
10%	0	8	69
20%	2	3	69
30.0%	3	0	69
40%	6	0	68
50%	11	0	70
70%	15	0	71
75%	19	1	74
80%	21	2	71

Optimized Home

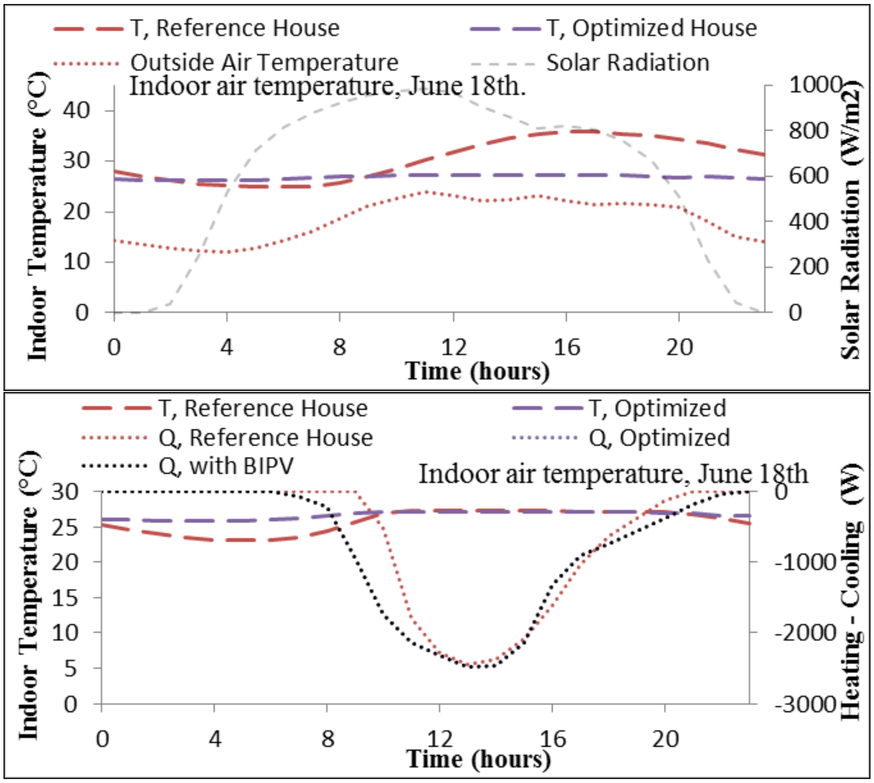

Figure 61: Passive response (top) and active response (bottom) for reference and optimized home for June 18th

Table 40: Daily heating, cooling energy consumption for the reference house, and optimized house with and without BIPV/T system

	Qheating for June 18th (kWh/m^2)	Qheating for December 21st (kWh/m^2)
Reference home (typical Yellowknife Home)	15.3	98.8
Optimized House without Thermal Energy from BIPV/T System	18.6	74.1
Optimized House with Thermal Energy from BIPV/T System	18.6	74.1

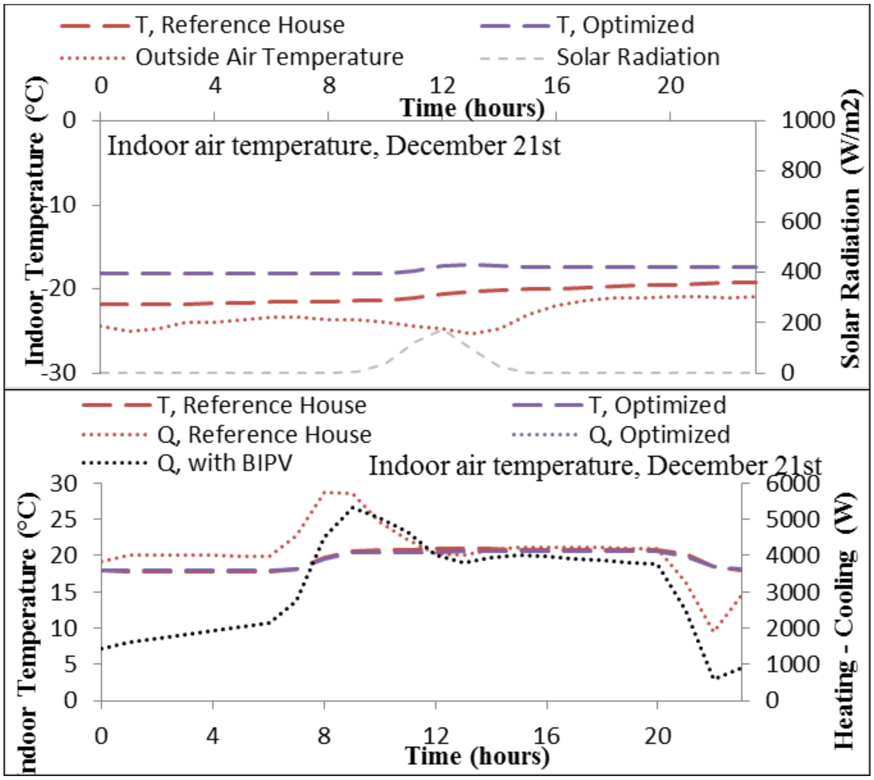

Figure 62: Passive response (top) and active response (bottom) for reference and optimized home for December 21st

Appendix E: MATLAB Code

```
% Thermal Model and Analysis of a Northern House:

%% Geometric Information:
% The house is a single, detached, rectangular, single storey house.

