A Lifecycle Assessment-Based Environmental Analysis of Building Operationally Energy Efficient Houses in Nova Scotia

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List of Abbreviations and Symbols

ACH	Air changes per hour
BOM	Bill of materials
CaGBC	Canada Green Building Council
CHBA	Canadian Home Builders' Association
CMHC	Canadian Mortgage and Housing Corporation
COP	Coefficient of performance
CNBC	Canadian National Building Code
CSA	Canadian Standards Association
DHW	Domestic hot water
DG	Double glazed
EPD	Electronic product declaration
ER	Energy rating
ERV	Energy recovery ventilator
ES	Energy Star
ESNH	Energy Star new home
GHC	Green home certifications
GHG	Greenhouse gas
HH	Human health
HRV	Heat recovery ventilator
HSPF	Heating season performance factor
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEED	Leadership in Energy and Environmental Design
Low-e	Low emissivity
MPPT	Maximum power point tracking
NRCan	Natural Resources Canada
NS	Nova Scotia
NZ	Net zero

NZE	Net zero energy
NZEB	Net zero energy building
NZR	Net zero ready
PV	Photovoltaic
SHEU	Survey of household energy use
SHGC	Solar heat gain coefficient
SRE	Sensible recovery efficiency
TG	Triple glazed
TRACI	Tool for Reduction and Assessment of Chemicals and other Environmental Impacts
VOC	Volatile organic compound

Abstract

In Nova Scotia, single-family dwellings account for approximately 67% of energy use in the residential sector. As a contribution to the province's energy goals, incentives have been developed by the province's energy efficiency utility to encourage homeowners to increase their home's efficiency. Although operational energy efficiency in homes has been well-studied, few studies use a lifecycle approach to analyzing the environmental impacts of single-family dwellings from material extraction through demolition and disposal. This project uses life cycle assessment (LCA) methodology to analyze five single-family dwellings in Nova Scotia with the same footprint but varying operational energy efficiencies with the aim to compare and highlight life-cycle stages and materials that have the highest environmental impacts over the lifecycles of the buildings. This will provide guidance for homeowners and builders on the environmental impacts of different efficiency measures over their lifecycles. LCA modelling including operational energy modelling is performed for all five houses.

The results of this study show that the largest environmental impact savings come from operational energy upgrades. The most efficient home in this project, the Net Zero home, which produces electricity using PV modules, has on average 96% lower environmental impacts than the project's baseline home. However, when considering only the embodied impacts (all life cycle stages excluding operational), the Net Zero home has 11% higher embodied impacts amongst the nine impact groups than the baseline home. Comparatively, the Net Zero Ready home, which mimics the Net Zero home but does not have any generation capabilities has on average 68% lower environmental impacts than the baseline home and 11% higher embodied impacts on average. Although embodied impacts increase as homes are built more efficiently, the impacts are minor compared to the saved impact created by decreasing the home's operational energy. Therefore, implementing operational energy efficiency upgrades rather than reducing embodied impacts is the most effective pathway to reducing lifecycle environmental impacts when building single family dwellings in Nova Scotia.

1.0 Introduction

Many countries are committing to developing strategies that will reduce their fossil fuel usage as a part of an overall effort to slow climate change. Canada was one of 190 countries that signed a legal agreement to maintain global warming below 2°C at the 2015 Paris Climate Conference (Government of Canada, 2016). In 2017, the United Nations reported that 36% of worldwide energy use and 39% of energy-related CO_2 emissions originate from buildings and construction (United Nations Environment, 2017). The construction industry has the potential to make a considerable contribution to Canada's goal to reduce greenhouse gas (GHG) emissions, especially given the expected increase in infrastructure demand as the population increases 1.9% annually (United Nations Environment, 2017).

Provincial governments also have a responsibility in contributing to Canada's goals. In Nova Scotia (NS), the government has committed by signing Bill No. 213, which states that their goal is to be net zero by 2050, meaning that GHG emissions will balance GHG removals (The Honourable Gordon Wilson, Minister of Environment, 2019). In NS, single-family dwellings account for approximately 67% of energy use in the residential sector, thus incentivizing the province to prioritize the reduction of their energy usage (Government of Canada, 2015). The development of passive and net-zero energy buildings (NZEBs) is becoming a more prevalent method to implement carbon-friendly technology and systems in the residential building sector. NZEBs require far less energy than buildings constructed according to the standards outlined by the national and provincial construction codes for residential dwellings (Roach & Ugursal, 2020). Voluntary standards have been developed by Natural Resources Canada (NRCan) called ENERGY STAR® for Homes and R-2000, which outline elevated standards for building homes in terms of energy efficiency, indoor air quality and environmental responsibility. Additionally, a net zero energy (NZE) standard for homes in Canada has been developed by the Canadian Home Builder's Association (CHBA), which specifies the requirements to build both a Net Zero (NZ) home and a Net Zero Ready home – in which case the home is built to the same standard as the NZ home but excludes electricity generating devices (CHBA, 2020).

Although it is evident that the operational energy of an NZEH is lower than a traditionally powered home, analyzing the "cradle to grave" environmental impact of both dwellings can be done by performing a whole-building life-cycle assessment (LCA). The LCA tool quantifies the impact of an entire building over its lifespan by considering its lifecycle stages including raw material extraction, manufacturing, transportation, building construction, operation, demolition and disposal. These inputs and outputs are evaluated and formed into data that can be used to interpret the effect of specific components and life-cycle stages on an LCA impact category. These categories include, but are not limited to global warming, ozone depletion, acidification and fossil-fuel consumption.

The project utilizes LCA methodology to analyze the difference in environmental impact between a single-family dwelling built strictly according to the NS building code and under four energy efficiency standards including the ENERGY STAR® for Homes standard, R-2000 standard, NZE Ready Home Standard and NZE Home Standard. The baseline home acts as the control for comparison purposes. The primary LCA software tool being used for the whole-building LCAs of the building structure is a Canadian software named Athena Impact Estimator. The operational energy component of the LCA is modelled according to each home's standard in a Natural Resource Canada's software called HOT 2000. The results of the assessment allows for a full analysis of the environmental impacts of a building home to various degrees of operational efficiency. The overall impact is broken down into categories and "hotspots" of environmental impact are highlighted in both building designs and construction methods throughout their lifespans.

This study aims to provide quantitative justification regarding the life cycle environmental impacts of building traditional homes as compared to energy efficient homes. This justification could lead to improvements in existing building codes by highlighting the potential for improved efficiency standards within the code for residential dwellings, thus contributing to local and global climate change goals.

2.0 Residential Energy Literature Review

2.1 Nova Scotia Electricity Grid Characteristics

Electricity generation is Nova Scotia's largest source of GHG emissions and accounts for 7% of Canada's electricity generated GHG emissions (Environmental Climate Change Canada, 2018). According to an equivalency agreement with the Federal Government, the Nova Scotia grid plans to be reliant upon fossil fuels for primary electricity generation for the next several years (Environmental Climate Change Canada, 2018),(Canadian Institute for Climate Choices, 2020). However, the Nova Scotia government has set some of the highest GHG emission reduction targets countrywide (Canadian Institute for Climate Choices, 2020). With electricity production contributing to 42% of provincial emissions, the province is working towards reducing their GHG emissions in this sector (Canada Energy Regulator, 2021b).

The province has made progress, evidenced by its reduction on fossil fuel dependence for electricity generation by 19% between 2007 and 2018 and that 12% of its electricity generation in 2018 came from renewable sources (Environmental Climate Change Canada, 2018). By 2050, NS hopes to reduce its GHG emissions by 80% from 2009 levels (Nova Scotia Governement, 2015). Although NS is moving in the right direction in terms of their electricity grid characteristics, the province is lacking comparatively, with its coal-fired plants contributing to 7% of Canada's total emissions in 2015 despite only compromising 3% of the population (Canadian Institute for Climate Choices, 2020).

While Nova Scotia's grid characteristics are not changing as quickly as other Canadian provinces, there is an opportunity to reduce electricity demand amongst residential buildings, which accounted for 26% of the province's total energy demand in 2017 (Canada Energy Regulator, 2021b). The NS government has recognized this opportunity and implements residential energy efficiency programs through its own efficiency utility, Efficiency Nova Scotia (Efficiency Nova Scotia, 2022). Nova Scotia has been able to reduce electricity consumed per person to 24% below the national average (Canada Energy Regulator, 2021).

2.2 Energy Costs

In Nova Scotia, the cost of electricity and other heating fuels including natural gas, oil and wood remain some of the highest in the country. Natural gas bills in NS average $155 / month compared to an average $97/month in other Canadian provinces that use natural gas (Canada Energy Regulator, 2021a).

Between 2004 and 2015, the cost of electricity in NS increased by 73.6% (Nova Scotia Governement, 2015). Although NS has programs implemented to provide support to low-income households (Efficiency Nova Scotia, 2021c) for heating costs and efficiency implementations, low to middle class homes pay 60% more on energy (including transportation) than other Canadians (Canadian Institute for Climate Choices, 2020). The high cost of electricity and relatively high grid emissions play roles in the desire to implement further energy efficiency opportunities for the NS residential sector.

2.3 Single Family Dwelling Characteristics in NS

According to the 2016 census, 65.5% of Nova Scotia's residential dwellings consisted of single-detached homes (Statistics Canada, 2017). Over half of NS homes were constructed between 1960 and 1990, while homes built between 2006 and 2016 accounted for 10.9% of total homes in 2016 (NS Department of Finance - Statistics, 2017). Although the province's population growth is small, at 0.2% increase between 2011 and 2016 (Statistics Canada, 2019b), the Halifax area in particular has seen record-breaking growth rates between 2016 and 2020 (Munro, 2021). Accordingly, the Halifax area is where the highest proportion of new homes were built between 2006 and 2016 (NS Department of Finance - Statistics, 2017). However, Halifax only contained 50% single detached homes, and had the highest proportion of rented residential properties (NS Department of Finance - Statistics, 2017). This project attempts to consider the most typical NS home such that the upgrades considered to achieve the desired green home certifications are relevant to a large proportion of the single detached homes in NS, despite their age.

In NS, the median above-grade living area of single-detached homes is 106 m^2 (1150 sqft) (Statistics Canada, 2019a). However, the size of new single detached homes has increased steadily since 1960, with new homes between 2016 and 2017 having a median above-grade living area of 1530 sqft (NS Department of Finance - Statistics, 2017).

The average annual energy use amongst single-detached homes in NS was 126 GJ in 2018, higher than the national average of 124.2 GJ (Government of Canada, 2019a, 2020c). Of this energy, 83% was used for space and water heating, 11% on appliances and the remaining on lighting and space cooling (Government of Canada, 2020b). This data provides useful information regarding the most beneficial areas to improve energy efficiency in the homes. In 2018, out of all residential buildings in NS, 51.7% use medium efficiency heating oil, 21.9% use electricity and 4.8% use heat pumps for space heating purposes (Government of Canada, 2020a). The use of oil is representative of the older building stock in NS. Despite the fact that 10.9% of homes in NS were built between 2006 and 2016, less than half of them use heat pumps for space heating.

Based on Canadian government's survey of household energy use (SHEU) in 2015, only 18.9% of homes in the Atlantic region had received an energy audit (Government of Canada, 2019b). However, 77% of homeowners that did receive an audit made a change as a result of the audit and 66% received a grant from a government home energy retrofit program to implement the change (Government of Canada, 2019b). This data is encouraging in terms of response to energy audits, but evidently the use of energy auditing programs like EnerGuide is not being widely used in the Atlantic region. The energy audits focus solely on operating energy reduction and lack a life cycle assessment approach.

2.4 Energy Efficiency Measures in Homes

2.4.1 Orientation

Orientation of the home affects the passive heating of rooms depending on the season. However, most tract housing developments prioritize land development over passive solar potential based on orientation (Center for Sustainable Climate Solutions, 2020). Optimally, in a Northern climate, the house would be positioned such that the side with the most aperture area faces south such that living spaces capture the sun during the winter but are shaded during the warmer summers (Zirnhelt, 2013).

In HOT 2000, the orientation corresponds to the usable solar gains fraction, which is the percentage of gross space-heating load provided by solar gains annually (NRCan, 2021b). The usable solar heat gains is determined by multiplying the solar utilization factor by the total solar heat gains, as determined in equation 1 (Barakat & Sander, 1986).

$$h = \lambda_{tot} - \eta_i \cdot G_{ti} - \eta_s \cdot G_{ts} \qquad \text{Eq. 1}$$

where,

- h is the total heating required for the season, in units of W
- λ_{tot} are the total monthly heat loss rate, in units of W
- η_i is the utilization factor for internal gains, unitless
- G_{ti} are the total internal heat gains, in units of W
- η_s is the utilization factor for solar gains, unitless
- G_{ts} is the total solar heat gains through windows

The utilization factor for internal gains describes the ratio of seasonal total internal gains to seasonal total loss for varying profiles of daily internal gains and thermal storage in Halifax. The utilization factor for solar gains describes the ratio of seasonal solar gains to total building load and was determined using an hour-by-hour simulation for Halifax. The resulting usable solar gains contributes to the space heating requirements of the home (NRCan, 2021b).

2.4.2 Windows

2.4.2.1 Window Tightness

The Canadian Standards Association (CSA) specifies window tightness into three categories – A1, A2 and A3 – based on the amount of air that would pass through the window in 40 km/h winds, with A1 being the least airtight and A3 being the most airtight. According to HOT 2000, A1 represents a window tightness of 1.86 L/s.m^2, A2 represents 1.5 L/s.m^2 and A3 represents 0.5 L/s.m^2 (NRCan, 2020b).

2.4.2.2 Fenestration Thermal Resistance

A window, door or skylight's ability to transmit non-solar energy is typically specified by a U-factor, which is the inverse of the thermal resistance. U-factors are measured in W/m^2 K to represent the heat in watts that can pass through an opening given its area and temperature difference. A window's labelled U-factor includes testing from the center of the glass, edge of the glass, frame and spacers (US Department of Energy, 2021). Every window has a different overall thermal resistance, as it accounts for the window's size through the measurements at different areas, the glass resistance, the inner gas resistance and the inside and outside air film resistances (Howell, 2017).

A window's solar heat gain coefficient represents the fraction of heat that enters the home by either transmission or absorption through the glass (US Department of Energy, 2021). Windows with higher solar heat gain coefficients capture more heat in the winter, while windows with lower solar heat gain coefficients let less heat enter the building and therefore are beneficial in the summer or in warm climates (US Department of Energy, 2021).

Windows can also be rated on the Energy Rating (ER) scale, which is calculated according to CSA Standard 440.1. and gives a comparative value for a window's solar heat gain coefficient, air leakage and thermal resistance (NRCan, 2020b).

The thermal resistance, solar heat gain coefficient and air leakage depend on the window's specifications. Window frame material affects the overall thermal resistance, as some materials like metals allow more heat loss than vinyl or fibreglass. Windows equipped with two or more panes of glass provide insulation and are often filled with a gas such as argon or krypton to increase insulation. Coatings on glass control the solar heat gain coefficient by selectively allowing light of certain wavelengths to pass to either increase or decrease solar gains. These coatings are typically described as low-emissivity (low e) as they reflect long-wave radiation (heat), trapping heat inside of the home in winter and reflecting unwanted solar heat in the summer.

Rather than including additional layers of glass, a newer technology called heat mirrors, consisting of a nanoscale metal coating is placed between layers of glass to reflect heat and therefore increase thermal resistance (Rahman, 2018). The installation of a single heat mirror in a double glazed windows improves its performance to the equivalent of a single pane mirror (Hesaraki, 2017). Heat mirrors are classified by numbers depending on their reflectance and transmittance properties, where higher numbers indicate increased solar gain (Hesaraki, 2017).

2.5 Ventilation

2.5.1 Natural Ventilation

Infiltration describes the natural passing of air through cracks and openings in a building, typically through doors, windows, walls or any small opening. This is a result of pressure differences between the outdoors and indoors. Air infiltration is measured in air changes per hour (ACH), or the number of times the total volume of air is changed in a space within an hour. In the summertime and warmer climates, intentional natural ventilation is induced through open windows, doors and other openings (Howell, 2017). Other sources of infiltration come from cracks and unintentional openings in the building envelope. A tightly built home may have an infiltration rate of 0.2 ACH, whereas a leaky house may have 2 ACH, with the median ACH for houses in NA being 0.5 (Howell, 2017). This rate can be converted to a volume change rate by multiplying ACH by volume and dividing by time.

2.5.2 Mechanical Ventilation

Mechanical ventilation improves indoor air quality by moving air through a building through fans, intake ducts and exhaust ducts (Howell, 2017). American Society of Heading, Refrigerating and Air-Conditioning Engineers (ASHRAE) suggests a minimum ventilation rate of 0.3 $L/s.m^2$ and 2 L/s per person (ASHRAE, 2019). Balanced mechanical ventilation can be incorporated into homes to exchange equal quantity of intake and exhaust air through the use of air exchangers, heating recovery ventilators (HRV) or energy recovery ventilators (ERV). Air exchangers use two fans to bring fresh air in (intake fan) or exhaust indoor air (exhaust fan). HRVs work in the same manner but have improved efficiency because the warm exhaust air is used to heat the incoming outdoor air, reducing indoor heating and cooling loads (Energy Star, 2020). HRVs can save 30-60% of total heat loss in a home, depending on the envelope and outdoor temperature. The sensible recovery efficiency (SRE) of an HRV is tested by manufacturers according to Standard CSA-C439 and is typically between 50-75%, with approximately 10% lower efficiency when tested at -25°C versus 0°C (NRCan, 2013b).

Energy recovery ventilators include heat and moisture control by removing moisture from incoming air in the summer - rather than requiring a separate dehumidifier – and transferring moisture from exhaust air to intake air in the winter to avoid uncomfortably dry indoor air (Energy Star, 2020).

2.6 Heating System

The heating system requirements depend on the heat losses and gains within the building. The highest heating demand occurs at the coldest outdoor temperature, which is typically early in the morning before solar and internal heat gains contribute (Howell, 2017). The design heating load is equal the design heat loss, which has contributions from infiltration, building envelope and ventilation losses (Howell, 2017). The heating system must contribute enough to meet the requirement of the comfortable indoor design temperature. Cumulatively, the design heating load can be determined as shown in Equation 1 (Howell, 2017).

$$Design\ Heating\ Load = \left[\, \Sigma_{i=1}^{n} U_i A_i + \left(\dot{m}_{inf} + \dot{m}_{vent}\right) c_P \right] (T_{Des,in} - T_{Des,out}) \qquad \text{Eq. 1}$$

where,

U_i = heat transfer coefficient of envelope component i

A_i = surface area of component envelope i

$\dot{m}_{inf}$ = mass flow rate of infiltrated air

$\dot{m}_{vent}$= mass flow rate of ventilation air

n = number of envelope components

C_P = specific heat of air

$T_{Des,in}$ = indoor design temperature

$T_{Des,out}$ = outdoor design temperature

2.6.1 Heat Pumps

Air-source heat pumps are an efficient and popular method of heating and cooling homes in Canada (NRCan, 2021a). During the heating season, these devices extract heat from the cold outside air and deliver it to the warm inside air, using the vapour compression refrigeration cycle.

The coefficient of performance of a heat pump (COP) is the ratio of heat delivered to electricity used (NRCan, 2021a). As the temperature difference between the indoor and outdoor air increases, the COP decreases, reducing the heat supplied (NRCan, 2021a). In the cooling season, the heat pump can reverse its operation to extract heat from inside and discharge it to the outdoors (NRCan, 2021a). The heating season performance factor (HSPF) is another measure that describes the energy provided by the heat pump over the heating season compared to the total energy (Watt hours) over the heating season (NRCan, 2021a).

The most common residential heat pumps in Canada are air to air heat pumps, which can be installed as either a ducted system such that the conditioned air is distributed to different areas of the home via ducts or a ductless system which distributes the conditioned air via one or more indoor units connected to the outdoor unit via refrigerant lines. Ductless heat pumps can be supplemented by baseboard electric heating or a furnace to provide heating when the heat pump capacity falls below the heating required due to low outside temperature. Horizontal ducted units act as a hybrid, by minimizing ductwork required to condition multiple zones.

2.7 Miscellaneous Energy Consumption

The U.S. Department of Energy provides simulation protocols guidelines for houses, which indicate correlations for miscellaneous electrical energy consumption including small appliances and phantom loads based on the number of rooms and floor area, as shown in Equation 2 (Hendron & Engebrecht, 2010).

$$Misellaneous\ loads\ \left(\frac{kWh}{year}\right) = 1703 + (266\ \times\ N_{br}) + (0.454\ \times\ FFA) \qquad \text{Eq 2}$$

where,

N_{br} = number of bedrooms

FFA = finished floor area (ft^2)

2.8 Water Heating

Domestic hot water heating accounts for approximately 24% of energy use in Canadian homes (NRCan, 2020g). Conventional hot water storage tanks heat and store hot water in a tank using a heating fuel. The tanks are sized based on the home's "first-hour rating", which accounts for the peak amount of hot water that could be required within an hour in the home (U.S. Department of Energy, 2021f). These tanks are typically highly insulated, but have standby losses associated with the loss of heat through the tank walls.

Tankless hot water heaters can improve the efficiency of water heating by approximately 30% depending on the unit and amount of hot water required (U.S. Department of Energy, 2021g). There are no standby losses associated with tankless water heaters, as cold water is instantaneously heated via heating units in the in-line heater, improving efficiency. However, since water has to be heated at the rate at which it is delivered, heater capacity needs to be larger with in-line heaters.

Heat pump water heaters can be twice as efficient as conventional tank heaters by using the heat pump cycle to remove heat from the surrounding and transfer it to a tank of water for heating purposes (U.S. Department of Energy, 2021a). Most models are a hybrid of the conventional and heat pump technology, with back-up electric resistance for cold climates in the winter. Since the heat pump extracts heat from the inside air, the efficiency decreases in the winter since the surrounding air is cooler and should be located in an unheated, unoccupied space such that more space heating is not required for the surrounding space (ENERGY STAR, 2022). A heat-pump water heater draws heat in from the surrounding air and transfers it to the hot water in a storage tank, cooling the surroudnings. This can be beneficial in a warm climate but can cause excessive cooling and additional space heating if in a conditioned area (ENERGY STAR, 2022). For this reason, heat pump water heaters are most effective and operate at higher efficiency when in a climate in which the temperature remains above 4°C all year (ENERGY STAR, 2022). Therefore, this device is not suitable for the Nova Scotia climate.

2.9 Solar Photovoltaics

Photovoltaic (PV) technology converts the sun's energy into electricity by placing semiconducting solar cells connected in series between protective glass or plastic and pointing the panel towards the sun (U.S. Department of Energy, 2021e). The DC electricity produced by the cells must then be run through an inverter to produce AC current that is compatible with the home electrical system and the utility grid. The most common type of solar cells are crystalline-silicon cells that produce a maximum of 150-200 W of electricity per square meter and thin-film photovoltaic sheets that can produce a maximum of 45-60 W of electricity per square meter but come at a lower cost (Roach & Ugursal, 2020).

The efficiency of typical PV cells in converting sun's energy to electricity varies from 15% to 25%. The lack of efficiency is partially due to the inability for the solar cell material to absorb some wavelengths of light, their inability to operate efficiently in high temperatures and losses associated with light that is reflected off of the cell due it the material's reflectivity (U.S. Department of Energy, 2021c). Orientation of the solar panels contributes significantly to the efficiency of the system. A system operates at its full capacity for a given orientation in full sun and cloud cover, which occurs during approximately 43% of possible daylight hours in Nova Scotia (Environment Canada, 2021). In the Northern hemisphere, systems can obtain the most amount of light by positioning the panels due south and tilted at an angle equal to the location's latitude (U.S. Department of Energy, 2021d).

There are three common types of inverters: string inverters, hybrid inverters and microinverters. String inverters are the most common type of inverter and consist of one unit that processes DC power from solar panels arranged in series (Efficiency NS, 2021). Hybrid inverters are capable of connecting to the utility grid and a battery system (Efficiency NS, 2021). Microinverters are connected to individual panels, maximizing each panel's output despite varying conditions such as shade and direction – a factor that can limit the output of panels connected in series (Efficiency NS, 2021). Inverters typically have efficiencies from 95%-98%, causing additional losses. Inverters use a technology called maximum power point tracking (MPPT), which adjusts the operating voltage of the module to maximize the power output as it varies with environmental conditions (Almutairi et al., 2020).

2.10 Solar Thermal Collectors for Domestic Hot Water Heating

Solar thermal collectors collect the sun's energy for thermal purposes- most often domestic water heating and typically consist of a simple flat plate collector with tubes of a glycol/water mixture running through them. The glycol mixture is run through a simple heat exchanger to transfer the heat to hot water heater tank. This technology is more efficient (83% conversion) and simpler than photovoltaic cells. However, due to the decreasing cost of PV systems, solar thermal collectors are becoming less popular.

3.0 Operational Energy Modelling and Energy Rating Systems Literature Review

3.1 Introduction to Green Home Certifications

There are several green home certifications (GHC) that can be obtained by homeowners and builders in Canada. Although the aim of each certification varies depending on the association that created the certification system, the overall purpose is to reduce the environmental footprint of building and operating homes in Canada. The requirements for these certifications vary depending on the improvement to be made to the home, compared to a reference home built to a local building code. In this project, a GHC system is chosen to provide a systematic approach to analyzing the life cycle environmental and economic effects of building increasingly efficient green homes in Canada. The main GHCs being considered for this project are Leadership in Energy and Environmental Design (LEED), EnerGuide, Energy Star, Natural Resource Canada (NRCan) Net Zero Ready (NZR) and Net Zero (NZ) Certifications, the R-2000 certification and the Passive House certification.

LEED is one of the leading worldwide green building certifications. In Canada, LEED is administered by the Canada Green Building Council (CaGBC), that has been certifying LEED buildings since 2002 (Natural Resources Canada, 2018b). NRCan runs EnerGuide, ENERGY STAR (ES), Net Zero Ready, Net Zero and the R-2000 certifications (CHBA, 2020b). The EnerGuide program provides homes with ratings depending on the amount of energy that they consume (Natural Resources Canada, 2020c). Although the EnerGuide rating can be considered a certification itself, NRCan has implemented auxiliary certification programs which provide guidance in home design to achieve certain EnerGuide scores (Natural Resources Canada, 2018b). The ENERGY STAR label aims to make energy efficiency improvements of 20% compared to a reference home built to code (Natural Resources Canada, 2011). The R-2000 certification has been used in Canada for over 35 years and aims to improve energy efficiency by 50% compared to a reference home built to code (Natural Resources Canada, 2018a). Similarly, the Net Zero Ready certification provides building guidelines for developing a home that is 80% more efficient than the EnerGuide reference home, requiring only the addition of a renewable energy source to make the home Net Zero (CHBA, 2021a). NRCan's Net Zero certification home must produce as much energy annually as it uses from the electricity grid (CHBA, 2021a).

3.2 GHC Descriptions

3.2.1 LEED Certification System

To date, over 3000 homes in Canada have been LEED certified (CaGBC, 2021). The LEED certification focuses on sustainability in construction, design and operation while prioritizing environmental, economic, social and community benefits (*LEED , 2021b*). Buildings can receive points towards a certification level by including implementations related to the following categories: location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation and regional priority (CaGBC, 2021). Under the most recent version of LEED for homes, v.4.1, buildings can earn points to become certified under the following levels: certified (40-49 points), silver (50-59 points), gold (60-79 points) or platinum (80-110 points) (CaGBC, 2021). For a non-LEED member, having the home certified can cost between $1250 and $2750 (LEED, 2021a). Although some provinces and cities such as Quebec, Calgary and Kitchener offer financial incentives in the form of grants for LEED certified homes, there is no rebate specific to LEED certified homes in Nova Scotia (Rana et al., 2021). However, there are provincial rebates available for certain heating components installed in the home such as heat pumps and solar panels (Efficiency Nova Scotia, 2021b) and banks across Canada will offer reduced mortgage and loan rates for green homes if the homes meet their criteria (Rana et al., 2021). Additionally, the Canadian Mortgage and Housing Corporation (CMHC) provides a 15% refund for LEED certified homes (Canada Mortgage and Housing Corporation, 2018).

3.2.2 EnerGuide Rating System

NRCan's EnerGuide program helps Canadian homeowners and builders make energy efficient decisions when designing, constructing, purchasing, renovating and operating homes (Natural Resources Canada, 2020b). This program is widely used and recognized within Canada, with over one million homes having been rated using the EnerGuide program (Natural Resources Canada, 2017).

The program aims to provide education to achieve lower home operating costs, lower environmental impact and increased occupancy comfort (Natural Resources Canada, 2020c). The rating produced is equivalent to the annual net energy consumption of the house in Gigajoules (GJ). The rated energy intensity and rated greenhouse gas emissions are also calculated in the analysis. An EnerGuide rating of zero means that the house has net-zero emissions, annually producing as much energy as it consumes. Houses that produce more energy than they consume (net positive homes) can receive a rating of 0*. The score can go as high as the GJ produced by the home per year. The software automatically generates a "reference" house, which mimics a model of the house being rated if it were built according to National Building Code of Canada 2015, Section 9.36. These calculations are performed using NRCan's energy simulation software, HOT2000. This software allows the user to build a model of the home by inputting all materials. According to the HOT2000 User Guide V15.10 (Natural Resources Canada, 2020b), the main categories used in the calculations within the software are:

1. Home envelope components
2. Windows and doors
3. Foundation type
4. Air infiltration and ventilation heat loss
5. House surface area and volume
6. Space heating/cooling system type and efficiencies
7. Domestic hot water supply system type and efficiencies
8. Internal heat gains
9. Solar heat gains through glazing
10. Geographical location
11. Fuel type
12. Renewable energy generation

In addition to the provincial rebates for installing efficient heating components above, Efficiency Nova Scotia provides EnerGuide evaluations, with the opportunity to receive up to $5000 in rebates depending on the efficiency score of the home (Efficiency Nova Scotia, 2021c). Having a HOT 2000 energy assessment done in Nova Scotia costs $100 (Efficiency Nova Scotia, 2021c).

3.2.3 Auxiliary NRCan Green Home Certifications

Although the EnerGuide rating can be considered a certification itself, NRCan has implemented supporting certification programs to provide guidance when designing homes to achieve certain EnerGuide scores (Natural Resources Canada, 2018b). These programs include the ENERGY STAR label, the R-2000 standard, the Net Zero Ready Home Certification and the Net Zero Home certification (CHBA, 2020b).

The R-2000 standard is a voluntary efficiency standard that was developed by NRCan 35 years ago with the purpose to provide a strict standard for new home construction in terms of energy efficiency, health and environmental benefits (Natural Resources Canada, 2018a). The standard targets water conservation, energy efficiency, indoor air quality, mechanical systems, envelope requirements, and environmental features (Canadian Office of Energy Efficiency, 2012). The standard provides detailed requirements for all building components within these categories and must include an additional two "environmental features" from the R-2000 Pick-List, such as specific flooring, insulation, appliances, or a further reduced energy target (Canadian Office of Energy Efficiency, 2012). The energy use target for space heating and domestic hot water use is 50% of the energy used by the reference house (Canadian Office of Energy Efficiency, 2012). R-2000 requirements must be verified using HOT 2000 or by a licensed R-2000 plan evaluator. In addition to the previously mentioned financial incentives for energy efficient homes in NS, the CMHC provides a 25% insurance premium refund for R-2000 homes.

The ENERGY STAR label is another NRCan initiative with lower energy savings expectations than R-2000, with a reduction of 20% energy use compared to the EnerGuide reference home (Natural Resources Canada, 2011). The focus is on ventilation, heating systems, cooling systems, envelope and ENERGY STAR labeled products, which represents the most energy efficient products available (Natural Resources Canada, 2011). ENERGY STAR products are what the program is best-known for and are often incorporated into more demanding green home certifications (Reynolds, 2012).

In 2017, the Canadian Home Builders' Association implemented two more certifications under the EnerGuide program, for Net Zero Ready Homes and Net Zero Homes (CHBA, 2021a). These certifications have strict building requirements that result in 80% and 100% more energy efficient homes than the reference home for the Net Zero Ready and Net Zero homes, respectively (CHBA, 2021a). The Net Zero home must produce as much energy as they consume annually, while the Net Zero Ready homes must be designed such that a renewable system is the only addition required to make the home Net Zero (CHBA, 2021a).

3.2.4 Passive House Certification

Passive House is a non-profit association that provides a high-efficiency building standard worldwide (Passive House Canada, 2021a). The German-based standard came to Canada in 2013 to provide guidelines for building homes that use little energy to maintain a comfortable temperature year-around, therefore requiring very little active space heating and cooling (International Passive House Association, 2014). The standard provides limits on space heating/cooling demands, energy demand on domestic appliances, air tightness and temperature levels by specifying requirements for insulation, windows, orientation, envelope, ventilation, and thermal bridging design customized to the local climate (International Passive House Association, 2014). The resulting homes are typically 80% more energy efficient than a similar home built to the local building code (Passive House Canada, 2021b). The Passive House Planning Package (PHPP) allows for an in-depth energy analysis of the home being modelled, with more detailed calculations than other energy simulation software to ensure that an accurate simulation is developed (Bleasby, 2018). With about 2000 homes having been certified as of 2017 (Chung, 2017), the program is less commonly used in Canada, potentially due to the price of certification, which is $3000 -$5000 (Passive House Canada, 2021b). Similarly to LEED, there are no financial incentives tied directly to the program, but financial incentives can be obtained for specific building components or if the owner chooses to get an EnerGuide rating after construction (Reynolds, 2012).

4.0 Green Home Certification Programs Comparison and Selection

For this project, there are a number of possible certifications that could be implemented to achieve the desired home models with varying iterations of efficiency levels. The LEED program could provide the desired efficiency iterations, using their certified, silver, gold or platinum certifications. Similarly, the EnerGuide rating scale could be used to provide customized model iterations with incrementally improving scores in terms of GJ of energy used annually. Alternatively, the HOT 2000 software could be used to build models that align with NRCan's auxiliary programs, including ENERGY STAR (20% improvement from reference), R-2000 (50% improvement from reference), Net Zero Ready (80% improvement from reference) or Net Zero (100% improvement from reference) certification programs. This combination of auxiliary NRCan certifications will be referred to as "Auxiliary NRCan certifications" as a method to analyze incrementally more efficient homes using the NRCan programs available. The Passive house certification only has one standard.

These certifications must be rated in terms of the priorities of this project. The following list consists of the priorities to be considered when selecting the GHC to be used for this project:

1. Program's recognition within Canada. Using a program that is popular amongst homeowners and builders will increase the relevance of the study in the current market.
2. The program should provide energy efficiency and economic benefits to the homeowner. These economic benefits could be lower electricity/heating bills, tax rebates, discounted insurance rates, discounted mortgage rates and/or grants (Rana et al., 2021).
3. A certification program that allows for a large variation in energy efficiency measures, ie. beginning with small measures like adding energy efficient appliances to the baseline home and at the most extreme case, being a net zero energy home. This will allow for a comprehensive analysis of several models of varying efficiency.
4. The program should focus primarily on improving energy use within the home.

These four scenarios are compared in terms of this project's priorities in Table 1.

Table 1: Green Home Certification Comparison

	LEED	**EnerGuide**	**NRCan certifications**	**Passive House**
Recognition	• 3000 homes in Canada certified [a] • Well-recognized in North America	• 1 million homes have been rated by EnerGuide [b]	• Energy Star is well known and widely used [c] • The net zero certifications are relatively new [d]	• 2000 homes in Canada [e] • Well-recognized worldwide
Financial benefits	• Government rebates for specific components incorporated [f] • High certification cost ($1250 to $2750) [g]	• Many government related financial incentives tied to EnerGuide [h] • Low certification cost ($100) [h]	• Many government related financial incentives tied to the use of EnerGuide's rating system, which these use [h] • Low certification cost ($100) [h]	• Government rebates for specific components incorporated [f] • High certification cost ($3000 to $5000) [i]
Potential variation in energy performance	• 4 degrees of performance: certified, silver, gold, platinum [a]	• Customizable iterations based on annual GJ output compared to reference [j]	• 4 iterations: Energy Star, R-2000, Net-Zero Ready, Net Zero	• One level possible: 80% more efficient than homes built to code [i]
Energy improvement as main focus	No	Yes	Yes	Yes

a: (CaGBC, 2021)

b: (Natural Resources Canada, 2017)

c: (Reynolds, 2012)

d: (CHBA, 2021a)

e: (Chung, 2017)

f: (Efficiency Nova Scotia, 2021b)

g: (*LEED,* 2021a)

h: (Efficiency Nova Scotia, 2021c)

i: (Passive House Canada, 2021b)

j: (Natural Resources Canada, 2020c)

When comparing these initiatives in terms of their focus, LEED has several priorities. While energy efficiency is a main component of the design, points are also awarded for location/transportation, sustainable sites, water efficiency, air quality, innovation and materials (LEED, 2021b). Since the focus of this project is to improve energy efficiency, it could be difficult to assign an accurate score to all of the LEED categories despite their importance to a building's design. However, the materials category could be beneficial to this study, as it focuses on choosing environmentally preferable materials, thus resulting in lower embodied emissions in terms of LCA. However, most LCA tools provide data for generic materials, and may not have access to embodied carbon data for environmentally friendly materials (The National Round Table on the Environment and The Economy, 2012). That is the benefit of using a LCA tool such as One Click, which uses EPDs, and therefore has the potential to access more diverse material choices (One Click LCA®, 2018). The other certifications do focus on energy efficiency as their main goals, making the LCA analysis more straightforward, as assigning arbitrary points to other categories to reach a certification level is not required and the required materials are common materials that are available in generic LCA databases.

In terms of recognition, LEED and Passive House are less common in Canada but are more progressive in terms of maintaining standards consistent with state-of-the-art green building trends worldwide (Paulsen, 2015). Additionally, the sophisticated energy analysis and calculations of the Passive House standard are beneficial to optimizing a design. However, NRCan has recently adapted to the modern standards by implementing the Net Zero Ready and Net Zero standards (Taggart, 2018). The NRCan certifications are the most applicable and accessible certifications for Canadians, given their popularity and lower cost.