Hh=2.5;                 %height of the house / m
Wh=8.66666666666;       %width of the house / m
Lh=15;                  %Length of the house / m

R_slope=52.5*pi/180;      %Roof Slope
R_slopeD=52.5;

WWRs=0.40;             %Window Wall Ratio
WWRe=0.00000000000000001;              %Window Wall Ratio

Asr=sqrt((Wh/2)^2+((Wh/2)*tan(R_slope))^2)*Lh; %South facing roof area(m2)
Anr=Asr;                                       %north facing roof area (m2)
Aer=(Wh/2)*(tan(R_slope))*(Wh/2);              %east facing roof area (m2)
Awr=Aer;                                       %west facing roof area (m2)

Vol=Hh*Wh*Lh;                                  %Volume of house (m3)
height_attic=tan(R_slope)*(Wh/2);              %Height of attic (m)
Vola=Hh*Wh*height_attic/3;                     %Volume of attic (m3)

% Window area

Aw1 =WWRs*(Lh*Hh);                             %area south window (m2)
Aw4=0.00000000000000000001;                    %area north window (m2)
Aw5=WWRe*Wh*Hh;                                %area east window (m2)
Aw3=WWRe*Wh*Hh;                                %area west window (m2)

% Wall areas:
Asw=(Lh*Hh)-Aw1;                               %area south wall (m2)
Aww=(Wh*Hh)-Aw3;                               %area west wall (m2)
Aew=(Wh*Hh)-Aw5;                               %area east wall (m2)
Anw=(Lh*Hh);                                   %area north wall (m2)
Af=(Lh*Wh);                                    %area of floor (m2)
Ac=(Lh*Wh);                                    %area of ceiling (m2)

% Constants (R-values)
Rg=(0.079/2);        %RSI value of gypsum board (half) m2*degC/watts
Rcon=(0.05/1.7);   %RSI value of concrete (half) m2*degC/watts (Floor Tiles
or  Concrete (0.1/1.7)

Rw=8;               %RSI value of walls m2*degC/watts
Rf=9;               %RSI value of floor m2*degC/watts
Rr=1;               %RSI value of roof m2*degC/watts

Rc=9;             %RSI value of ceiling m2*degC/watts
```

```
hi=8.29;                     %Interior film coefficient watts/m2*degC
ho=22;                       %Exterior film coefficient watts/m2*degC
%Uw=1/(1/0.894-1/ho-1/hi);    %Window U-Value watts/m2*degC (Triple Glazed)
%Uw=1/(1/1.689-1/ho-1/hi);   %Window U-Value watts/m2*degC (Double Glazed)
Uw=1/(1/0.855-1/ho-1/hi);  %Window U-Value watts/m2*degC (Double Glazed with
film)

as=0.7;             % wall absorptance.

% Thermals capacitances: C=c*p*A*L

cg=750;                 %Specific heat of gypsum (Joules/Kg*C)
cc=800;                 %Specific heat of concrete (Joules/Kg*C)
cf=2492.1;              %Specific heat of engineered floor tiles
(Joules/Kg*C)
pg=800;                 %Density of gypsum (kg/m3)
pc=2200;                %Density of concrete (kg/m3)
pf=571;                 %Density of engineered floor tiles (kg/m3)
Lg=0.013;               %Thickness of gypsum (m)
Lc=0.05;                %Thickness of concrete (m)
Lf=0.006;               %Thickness of engineered floor tiles (m)

Cs=cg*pg*Lg*Asw;        %Thermal Capacitance of South Wall (Joules/degC)
Cw=cg*pg*Lg*Aww;        %Thermal Capacitance of west Wall (Joules/degC)
Ce=cg*pg*Lg*Aew;        %Thermal Capacitance of east Wall (Joules/degC)
Cc=cg*pg*Lg*Ac;         %Thermal Capacitance of ceiling Wall (Joules/degC)
Cn=cg*pg*Lg*Anw;        %Thermal Capacitance of north Wall (Joules/degC)
Cf=cc*pc*Lc*Af;        %Thermal Capacitance of Floor, concrete (Joules/degC)
%Cf=cf*pf*Lf*Af;          %Thermal Capacitance of Floor, floor
tiles(Joules/degC)

%Calculation of infiltration

ach=0.3;                                    %air change per hour.
cp_air=1000;                                %specific heat (joule/KG.C)
p_air=1.2;                                  %density of air kg/m3)
Uinf=(ach*Vol*p_air*cp_air)/3600;           %Infiltration in room (Watt/C)
Uinfa=(ach*Vola*p_air*cp_air)/3600;         %Infiltration in attic (Watt/C)

%% Properties for BIPV/T ROOF MODEL:
% Air properties:
pressure_pv=101325;      %Atmospheric Pressure (pascal)
Ra_pv=287.08;            %Joule/Kg*K
c_pv=1000;               %specific heat of air (Joule/kg*C)
visc_pv=17.6*(10^-6);    %Viscosity, Kg/m*s
k_pv=0.0247;             %Conductivity, watt/m*C
u_air=1.8*10^-5;         %Pa*s

% Air Flow Rate:
L_pv=0.04;              %Thickness of air channel (m)
W_pv=15;                %Width of Channel
H_pv=0.75;              %The PV section is divided into 5 sections. (0.75m)

A_pv=W_pv*H_pv;         %Surface area of first section.
```

```
eff_stnd=0.15;          %Standard efficiency is 15%, assumed

A_panel_all=75;         %Area of panel (m)
A_panel=A_panel_all/5;

Vel=0.5;                %air speed, assumed (m/s)
M_pv=Vel*L_pv*W_pv;     %Flow rate.

a_pv=0.9;               %Roof Solar Absortance.

%% Calculating Wall Admittance
%The self-admittance and the transfer admittance will be calculated for
%each wall considering the thermal capacity of the room's interior layer.
%The admittance will be used to calculated the maximum capacity of the heat
%pump or furnance - which will give us our Kp (estimate of a "good
%proportional control constant".)

% Steady State admittance to interior surface is equal to wall U-value
% (excluding interior film).