Although Passive House's comprehensive analysis is attractive, it lacks flexibility in variation of energy performance with only one certification level possible. Both LEED and the NRCan certifications provide four variations of efficiency with respect to a baseline home, which is ideal for the analysis being proposed in this project. The use of EnerGuide's rating system to choose energy efficiency levels provides the most flexibility but lacks structure in that it would make it difficult to arbitrarily make upgrades to a model to receive a certain energy score. Using the EnerGuide rating system with the auxiliary NRCan certifications would provide more structure to iterative model upgrades in order to obtain a certain certification.

In terms of financial incentives available to homeowners using the EnerGuide rating system provides the most benefits, as Efficiency NS provides rebates for the ratings (Efficiency Nova Scotia, 2021c, 2021b). All of the GHCs considered in for this project have the ability to receive incentives for mortgage rates, loan rates, insurance rates, efficient building components, and lower electricity bills (Rana et al., 2021).

In a comprehensive review of the prevalent tools available, the combination of EnerGuide's rating system with NRCan's certification levels are used for this project due to the relevance for Canadian homeowners and builders. A review of the life cycle environmental impact of homes with these certification levels provides the most beneficial analysis for highlighting attainable improvements in local building codes and green home certifications. HOT 2000 provides energy modeling capabilities for the NRCan certifications.

5.0 HOT 2000 Energy Simulation Modelling Software Background

HOT 2000 is the operational energy modelling software used in this project. Natural Resources Canada developed HOT 2000 as an energy simulation modelling software with the purpose of supporting the EnerGuide Rating system and the certifications associated with achieving certain EnerGuide scores including Energy Star, R-2000, Net-Zero Ready and Net Zero Homes. The modelling software is designed specifically for low-rise multi-unit and single-unit residential buildings in Canada. The following information regarding the HOT 2000 software is summarized from the HOT 2000 Technical Modelling Features published by Natural Resources Canada in the HOT 2000 Help Topics document (Natural Resources Canada, 2022) and the HOT 2000 User Guide (Natural Resources Canada, 2020a). A copy of the HOT 2000 Technical Modelling Features document is given in Appendix A.

The process of modelling a home in HOT 2000 begins by inputting generic building information including:

- Building type
- Building area
- Number of stories
- Orientation
- Occupancy
- Building location
- Fuel type
- Age
- Soil condition

Next, the user inputs all envelope assemblies including floors, roof, walls and foundation with the follow details:

- Assembly dimensions
- Framing type/dimensions
- Insulation layers
- Sheathing type /thickness
- Cladding
- Foundation construction

Heat losses/gains are calculated for above grade and below grade opaque assemblies (walls, ceilings, floors), windows / doors (including solar heat gains through windows) and inter-zone heat transfer (including different internal temperature setpoints for main floors and basement). The heat loss for each envelope assembly is calculated using a monthly bin analysis that considers the effective thermal resistance, average monthly weather, the indoor temperature setpoints and envelope area. Wall and roof emissivity are used in the calculation of wall and ceiling heat losses/gains but are left at default values for wall and roof colour. The thermal resistance (RSI value) calculation of each envelope assembly accounts for thermal bridging and compression of attic insulation along eaves.

The user specifies each window's orientation, style, glazing, coatings, fill type, spacer type and frame material. HOT 2000 calculates each window's effective thermal resistance (RSI value). The material and RSI of exterior doors are manually inputted to HOT 2000. Solar radiation on planar and glazed surfaces for each orientation is calculated and considered in the monthly passive solar gains along with building mass and the local climate.

HOT2000 follows the CSA F280-2012 standard for calculating the "House Heat Balance", which uses average monthly and annual outdoor weather files of the house location (CSA, 2012). The annual bin method specifies the following conditions for the local climate:

- Heating degree days
- Design heating dry bulb temperature
- Design cooling temperature: dry-bulb and wet-bulb
- Average deep ground temperature
- Solar index

The monthly bin specifies the following average climatic characteristics:

- Solar radiation: global and diffuse
- Temperature: dry-bulb, wet-bulb, amplitude (difference between high and low temperature during that month)
- Wind speed

The monthly bins are used such that solar effects can me modelled more accurately than on an annual basis.

Heat transfer due to mechanical ventilation and natural air infiltration is also considered in the home's heat transfer model. To comprehensively calculate the heat loss, heat gains and energy consumption in the home, the following details regarding building systems are inputted:

- Air infiltration
- Ventilation system
- Space heating / cooling systems and efficiencies
- Hot water heating system and efficiency
- Renewable energy generation

The air infiltration for the home is manually entered by the user based on blower-door test results or choosing typical values from a list based on building standard. The infiltration due to wind is calculated based on the proximity to other buildings (input by user), airtightness, the location's wind speed and temperatures. The building's design heat loss for the home uses January 2.5% design temperatures –published historical averages describing the 2.5% lowest outdoor hourly temperatures in January in Halifax.

The energy modelling in HOT 2000 is based on an hourly bin analysis. Hourly bin analysis method evaluates time periods within specific temperature ranges separately. The energy consumption within each bin is calculated for the range of outdoor temperatures within that bin and multiplied by the number of hours that occur in the temperature interval (Howell et al., 2014).

The energy used by the ventilation unit's fan is based on a normalized temperature distribution required to maintain the indoor design temperature which allows for heating loads to be determined. The heat loss and air leakage in the ducts carrying air from the ventilation unit is considered in the model. The modelling of heat pump capacity, COP and energy consumption is done using an hourly temperature and heat loss bin distribution. The same method is used to find the energy consumption and time necessary for the backup space heating system to operate. When modelling the domestic hot water (DHW) energy consumption, the model considers standby losses, hot water temperature, room temperature, location of heater and occupancy.

Standby DHW losses, electrical systems and occupant heat are considered in the monthly utilization factor of internal heat gains. The utilization factor represents the usefulness of the internal gains in terms of offsetting thermal loss. Natural Resources Canada calculates it as: "These utilization factors are expressed as a function of the ratio of seasonal total internal gains to seasonal total reference loss for three daily profiles of internal gains and four levels of thermal storage. Curves are presented for conditions of constant room temperature and for allowable temperature rises of 2.75 and 5.5 degrees Celsius. For houses with a ratio of internal gains to reference heat loss of less than 0.4, all internal gains can be utilized to offset thermal losses" (Barakat & Sander, 1986). A full explanation of the use of the internal heat gain utilization factor in the whole house balance is shown in Appendix B.

Using the specific inputs and a database of local climate data, the software evaluates internal heat gains, solar heat gains, heat losses through envelope and energy consumption. HOT 2000 presents the energy consumption of the home on a month-by-month basis based on an hourly-bin analysis. The bin-analysis uses historical average outdoor dry-bulb temperatures to determine the number of hours that have temperatures that fall within a range of temperatures – representing a "bin". Based on the average number of hours in each bin, the predicted temperature for some time period can be determined.

6.0 Operational Energy Modelling Methodology

6.1 Baseline Home

This project aims to analyze the life cycle environmental impacts of building energy efficient homes. The baseline home represents a newly constructed house built according to the NS building code with very few energy efficiency upgrades. The baseline home acts as a reference for which the life cycle environmental impacts of the energy efficient homes can be compared.

For this project, the baseline home considers a typical newly constructed home in NS, built according to the Canadian National Building Code (CNBC) and statistics for common building practices in NS. In Canada, provinces and territories are able to adopt the CNBC or publish their own building codes (NRCan 2019). In Nova Scotia, the CNBC has been adopted with only minor modifications (NRCan, 2019). The requirements from CNBC included in the baseline home are quoted in Appendix C.

All homes modelled in HOT 2000 are compared to the NRCan's Energuide reference home which strictly follows the CNBC energy efficiency section. However, further specifications used in the baseline model are based on a commonly encountered newly constructed home in NS and data from Natural Resource Canada's Survey of Household Energy Use (SHEU, 2015). In an attempt to model the baseline home to represent the most commonly built new home in NS, the baseline home incorporates some energy efficiency measures above code requirements, based on statistics from SHEU regarding the most common practices when building new homes in NS.

6.1.1 Baseline Home Specifications

6.1.1.1 Typical NS Home Statistics

The size of new single detached homes has increased steadily since 1960, with new homes between 2016 and 2017 having a median above-grade living area of 142 m^2 (1,530 sqft) (NS Department of Finance - Statistics, 2017). In addition, Statistics Canada (2019) indicates that the typical size of a finished basement is 16% of the above grade living space, meaning a typical house has a total area of approximately 167 m^2 (1800 sqft). The baseline home in this project is modelled to have an above grade living area of 176 m^2. Floor plans are shown in Appendix D. The baseline home is modelled with three bedrooms, as single-detached homes in NS have an average of 2.5 bedrooms (Statistics Canada, 2018). The SHEU report presents the most prevalent household characteristics for the Atlantic region for homes built after 2011 (SHEU, 2015). Additional features used to design the baseline home are based on the SHEU 2015 and various other studies as noted in Table 2 (SHEU, 2015).

Table 2: Typical Single-Detached Home Characteristics

Characteristic	Prevalent specification
Foundation type	• Heated basement with 75-100% insulated outside walls (SHEU, 2015)
Framing type	• Wood frame (SHEU, 2015)
Attic	• Attic with insulated floor but not walls (SHEU, 2015)
Garage presence	• 2 car garage, not heated but fully insulated (SHEU, 2015)
Window type	• Standard double pane windows (SHEU, 2015)
Main heating system	• Electric baseboards / Air-source heat pump (SHEU, 2015)
Air conditioning	• No (SHEU, 2015)
Mechanical Ventilation type	• HRV (SHEU, 2015)
Thermostat	• Two or more mechanical wall unit thermostats (SHEU, 2015)
Hot water heating	• Standard electric hot water heater tank (SHEU, 2015) 189 L (50 gallon) electric storage tank (Waters, 2020)
Refrigerator presence	• One present, ENERGY STAR rated (SHEU, 2015)
Stand Alone Freezer	• One, ENERGY STAR rated (SHEU, 2015)
Dishwasher	• One, ENERGY STAR rated (SHEU, 2015)(SHEU, 2015)
Stove/Range energy source	• Electric (SHEU, 2015)
Washing machine	• One front-loading, ENERGY STAR rated washer (SHEU, 2015)
Clothes Dryer	• One electric ENERGY STAR rated clothes dryer with moisture detector (SHEU, 2015)
Light bulbs	• 11-20 incandescent light bulbs (SHEU, 2015) • Used for 4 hours in summer and 7-9 hours in winter (SHEU, 2015)
Air/vapour barrier	• Polyethylene sheet material (EcoHome, 2013)
Exterior wall construction	• 38 x 140 mm (2” x 6”) stud walls (Efficiency NS, 2020) • Plywood sheathing (Efficiency NS, 2020) • Fibreglass batt insulation (Efficiency NS, 2020)
Exterior door material	• Wood (Efficiency Nova Scotia, 2021a)
Garage door	• Steel sectional double garage door (EiEi Home, 2017)
Flooring	• Hardwood in living areas: kitchen, family room, living room, study, upstairs stairs and upstairs hallway • Nylon carpet: basement, bedrooms, downstairs stairs (CBC, 2017) • Ceramic tile: laundry rooms, bathrooms (Baiceanu, 2020)
Roof pitch	• 4:12 (Canadian Timber Frames, 2015)

The characteristics listed in Table 2 are used to guide the modeling of the baseline home, which represents a typical newly built home in NS.

6.1.1.2 Floor Plans Based on Typical NS Home

Specific structural and dimensional data are based on a typical 176m^2 (1,898 sqft) NS home that aligns with the data given in the 2015 SHEU report. The home has an unfinished garage and basement, but the square footage of the house does not include the unfinished basement or garage, as it is not common practice to include these in reporting area in NS (NS Department of Finance, 2019). The typical home that provides details including basic dimensions and finishes, as outlined in Table 3, is the Beaufort home model constructed by a local NS contractor, Collins Homes & Renovations (Collins Homes & Renovations Ltd, 2021). Floor plans of the home are given in Appendix D.

Table 3: Collins Beaufort Home Details (Collins Homes & Renovations Ltd, 2021)

Feature	**Details**
Outer dimensions	17 x 8 m (56' x 26')
Windows	2x 1.02 x 0.76 m (40"x30") 4x 1.02 x 0.81 m (40"x32") 4x 1.02 x 0.91 m (40"x36") 1x 0.91 x 1.42 m(36"x56") 2x 1.52 x 1.42 m(60"x56") 1x 2.29 x 1.42 m(90"x56") 2x 2.44 x 1.42 m(96"x56")
Bathrooms	2 full 1 half
Bedrooms	3
Exterior wall material	Vinyl siding
Roof material	Asphalt shingles
Interior wall finish	Gypsum board
Number of exterior doors	3
Number of interior doors	13
Above grade heated floor area	176 m^2 (1,898 sqft)
Below grade heated floor area	94 m^2 (1,013 sqft)
Basement type	Full foundation, unfinished

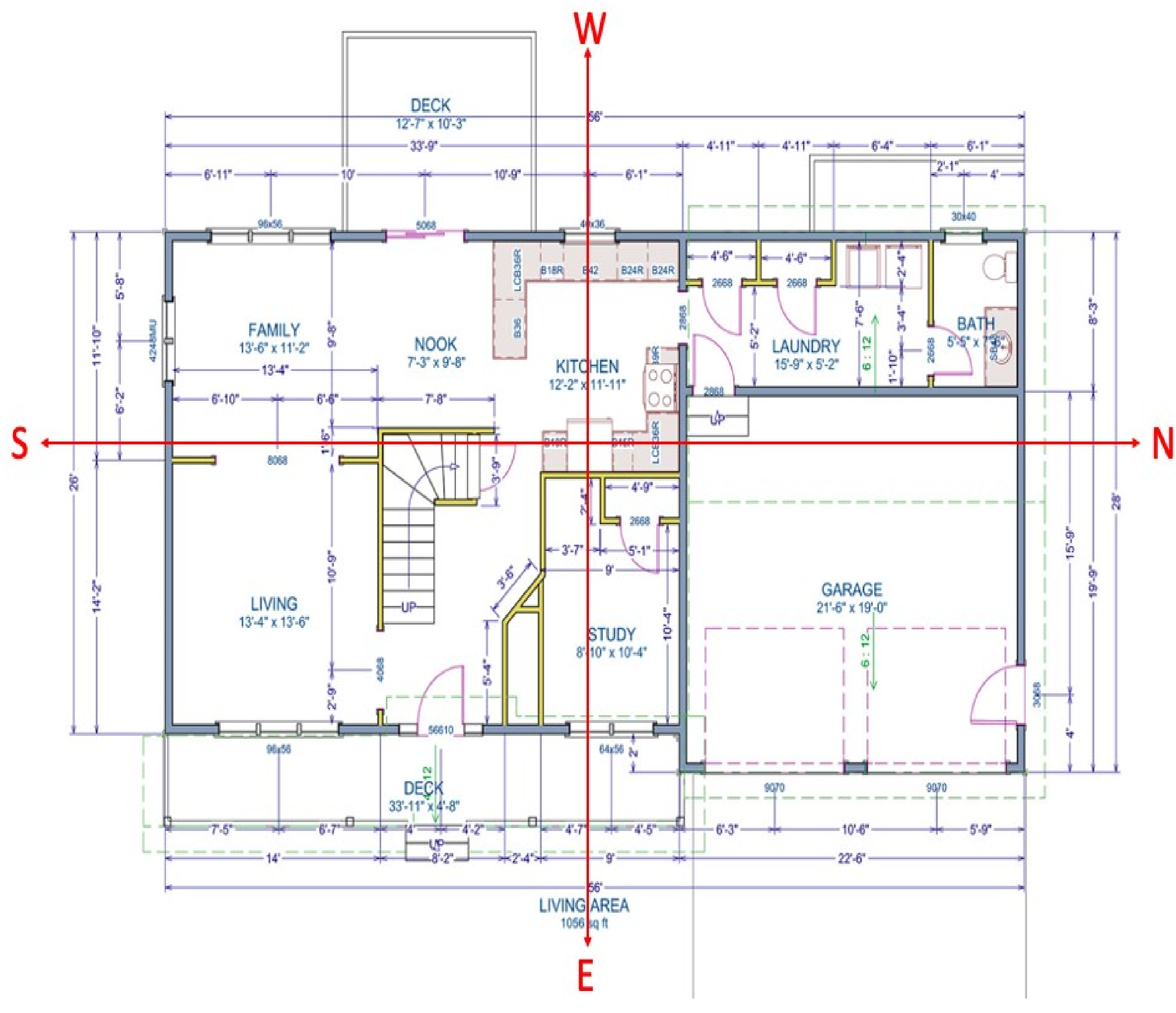
6.1.2 Baseline Home HOT2000 Energy Modelling

The purpose of the baseline home is to act as a reference in terms of energy use and life cycle impact. The following details describe and justify the baseline home's HOT 2000 energy modelling inputs.

6.1.2.1 House Orientation

The baseline home is modelled as if it is in a tract housing neighborhood with a non-optimal solar orientation since the baseline home is meant to represent a non-optimal house in terms of energy efficiency. In the case of the Collins Beaufort home, both the front and back of the house have approximately 11.6 m (125 sqft) of aperture area, therefore either would be an optimal side to face south. To obtain the non-optimal orientation in terms of passive heating, the house is modelled with the front facing east as shown in Figure 1, such that it receives mostly morning light and is unable to capture the winter sun. HOT 2000 uses this data and local climate data to determine the usable solar gains fraction that contributes to annual space heating in the home (NRCan, 2021b).

Figure 1: Baseline home orientation



Note. Baseline home floorplan (Collins Homes & Renovations Ltd, 2021)

6.1.2.2 Insulation Details

The following requirements for insulation throughout the home are based on CNBC Section 9.36.2.6. (CNBC, 2015) and are presented in effective thermal resistance values in RSI ($m^2 \cdot K/W$) and R-values ($ft^2 \cdot °F \cdot h/BTU$) in brackets.

- Attic: 8.67 RSI (R50)
- Walls: 2.97 RSI (R16.9)
- Floors over unheated spaces: 4.67 RSI (R27)
- Foundation walls: 2.97 RSI (R17)
- Unheated floors below frost line: no insulation
- Below grade heated floors: 2.29 RSI (R13)
- Fenestration and door minimum energy rating: 0.625 RSI (R3.5)

6.1.2.3 Attic

The attic below the gable style roof is insulated using blown cellulose insulation with a nominal RSI value of 8.67 $m^2 \cdot K/W$ (R51) (Efficiency NS, 2020). As required by the CNBC, the inner ceiling consists of 12.7mm gypsum board, the roof has a 4:12 pitch, and the construction consists of 38 x 140 mm (2"x6") wood framing with 304 mm (12") joint spacing (CNBC, 2015). The length of the ceiling is 7.6m (25ft) and the area is 79 m^2 (850 sqft), according to the Collins Beaufort home plans (Collins Homes & Renovations Ltd, 2021).