n=1:4;                %Number of Harmonics.

U_1=Asw*hi;           %Interior surface conductance of south Wall
U_2=Aww*hi;           %Interior surface conductance of west Wall
U_3=Aew*hi;           %Interior surface conductance of east Wall
U_4=Anw*hi;           %Interior surface conductance of north Wall
U_5=Af*hi;            %Interior surface conductance of floor Wall
U_6=Ac*hi;            %Interior surface conductance of ceiling Wall

u_w=1/((Rw+Rg)-1/hi); %Conductance of wall excluding interior layer + film
u_f=1/(Rf-(1/hi));    %Conductance of floor excluding interior layer + film
u_c=1/(Rc-(1/hi));    %Conductance of ceiling excluding interior layer + film

Uw_1=Uw*(Aw1+Aw4+Aw5+Aw3);

k_w=0.16;       %watt/m*C
c_w=750;        %Speciic heat of wall (joule/Kg*C)
p_w=800;        %Density of wall (kg/m3)
L_w=0.013;      %Thickness of wall (m)

Ys0_1=Asw/(Rw-(1/hi));  %Self admittance 0 frequency, south wall.
Ys0_2=Aww/(Rw-(1/hi));  %Self admittance 0 frequency, west wall.
Ys0_3=Aew/(Rw-(1/hi));  %Self admittance 0 frequency, east wall.
Ys0_4=Anw/(Rw-(1/hi));  %Self admittance 0 frequency, north wall.
Ys0_5=Af/(Rf-(1/hi));   %Self admittance 0 frequency, floor.
Ys0_6=Ac/(Rc-(1/hi));   %Self admittance 0 frequency, ceiling.

Yn0_1=(Ys0_1*U_1)/(Ys0_1+U_1);  %Wall admittances, south wall.
Yn0_2=(Ys0_2*U_2)/(Ys0_2+U_2);  %Wall admittances, west wall.
Yn0_3=(Ys0_3*U_3)/(Ys0_3+U_3);  %Wall admittances, east wall.
Yn0_4=(Ys0_4*U_4)/(Ys0_4+U_4);  %Wall admittances, north wall.
Yn0_5=(Ys0_5*U_5)/(Ys0_5+U_5);  %Wall admittances, floor wall.
Yn0_6=(Ys0_6*U_6)/(Ys0_6+U_6);  %Wall admittances, ceiling wall.
```

```
YY=sqrt(1j*((2*pi*n)/((k_w*86400)/(c_w*p_w))));

%The following the admittance for all 4 harmonics

for X=1:4;

Ys_1(X)=Asw*((u_w+k_w*YY(X)*tanh(YY(X)*L_w))/(((u_w*tanh(YY(X)*L_w))/(k_w*YY(
X)))+1);
Ys_2(X)=Aww*((u_w+k_w*YY(X)*tanh(YY(X)*L_w))/(((u_w*tanh(YY(X)*L_w))/(k_w*YY(
X)))+1);
Ys_3(X)=Aew*((u_w+k_w*YY(X)*tanh(YY(X)*L_w))/(((u_w*tanh(YY(X)*L_w))/(k_w*YY(
X)))+1);
Ys_4(X)=Anw*((u_w+k_w*YY(X)*tanh(YY(X)*L_w))/(((u_w*tanh(YY(X)*L_w))/(k_w*YY(
X)))+1);
Ys_5(X)=Af*((u_f+k_w*YY(X)*tanh(YY(X)*L_w))/(((u_w*tanh(YY(X)*L_w))/(k_w*YY(X
)))+1);
Ys_6(X)=Af*((u_c+k_w*YY(X)*tanh(YY(X)*L_w))/(((u_w*tanh(YY(X)*L_w))/(k_w*YY(X
)))+1);

Yt_1=Asw/(((cosh(YY(X)*L_w))/(u_w))+((sinh(YY(X)*L_w))/(k_w*YY(X))));
Yt_2=Aww/(((cosh(YY(X)*L_w))/(u_w))+((sinh(YY(X)*L_w))/(k_w*YY(X))));
Yt_3=Aew/(((cosh(YY(X)*L_w))/(u_w))+((sinh(YY(X)*L_w))/(k_w*YY(X))));
Yt_4=Anw/(((cosh(YY(X)*L_w))/(u_w))+((sinh(YY(X)*L_w))/(k_w*YY(X))));
Yt_5=Af/(((cosh(YY(X)*L_w))/(u_f))+((sinh(YY(X)*L_w))/(k_w*YY(X))));
Yt_6=Af/(((cosh(YY(X)*L_w))/(u_c))+((sinh(YY(X)*L_w))/(k_w*YY(X))));

Yn_1(X)=(Ys_1(X)*U_1)/(Ys_1(X)+U_1);
Yn_2(X)=(Ys_2(X)*U_2)/(Ys_2(X)+U_2);
Yn_3(X)=(Ys_3(X)*U_3)/(Ys_3(X)+U_3);
Yn_4(X)=(Ys_4(X)*U_4)/(Ys_4(X)+U_4);
Yn_5(X)=(Ys_5(X)*U_5)/(Ys_4(X)+U_5);
Yn_6(X)=(Ys_6(X)*U_6)/(Ys_4(X)+U_6);

Yz(X)=Uinf+Uw_1+Yn_1(X)+Yn_2(X)+Yn_3(X)+Yn_4(X)+Yn_5(X)+Yn_5(X)+Yn_6(X);

end

%Zone admittance Yz.

Yz0=Uinf+Uw_1+Yn0_1+Yn0_2+Yn0_3+Yn0_4+Yn0_5+Yn0_6; %Yz0 is simply the total
U-value of the house

Y_f=abs(Yz(1)); %Magnitude of abs(Yz(1)) gives us an indication of the daily
dynamics of the spaces.

%% Solar Radiation

%The following function gives incidence angle for surfaces of the home.
%sI gives incidence angle in degrees for south wall, and sIR gives
%incidence angle in radian for south wall, and so forth.

[sI,sIR] = Solar_Radiation(0, 90);              %South Facing Wall:
```

```
[wI,wIR] = Solar_Radiation(90, 90);             %West Facing Wall:
[nI,nIR] = Solar_Radiation(180, 90);            %North Facing Wall:
[eI,eIR] = Solar_Radiation(-90, 90);            %East Facing Wall:
[rsI,rsIR] = Solar_Radiation(0, R_slopeD);      %South Facing roof:
[rnI,rnIR] = Solar_Radiation(180, R_slopeD);    %North Facing roof:

%'Temperature.xlsx' is the excel file that contains weather data on cities.
%Column 1: Outdoor Temperature;
%Column 2: Wind Speed (m/s);
%Column 3: Wind Direction;
%Column 4: Site Diffused, Solar Radiation;
%Column 5: Site Direct Solar Radiation;
%Column 6: Snow on Ground (1 for yes, 0 for no.)

%Weather data distributed across a year per every hour (the function below
extract weather data from an excel file.)

Tinfo= xlsread('Temperature.xlsx','Yellowknife');


        for X=1:8760,

        T_out(X)=Tinfo(X,1);                 %Hourly outdoor temperature
        Ion(X)=Tinfo(X,5);                   %Hourly direct solar radiation
        Ids(X)=Tinfo(X,4);                   %Hourly diffused solar radiation
        Tsp_Hour(X)=Tinfo(X,7);              %Hourly outdoor temperature
        Night_Shutter_hour(X)=Tinfo(X,8); %Night Shutter Schedule

        end

%% The critical time step for this calculation is less than 1 hour, thus
% linear interpolation is used to obtain

X=0;        %For code purposes, resets X value for each iteration.
X3=1;       %For code purposes
X1=0;       %For code purposes

for D=1:8736, %Iteration for each hour.

               X1=D;
               X2=X1+1;
               N=0;

                for ZA=1:48, %48 iterations per hour.

                   X=X+1; % Represents the iteration number - in total
                   %there is 419 328 iteration for the whole year.

                   X3=X3+0.0208333333333333333333333333;
                   % X3 represents the exact hour of iteration, each
                   % iteration is 0.0208 hours.

                   % The follow are linear interpolation:
```

```
                   % Outdoor Temperature:
                   To(X)=((X3-X1)*(T_out(X2)-T_out(X1))/(X2-X1))+T_out(X1);
                   %Setpoint Temperature
                   Tsp(X)=((X3-X1)*(Tsp_Hour(X2)-Tsp_Hour(X1))/(X2-
X1))+Tsp_Hour(X1);
                   %Setpoint Temperature
                   Night_Shutter(X)=((X3-X1)*(Night_Shutter_hour(X2)-
Night_Shutter_hour(X1))/(X2-X1))+Night_Shutter_hour(X1);
                   %Direct Solar Radiation:
                   Ia(X)=((X3-X1)*(Ion(X2)-Ion(X1))/(X2-X1))+Ion(X1);
                   %Diffused Solar Radiation:
                   Id(X)=((X3-X1)*(Ids(X2)-Ids(X1))/(X2-X1))+Ids(X1);
                   %Incident Angle on the south, west, north, east, and
                   %roofs.
                   XsIR(X)=((X3-X1)*(sIR(X2)-sIR(X1))/(X2-X1))+sIR(X1);
                   XwIR(X)=((X3-X1)*(wIR(X2)-wIR(X1))/(X2-X1))+wIR(X1);
                   XnIR(X)=((X3-X1)*(nIR(X2)-nIR(X1))/(X2-X1))+nIR(X1);
                   XeIR(X)=((X3-X1)*(eIR(X2)-eIR(X1))/(X2-X1))+eIR(X1);
                   XrsIR(X)=((X3-X1)*(rsIR(X2)-rsIR(X1))/(X2-X1))+rsIR(X1);
                   XrnIR(X)=((X3-X1)*(rnIR(X2)-rnIR(X1))/(X2-X1))+rnIR(X1);
                   %Beam, diffused, reflected and total radiation on South
Facade:

                   pg=1;
                   sIb(X)=Ia(X)*cos(XsIR(X)); %Beam Radiation
                   sIds(X)=Id(X)*(1+cos(90*pi/180))/2; %Diffuse radiation
                   sIdg(X)=Id(X)*pg*(1+cos(90*pi/180))/2;%Reflected Radiation
                   sIt(X)=(sIb(X)+sIds(X)+sIdg(X)); %Total Radiation



%Beam, diffused, reflected and total radiation on West Facade:
                   wIb(X)=Ia(X)*cos(XwIR(X)); %Beam Radiation
                   wIds(X)=Id(X)*(1+cos(90*pi/180))/2; %diffuse radiation
                   wIdg(X)=Id(X)*pg*(1+cos(90*pi/180))/2;%Reflected Radiation
                   wIt(X)=(wIb(X)+wIds(X)+wIdg(X)); %Total Radiation...

%Beam, diffused, reflected and total radiation on North Facade:
                   nIb(X)=Ia(X)*cos(XnIR(X)); %Beam Radiation
                   nIds(X)=Id(X)*(1+cos(90*pi/180))/2;%diffuse radiation
                   nIdg(X)=Id(X)*pg*(1+cos(90*pi/180))/2;%Reflected Radiation
                   nIt(X)=(nIb(X)+nIds(X)+nIdg(X));%Total Radiation...