6.1.2.4 Main and Second Floor Walls

In order to achieve the required effective thermal resistance values of RSI 2.97 $m^2 \cdot K/W$ (R16.9) for the exterior walls, 140 mm (5.5") thick fibreglass batt insulation rated at RSI 3.87 $m^2 \cdot K/W$ (R22) is modelled in the baseline home, as per the standard building practices in NS (Efficiency NS, 2020). The system RSI reported in the full house energy report from HOT 2000 accounts for thermal bridging in framing, exterior finishes, interior finishes and air film coefficients, whereas the effective RSI accounts for the overall effective thermal resistance including openings in the wall (NRCan, 2021b). The effective thermal resistances for the main and second floor walls are both 3.10 RSI.

The walls are modelled with 38 x 140 mm (2" x 6") studs spaced at 406 mm (16") (CMHC, 2013). The interior wall consists of 12.7 mm (½") gypsum board and 12.7 mm (½") plywood sheathing

(Efficiency NS, 2020). Vinyl cladding is modelled as the exterior layer as per a typical newly constructed NS home (Collins Homes & Renovations Ltd, 2021). Lintels are assumed to be one layer (CMHC, 2013). The main floor walls have a perimeter of 51 m (168ft), with 11 wall intersections and 5 corners, where a wall intersection means an inside partition wall meeting an outside wall and a corner means two outside walls meeting, as per the Collins Beaufort home (Collins Homes & Renovations Ltd, 2021). The second-floor walls will have a perimeter of 36m (118 ft) with 7 wall intersections and 4 corners as per the Collins Beaufort home (Collins Homes & Renovations Ltd, 2021). The second floor is modelled as a space adjacent to an unconditioned space, due to the adjacent attic. The ceiling height of both floor levels is 2.7 m (9ft).

6.1.2.5 Windows

According to CNBC Section 9.7.3.3, all windows in Nova Scotia must meet the maximum U-value of 2.0 W/(m^2-K) (RSI 0.5) (CNBC, 2015) assuming that the 2.5% January design temperature in Halifax is -16.5°C (ASHRAE, 2017a) .

Based on SHEU data, most Atlantic Canadian homes built after 2011 have standard double pane windows that are Argon-filled (SHEU, 2015). The windows that are modelled in the baseline home are therefore double glazed, filled with 13mm of argon, have an insulating spacer, have a low e-coating of 0.1 and a vinyl frame. The windows being modelled have a curtain factor of 1, meaning the curtains are always completely open. Based on these inputs and the inputted window orientation, HOT 2000 determines the RSI value, the Energy Rating (ER) and solar heat gain coefficient (SHGC) from a database of windows that have been tested (NRCan, 2013a). HOT 2000 calculates the RSI and SHGC at the center of the glass, edge of the glass and the frame. Therefore, different sized windows constructed in the same manner have different overall RSI values that cannot be changed in HOT 2000 (NRCan, 2021b). Within HOT 2000, the window tightness for all windows in the baseline home is modelled as CSA – A1 or 1.86 L/s·m^2.

The number of windows and dimensions are based on the Collins Beaufort home to represent a typical newly constructed NS home. Table 4 describes the location, size, and type of windows in the baseline home based on the Collins Beaufort home (Collins Homes & Renovations Ltd, 2021).

Table 4: Window Details (Beaufort | Collins Homes & Renovations Ltd, 2021)

Location	Type	Side of house	Window Size	RSI
Patio door	Patio door	West	1.52 x 2.03 m (60” x 80”)	0.52
Study	Slider with sash	East	1.63 x 1.42 m (64” x 56”)	0.54
Living room	Picture	East	2.44 x 1.42 m (96” x 56”)	0.60
Family room	Picture	West	2.44 x 1.42 m (96” x 56”)	0.60
Kitchen	Slider with sash	West	1.02 x 0.91 m (40” x 36”)	0.50
Main floor bathroom	Slider with sash	West	0.76 x 1.02 m (30” x 40”)	0.50
Master bedroom	Slider with sash	East	2.29 x 1.42 m (90” x 56”)	0.50
Master bath	Slider with sash	South	0.91 x 1.02 m (36” x 40”)	0.50
Master bath	Slider with sash	West	0.91 x 1.02 m (36” x 40”)	0.50
Second floor bathroom	Slider with sash	West	0.76 x 1.02 m (30” x 40”)	0.50
Bedroom 1	Slider with sash	West	0.91 x 1.42 m (36” x 56”)	0.52
Bedroom 2	Slider with sash	East	1.52 x 1.42 m (60” x 56”)	0.54
Closet	Picture	East	0.91 x 1.02 m (36” x 40”)	0.57
Basement	Slider with sash	South	1.02 x 0.81 m (40” x 32”)	0.50
Basement	Picture	West	1.02 x 0.81 m (40” x 32”)	0.56
Basement	Picture	West	1.02 x 0.81 m (40” x 32”)	0.56
Basement	Picture	North	1.02 x 0.81 m 40” x 32”	0.56

Although some of the windows are rated at an RSI of 0.49, rather than the required RSI 0.5, the small discrepancy is ignored.

6.1.2.6 Exterior Doors

The baseline home contains three 0.81 x 2.03 m (32”x80”) exterior doors and one sectional steel double garage door which comply with the maximum 1.22 W/(m^2-K) (0.82 RSI). The exterior doors are made with a fibreglass polystyrene core, which has a thermal resistance of 0.85 RSI.

6.1.2.7 Exposed Floors

The garage floor in the baseline model is modelled as a 76.2 mm (3”) thick insulating concrete block. Three inches is the minimum thickness required for concrete floors on-ground according to CNBC section 9.16.4.3 (CNBC, 2015). It is supported by the foundation, as required by CNBC section 9.35.3.1 (CNBC, 2015).

6.1.2.8 Foundations

The foundation is modelled as a concrete basement-type in HOT 2000 with a length of 7.9 m (26ft) and width of 17.1 m (56ft). The baseline home has an unfinished and unheated basement, as per the Collins Beaufort home plans (Collins Homes & Renovations Ltd, 2021). The concrete wall height is assumed to be 2.5 m (8.2ft), with 1.9 m (6.2ft) below grade (NRCan, 2020b). According to CNBC Tables 9.36.2.6.-B and 9.36.2.8.-B, the effective thermal resistance of walls above and below-grade in homes with an HRV must have insulation of RSI 2.98 $m^2 \cdot K/W$ (R17). Therefore, the inside of the foundation walls consists of 12.7 mm (½") gypsum board , fibreglass batt insulation rated at 2.11 RSI (R12), a 25 mm (1 inch) layer of medium density spray foam and 38 x 140 mm (2" x 6") framing, resulting in an effective thermal resistance of 3.00 RSI (NRCan, 2021b).

The main floor above the foundation must comply with the code for floors above an unheated space, with an RSI value of 4.67 $m^2 \cdot K/W$ (R27) (CNBC, 2015). Therefore, the main floor is modelled as a 38 x 140 mm (2"x6") wood framed floor spaced at 0.4 m (16"), containing one layer of 241 mm (9") fibreglass batt insulation (4.23 RSI (R24)) and one layer of 25 mm (1") medium density spray foam. This provides the floor with an effective thermal resistance of 4.78 RSI. The ceiling consists of 12.7mm (½") gypsum board and the subfloor above the main floor has 12.7 mm (½") plywood.

6.1.2.9 Base Loads

6.1.2.9.1 Occupancy

NRCan's HOT 2000 guidelines suggest that the reference house has an occupancy of two adults and two children, who are home 50% of the time (NRCan, 2013a). The program assumes that 70 W (238 BTU/hr) of sensible heat is given off by a seated male, and that women release 90.5% of that heat (NRCan, 2021b), which is consistent with Chapter 18 of the ASHRAE Handbook (2017). The sensible heat gains assumed for adults is therefore 63.4 W (218 BTU/hr) – an average of the male and female sensible heat gains. Similarly, a smaller fraction of the resting male heat is released by children. Assuming 50% occupant rates, or 12 hours/day, results in 0.8 kWh/day/occupant released. These occupancy levels align with the expected levels for the three-bedroom house being modelled, and therefore are used for baseline home modelling. It is assumed that only 10% of the internal gains are applied to the basement, since it is unfinished.

6.1.2.9.2 Electrical Base Loads

NRCan's HOT 2000 guidelines suggest that a standard baseload energy use for the household is approximately 20 kWh/day (NRCan, 2013a). This standard is consistent with Canadian home energy-use surveys, which also indicate that approximately 2600 kWh/year of this usage comes from major appliances including refrigerators, ranges, dishwashers, clothes washers and clothes dryers (Parekh & Wang, 2013). The breakdown of energy per appliance is as follows (NRCan, 2020d).

- Clothes dryer: 916 kWh/year
- Clothes washer: 197 kWh/year
- Dishwasher: 260 kWh/year
- Electric range: 565 kWh/year
- Refrigerator: 639 kWh/year

Smaller appliances and "phantom loads", which draw power when plugged in but are not being used, account for approximately 2,430 kWh/year, based on a audits performed on 720 Canadian homes (Parekh & Wang, 2013). The audits were performed by Natural Resources Canada in 2012 to gather data regarding end-use of electricity in Canadian homes. The audit results showed that the average Canadian home consumed 1500 kWh/yr for home entertainment and office devices, 700 kWh/yr for small appliances (kitchen, cleaning, hygiene) and 200 kWh/yr for seasonal devices (fans, humidifiers, power tools, electric lawn mowers, recreational loads like treadmills). An additional 10% of the total 2400 kWh/yr used is added to account for loads that draw energy while not being actively used – resulting in 2,430 kWh/yr. Collectively, 5000 kwh/yr or 13.7 kWh/day of energy use comes from major appliances, small appliances and phantom loads.

According to SHEU 2015, the average home uses 11-20 incandescent light bulbs for 4 hours a day during summer and 8 hours a day during winter (SHEU, 2015). Therefore, if sixteen 60-Watt incandescent light bulbs are used for 6 hours per day, approximately 5.8 kWh/day is used for lighting over the year. However, the NRCan guidelines suggest 2.6 kWh/day (NRCan, 2020d) is used for lighting because it is reasonable to assume that not all of the light bulbs in the home are turned on for 6 hours a day. As a compromise between the two, a lighting energy use of 4 kWh/day is estimated for the baseline home.

Cumulatively, the base load energy usage is 21.7 kWh/day, with 7.1 kWh being used by major appliances, 4.0 kWh by lighting and 6.6 kWh by other electrical sources. There are no electricity generating devices in the baseline home. All electricity comes from the grid.

6.1.2.9.3 Water Usage Base Loads

The parameters that are considered in calculating the base hot water load include bathroom faucet usage and flowrates, shower temperature and duration, number of clothes washes performed, clothes washer energy consumption, clothes washer capacity, number of dishwasher cycles used, energy consumption of dishwasher, and dishwasher capacity.

Based on the HOT2000 options available, standard 8.3 L/min (2.2 US gpm) faucets are modelled with a usage rate of 1.75 minutes/occupant/day, which accumulates to a typical usage of 58.1 L per household/day (15.4 gallons per household/day (gphd)) (DeOreo et al., 2016). A standard shower head flow rate of 9.5 L/min (2.5 US gpm) and 41°C temperature is modelled with an average shower duration of 6.5 minutes and frequency of 5.2 showers/occupant/week, resulting in a usage of 184 L/day (NRCan, 2020d).

Based on the SHEU 2015 reports (SHEU, 2015), the clothes washer modelled is Energy Star rated, and therefore uses an average of 52 L of hot water per load (Energy Star, 2021b), assuming 1.9 loads/occupant/week (NRCan, 2020e). This results in 56 L/day. Similarly, the dishwasher is Energy Star rated (SHEU, 2015) and therefore uses 19L of hot water per load (Energy Star, 2021a). Assuming 1.37 cycles/occupant/week. This results in 14.9 L/day.

As recommended by the HOT 2000 standard conditions, an additional 2.9 L are accounted for per day (NRCan, 2020b). Cumulatively, accounting for the faucet, shower, clothes washer and dishwasher use, the base load of hot water use in the baseline home is 316 L/day.

6.1.2.10 Air Infiltration

The volume of the baseline home considered for natural air infiltration is assumed to be approximately 514 m^3 (18,154 ft^3) based on the floor area of the Beaufort home, the 0.6 m height of foundation above ground and the 2.7 m (9 ft) high ceilings on the main and second floors. An air tightness value at 50 Pa of 2.5 ACH is modelled, as this represents an average newly constructed home (Braman & Manclark, 2014; NRCan, 2020d). In the modelling, it is assumed that 20% of leakage occurs in the ceiling, 65% occurs in walls and 15% occurs in floors (NRCan, 2020d). Other assumptions made for modelling the natural air infiltration include the location being a suburb surrounded by forest, light shielding by neighboring walls, and that the highest ceiling above grade is at a height of 6 m, considering 2.7 m storeys (9ft) and 0.6 m of the foundation above grade.

6.1.2.11 Ventilation

The ventilation of the baseline home is accomplished using an HRV, as this is the most popular mechanical ventilation type in new homes in NS (SHEU, 2015).

CNBC Section 9.32.3.3. requires an exhaust rate between 22 L/s and 32 L/s for an exhaust fan in a 3-bedroom house (CNBC, 2015). Therefore, the HRV for the baseline home is modelled with a supply and exhaust flow rate of 25 L/s, such that the system is balanced. This corresponds to 0.2 ACH. For the baseline home, an HRV with sensible heat recovery efficiency of 55% at 0°C and 45% at -25°C is assumed, as these efficiencies are below the Energy Star requirements and representative of a typical home's HRV (NRCan, 2013b). It is assumed that the operation of the HRV occurs for 8 hours a day (NRCan, 2020e). Additional ventilators for bathrooms are not included, but the dryer ventilation is included at an exhaust flow rate of 38 L/s. It is assumed that the dryer operates for 30 minutes per day or approximately one load every second day.

6.1.2.12 Heating/Cooling System

There is no cooling considered for the baseline home since SHEU 2015 results indicate that the majority of new homes in NS do not have air conditioning (SHEU, 2015). Electric baseboard heating is used throughout the house for space heating purposes as it is the most popular heating source in NS new construction (SHEU, 2015). The design heating load required for the house must equal the design heat loss, which is calculated in HOT 2000 by considering the building envelope, infiltration and ventilation losses (Howell, 2017). For the baseline home, the design heating losses accumulate to 9.6 kW. Therefore, there must be 9.6 kW of heating provided by the baseboards, which is used as an input to model the heating required for the baseline home.

6.1.2.13 Indoor Temperatures

According to the CNBC Section 9.36.5.4, the recommended heating set points for modelling purposes are as follows (CNBC, 2015):

- Above grade living space heat set point: 21°C
- Unfinished basement: not heated
- Sizing indoor design temperature: 21°C

The heating setpoints above are consistent with NS Power's recommended setpoints (NS Power, 2021) and the SHEU results (SHEU, 2015). SHEU results show that the majority of Atlantic Canadians reduce the temperature setpoint to 17 °C overnight (SHEU, 2015). However, assuming that the occupant behaviour is the least energy efficient, no setback for the overnight period is considered for the baseline home. Therefore, the heating setpoint is 21°C throughout the day and night. The indoor design temperature corresponds to comfortable indoor conditions in a residential unit in winter (Howell, 2017).

6.1.2.14 Domestic Hot Water

A standard electric hot water heater is used as the domestic hot water source as the SHEU 2015 results indicate that this is the most common method of heating domestic hot water in NS (SHEU,2015). A 189 L (50 US gal) tank is modelled based on water demand assumptions shown in Table 5 for the home's peak hour demand (U.S. Department of Energy, 2021b). Peak hour demand is the capacity of hot water that a hot water tank can supply within an hour, beginning with a full tank of hot water (U.S. Department of Energy, 2021)

Table 5: Hot water peak hour demand (U.S. Department of Energy, 2021)

Use	**Average litres (gallons) of hot water per usage**	**Frequency of use during 1 hour**	**Litres (gallons) used during 1 hour**
Shower	62.4 (16.5)	2	124.8 (32.0)
Bathroom Faucets	8.3 (2.2)	2	16.6 (6.6)
Hand dishwashing/food preperation	8.3 (2.2)	3	24.9 (6.6)
Dishwasher	19 (6)	1	19
Clothes washer	52 (7)	1	52
Total peak hour demand:			**237.3 (62.6)**

A typical 189 L (50 gal) tank has a peak hour rating of 237 L (62 gal) (A.O. Smith, 2021b) and is therefore sufficient for the peak hour demand in the baseline home. The shower usage is based on the 9.5 L/min showerhead and 6.5 minute showers. The bathroom and kitchen sink faucet consumption assumes that the 8.3 L/min faucets are used for one minute at a time. The dishwasher and clothes washer are assumed to use 19 L and 52 L per use respectiveley, based on the typical usage of these Energy Star rated appliances (Energy Star, 2021a, 2021b).

According to the CNBC Table 9.36.4.2, the total standby losses of the heating system must be less than 75 W (CNBC, 2015). The tank being modelled has a standby loss of 70 W with an input capacity of 6 kW (A.O. Smith, 2021a). There is no insulating blanket considered, because the CNBC (CNBC, 2015) does not require storage water tanks to be insulated.

6.2 Energy Star Home

The next iteration of the home follows the Energy Star for New Homes (ESNH) program requirements. This program is a part of the larger ENERGY STAR® label, which was developed in 1992 by the U.S. Environmental Protection Agency to promote the use of energy efficient products internationally (NRCan, 2020b). The ESNH standards have been developed to provide guidelines to homebuilders hoping to save on their energy bills and reduce their energy use by 20% compared to the EnerGuide reference home (NRCan, 2020b). The EnerGuide reference home is a replica of the home modelled in HOT2000, but uses specifications that comply with the CNBC Section 9.36, which outlines energy efficiency requirements (NRCan, 2020b). Energy Star homes must be built by an ES certified builder and evaluated for certification by an independent energy advisor licensed by Natural Resources Canada (NRCan, 2020b). The energy efficiency upgrades involve heating and cooling systems, fenestrations, building envelope components, airtightness and electrical loads (NRCan, 2020b).

According to ES requirements (NRCan, 2020b), an ES house must use 20% less energy then the EnerGuide reference house. The EnerGuide reference house for this project consumes 93 GJ/year (based on HOT 2000 simulation conducted), which is 2 GJ/year less than the baseline home's energy usage. The ES home iteration must have an EnerGuide score of 75 GJ/year in order to meet the ES home certification requirements.

6.2.1 Energy Star New Home Certification Requirements

The requirements that are incorporated into the ES home model are based on the ENERGY STAR® for New Homes Standard – Version 17.1 that was released by Natural Resources Canada in 2015 (NRCan, 2020b) and is described in Table 6. A column is included in Table 6 for comparison purposes. All thermal resistances in Table 6 are effective thermal resistance values. The requirements are based on the minimum requirements outlined in section 4 of the standard and comply with the ES home Performance Approach which provides guidelines for Nova Scotia, indicating that an ES home must be 20% more efficient than the EnerGuide reference house (NRCan, 2020b). The NS Builder Option Package is an alternative to the Performance Approach that provides specifications for the ES home's construction (NRCan, 2020b). The Builder Option Package for NS is used for guidance in upgrading the features for the ES home in this project.

Table 6: ESNH Requirements (NRCan, 2020b)

Measure	Section of ES Home Standard	Energy Star Requirement (NRCan, 2020b)	Baseline Home Specification (CNBC, 2015)
Air tightness	4.2.1	2.5 ACH @ 50Pa	2.5 ACH @ 50Pa
Thermal resistance of attic	4.2.2.1	RSI 8.67 (R49.2)	RSI 8.67 (R49.2)
Thermal resistance of walls above grade	4.2.2.1	RSI 3.08 (R17.5)	RSI 2.97 (R16.9)
Thermal resistance of floors over unheated spaces	4.2.2.1	RSI 4.67 (R26.5)	RSI 4.67 (R26.5)
Thermal resistance of foundation walls below or in contact with the ground	4.2.2.1	RSI 2.98 (R16.9)	RSI 2.98 (R16.9)
Thermal resistance of unheated floors on ground above frost line	4.2.2.1	RSI 1.96 (R11.1)	No insulation
Thermal resistance of unheated floors below frost line	4.2.2.1	Not required	Not required
Allowable insulation materials	4.2.2.2	See section 4.2.2.2	See CNBC 9.25.2.2
Window and door thermal requirements	4.2.3, (NRCan, 2020c)	Energy Star rated with maximum U-factor of 1.22 $W/m^2 \cdot K$ or ER of 34. One exterior door need not comply with standards.	Maximum U-factor of 2.0 $W/m^2 \cdot K$
	4.2.3.3	Solar heat gain coefficient less than 0.3	No requirements
Space heating and cooling equipment	4.3	No guidelines for electric baseboard heating	No guidelines for electric baseboard heating
Drain heat water recovery	4.4	Not required. If installed, must remove heat from at least one shower and be on NRCan's searchable product list	Not required

__Table 6__ (continued).

Measure	Section of ES Home Standard	Energy Star Requirement (NRCan, 2020b)	Baseline Home Specification (CNBC, 2015)
Ventilation system	4.7.1.1	Ventilation shall be achieved through an HRV, ERV or IMS	Baseline home modelled with an HRV
	4.7.1.2	HRV and ERVs must be ES, tested at 0°C and -25°C. Supply and exhaust fans balanced within 10%.	HRV must be tested at 0°C and -25°C. (CNBC, 2015)
	4.7.1.2	SHRE* of HRV and ERVs must be testes at 0°C and a minimum airflow rate of 22 L/s.	Principal ventilation fan must have a capacity of 22 L/s (CNBC, 2015)
	4.7.2.2	Ducts must be within the heated boundary	Ducts within heated boundary
Electrical	4.8	Home must have at least 75% Energy Star certified fixtures or light bulbs	No Energy Star certified fixtures or light bulbs
EnerGuide score	6.7.2	At least 20% less than the EnerGuide Rating System Reference House	No requirement

*Sensible heat recovery efficiency

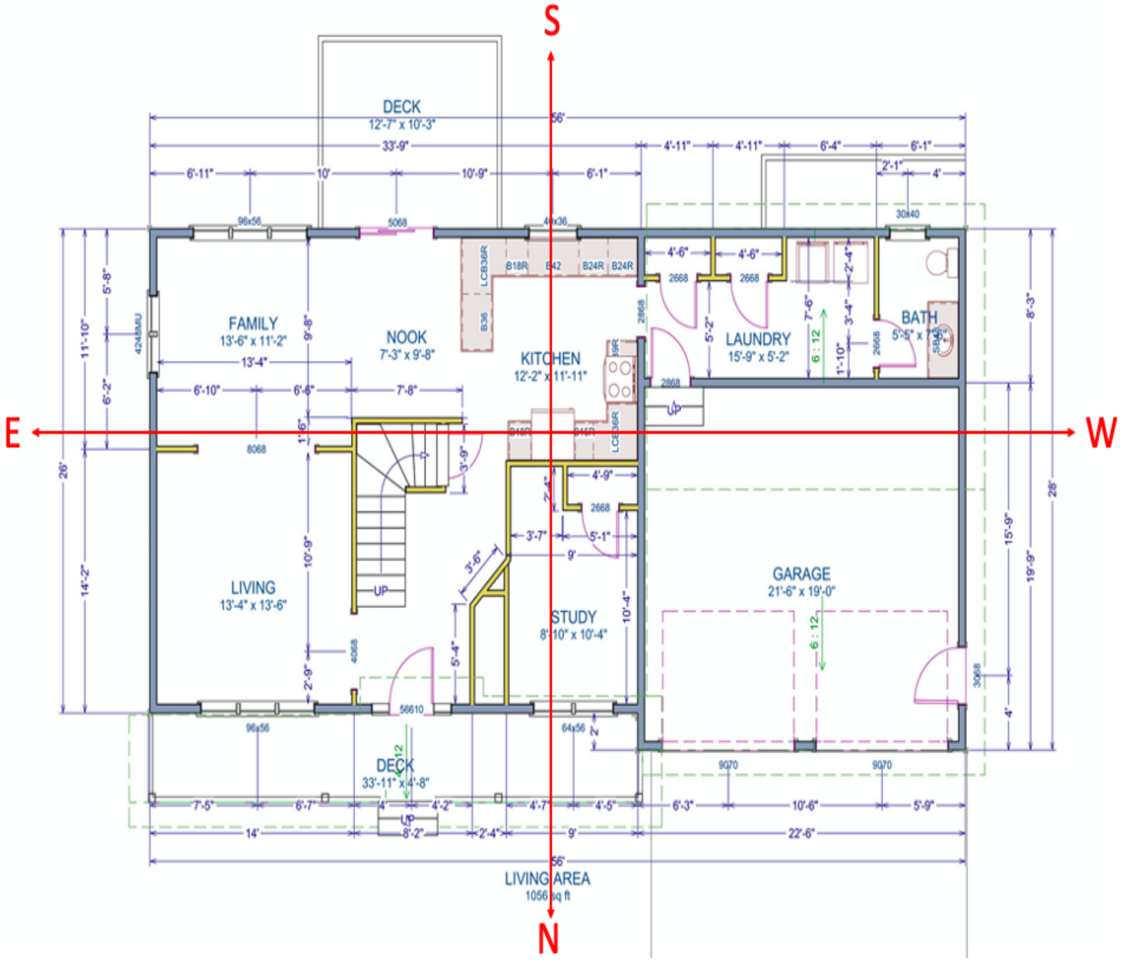
Comparing the ES home requirements to the specifications used for the baseline home specifications, the major differences appear in airtightness requirements (reducing to 2.5 ACH @ 50Pa rather than 4.55 ACH at 50 Pa), the maximum U-factor of windows and doors (reducing by 0.78 $W/m^2 \cdot K$), an increase in Energy Star certified lighting by 75% and an EnerGuide score of at least 20% less than the EnerGuide Rating System Reference House. Upgrades that are required to accomplish the 20% improved EnerGuide score (77.6 GJ/year) are primarily based on the ESNH builder option package details, which describe recommended upgrades.

6.2.2 Energy Star Home HOT2000 Energy Modelling

6.2.2.1 House Orientation

To contribute to the required 20% reduction in energy use for the ESNH model compared to the baseline model, the orientation of the ESNH model is adjusted to benefit the potential of obtaining solar heat gains and reduce space heating demand in the winter. The back of the house has 11.6 m^2 (125 ft^2) of aperture area, which is equal to the aperture area on the front of the house. Therefore, the back of the house faces south, as shown in Figure 2 for the ESNH model for optimal solar heat gain.

Figure 2: ESNH Orientation



6.2.2.2 Attic

The attic is modelled identically to the baseline model, providing insulation of 9.0 RSI (R51), as required by the ESNH standards (NRCan, 2020b).

6.2.2.3 Main and Second Floor Walls

Both the main and second floor walls are modelled identically to the baseline model, as it provides the required effective thermal resistance of 3.08 RSI (R17.5), as required by the ESNH standards (NRCan, 2020b).

6.2.2.4 Windows

The windows for the ESNH home are modelled with an airtightness of CSA A2, or 1.5 L/s.m^2 (ENCORE Windows, 2021), which is 0.36 L/s.m^2 more airtight than the windows in the baseline home. The ESNH standard requires that all windows have a solar heat gain coefficient (SHGC) less than 0.3, whereas the CNBC has no specifications for SHGC of glazing. The ESNH standard requires a maximum U-value of 1.22 W/m^{2}K or an minimum RSI of 0.819 m^{2}K/W (NRCan, 2020e), whereas the baseline home's windows are designed according to the CNBC requirement of 2.0 W/m^{2}K (R3.5). In order to achieve the required thermal resistance for the ESNH requirements, the windows mimic the baseline home windows, but include heat mirrors for additional insulation. The types and number of heat mirrors vary depending on the window's effective thermal resistance. In some windows for example, two heat mirrors are required in order to achieve an effective thermal resistance of 0.819 m^{2}K/W. All windows in the ES home model share the following characteristics:

- Double glazed
- Soft low e-coating (emissivity 0.10)
- Filled with 13 mm argon gas
- Insulating spacer
- Vinyl frame
- Curtain shading factor: 1 (no curtain shading considered)

The number of windows, dimensions and type of windows are based on the Collins Beaufort home to represent a typical newly constructed NS home (Collins Homes & Renovations Ltd, 2021). Table 7 describes the location, size, heat mirror type, resulting RSI and SHGC of the windows in the ES home.

Table 7: Window Details (Beaufort | Collins Homes & Renovations Ltd, 2021)

Window Location	Side of house	Window Size	Window type	Mirror quantity and type (% of visible light transmittance)	RSI	SHGC
Patio door	South	1.52 x 2.03 m (60” x 80”)	Patio door	1 x 66% T_{vis}	0.89	0.300
Study	North	1.63 x 1.42 m (64” x 56”)	Slider with sash	1 x 66% T_{vis}	0.86	0.265
Living room	North	2.44 x 1.42 m (96” x 56”)	Picture	1 x 66% T_{vis}	1.07	0.300
Family room	South	2.44 x 1.42 m (96” x 56”)	Picture	1 x 66% T_{vis}	1.07	0.300
Kitchen	South	1.02 x 0.91 m (40” x 36”)	Slider with sash	2 x 88% T_{vis}	0.86	0.289
Main floor bathroom	South	0.76 x 1.02 m (30” x 40”)	Hinged	2 x 88% T_{vis}	0.86	0.276
Master bedroom	North	2.29 x 1.42 m (90” x 56”)	Slider with sash	1 x 66% T_{vis}	0.91	0.275
Master bath	South	0.91 x 1.02 m (36” x 40”)	Hinged	2 x 88% T_{vis}	0.90	0.299
Master bath	East	0.91 x 1.02 m (36” x 40”)	Hinged	2 x 88% T_{vis}	0.90	0.299
Second floor bathroom	South	0.76 x 1.02 m (30” x 40”)	Hinged	2 x 88% T_{vis}	0.86	0.289
Bedroom 1	South	0.91 x 1.42 m (36” x 56”)	Slider with sash	1 x 88% T_{vis}	0.88	0.29
Bedroom 2	North	1.52 x 1.42 m (60” x 56”)	Slider with sash	1 x 66% T_{vis}	0.85	0.262
Closet	North	0.91 x 1.02 m (36” x 40”)	Picture	1 x 66% T_{vis}	0.93	0.281
Basement	South	1.02 x 0.81 m (40” x 32”)	Picture	1 x 66% T_{vis}	0.91	0.277
Basement	South	1.02 x 0.81 m (40” x 32”)	Picture	1 x 66% T_{vis}	0.91	0.277
Basement	East	1.02 x 0.81 m (40” x 32”)	Picture	1 x 66% T_{vis}	0.91	0.277

6.2.2.5 Exterior Doors

The ES home contains three 0.81 x 2.03 m (32”x80”), fibreglass polystyrene core exterior doors and one sectional steel double garage which comply with the maximum U-value of 1.22 W/(m^2-K) (0.82 RSI). The doors in the ES home mimic those in the baseline home.

6.2.2.6 Exposed Floors

The ESNH standard require unheated floors above the frostline to have an RSI value of 1.96 $m^2 \cdot K/W$ (NRCan, 2020b). Therefore, the garage floor is modelled as an insulating concrete block with an RSI value of 1.96 $m^2 \cdot K/W$.

6.2.2.7 Foundations

The ESNH standards are the same as the CNBC baseline home requirements in that floors above unheated spaces require thermal resistance of 4.67 RSI and unheated floors below the frostline require no insulation. Therefore, the main floor above the unheated basement and the foundation slab are identical to those modelled in the baseline home, as they meet this requirement with an effective thermal resistance of 4.78 RSI. Similarly, the foundation walls are modelled the same as the baseline home, however the additional layer of medium density spray foam insulation is increased from 25 mm (1 inch) to 51 mm (2 inches), resulting in an effective thermal resistance of 3.93 RSI for the wall.

6.2.2.8 Base Loads

6.2.2.8.1 Occupancy

The occupancy levels for the ES home are the same as the baseline home, with two adults and two children who are home 50% of the time.

6.2.2.8.2 Electrical Base Loads

There are no electrical baseloads requirements outlined in the ESNH requirements for Performance Approach, however the ESNH Building Option Package for Nova Scotia suggests using three ENERGY STAR® rated appliances (NRCan, 2020b). Therefore, the ES home is modelled with an ENERGY STAR® clothes dryer, clothes washer and refrigerator. All appliances were in the mid-range of efficiency for their respective Energy Star category. The refrigerator is assumed to consume 500 kWh/year, based on a typical 0.62 m^3 (22 ft^3) ENERGY STAR® fridge (Energy Star, 2021g). The clothes dryer is assumed to consume 608 kWh/year, based on a typical 0.20 m^3 (7 ft^3) ENERGY STAR® clothes dryer and 5.4 cycles/week (ENERGY STAR, 2021a). The clothes washer is assumed to consume 123 kWh/year, based on a typical 0.11m^3 (4 ft^3) ENERGY STAR® clothes washer and 6 loads/week (ENERGY STAR, 2021c). The remaining major appliances including the dishwasher and electric range are assumed to have the same annual consumption as the baseline home. However, the dishwasher in the baseline home is assumed to consume 260 kWh/yr, which is a typical consumption of an Energy Star dishwasher assuming 4 loads/week (ENERGY STAR, 2021e). Cumulatively, this reduces the electrical base load from major appliances by approximately 20% with respect to the baseline home, reducing usage from 2,600 kWh/year (7.12 kWh/day) to 2,056 kWh/year (5.63 kWh/day). Small appliances and phantom loads are assumed to be the same as the baseline home, consuming 2,430 kWh/year (6.6 kWh/day).

ESNH requirements indicate that 75% of light bulbs and fixtures in the home must be Energy Star rated (NRCan, 2020b). The ESNH uses sixteen light bulbs – the same number as the baseline home. Based on the Energy Star light bulb savings calculator and recommendations, the 60-Watt incandescent light bulbs used in the baseline home are replaced with 9.0 W LED bulbs for comparable light output (NRCan, 2019). The 9.0 W LED bulbs use 85% less energy than the incandescent bulbs. Making the same assumptions as the baseline home - sixteen light bulbs are used for 6 hours a day each, results in energy consumption of 0.86 kWh/day. Since the exterior energy use is due to exterior lighting, the same assumption is made – that 85% less energy will be used for exterior use, reducing the exterior use to 0.14 kWh/day.

Cumulatively, the base load energy usage is 13 kWh/day, with 5.63 kWh being used by major appliances, 0.86 kWh by lighting, 6.6 kWh by other electrical sources and There are no electricity generating devices in the baseline home. All electricity comes from the grid.

6.2.2.8.3 Water Usage Base Loads

The ES home models the water usage base load identically to the baseline home, using 314 L/day, since there are no requirements outlined by the ESNH requirements.

6.2.2.8.4 Air Infiltration

ESNH standards require the home to have an air tightness value of 2.5 ACH at 50 Pa. The ESNH is modelled with 1.5 ACH at 50 Pa. All other assumptions in natural air infiltration modelling remain the same as the baseline home.

6.2.2.9 Ventilation

The ESNH is modelled with an ERV[1], since moisture control in an airtight home is essential to healthy air quality (NRCan, 2018a). The principal ventilation requirements remain the same as the baseline home, at 25 L/s (0.2 ACH) operating for eight hours per day. The dryer ventilation remains the same as the baseline home, at an exhaust rate of 38 L/s.

ESNH requirements indicate that the ERV must be Energy Star rated. The sensible heat recovery efficiency of the ERV at 0°C is modelled as 75% and at -25°C as 65% as suggested for an Energy Star rated ERV by the ESNH Building Package Option for NS (NRCan, 2020b). The ESNH building package option for NS also suggests that the fan efficacy is greater than 0.57 L/s/W at 0°C, which is a 43 W fan for a home with 25 L/s of ventilation (NRCan, 2020b). Therefore, the fan is modelled to consume 43W at 0°C and 52W at -25°C, as a proportional 20% increase based on the 20% increase in the power usage with the same temperature change of the default fans modelled in HOT 2000.

6.2.2.10 Heating/Cooling System

The ESNH Builder Option Package for NS recommends installing a heat pump to save energy for space heating purposes (NRCan, 2020b). In NS, the most common type of heat pump used is an air source heat pump (Efficiency Nova Scotia, 2021d). For the ESNH, a mini-split ductless heat pump with one outdoor unit and one indoor unit is modelled for the purpose of heating the large common area of the main floor, which includes the living room, family room, eating area and kitchen. Using NRCan's Air-Source Heat Pump Sizing and Selection guide, the heat pump's capacity is sized by proportioning the design heat load required for the large common, as shown in Equation 3 (NRCan, 2020b).

$$Common\ area\ heating\ load = \frac{Area\ of\ common\ area}{Total\ heated\ area} \times Total\ desgin\ heating\ load \qquad \text{Eq.3}$$

In the case of the ES home, the area of the common area is 46 m^2 (500 ft^2), the total heated area is 176 m^2 (1898 ft^2) and the total design heating load given by HOT2000 is 8.1 kW. Therefore, the heating load for the common area to be supplied by the heat pump is 2.1 kW (7200 Btu/h). A 2.93 kW (10000 Btu/hr) Energy Star rated Daikin heat pump (model RX09QMVJU) is modelled with a heating seasonal performance factor of 11.7 for NS and a COP of 4.58 (Daikin, 2018).

The remaining 6 kW heating load is provided by baseboard heaters. The baseboard heating system is sized to 8 kW to provide sufficient heating for the entire design heating load in the case outside temperature is below the heat pump's cut-off temperature.

6.2.2.11 Indoor Temperatures

SHEU results show that the majority of Atlantic Canadians reduce the temperature setpoint to 17°C overnight. Therefore, an overnight temperature of 17°C is considered for the 8-hour overnight period.

6.2.2.12 Domestic Hot Water

As per the baseline home, the same 189 L (50 US gal) hot water tank is modelled for the ES home (A.O. Smith, 2021b).

6.3 R-2000 Home

The next iteration of the home follows the R-2000 certification – a voluntary Canadian home standard which aims to reduce the energy consumption by approximately 50% compared to the equivalent home built to code. This program was developed over 30 years ago by the Government of Canada and associated researchers with the purpose of building homes to reduce energy use, improve air quality and implement environmentally responsible building practices (NRCan, 2018b). R-2000 homes must be built by a certified builder and have inspections before, during and after construction by a certified inspector (NRCan, 2018b).