%Beam, diffused, reflected and total radiation on East Facade:
                   eIb(X)=Ia(X)*cos(XeIR(X)); %Beam Radiation
                   eIds(X)=Id(X)*(1+cos(90*pi/180))/2;%diffuse radiation
                   eIdg(X)=Id(X)*pg*(1+cos(90*pi/180))/2;%Reflected Radiation
                   eIt(X)=(eIb(X)+eIds(X)+eIdg(X)); %Total Radiation...

%Beam, diffused, reflected and total radiation on South Facade (roof):
                rsIb(X)=Ia(X)*cos(XrsIR(X)); %Beam Radiation
                rsIds(X)=Id(X)*(1+cos(90*pi/180))/2; %diffuse radiation
                rsIdg(X)=Id(X)*pg*(1+cos(90*pi/180))/2;%Reflected Radiation
                rsIt(X)=(rsIb(X)+rsIds(X)+rsIdg(X));%Total Radiation...
```

```
%Beam, diffused, reflected and total radiation on North Facade (roof):
                rnIb(X)=Ia(X)*cos(XrnIR(X)); %Beam Radiation
                rnIds(X)=Id(X)*(1+cos(90*pi/180))/2; %diffuse radiation
                rnIdg(X)=Id(X)*pg*(1+cos(90*pi/180))/2;%Reflected Radiation
                rnIt(X)=(rnIb(X)+rnIds(X)+rnIdg(X)); %Total Radiation...

                end

end

        DT = 75; %Time step in seconds

        qmax=Yz0*105;       %Maximum auxiliary heat or cooling . 105
        Kp=qmax/2;          %good proportional constant.
        Kp=0;               %To turn heating/cooling off - Kp=0.

%% The following for statement goes through each equation based on previous
%time step.

K=1; % FCP: resetting value of K to 1.

for K=1:24 %This iteration helps reduce error from initial temperature
values.

            X=0;
            K=K+1;
            PV_sim=1;

                if K>2,
                    % On the second time step, initial values are estimated
                    % based on the first 24 iteration.

                    G=24; %The number of time the iteration is ran)

                    TR(1)= sum(TR(1:G))/G;
                    T2(1)= sum(T2(1:G))/G;
                    Ta(1)=sum(Ta(1:G))/G;
                    T3(1)=sum(T3(1:G))/G;
                    T5(1)= sum(T5(1:G))/G;
                    T56(1)= sum(T56(1:G))/G;
                    T6(1)= sum(T6(1:G))/G;
                    T7(1)= sum(T7(1:G))/G;
                    T8(1)= sum(T8(1:G))/G;
                    Tca(1)= sum(Tca(1:G))/G;
                    Tcb(1)= sum(Tcb(1:G))/G;
                    Tcc(1)= sum(Tcc(1:G))/G;
                    Tcd(1)= sum(Tcd(1:G))/G;
                    T9(1)= sum(T9(1:G))/G;
                    T11(1)= sum(T11(1:G))/G;
                    T11a(1)= sum(T11a(1:G))/G;
                    T12(1)= sum(T12(1:G))/G;
                    T14(1)=sum(T14(1:G))/G;
                    T14a(1)=sum(T14a(1:G))/G;
```

```
    T15(1)= sum(T15(1:G))/G;

    TA(1)= sum(TA(1:G))/G;
    TA2(1)= sum(TA2(1:G))/G;
    TA4(1)= sum(TA4(1:G))/G;
    TA5(1)= sum(TA5(1:G))/G;
    TA6(1)= sum(TA6(1:G))/G;
    TA8(1)= sum(TA8(1:G))/G;
    TA10(1)= sum(TA10(1:G))/G;

    Tw2(1)=sum(Tw2(1:G))/G;
    Tw4(1)=sum(Tw4(1:G))/G;
    Tw6(2)=sum(Tw6(1:G))/G;

    ql_walls(1)=0;
    ql_ceiling(1)=0;
    ql_floor(1)=0;
    ql_airleakage(1)=0;
    ql_window(1)=0;

    T_pv(1)=64;   %Assumed valued
    T_pv_2(1)=64; %Assumed valued
    T_pv_3(1)=64; %Assumed valued
    T_pv_4(1)=64; %Assumed valued
    T_pv_5(1)=64; %Assumed valued
    Tb_pv(1)=50;  %Assumed valued

    Ti_1(1)=To(1);
    Ti_2(1)=To(1);
    Ti_3(1)=To(1);
    Ti_4(1)=To(1);
    Ti_5(1)=To(1);

else

    Qaux(1)=0;
    TR(1)= 18;
    T2(1)= 3;
    Ta(1)=6.8;
    T3(1)=7;
    T5(1)= 7.3;
    T56(1)= 7.7;
    T6(1)= 7.1;
    T7(1)= 7.5;
    T8(1)= -13.5;
    Tca(1)= -6;
    Tcb(1)= -6;
    Tcc(1)= -6;
    Tcd(1)= -6;
    T9(1)= 12.7;
    T11(1)= 7;
    T11a(1)= 7.4;
    T12(1)= 7;
    T14(1)= 7.18;
    T14a(1)= 7.4;
```

```
        T15(1)= 7;

        TA(1)= -28;
        TA2(1)= -28;
        TA4(1)=-28;
        TA5(1)= -28;
        TA6(1)=3.8;
        TA8(1)=-28;
        TA10(1)= -28;

        Tw2(1)=1;
        Tw4(1)=1;
        Tw6(1)=1;

        ql_walls(1)=0;
        ql_ceiling(1)=0;
        ql_floor(1)=0;
        ql_airleakage(1)=0;
        ql_window(1)=0;

        T_pv(1)=64;   %Assumed valued
        T_pv_2(1)=64; %Assumed valued
        T_pv_3(1)=64; %Assumed valued
        T_pv_4(1)=64; %Assumed valued
        T_pv_5(1)=64; %Assumed valued
        Tb_pv(1)=50;  %Assumed valued

        Ti_1(1)=To(1);
        Ti_2(1)=To(1);
        Ti_3(1)=To(1);
        Ti_4(1)=To(1);
        Ti_5(1)=To(1);

    end



for D=1:8736, %Number of days per year.