In this project, the R-2000 model iteration aims to be more efficient than the baseline home and ES home. R-2000 homes use 40%-50% less energy than a home built to code because the energy target is only for space heating and hot water heating and varies depending on the home's location and size.

6.3.1 R-2000 Certification Requirements

The requirements that are incorporated into the R-2000 model are based on the 2012 R-2000 Standard and are described in Table 8. A column is included in Table 8 showing the baseline home specifications for comparison purposes. All thermal resistances in Table 8 are effective thermal resistance values.

Table 8: ESNH Requirements (NRCan 2020b)

Measure	R-2000 Standard Section	R-2000 Requirement (NRCan, 2020b)	Baseline Home Specification (CNBC, 2015)
Air tightness	4.3	1.5 ACH @ 50Pa	2.5 ACH @ 50Pa
Thermal resistance of ceilings below attics	4.2.2.1	RSI 8.67 W/m^2K (R49.2)	RSI 8.67 W/m^2K (R49.2)
Thermal resistance of walls above grade	4.1	RSI 2.97 W/m^2K (R16.9)	RSI 2.97 W/m^2K (R16.9)
Thermal resistance of floors over unheated spaces	4.1	RSI 4.67 W/m^2K (R26.5)	RSI 4.67 W/m^2K (R26.5)
Thermal resistance of foundation walls below or in contact with the ground	4.2	RSI 2.98 W/m^2K (R16.9). Must cover substantial portion of basement walls.	RSI 2.98 W/m^2K (R16.9)
Thermal resistance of unheated floors on ground above frost line	4.1	No insulation	No insulation
Thermal resistance of unheated floors below frost line	4.1	Not required	Not required
Window and door thermal requirements	4.4	Windows: Double-glazed, low-e coating, inert gas filled, insulated spacer and wood, vinyl or fibreglass frames	Maximum U-factor of 2.0 $W/m^2 \cdot K$
Space heating and cooling equipment	4.3	No guidelines for electric baseboard heating	No guidelines for electric baseboard heating
Hot water heating requirements	5.1.3	Standby losses <65 Watts for 175 L tank and <80 Watts for 270 L tank. Otherwise. Mandatory insulating blanket with minimum 1.8 RSI.	No specific requirements
		DWHR recommended as additional measure to reach energy target	Not required
Water Conservation	8.1	Ultra-low flush toilets: 4.8 litres/flush or less. Low-flow showerheads: 7.6 litres/min or less. Bathroom faucets using 5.7 litres/min or less.	Not required

Table 8 (continued)

Measure	R-2000 Standard Section	R-2000 Requirement (NRCan, 2020b)	Baseline Home Specification (CNBC, 2015)
Ventilation system	4.7.1.1	Ventilation system must meet CAN/CSA-F326- M91 (R2010) *Residential Mechanical Ventilation Systems.* HRVs and ERVs must be certified by Home Ventilating Institute (HVI)	Baseline home modelled with an HRV
		Ducts carrying outdoor air must be insulated with RSI of 0.5 and have a sealed vapour barrier.	Not required
Energy Target	6	Energy target for space heating and hot water energy comply to equations in Appendix B – specifying that they be 50% of the load calculated in HOT 2000	N/A
Indoor Air quality	7.1	Incorporate three features from the Indoor Air Quality Pick-List from Appendix A	Not required
Environmental Features	8.2	Incorporate two features from the Environmental Features Pick-List from Appendix B	Not required

Comparing the R-2000 requirements to the specifications used for the baseline home, the major differences appear in airtightness requirements (reducing from 2.5 ACH to 1.5 ACH @ 50Pa), the energy target (reducing space heating and hot water by 50%) and the incorporation of pick-list features. The R-2000 requirements have fewer qualitative targets than the Energy Star requirements, as they allow for the designer to make flexible choices in modelling to meet the requirements provided in the standard (NRCan, 2018b). For example, the R-2000 certification requirements specify only that the insulation in the home meet local building code but encourage designers to include additional insulation to meet the energy target.

The pick-list feautures in the R-2000 standard aim to provide increased occupant comfort and building methods/materials. The pick list feautures chosen for the R-2000 home are listed in Table 9.

Table 9: R-2000 pick-list features included

Pick-List Category	Feature
Indoor air quality	Carpeting labelled under the Canadian Carpet Institute's Green Label Program Kitchen cupboards and bathroom vanities made of solid wood Basement waterproofing included
Environmental	Mineral fibre batt insulation used in main floor walls that meets the EcoLogo^{CM} Program for raw material from recycled paper Drywall that contains recycled gypsum board and/or newsprint

The specified carpeting labelled under the Green label program must have a low percentage of volatile organic compounds (VOCs) in it, to improve indoor air quality (The Carpet and Rug Institute, 2021). The Canadian EcoLogo^{CM} Program which the main floor wall insulation must meet helps consumers identify the most environmentally preferred materials in terms of life-cycle impact (Government of Canada, 2012).

6.3.2 R-2000 HOT2000 Energy Modelling

6.3.2.1 House Orientation

As in the ES home model, the back of the R-2000 house faces south for optimal solar heat gain. However, in order to optimize the southern solar gains on the back of the house, the study and the laundry room switch locations, such that the window in the study is in the back of the house. Additionally, the windows in the upstairs bedrooms switch location, since the window in the front bedroom is 1.52 x 1.42 m (60" x 56") and the window in the back bedroom is 0.91 x 1.42 m (36" x 56").

By changing the location of the windows, the larger window will have southern exposure on the back of the house to increase useful solar heat gain.

6.3.2.2 Attic

The attic is modelled with blown cellulose insulation of 10.57 RSI (R60) and a 25mm (1-inch) medium density spray foam layer. The ceiling framing and interior finish is not altered from ESNH models. The resulting effective thermal resistance is 10.52 RSI.

6.3.2.3 Main and Second Floor Walls

Both the main and second floor walls are modelled with 4.23 RSI (R24) fibreglass batt insulation and a 25mm (1-inch) layer of medium density spray foam insulation, increasing the effective thermal resistance of the walls to 4.4 RSI. The remaining components of the walls including the framing and interior finish are not altered from the ESNH model.

6.3.2.4 Windows

Windows in the R-2000 home must be inert gas filled, double-glazed, have low-e coating, insulated spacer and wood, vinyl or fibreglass frames. These characteristics are modelled in the windows specified for the ES home. Therefore, the windows modelled for the R-2000 home are identical to the ES home windows. However, the window air tightness rating for the R-2000 home is CSA – A3, ie. only 0.5 L/s m^2 is allowable.

6.3.2.5 Exterior Doors

There is no specification for doors in the R-2000 standard. However, to contribute to the energy target, the exterior doors of the R-2000 home are steel with medium density spray foam core, with a thermal resistance of 1.14 RSI.

6.3.2.6 Exposed Floors

The garage floor of the R-2000 home is modelled as a 203 mm (8-inch) concrete block with 2 layer of XTPS IV insulation board, resulting in an effective thermal resistance of 3.78 RSI.

6.3.2.7 Foundation

The foundation walls for the R-2000 model are modelled with interior or exterior insulation. The interior foundation walls consist of 38 x 140 mm (2” x 6”) framing, one layer of 2.11 RSI (R12) fibre batt insulation and 12 mm (1/2”) gypsum board, resulting in an effective thermal resistance of 2.10 RSI. The exterior insulation consists of 64 mm extruded polystyrene (XTPS) rigid foam board, which provides an additional 2.22 RSI. The floor above the foundation is modelled the same as the ES home, but with a 51 mm (2 inch) layer of medium density spray foam, rather than 25 mm (1 inch), increasing the effective thermal resistance of the main floor to 5.69 RSI.

6.3.2.8 Base Loads

6.3.2.8.1 Occupancy

The occupancy levels for the R-2000 home are the same as the baseline home, with two adults and two children who are at home 50% of the time.

6.3.2.8.2 Electrical Base Loads

There are no requirements outlined in the R-2000 requirements for electrical usage. Therefore, the same ENERGY STAR® rated clothes dryer, clothes washer, dishwasher, refrigerator and electric range from the ESNH model are modelled for the R-2000 home. The small appliance, lighting and outdoor base load usage remain the same as the ESNH. Therefore, the baseloads electrical consumption remains the same as the ESNH, at 13 kWh/day. There are no power generating devices included in the R-2000 home. All energy comes from the grid.

6.3.2.8.3 Water Usage Base Loads

The hot water usage of the R-2000 home must comply with the requirements for low flow faucets and showerheads. Assuming that the faucets used meet the minimum requirements, the two showerheads have flow rates of 7.6 L/min and the three faucets have flow rates of 5.7 L/min. Assuming 5.2 showers/occupant/week and 6.5 minute/shower results in 146 L/day. Assuming each occupant uses the faucets for 1.75 minutes/day results in 40 L/day.

The Energy Star rated washing machine – the Whirlpool WFW560CH model- modelled uses 52 L/day. The Energy Star rated dishwasher – the Electrolux E24ID75 model - modelled uses 10 L of water per load. Assuming 1.37 cycles/occupant/week results in 7.8 L/day. Cumulatively, the R-2000 home model uses 246 L/day of hot water.

6.3.2.9 Air Infiltration

As required by the R-2000 standards, this home is modelled with a natural air infiltration of 1.5 ACH at 50 Pa.

6.3.2.10 Ventilation

The R-2000 standards require that the mechanical ventilation comply with CAN/CSA-F326-M91 (R2010), a Canadian residential mechanical ventilation system standard. This standard requires ventilation of the following flow rates be implemented in each room type:

- Master bedroom: 10 L/s
- Bedroom: 5 L/s
- Living room: 5 L/s
- Kitchen: 5 L/s
- Bathroom: 5 L/s
- Basement: 5 L/s if unfinished area is less than 2/3 basement area or 10 L/s if unfinished area is more than 2/3 basement area
- Other room: 5 L/s

Therefore, considering one master bedroom, two other bedrooms, one living room, one kitchen, one family room, three bathrooms, one study, one laundry room and a basement with unfinished area more than 2/3 of the basement area, the whole house requires mechanical ventilation that provides 70 L/s. An ERV will be used to achieve this ventilation rate. The ERV that is modelled is the Energy Star rated Lifebreath 130ERVD, which supplies 73 L/s at 50 Pa, sufficient to provide the 70 L/s required (Lifebreath, 2021). At 0°C, the ERV has a sensible heat recovery efficiency of 75% and uses 66 W of power. At -25°C, the ERV has a sensible heat recovery efficiency of 60% and uses 102 W of power (Lifebreath, 2021).

6.3.2.11 Heating/Cooling System

In contribution to achieving the desired energy target, a multi-zone mini-split ductless heat pump is modelled to reduce space heating energy use. This allows for temperature control in each zone controlled by an indoor unit. The same approach that was used to size the heat pump for the ESNH is used to size the heat pump for the R-2000 home – proportioning the design heat loss of the zone based on the area to be heated. The total design heat loss of the R-2000 home is 7.2 kW.

One Daikin 3MXL24RMVJU air source heat pump with a 7.0 kW (24000 BTU/hr) heating capacity is modelled for space heating the R-2000 home (Daikin, 2021). This outdoor unit has three ports for connection to indoor units in multiple zones and is rated for cold climates, operating in heating mode from -25°C to 15°C with a COP of 3.33 when used in conjunction with ducted and non-ducted indoor units (Daikin, 2021). Only two of the three ports are used for this application. The main floor common area is heated using a wall-mounted indoor unit, similar to the ESNH model. The second floor is heated using a slim-ducted unit, which is installed in the insulated attic and ducted to the three bedrooms, two bathrooms and master closet. Details regarding the indoor units are shown in Table 10.

Table 10: Heat pump indoor units (Daikin, 2021)

Zone	Heating Demand	Indoor Unit Model	Indoor Unit Capacity
Main floor common area (kitchen, family room, living room)	2.1 kW	FTXS09LVJU wall mounted-unit	2.5 kW (9,000 BTU/hr)
Second floor	3.2 kW	FDXS12LVJU slim ducted unit	3.5 kW (12,000 BTU/hr)

A supplemental system of baseboard heating for the design heating loss capacity (7.2 kW) must be included in the home for redundancy and safety in case of an outage or the outside temperature being below the heat pump's cut-off temperature.

6.3.2.12 Temperatures

The eight-hour overnight setpoint of 17 °C and daytime setpoint of 21°C are maintained in the R-2000 home, in keeping with the SHEU findings (SHEU, 2015).

6.3.2.13 Domestic Hot Water

The decreased flow rates of the bathroom faucets and showerheads decrease the hot water peak hour demand, which is used to size the hot water tank required, as shown in Table 11.

Table 11: Hot water peak hour demand

Use	**Average litres (gallons) of hot water per usage**	**Frequency of use during 1 hour**	**Litres (gallons) used during 1 hour**
Shower	53 (14.0)	2	106 (28.0)
Bathroom faucets	7.6 (2.0)	2	15.2 (4.0)
Hand dishwashing/food preperation	5.7 (1.5)	3	17.1 (14.5)
Dishwasher	10 (2.6)	1	10 (2.6)
Clothes washer	52 (13.7)	1	52 (11.1)
Total peak hour demand:			**200 (52.8)**

The shower usage is based on the 7.6 L/min showerhead and 7 minute long showers. The bathroom and kitchen sink faucet consumption assumes that the 5.7 L/min faucets are used for one minute at a time. The dishwasher and clothes washer consumption are assumed to use 10 L and 52 L per use, respectively, as per the specified appliances in Section 3.8.3 above describing the base load water usage in the home.

A 189 L (50 US gal) A.O.Smith EPSX 50 model hot water tank is modelled for the R-2000 home. This hot water tank is more energy efficient than the tanks in the baseline and ESNH model, with 6 kW input, 53 W standby losses and 227 L (60 gal) first hour rating (A.O.Smith, 2019). To further minimize losses, an insulating fibreglass blanket with thermal resistance of 1.76 RSI (R10) is added to the water tank.

Drain water heat recovery for the showers in the R-2000 home is modelled as an additional measure to reduce energy consumption. A EcoDrain model V1000-4-72 is modelled as the recovery unit, with an efficiency of 67.5% at 9.5 L/min.

6.3.2.14 Base Loads / Energy Target

The R-2000 standard specifies that “the annual household energy consumption target for space heating and domestic hot water heating combined shall be that calculated using the current authorized version of HOT2000 and multiplied by 50% ” (NRCan, 2012). Equations 4 and 5 specify the allowable sum of energy consumption for space heating and domestic hot water, as described in Appendix B of the R-2000 standard (NRCan, 2012).

$$Space\ heating: Q_S = S \times \left(\frac{49 \times DD}{6000}\right) \times \left(\frac{40+V}{2.5}\right) \qquad \text{Eq.4}$$

Where:

S = 1 kWh for an electric space heating system

DD = Celsius heating degree days for locality

V = interior heated volume (m^3)

$$Domestic\ Hot\ Water: Q_W = 4745 \times W \times \frac{55 - T_W}{55 - 9.5} \qquad \text{Eq. 5}$$

Where:

T_W = local water mains temperature

W = 1.075 kWh for electric hot water systems

An average of 4123 Celsius heating degree days is used for Nova Scotia (Halifax Regional Municipality, 2014). The local water mains temperature is assumed to be 10ºC (Health Canada, 2005). The interior heated volume of the home, excluding the basement since it is unheated, is 514 m^3. This results in space and domestic hot water heating energy targets of 8,270 kWh and ,045 kWh respectively. Equation 6 describes the overall energy target (NRCan, 2012).

$$Annual\ Energy\ Target = (Q_S + Q_W) \times 0.5 \qquad \text{Eq. 6}$$

The overall annual energy target for the R-2000 home is 6,666 kWh. This target must be met in a HOT 2000 simulation of the home under specific operating conditions outlined in the R-2000 standard. Therefore, the R-2000 model is modified to the specified standard conditions for compliance with the energy target. However, for the purpose of maintaining consistency amongst models, some R-2000 standard conditions including occupant behaviour and equipment selection are modified for this project. The conditions for the model being tested for R-2000 energy target purposes and the model being used for this project's results are outlined and justified in Table 12.

Table 12: R-2000 Standard and Project Conditions

	R-2000 standard conditions	**Project conditions**	**Notes**
Main floor heating setpoint	21 °C	21 °C	
Basement heated	Yes	No	
Basement cooled	No	No	
Basement setpoint	19 °C	N/A	
Basement separate thermostat	No	N/A	
Allowable daily temperature rise	3.5 °C	5.5 °C	
Interior loads, lighting	3 kWh/day	0.86 kWh/day	Based on 16 x 9.0 W LED bulbs
Interior loads, appliances	14 kWh/day	5.63 kWh/day	Based on washer, dryer, dishwasher, fridge, range
Interior loads, other	3 kWh/day	6.6 kWh/day	Based on estimate of small appliances and phantom loads in 3 bedroom home (Hendron & Engebrecht, 2010)
Average exterior use	4 kWh/day	0.14 kWh/day	Based on 5 x 9.0W LED bulbs
Hot water load	225 L/day	235 L/day	Based on same faucet and shower usage as previous models and more efficient washer + dishwasher
Hot water temperature	55 °C	55 °C	
Fraction of internal gains in basement	0.15	0.1	Lower because not finished
Adult occupants	2, 50%	2, 50%	
Child occupants	2, 50%	2, 50%	
Terrain, building site	suburb, forest	suburb, forest	
Local shielding, walls	Very heavy	Light	Typical NS suburb is not heavily shielded
Local shielding, flue	Light local shielding	None	No flue
Ventilation sizing, including HRV	As per CSA F326	As per CSA F326	

Using the R-2000 standard conditions for modelling, the home consumes 12.5 GJ in space heating and 11.0 GJ in domestic hot water use. Cumulatively, the energy target of 24 GJ is met.

6.4 Net Zero Energy Ready Home

The next home iteration further improves upon the efficiency of the home by following Canadian Home Builders' Association (CHBA) Net Zero Ready (NZR) labelling program, which was launched in 2017 in conjunction with the Net Zero (NZ) Home labelling program by the Canadian Home Builders' Association (CHBA, 2017). The NZR home and NZ home are built according the same efficiency standard – only requiring the addition of a renewable energy source to upgrade from an NZR to a NZ home (CHBA, 2021b). The NZR and NZ homes focus on reducing their energy consumption load through extremely airtight construction, significant insulation, Energy Star rated equipment and high-performance windows (CHBA, 2021a). CHBA estimates that a NZ home is 80% more efficient than a home built to code, as renewable energy generation offsets the home's energy consumption resulting in zero energy use annually (CHBA, 2021a). Some NZ homes use batteries to store energy for use during peak hours or power outages (CHBA, 2019).

In this project, the NZR home is developed to meet the requirements of the NZR standard. The EnerGuide score of the NZR home in GJ/year represents the quantity of energy generation required to offset the home's energy use. The NZ home is then modelled by adding a renewable energy production system to the NZR model to achieve a 0 GJ/year EnerGuide rating.