   X1=D;
   X2=X1+1;

   Time=0;

       for Z=1:48, %Number of iterations per day.

       X=X+1;

       % There are two temperature sets back. When temperature
       % drops below 21C, temperature is set to 21C, if the
       % temperature is greater than 27C, than,
       % temperature is set to 27C.
```

```
% Similarly, night time setback outside the hours of
% 8am, and 10pm.


if TR(X)>=21

        Tsp(X)=TR(X);

end

if TR(X)>=21

        Night_Shutter(X)=0;

end

if TR(X)>=26.5

        Tsp(X)=26.5;
        Uinf=(2*Vol*p_air*cp_air)/3600;

else

        Uinf=(ach*Vol*p_air*cp_air)/3600;

end

%Auxiliary heating/cooling sets in if indoor
%temperatures is below 18C (at night), or below 21C
%in the day or higher than 24C.

if TR(X)<=18 || Tsp(X)==21  || Tsp(X)==26.5, %||
Tsp(X)==26.5

    qaux(X+1)=Kp*(Tsp(X)-TR(X));
else
    qaux(X+1)=0;
end


%if TR(X)<21 || TR(X)>=27,
    %qaux(X+1)=Kp*(Tsp(X)-TR(X));
%else
    %qaux(X+1)=0;
%end

% qaux cannot heat/cool more than equipment's capacity.
if qaux(X)>qmax,
   qaux(X)=qmax;
end

% If qaux is heating:
if qaux(X)>0,
    qauxH(X)=qaux(X);
```

```
                   else
                       qauxH(X)=0;
                   end

                    % If qaux is cooling:
                   if qaux(X)<0,
                       qauxC(X)=qaux(X);
                   else
                       qauxC(X)=0;
                   end

                   % internal gains =200 watts + 250 watts when occupants
                   % are home.
                   if Z<16 || Z> 36
                        qgains=450;
                   else
                        qgains=200;
                   end

                   %NIGHT SHUTTER

                   Uw=1/(1/0.855-1/ho-1/hi);

                   if Night_Shutter(X)==1;

                     Uw=1/(1/0.855-1/ho-1/hi+(2));

                   end

                   awindow=0.1;

%When the BIPV/T system is simulated, the follow functions calculate useful
heat from the BIPV/T system.
                   %if qaux(X)>0,

                       %qaux_BIPVT(X)=qaux(X)-E_thermal(X);

                   %else

                       %qaux_BIPVT(X)=0;

                   %end

                   %if qaux_BIPVT(X)>0,

                       %qaux_BIPVT(X)=qaux_BIPVT(X);

                   %else

                       %qaux_BIPVT(X)=0;

                   %end
```

```
                    % The follow are calculation for equivalent Temperatures
                    Teq1(X+1)=To(X)+(sIt(X)*as/ho);       %South Facade
                    Teq4(X+1)=To(X)+(nIt(X)*as/ho);       %north Facade
                    Teq10(X+1)=To(X)+(wIt(X)*as/ho);      %west Facade
                    Teq13(X+1)=To(X)+(eIt(X)*as/ho);      %east Facade
                    TeqA1(X+1)=To(X)+(rnIt(X)*as/ho);     %North Roof Facade
                    TeqA3(X+1)=To(X)+(rsIt(X)*as/ho);     %South Roof Facade
                    TeqA7(X+1)=To(X)+(eIt(X)*as/ho);      %East roof Facade
                    TeqA9(X+1)=To(X)+(wIt(X)*as/ho);      %West roof Facade
                    Teqw1(X+1)=To(X)+(sIt(X)*awindow/ho);
                    Teqw3(X+1)=To(X)+(sIt(X)*awindow/ho);
                    Teqw5(X+1)=To(X)+(sIt(X)*awindow/ho);

                    % Solar Heat gain coefficient for south, east and west
                    % facing windows, three types of windows simulated.

                    %TG
                    %SHGCw1(X)=((-1*10^-
7)*((XsIR(X))*180/pi)^2+0.0053*((XeIR(X))*180/pi)+484.25)/1000; % SHGF South
Facade
                    %SHGCw3(X)=((-1*10^-
7)*((XwIR(X))*180/pi)^2+0.0053*((XeIR(X))*180/pi)+484.25)/1000; % SHGF West
Window
                    %SHGCw5(X)=((-1*10^-
7)*((XeIR(X))*180/pi)^2+0.0053*((XeIR(X))*180/pi)+484.25)/1000; % SHGF East
Window

                    %DG
                    %SHGCw1(X)=((-1*10^-
7)*((XsIR(X))*180/pi)^2+0.0068*((XeIR(X))*180/pi)+554)/1000; % SHGF South
Facade
                    %SHGCw3(X)=((-1*10^-
7)*((XwIR(X))*180/pi)^2+0.0068*((XeIR(X))*180/pi)+554)/1000; % SHGF West
Window
                    %SHGCw5(X)=((-1*10^-
7)*((XeIR(X))*180/pi)^2+0.0068*((XeIR(X))*180/pi)+554)/1000; % SHGF East
Window

                    %DG + F
                    SHGCw1(X)=((-1*10^-
7)*((XsIR(X))*180/pi)^2+0.0052*((XeIR(X))*180/pi)+458)/1000; % SHGF South
Facade
                    SHGCw3(X)=((-1*10^-
7)*((XwIR(X))*180/pi)^2+0.0052*((XeIR(X))*180/pi)+458)/1000; % SHGF West
Window
                    SHGCw5(X)=((-1*10^-
7)*((XeIR(X))*180/pi)^2+0.0052*((XeIR(X))*180/pi)+458)/1000; % SHGF East
Window

                    % Total heat (watts/m2) transfer by windows,
                    % The SGHC for diffused component.
                    %TG=0.439;
                    %DG=0.451;
                    %DG+F=0.422;
```

```
                   Qw1(X)=SHGCw1(X)*sIb(X)+0.422*(sIds(X)+sIdg(X));
                   Qw3(X)=SHGCw3(X)*wIb(X)+0.422*(wIds(X)+wIdg(X));
                   Qw5(X)=SHGCw5(X)*eIb(X)+0.422*(eIds(X)+eIdg(X));

                       if TR(X)>26.5, %(Blind schedules based on indoor
temperature.)
                                  Qw1(X)=Qw1(X)*0.10;
                                  Qw3(X)=Qw3(X)*0.10;
                                  Qw5(X)=Qw5(X)*0.10;

                      else
                           Qw1(X)=SHGCw1(X)*sIb(X)+0.439*(sIds(X)+sIdg(X));
                           Qw3(X)=SHGCw3(X)*wIb(X)+0.439*(wIds(X)+wIdg(X));
                           Qw5(X)=SHGCw5(X)*eIb(X)+0.439*(eIds(X)+eIdg(X));
                       end



                   %Total heat gains to the floor.
                   Qf(X)=0.7*(Qw1(X)*Aw1+Qw3(X)*Aw3+Qw5(X)*Aw5);

%Energy balance equation for south facade
      T2(X+1)=(Teq1(X)*Asw/Rw+Ta(X)*Asw/Rg)/(Asw/Rw+Asw/Rg);
      Ta(X+1)=(DT/Cs)*((T2(X)-Ta(X))*Asw/Rg+(T3(X)-Ta(X))*Asw/Rg)+Ta(X);
      T3(X+1)=(Ta(X)*Asw/Rg+TR(X)*hi*Asw)/(hi*Asw+Asw/Rg);


%Energy balance equation for north facade
      T5(X+1)=(Teq4(X)*Anw/Rw+T56(X)*Anw/Rg)/(Anw/Rw+Anw/Rg);
      T56(X+1)=(DT/Cn)*((T5(X)-T56(X))*Anw/Rg+(T6(X)-T56(X))*Anw/Rg)+T56(X);
      T6(X+1)=(0.3*Qw1(X)*Aw1+T56(X)*Anw/Rg+TR(X)*hi*Anw)/(hi*Anw+Anw/Rg);

%Energy balance equation for floor
      T7(X+1)=(To(X)*Af*ho+T8(X)*Af/Rf)/(Af/Rf+(ho*Af));
      T8(X+1)=(T7(X)*Af/Rf+Tca(X)*Af/Rcon)/(Af/Rf+Af/Rcon);
      Tca(X+1)=(DT/Cf)*((T8(X)-Tca(X))*Af/Rcon+(T9(X)-
Tca(X))*Af/Rcon)+Tca(X);
      Tcb(X+1)=(DT/Cf)*((Tca(X)-Tcb(X))*Af/Rcon+(Tca(X)-
Tcb(X))*Af/Rcon)+Tcb(X);
      Tcc(X+1)=(DT/Cf)*((Tcb(X)-Tcc(X))*Af/Rcon+(Tcb(X)-
Tcc(X))*Af/Rcon)+Tcc(X);
      Tcd(X+1)=(DT/Cf)*((Tcc(X)-Tcd(X))*Af/Rcon+(Tcc(X)-
Tcd(X))*Af/Rcon)+Tcd(X);
T9(X+1)=(Qf(X)+Tcd(X)*Af/Rcon+TR(X)*hi*Af)/(hi*Af+Af/Rcon);

%Energy balance equation for east facade
      T14(X+1)=(Teq13(X)*Aew/Rw+T14a(X)*Aew/Rg)/(Aew/Rw+Aew/Rg);
      T14a(X+1)=(DT/Ce)*((T14(X)-T14a(X))*Aew/Rg+(T15(X)-
      T14a(X))*Aew/Rg)+T14a(X);
      T15(X+1)=(0.3*Qw3(X)*Aw3+T14a(X)*Aew/Rg+TR(X)*hi*Aew)/(hi*Aew+Aew/Rg);

%Energy balance equation for west facade
      T11(X+1)=(Teq10(X)*Aww/Rw+T11a(X)*Aww/Rg)/(Aww/Rw+Aww/Rg);
```

```
       T11a(X+1)=(DT/Cw)*((T11(X)-T11a(X))*Aww/Rg+(T12(X)-
       T11a(X))*Aww/Rg)+T11a(X);
       T12(X+1)=(0.3*Qw5(X)*Aw5+T11a(X)*Aww/Rg+TR(X)*hi*Aww)/(hi*Aww+Aww/Rg);

%Energy balance equation for the attic.