6.4.1 Net Zero Ready Certification Requirements

The requirements that are incorporated into the NZR home model are based on the CHBA Net Zero Home Labelling Program Version 1.3, effective on December 15, 2020 (CHBA, 2020c) and are described in Table 13. A column is included in Table 13 showing the corresponding efficiency measure used in the baseline home for comparison purposes. All thermal resistances in Table 13 are effective thermal resistance values. The energy performance of the homes modelled using this standard are tested under specified standard operating conditions and are then modified for the actual home's conditions.

Table 13: NZ Home Requirements (CHBA, 2020c)

Measure	Section of NZ Home Standard	NZR Standard Requirement (NRCan, 2020b)	Baseline Home Specification (CNBC, 2015)
Air tightness	3.2.1	2.5 ACH @ 50Pa	2.5 ACH @ 50Pa
Thermal resistance of attic	3.3.1	RSI 8.67 (R49.2)	RSI 8.67 (R49.2)
Thermal resistance of walls above grade	3.3.1	RSI 3.08 (R17.5)	RSI 2.97 (R16.9)
Thermal resistance of floors over unheated spaces	3.3.1	RSI 4.67 (R26.5)	RSI 4.67 (R26.5)
Thermal resistance of foundation walls below or in contact with the ground	3.3.1	RSI 2.98 (R16.9)	RSI 2.98 (R16.9)
Thermal resistance of unheated floors on ground above frost line	3.3.1	RSI 1.96 (R11.1)	No insulation
Thermal resistance of unheated floors below frost line	3.3.1	RSI 0.88 (R5.0)	Not required
Window thermal requirements	3.4.1	Energy Star certified for NS or double-glazed, low-e glass, inert-gas filled, have insulating spaces and a thermally broken frame if metal	Maximum U-factor of 2.0 $W/m^2 \cdot K$
Door thermal requirements	3.4.2	Energy Star certified for NS	Maximum U-factor of 2.0 $W/m^2 \cdot K$
Space cooling equipment	2.2.3	• Must be sized in accordance with CSA F280-12. • Space cooling required if cooling load exceeds 0.55 kWh/m^3. • If space cooling not supplied, energy base loads to be modelled with allowance for an “off the shelf” space cooling system that could be installed in the future	Not required
Space heating equipment	4.2.1	• Must be sized in accordance with CSA F280-12. • Air source heat pumps must be tested in accordance with CSA C656-14	No guidelines for electric baseboard heating
Hot water heating requirements	4.6.1	DWHR units must comply with CSA B55.2-15 and their efficiency confirmed by CSA B55.1-15	No specific requirements
Combined space and water heating systems	4.3.1	Must be of the condensing type and tested according to CSA P.911	No requirements

Table 13 (continued)

Measure	Section of NZ Home Standard	NZR Standard Requirement (NRCan, 2020b)	Baseline Home Specification (CNBC, 2015)
Ventilation system	4.7	• Balanced ventilation with heat recovery to meet principal ventilation air flow required. • An HRV, ERV or IMS can be used to provide principal ventilation required. • HRVs/ERVs must be Energy Star certified or follow Canada's Energy Efficiency Regulations and have a defrost mechanism. • System must be balanced within 10% at high speed. SRE taken at airflow of at least 22 L/s. • HRVs and ERVs must have SRE of 60% at 0 ºC • Ducts carrying conditioned air outside of the plane of insulation must have insulation that is of the same level as above grade walls and have all joints sealed. • Ducts in floors or ceilings must have effective thermal resistance of RSI 2.78.	Baseline home modelled with an HRV
Energy Target	2.22	Under specified operating conditions, annual heating consumption must be at least 33% lower than EnerGuide reference house	N/A
Energy Production (NZ Home only)	2.2.4	Sufficient renewable energy sources installed to provide net 0 GJ consumption annually	Not required
Energy Monitoring	2.5.4	System must report current, daily, weekly and monthly electricity production and consumption	

Comparing the NZR Home requirements to the specifications used for the baseline home, the major differences appear in thermal resistance increases, a 33% reduced space heating energy consumption target in comparison to the EnerGuide reference house and the installation of an energy production system in the case of the NZ home.

6.4.2 NZR Home HOT2000 Energy Modelling

6.4.2.1 House Orientation

The back of the NZR house faces south for optimal solar heat gain, with the study on the southern-facing wall house and the laundry room in the northern wall, as in the R-2000 model.

6.4.2.2 Attic

The attic is modelled with blown cellulose insulation of 10.57 RSI (R60) and a 76 mm (3-inch) medium density spray foam layer. The ceiling framing and interior finish is not altered from other home models. The resulting effective thermal resistance is 12.13 RSI.

6.4.2.3 Main and Second Floor Walls

Both the main and second floor walls are modelled with 4.9 RSI (R28) fibreglass batt insulation and a 76 mm (3-inch) layer of medium density spray foam insulation, increasing the effective thermal resistance of the walls to 6.1 RSI. Due to the increased thickness of insulation, the studs are increased to in thickness to 2” x 8”. The spacing and interior wall finishes remain the same.

6.4.2.4 Windows

The NZ Home standard requires that windows be Energy Star certified for NS or double-glazed, low-e glass, inert-gas filled, have insulating spaces and a thermally broken frame if metal. The windows modelled in the R-2000 home meet these criteria, but several windows are upgraded in the NZR home to provide increased thermal resistance. Table 14 describes the windows characteristics in the NZR home including their size, type, glazing details (double-glazed (DG) or triple glazed (TG) and number of coatings), emissivity (e) of coatings, number and type of heat mirrors in windows and effective thermal resistance (RSI). All windows in the NZR home have insulated spacers and vinyl frames.

Table 14: Window Details

Window Location	Side of house	Window size	Window type	Glazing	Coating/Tint	Mirror type	RSI
Patio door	South	1.52 x 2.03 m (60" x 80")	Patio door	DG + 1 coating	Low-e 0.1 (soft)	1 x 66% T_{vis}	0.89
Study	South	1.63 x 1.42 m (64" x 56")	Picture	TG + 2 coatings	Low-e 0.4 (soft)	No mirror	1.09
Living room	North	2.44 x 1.42 m (96" x 56")	Picture	DG + 1 coating	Low-e 0.1 (soft)	1 x 66% T_{vis}	1.07
Family room	South	2.44 x 1.42 m (96" x 56")	Picture	DG + 1 coating	Low-e 0.1 (soft)	1 x 66% T_{vis}	1.07
Kitchen	South	1.02 x 0.91 m (40" x 36")	Hinged	DG + 1 coating	Low-e 0.1 (soft)	2 x 88% T_{vis}	0.90
Main floor bathroom	South	0.76 x 1.02 m (30" x 40")	Hinged	DG + 1 coating	Low-e 0.1 (soft)	2 x 88% T_{vis}	0.86
Master bedroom	North	2.29 x 1.42 m (90" x 56")	Slider with sash	TG + 2 coatings	Low-e 0.04 (soft)	No heat mirror	0.95
Master bath	South	0.91 x 1.02 m (36" x 40")	Hinged	DG + 1 coating	Low-e 0.04 (soft)	2 x 88% T_{vis}	0.92
Master bath	East	0.91 x 1.02 m (36" x 40")	Hinged	DG + 1 coating	Low-e 0.04 (soft)	2 x 88% T_{vis}	0.90
Second floor bathroom	South	0.76 x 1.02 m (30" x 40")	Hinged	DG + 1 coating	Low-e 0.04 (soft)	2 x 88% T_{vis}	0.88
Bedroom 1	South	0.91 x 1.42 m (36" x 56")	Slider with sash	DG + 1 coating	Low-e 0.04 (soft)	2 x 88% T_{vis}	0.99
Bedroom 2	North	1.52 x 1.42 m (60" x 56")	Slider with sash	DG + 1 coating	Low-e 0.04 (soft)	2 x 88% T_{vis}	0.89
Closet	North	0.91 x 1.02 m (36" x 40")	Picture	TG + 2 coatings	Low-e 0.04 (soft)	No heat mirror	0.97
Basement	South	1.02 x 0.81 m (40" x 32")	Picture	TG + 2 coatings	Low-e 0.04 (soft)	No heat mirror	0.95
Basement	South	1.02 x 0.81 m (40" x 32")	Picture	TG + 2 coatings	Low-e 0.04 (soft)	No heat mirror	0.95
Basement	East	1.02 x 0.81 m (40" x 32")	Picture	TG + 2 coatings	Low-e 0.04 (soft)	No heat mirror	0.95
Basement	West	1.02 x 0.81 m 40" x 32"	Picture	TG + 2 coatings	Low-e 0.04 (soft)	No heat mirror	0.95

6.4.2.5 Exterior Doors

The NZR home's exterior doors are steel with medium density spray foam core, with a thermal resistance of 1.14 RSI. These are the same doors modelled in the R-2000 home.

6.4.2.6 Exposed Floors

The garage floor of the NZR home mimics that of the R-2000 home, with a 203 mm (8-inch) concrete block with 2 layers of XTPS IV insulation board, resulting in an effective thermal resistance of 3.78 RSI.

6.4.2.7 Foundations

The foundation walls and insulation for NZR model are modelled to mimic the R-2000 home's framing, interior insulation and exterior insulation, resulting in an effective RSI of 4.2 for the foundation walls. The floor above the foundation is modelled with the same framing as the other models, one layer of 4.2 RSI (R24) fibre batt insulation and an 89 mm (3.5 inch) layer of medium density spray foam, increasing the effective thermal resistance of the main floor to 7.1 RSI.

6.4.2.8 Base Loads

The standard consumer behaviour used in the other home models to calculate electrical and water base loads is not used for the NZR home, as it is assumed that owners building a NZR home are energy conscious and therefore implement behavioural changes to reduce their energy consumption, especially given the energy monitoring system that must be installed in any NZR home.

6.4.2.8.1 Occupancy

The occupancy levels for the NZR home are the same as the baseline home, with two adults and two children who are at home 50% of the time.

6.4.2.8.2 Electrical Base Loads

The appliances modelled in the NZR home are more efficient Energy Star rated appliances as compared to those modelled in the other homes. The size/annual electricity usage of the appliances selected are listed in Table 15.

Table 15: NZR Home Appliance Specifications

Appliance	Size (m^3 /ft^3)	Cycles/wk (Hicks et al., 2018)	Annual Energy Use (kWh/yr)	Reference
Clothes dryer	0.20 m^3 (7 ft^3)	1.2	102	(Energy Star, 2021b)
Clothes washer	0.12 m^3 (4.4 ft^3)	4	33	(Energy Star R, 2021d)
Refrigerator	0.52 m^3 (18.3 ft^3)	N/A	365	(Energy Star, 2021g)
Dishwasher	Standard	4	234	(Energy Star, 2021f)
Electric Range	N/A	N/A	565	(NRCan, 2020b)

The annual energy consumption is based on "active occupant" behaviour, meaning the occupant is actively aware of their energy consumption and takes action to reduce usage (Hicks et al., 2018). The number of cycles used to estimate the annual energy consumption for the clothes dryer, washer and dishwasher are based on a behavioral based energy consumption study done in Ottawa, Canada that outlines the typical behavior of an "active occupant" (Hicks et al., 2018). Cumulatively, 1300 kWh/yr of electricity is used for major appliances in the NZR home – a 37% reduction in electricity use as compared to the major appliance load in the R-2000 home.

The small appliance/phantom load usage in the NZR is reduced by 10% as compared to the other home models, as studies have shown that energy monitoring systems typically result in energy savings as a result of behavior change of 4-12%, with peak users reaching 20% reduction (Nachreiner et al., 2015). Therefore, the small appliance/phantom loads usage is reduced to 2,190 kWh/yr, as compared to the previous estimated load of 2,430 kWh/yr. The lighting energy consumption remains the same as other home models, assuming all light bulbs are LED, resulting in 0.86 kWh/day.

Therefore, the NZR home consumes 3.6 kWh/day in major appliances, 6 kWh/day in small appliances/phantom loads, and 0.86 kWh/day for lighting. Cumulatively, the average daily energy use of the NZR home is 10.5 kWh/day – a 20% reduction in electricity use compared to the R-2000 home.

6.4.2.9 Water Usage Base Loads

The NZR uses low flow faucets and showerheads to reduce hot water demand. The two showerheads are assumed to use 5.7 L/min (The Home Depot Canada, 2021). An average flow rate of 3.8 L/min is also assumed for the two bathroom faucets, and 5.7 L/min is assumed for the kitchen faucet (U.S. Environmental Protection Agency, 2016). Assuming shower time is reduced to seven minutes/showers (Hasan & Razali, 2021), and the same frequency of 5.2 showers/occupant/week results in 118 L/day.

Assuming faucet usage is reduced to 0.75 minutes/day/occupant for the bathroom and 4 minutes/day/household for the kitchen faucet (Hasan & Razali, 2021) results in 34 L/day.

The Energy Star rated washing machine – the Electrolux ELFW7337 - modelled uses 29 L/day, based on 4 loads/week. The Energy Star rated dishwasher – the Whirlpool UDT555SAHP - modelled uses 3.5 L of water per load, resulting in 2 L/day based on 4 cycles/week. Cumulatively, the NZR home model uses 183 L/day of hot water.

6.4.2.10 Air Infiltration

This home is modelled with a natural air infiltration of 1.5 ACH at 50 Pa. All other factors including the building site and local shielding remain the same as previous models.

6.4.2.11 Ventilation

The NZR home requirements must follow the CNBC 2015 requirements, with a minimum ventilation rate of 22 L/s for a three bedroom home (CNBC, 2015). The ventilation must be achieved through an HRV or ERV that is Energy Star certified and have a defrost mechanism (CHBA, 2020c). The chosen Energy Star rated ERV is the Napoleon 2400T, which can provide between 30 L/s and 99 L/s, maintaining a sensible heat recovery of 84% at 0°C and 65% at -25°C (Napoleon, 2021). There are two defrost mechanisms which prevent frost formation in average and cold weather climates (Napoleon, 2021). This ERV is modelled with a supply and exhaust rate of 30 L/s, operating for 480 min/day.

6.4.2.12 Heating/Cooling System

The design heating load for the NZR home is 5.6 kW. The heating/cooling is performed by a central split system air-source heat pump manufactured by Nordic. This heat pump is manufactured to suit the Atlantic Canadian provinces by optimizing performance at low temperatures (-21°C) using R410a refrigerant (Nordic, 2021). The heat pump's performance in heating mode is summarized in Table 16.

Table 16: Heat pump performance (Nordic, 2021)

Temperature (°C)	Input Power (kW)	Capacity (kW)	COP
-21	2,109	4,032	1.91
-8.3	2,100	5.8	2.74
1.7	2,240	7.5	3.34
8.3	2,290	8.8	3.85
18	2,454	10.8	4.41

A 7kW back-up plenum heater is installed inside the indoor unit for outages and low temperatures when the design space heating load is not met entirely by the heat pump. The outdoor unit is located on the east side of the home, with connections running to the indoor unit in the basement. Ductwork runs throughout the home, with thermostats in each bedroom, bathroom, living room and one thermostat to control the family/kitchen area. The supply ductwork is 20 x 76 cm (8 x 30 inches) with 15 cm (6 inch) round take-offs and the return ductwork is 20 x 102 cm (8 x 40 inches) to accommodate the 540 L/s (1150 cfm) airflow leaving the indoor unit at a full heating load. A ducted unit was chosen for the NZR home because several indoor and two outdoor units would be required to accomplish the same heating abilities if mini-splits were used.

6.4.2.13 Temperatures

The heating setpoint of the NZR home is 19°C during hours in which the occupant is home and 16°C during vacant hours, which include 8am-5pm and 12am-6am. These assumptions are based on the behaviour of "active occupants" who take action to reduce their energy consumption (Hicks et al., 2018).

6.4.2.14 Domestic Hot Water

Two processes contribute to the heating of DHW in the NZR home. The air-to-air heat pump selected to provide space heating for the home is also capable of providing heat for heating water using 5% of its capacity at a given temperature (440 W at 8.3°C) because the refrigeration circuit is installed within the indoor unit, eliminating the concern of the domestic hot water being run outdoors in below freezing temperatures (Nordic, 2021). This is done using a desuperheater with a built-in circulation pump which acts as a heat exchanger that extracts waste heat from the refrigeration cycle and uses it to preheat DHW and circulates it through an insulated 30-gallon pre-heat tank (Nordic, 2021). The desuperheater only provides heat to the pre-heat tank when the heat pump compressor is running and is capable of heating water up to 60°C (140°F) (Nordic, 2021). As a back-up means of domestic hot water heating, a conventional 130 L (30 gallon) tank with a first-hour rating of 170 L (45 gallon) is installed as a final means to provide heat when the water in the pre-heat tank has not reached the final temperature of 60°C (140°F) (Rheem, 2021). This is possible when the compressor is not running, or domestic hot water demand is higher than the desuperheater can provide. The size of the final heating tank is based on the first hour rating as shown in Table 17.

Table 17: NZR Home Hot Water Peak Hour Demand

Use	Average litres (gallons) of hot water per usage	Frequency of use during 1 hour	Litres (gallons) used during 1 hour
Shower	40 (10.6)	2	80 (21.2)
Bathroom faucets	3.8 (1.0)	2	7.6 (2.00)
Hand dishwashing/food preparation	5.7 (1.5)	3	17.1 (6.0)
Dishwasher	3.5 (0.9)	1	3.5 (0.9)
Clothes washer	52 (13.7)	1	52.0 (13.7)
Total peak hour demand:			**160 (42)**

The shower usage is based on the 5.7 L/min showerhead and 7-minute showers. The bathroom faucet consumption assumes that the 3.8 L/min faucets are used for one minute at a time. The kitchen faucet consumption assumes that the 5.7 L/min faucets are used for one minute at a time. The dishwasher and clothes washer consumption are assumed to use 3.5 L and 52 L per use, respectively, as per the specified appliances. The frequency of use for the devices are the same as the other home models for consistency and potential peak-hour usage in the NZR home, despite the energy conscious occupants.

Two drain water heat recovery units for the showers in the NZR home are modelled as an additional measure to reduce energy consumption. A Power-Pipe model R4-120 is modelled as the recovery unit, with an efficiency of 72.8% at 5.7 L/min.

6.4.2.15 Base Loads / Energy Target

The NZ Ready home standard requires that the home is 33% more efficient in terms of space heating in comparison to the EnerGuide reference house when modelled with the operating conditions in Table 18.

Table 18: Standard Conditions for Energy Loss Target (CHBA, 2020c)

Condition	Efficiency
Space heating: baseboard heating	100%
Electric water heating	0.86 Energy Factor
Balanced ventilation system with heat recovery	SRE: 60% at $0^{O}C$, 55% at $-25^{O}C$. Fan efficacy: 0.48 L/s/W at $0^{O}C$

Given the above conditions, a conventional 151 L (40 gallon) electric hot water tank with an energy factor of 0.86 and input capacity of 6000 W is modelled. An HRV providing 30 L/s supply air with the specified SREs are modelled for the home's version with standard operating conditions. The results under the standard operating condition result in a home that has an EnerGuide score 35% lower than the EnerGuide reference house, meeting the required 33%.