       TA4(X+1)=(TeqA3(X)*Asr/Rr+TA(X)*hi*Asr)/(hi*Asr+Asr/Rr);
       TA2(X+1)=(TeqA1(X)*Anr/Rr+TA(X)*hi*Anr)/(hi*Anr+Anr/Rr);
       TA10(X+1)=(TeqA9(X)*Awr/Rr+TA(X)*hi*Awr)/(hi*Awr+Awr/Rr);
       TA8(X+1)=(TeqA7(X)*Aer/Rr+TA(X)*hi*Aer)/(hi*Aer+Aer/Rr);
       TA5(X+1)=(TA6(X)*Ac/Rc+TA(X)*hi*Ac)/(hi*Ac+Ac/Rc);
       TA6(X+1)=(TA5(X)*Ac/Rc+TR(X)*hi*Ac)/(hi*Ac+Ac/Rc);

TA(X+1)=(hi*(Anr*TA2(X)+Asr*TA4(X)+Awr*TA10(X)+Aer*TA8(X))+TA5(X)*Ac*hi+To(X)
*Uinfa)/(Asr*hi+Anr*hi+Aer*hi+Awr*hi+Ac*hi+Uinfa);

%Energy balance equation for windows
       Tw2(X+1)=(Teqw1(X)*Aw1*Uw+TR(X)*hi*Aw1)/(Aw1*Uw+hi*Aw1);
       Tw4(X+1)=(Teqw3(X)*Aw3*Uw+TR(X)*hi*Aw3)/(Aw3*Uw+hi*Aw3);
       Tw6(X+1)=(Teqw5(X)*Aw5*Uw+TR(X)*hi*Aw5)/(Aw5*Uw+hi*Aw5);

%Energy Balance for Room node


TR(X+1)=(qaux(X)+qgains+hi*(T3(X)*Asw+T6(X)*Anw+T9(X)*Af+T15(X)*Aew+T12(X)*Aw
w+Tw2(X)*Aw1+Tw4(X)*Aw3+Tw6(X)*Aw5+TA6(X)*Ac)+Uinf*To(X))/(hi*(Asw+Anw+Af+Aew
+Aww+Aw1+Aw3+Aw5+Ac)+Uinf);

                   end

            end

end

%The following section inverses the linear interpolation and puts
%temperatures and variables back in an hour format for an year.

for H=1:8735,

    X=H;

    X1=H*48-24; X2=H*48+24;

    TR_hour(X)=sum(TR(X1:X2))/48;
    To_hour(X)=sum(To(X1:X2))/48;
    Qf_hour(X)=sum(Qf(X1:X2))/48;
    Ia_hour(X)=sum(Ia(X1:X2))/48;
    qaux_hour(X)=sum(qaux(X1:X2))/48;
    qauxH_hour(X)=sum(qauxH(X1:X2))/48;
    qauxC_hour(X)=sum(qauxC(X1:X2))/48;
    XsIRcheck(X)=sum(XsIR(X1:X2))/48;

    E_Gen_hour(X)=sum(E_Gen_total(X1:X2))/48;
    T_pv_5_hour(X)=sum(T_pv_5(X1:X2))/48;
    %E_thermal_hour(X)=sum(E_thermal(X1:X2))/48;
```

```
    %Ti_5_hour(X)=sum(Ti_5(X1:X2))/48;
    %qaux_BIPVT_hour(X)=sum(qaux_BIPVT(X1:X2))/48;



end

    TR_hour(1)=sum(TR(1:2))/12;
    To_hour(1)=sum(To(1:12))/12;
    Qf_hour(1)=sum(Qf(1:12))/12;
    Ia_hour(1)=sum(Ia(1:12))/12;
    qaux_hour(1)=sum(qaux(1:12))/12;
    qauxH_hour(1)=sum(qauxH(1:12))/12;
    qauxC_hour(1)=sum(qauxC(1:12))/12;
    XsIRcheck(1)=sum(XsIR(1:12))/12;

    E_Gen_hour(X)=sum(E_Gen_total(1:12))/12;
    T_pv_5_hour(X)=sum(T_pv_5(1:12))/12;
    %E_thermal_hour(X)=sum(E_thermal(1:12))/12;
    %Ti_5_hour(X)=sum(Ti_5(1:12))/12;
    %qaux_BIPVT_hour(X)=sum(qaux_BIPVT(1:12))/12;


    %

    TR_hour(8736)=sum(TR(419316:419328))/12;
    To_hour(8736)=sum(To(419316:419328))/12;
    Qf_hour(8736)=sum(Qf(419316:419328))/12;
    Ia_hour(8736)=sum(Ia(419316:419328))/12;
    qaux_hour(8736)=sum(qaux(419316:419328))/12;
    qauxH_hour(8736)=sum(qauxH(419316:419328))/12;
    qauxC_hour(8736)=sum(qauxC(419316:419328))/12;
    XsIRcheck(8736)=sum(XsIR(419316:419328))/12;

    E_Gen_hour(X)=sum(E_Gen_total(419316:419328))/12;
    T_pv_5_hour(X)=sum(T_pv_5(419316:419328))/12;
    %E_thermal_hour(X)=sum(E_thermal(419316:419328))/12;
    %Ti_5_hour(X)=sum(Ti_5(419316:419328))/12;
    %qaux_BIPVT_hour(X)=sum(qaux_BIPVT(419316:419328))/12;


    % Total heating requirement in KWH and MJ
    qheating_KWH=sum((qauxH_hour(1:8736)))/(1000*130);      %KWH
    qheating_MJ=qheating_KWH*3.6;                       %MJ

    % Total cooling requirement in KWH and MJ
    qcooling_KWH=sum((qauxC_hour(1:8736)))/(1000*130);      %KWH
    qcooling_MJ=qcooling_KWH*3.6;                       %MJ

    % Total heating and cooling requirement in KWH and MJ
    q_KWH=qheating_KWH+(-1*qcooling_KWH);               %KWH
    q_MJ=qheating_MJ+(-1*qcooling_MJ);                  %MJ
```

```
%E_Gen_KWH=sum((E_Gen_hour(1:8735)))/(1000*130);      %KWH
%E_thermal_KWH=sum((E_thermal_hour(1:8735)))/(1000*130);      %KWH
%qaux_BIPVT_KWH=sum((qaux_BIPVT_hour(1:8735)))/(1000*130);


% end of Code
```