6.5 Net Zero Home

The next home iteration involves installing a renewable energy system for the NZR home, making it a Net Zero home. This iteration follows the same 2017 CHBA Net Zero Labelling program as the NZR home, with the addition of renewable energy to offset the emissions produced by the house. The CHBA's definition of a net zero home is that the home must produce as much electricity as it consumes on an annual basis using onsite renewable sources of energy (CHBA, 2020a). The electricity grid acts as a sink and source for the home by extracting extra electricity from the grid when the onsite renewables do not meet the demand and send excess, unused energy produced back to the grid (CHBA, 2020a). The energy monitoring system that is required to track the residents' energy consumption must also be capable of tracking the energy production and its interaction with the grid (CHBA, 2020a).

6.5.1 PV Modules

In addition to the 2,940 kWh of usable solar gains that can be harnessed through the windows of the NZ home, grid-tied solar photovoltaic modules on the roof of the NZ home are modelled as the means to produce onsite renewable energy. Wind was eliminated as an alternative method due to the inefficiency of small-scale turbine (Roach & Ugursal, 2020). The solar panels that are modelled are the CSA-approved Hanwha Q cells DUO L-G8 panels, which consist of mono-crystalline silicon cells. Further specifications of the modules are given in Table 19.

Table 19: Solar Panel Specifications

Characteristic	Specification
Number of cells	72
Size of cells, mm	161
Total cell area, m^2	2.03
Module length, m	2.08
Module width, m	0.98
Module area, m^2	2.04
Module power, W, at STC*	430
Module efficiency, %	21
Module Voc, at 25°C	49.3
Module Vmp, at 25°C	41.7
Temperature coefficient for power, %/°C	-0.35
Module power at 50°C, 1000 W/m^2, W	38.1
Module power at -10°C, 1000 W/m^2, W	46.8

*STC refers to standard test conditions at 25 °C and 1000 W/m^2

In order to maximize the sun exposure, the panels have a due south azimuth since NS is located in the Northern Hemisphere. Although a 45° tilt angle to match Halifax's 45° North latitude would produce optimal exposure, most roof pitches vary from 4:12 to 9:12. Therefore, a roof pitch of 9:12 (36°) is modelled, as the difference has little impact on the annual electricity generation (Roach & Ugursal, 2020). The south facing portion of the roof above the 2nd floor (not including roof covering garage) provides a 36 m^2 (5m x 10m area leaving 1m of perimeter) area for PV modules and/or thermal collectors.

During a typical year in Halifax, a south-facing surface tilted at 45° receives 1,400 kWh/m^2 (Allen, 2021b). In NS, a typical solar system generates 1,150 kWh per kW of electricity per year, after accounting for a 3% loss of efficiency in the inverter (Efficiency NS, 2021; Roach & Ugursal, 2020) and therefore an 6.2 kW system is suitable to produce the 6,900 kWh of electricity that is required for the NZR home in a year. The selected solar panels have a 21% efficiency and therefore 32,900 kWh of solar energy must be captured to meet the 6,900 kWh demand. Given the insolation of 1400 kWh/m^2, 24 m^2 of solar panels are required. However, as a safety factor to account for potential shade, an extra 4 m^2 of modules is modelled, resulting in a total of 14 modules. A summary of the PV energy production compared to the grid electricity consumption to prove that the home is net zero is shown in Table 20.

Table 20: PV Module Monthly Performance

Month	**Solar radiation on tilted surface ($kWh/m^2/day$)**	**Average solar power (Watts)**	**Available PV energy (kWh)**	**Electrical load (kWh)**	**Net grid consumption (kWh)**
January	2.8	695	442	1,026	584
February	3.7	982	564	839	275
March	4.5	1,222	777	705	-72
April	4.6	1,263	777	524	-253
May	4.9	1,278	813	390	-423
June	4.9	1,261	776	342	-434
July	5.1	1,280	814	342	-472
August	4.9	1,270	808	345	-463
September	4.4	1,134	698	362	-336
October	3.3	842	536	460	-76
November	2.2	547	337	656	319
December	2.0	495	313	896	583
Annual	**3.9**	**1,022**	**7,655**	**6,887**	**-768**

The CSA-approved Fronius Primo 8.2kW inverter with smart metering is modelled for the NZ home (Fronius, 2021). This inverter uses MPPT, is 97% efficient and can operate at 1000 V DC of input, which is suitable for the 686 V DC incoming from the sixteen 49V modules connected in series (Fronius, 2021).

6.5.2 Solar Thermal Collectors

Flat plate solar thermal collectors are modelled to provide domestic hot water heating to the NZ home. The collectors being modelled are the Thermo Dynamic G32-P collectors, made with low-iron glass and have an efficiency of 0.7. The system consists of a series of thermal collectors that uses a water-glycol mixture as the heat transfer fluid, a pump for the glycol mixture, a hot water storage tank, a heat exchanger to transfer heat from glycol loop to hot water and a controller for the pump (U.S. Department of Energy, 2011). The estimated area, A, required for the thermal collectors is calculated using Equation 7 (Allen, 2021c).

$$A = \frac{L}{\eta_{solar}\, I} \quad \text{Eq. 7}$$

where:

L= DHW load (kWh/day)

η_{solar} = efficiency of solar collectors

I = Solar radiation (kWh/m^2/day)

The monthly average solar radiation, I, delivered to Nova Scotia and the average monthly energy load for DHW based on the NZR home's results are used to calculate the theoretical area of solar collectors required to satisfy the average daily load in each month, as shown in Table 21 (Allen, 2021a).

Table 21: Solar Collector Area Requirements

Month	**Average solar radiation, I (kWh/m^2/day)**	**DHW energy load, L (kWh/month)**	**Average area required per day (m^2)**
January	1.4	202	6.7
February	2.2	184	4.3
March	3.4	202	2.7
April	4.1	192	2.2
May	4.7	193	1.9
June	5.6	196	1.7
July	5.3	199	1.7
August	4.9	198	1.9
September	3.8	193	2.4
October	2.5	188	3.5
November	1.5	187	5.9
December	1.0	198	9.1

The expected solar collector area required for a typical day in each month varies between 1.7 m^2 and 9.1 m^2. Therefore, two of the 3.0 m^2 G-series collector panels with an efficiency of 0.7 and generation capacity of 1667 kWh/yr (Natural Resources Canada, 2015) are modelled on the 9:12 south facing roof above the garage (Thermo Dynamic, 2021). This area of collectors provides sufficient energy for seven months of the year. During the five months that the DHW load is greater than the collector's production, the PV system is sized to produce enough hot water to compensate using the heat pump desuperheater. The desuperheater modelled in the NZ ready home provides electric back-up for the solar collectors. The preheat tank is operated by the desuperheater whilst the final tank is operated by the solar collectors, as opposed to a conventional electric resistance, as in the NZ Ready home.

7.0 Operational Energy Modelling Results

The energy modelling methodology provides energy use results that are used for the life cycle assessment modelling of the home's operational phase. The operational phase energy use results contribute to analyzing the environmental impacts incurred due to the use of grid electricity that is required to provide energy to the home and ultimately contributes to analyzing the environmental impacts of the building's entire lifecycle. The operational phase of the building is a significant contributor to the life cycle environmental impacts of the building. Therefore, this section describes and compares the results of the operational energy modelling for the five iterations of buildings studied; the baseline home, the Energy Star Home, the R-2000 home, the Net-Zero Ready home and the Net Zero home. Table 22 gives a detailed synopsis of the upgrades made to each home for operational energy use reduction.

Table 22: Operational Energy Modifications

Measure	Baseline Home	Energy Star Home	R-2000 Home	NZR Home	NZ Home
Air tightness (ACH @ 50Pa)	4.55	1.5	1.5	1.5	1.5
House Orientation	Front faces east	Front faces north	Front faces north	Front faces north	Front faces north
Thermal resistance of ceilings below attics	8.67	9.0	10.5	12.0	12.0
Thermal resistance of walls above grade (RSI)	3.1	3.1	4.1	5.8	5.8
Thermal resistance of floor over basement (RSI)	4.8	4.8	5.7	7.1	7.1
Thermal resistance of foundation walls (RSI)	3.0	3.9	4.2	4.2	4.2
Thermal resistance of garage floor (RSI)	No insulation	2.0 RSI	3.8	3.8	3.8
Windows (minimum RSI)	0.5	0.85	0.85	0.85	0.85
SHGC (maximum)	0.58	0.3	0.3	0.6	0.6
Doors (RSI)	0.63	0.82	1.1	1.1	1.1
Space heating equipment	8 kW baseboard heating	2.92 kW mini-split ductless heat pump and 8 kW baseboard heating	7.0 kW multi-zone mini-split ductless heat pump and 7.2 kW baseboard heating	5.6 kW central split air-source heat pump and 7kW backup plenum heater	5.6 kW central split air-source heat pump and 7kW backup plenum heater
Temperature setpoints	21°C during day and night	21°C day and 17°C night	21°C day and 17°C night	19°C from 5pm-12am 16°C from 8am-5pm and 12am-6am.	19°C from 5pm-12am 16°C from 8am-5pm and 12am-6am.
Ventilation system	25 L/s HRV with efficiency of 55% at 0°C and 45% at -25°C	25 L/s ERV with efficiency of 75% at 0°C and 65% at -25°C	73 L/s ERV with efficiency of 75% at 0°C and 60% at -25°C	30 L/s ERV with efficiency of 84% at 0°C and 65% at -25°C	30 L/s ERV with efficiency of 84% at 0°C and 65% at -25°C
Electrical	No Energy Star light bulbs	100% Energy Star LED light bulbs	100% Energy Star LED light bulbs	100% Energy Star LED light bulbs	100% Energy Star LED light bulbs
Daily water usage baseload (L)	316	316	236	183	183

Table 22 (continued)

Measure	Baseline Home	Energy Star Home	R-2000 Home	NZR Home	NZ Home
Hot water heater	189 L (50 gal) tank with 70kW standby losses	189 L (50 gal) tank with 70 kW standby losses	189 L (50 gal) tank with 53 kW standby losses	Pre-heat tank powered by 5% of heat pump’s capacity and back-up 30-gallon conventional tank	6 m^2 solar thermal collectors, pre-heat tank powered by 5% of heat pump’s capacity and back-up 30-gallon conventional tank
PV system	N/A	N/A	N/A	N/A	$28m^2$ PV system with mono-crystalline silicon cells

The baseline home acts as a reference to a typical newly built NS home. The energy consumption of the baseline home is 102 GJ/yr. In comparison to the EnerGuide reference house, the baseline home consumes an additonal 2 GJ/yr, meaning the typical NS home does not use significantly more energy than an identical home built strictly to the CNBC. The small difference is a result of modifications made to the model the baseline home to reflect the most common building practices and occupant behavior in NS, while still following building code.

The ES home uses 35% less energy than the equivalent EnerGuide reference home, meeting the requirements of the ESNH Performance Approach, which requires the home to consume 20% less energy than the equivalent EnerGuide reference (CHBA, 2020) (NRCan, 2020b). The most significant contributions to the reduction of energy use in the ES home come from the improved envelope components (insulation, windows) and optimized orientation, which decreases the design heat loss by 8kW as compared to the baseline home. The change to 75% LED bulbs also decreases the load from lighting by 85% compared to the baseline home. The addition of a heat pump, an increase in thermal resistance, and an increase in airtightness decreased the annual space heating energy use by 9,830 kWh per year.

The R-2000 home uses 50 % less operational energy than the equivalent EnerGuide reference home. Additonally, the R-2000 home's space heating and hot water heating loads when modelled under R-2000's specific operating conditions are 50% less than those of the equivalent EnerGuide reference home, meaning the energy target for the R-2000 standard is met. However, it should be noted that the EnerGuide score of the reference home in the R-2000 iteration increased by 10 GJ/yr to 104 GJ/yr compared to the baseline and Energy Star homes due to the increased ventilation requirements. Therefore, comparing the energy use per year of the R-2000 home to that of the EnerGuide reference house used for the baseline and Energy Star home (94 GJ/yr), a 44% reduction in energy use is accomplished. The components that contribute most significantly to the reduction include increased thermal resistance of envelope components (doors, increased insulation), larger heat pump and decreaed daily water usage.

The NZR home has an EnerGuide score that is 54% less than the equivalent EnerGuide reference home and meets the NZR requirement of 33% reduction in annual heating energy consumption as compared to the EnerGuide reference home. Comparing the scores of the NZR to the other models, a 54% improvement is made compared to the baseline home, a 30% improvement compared to the ES home and a 16% improvement compared to the R-2000 home. The updated component that contributes most significantly to the reduction in energy use in the NZR home is the installation of a ducted heat pump that conditions the entire home and heats a portion of the required hot water for the home.

The NZ home is modelled identically to the NZR home but includes solar thermal collectors and a PV system that generates electricity. The NZ home uses 100% less energy than the EnerGuide reference home, as the annual net energy use of the home is 0 GJ/yr.

The upgrades made to each home iteration resulted in the reduction in energy use throughout the home via reduced air leakage, DHW heating, space heating and base electrical loads. The detailed results for the annual energy use in each of these categories is shown in Table 23.

Table 23: Annual Energy Use Comparison

	Baseline home	Energy Star home	R-2000 home	Net Zero Ready home	Net Zero home
Air leakage and mechanical ventilation					
Gross air leakage and mechanical ventilation load (kWh)	3,692	2,056	2,747	1,714	1,714
Seasonal HRV efficiency (%)	54	73	74	82	82
Ventilation electrical load (kWh)	150	114	194	61	61
Net air leakage and mechanical ventilation load (kWh)	3,972	2,017	2,542	1,614	1,614
Domestic hot water (DHW) heating					
DHW heating load (kWh)	6,200	6,200	4,861	3,611	3,611
Reduction in load due to DHWR (kWh)	N/A	N/A	639	514	514
Solar DHW system contribution (kWh)	N/A	N/A	N/A	N/A	2,175
DHW heating energy consumption (kWh)	6,808	6,856	4,500	2,538 (45% heat pump, 54% conventional tank)	925
DHW system seasonal efficiency (%)	91.1	90.4	93.9	Heat pump: 190 Conventional tank: 63.2	100
Space heating					
Design heat loss at -18°C (kW)	9.6	7.7	6.2	5.1	5.1
Gross space heat loss (kWh)	27,017	20,692	17,389	12,417	12,306
Usable internal heat gains (kWh)	6,806	5,078	4,917	4,217	4,217

Table 23 (continued)

	Baseline home	Energy Star home	R-2000 home	Net Zero Ready home	Net Zero home
Usable internal heat gains fraction (%)	25.2	24.6	28.3	34	34
Usable solar gains (kWh)	5,514	3,750	3,844	3,028	3,028
Usable solar gains fraction (%)	20.4	18.2	22.1	24.3	24.3
Space heating load (kWh)	14,694	11,553	8,389	4,597	4,597
Heat pump and auxiliary electric heater combined COP	N/A	2.01	1.98	2.01	2.01
Heat pump energy consumption (kWh)	N/A	2289	3294	1683	1683
Auxiliary electric heater energy consumption (kWh)	14694	2569	100	19	19
Space heating energy consumption (kWh)□	14694	4858	3389	1703	1703
Base Electrical					
Interior lighting (kWh)	1,460	314	314	314	314
Appliances (kWh)	2,580	2,050	2,050	1,310	1,310
Other (kWh)	2,430	2,430	2,430	2,190	2,190
HRV/exhaust fan (kWh)	160	130	194	61	61
Space heating fan (kWh)	0	600	498	314	314
Total electrical (kWh)	6,630	5,520	5,490	4,190	4,190
Energy consumption summary					
Space heating energy consumption					
MJ	52,900	17,490	12,200	6,130	6,130
kWh	14,700	4,860	3,390	1,700	1,700

Table 23 (*continued*)

	Baseline home	**Energy Star home**	**R-2000 home**	**Net Zero Ready home**	**Net Zero home**
HRV/ventilation electrical consumption					
MJ	540	410	630	180	180
kWh	150	110	175	50	50
DHW energy consumption					
MJ	24,510	24,680	16,200	8,400	3,330
kWh	6,810	6,855	4,500	2,330	925
Base electrical loads including space heating fan					
MJ	23,870	19,870	19,760	15,080	15,080
kWh	6,630	5,520	5,490	4,190	4,190
TOTAL (GJ)	102	62	49	30	25
TOTAL (kWh)	**28,290**	**17,340**	**13,550**	**8,270**	**6,870**
Photovoltaic contribution (kWh)	N/A	N/A	N/A	N/A	7,500

The baseline home's space heating needs account for 52% of the total annual use, whereas the Energy Star home's space heating needs only account for 28% of its total annual energy use due to the installation of mini-split heat pump and increase in envelope thermal resistance. Similarly, as the size of heat pumps and envelope thermal resistances increase in the R-2000 and NZ home, the space heating contribution decreases to 25% and 20% of the total annual energy use respectivley.

The DHW heating uses the largest proportion of annual energy use in all homes except the baseline home and net zero home. Space heating is the largest contributor to the baseline home's annual energy use and the NZ home uses solar thermal collectors for 70% of the hot water heating, therefore reducing the quantity of electricity required for heating the remaining hot water to 29% of the home's total annual energy use. The electricity required to heat DHW in the Energy Star home, R-2000 home and NZR home accounts for 40%, 33% and 28% of the total annual energy use respectiveley. The major contributions in decreasing the energy use for hot water heating include domesitic hot water recovery (in R-2000, NZR and NZ homes) more efficient hot water heating tanks and the heat pump desuperheater that preheats the domestic hot water in the NZR home.

The base electrical loads only decrease by 35% between the baseline home and NZ home. As a result, the base electrical loads account for a larger proportion of the total annual energy use in the more efficient homes than the baseline home. For example, the base electrical loads contribute to 23% of the baseline home's annual energy usage, but 51% of the NZR home's annual energy usage due to the reduction in other energy use categories such as space heating and DHW heating in the NZR home. A 17% reduction in base electrical load usage occurs between the baseline and ESNH due to the installtion of energy efficient appliances and switching the lighting to LED. There is a minor reduction in base electrical load for the R-2000 home as compared to the ESNH due to the installation of more efficient space heating fan. The baseline home, ESNH and R-2000 home have the same small appliance and phantom loads. However, the 24% reduction in the base electrical loads between the NZR home and R-2000 home is a result of more efficient major appliances and the assumption that the occupants are activley attempting to reduce their energy usage and that the installation of the energy monitoring system contributes to that reduction.

For each home, the HRV or ERV usage is small in comparison to the total annual energy use, with the largest contribution occuring in the R-2000 home with 1.29% of total annual energy use because the ventilation requirements for the R-2000 standard are higher than the other homes.

A breakdown of the monthly energy usage for each category in the baseline home, ESNH, R-2000 home and NZR/NZ Home are shown in Figure 3, Figure 4, Figure 5 and Figure 6 respectively. The NZ home monthly energy usage is the same as the NZR home energy usage, the only difference being that the energy for the NZR home is supplied by the electricity grid and the energy for the NZ home is supplied by solar thermal collectors and PV modules. The scales in Figures 3 through 6 are the same to highlight the differences in energy use amongst the homes.

Figure 3: Baseline Home Annual Energy Consumption by Device

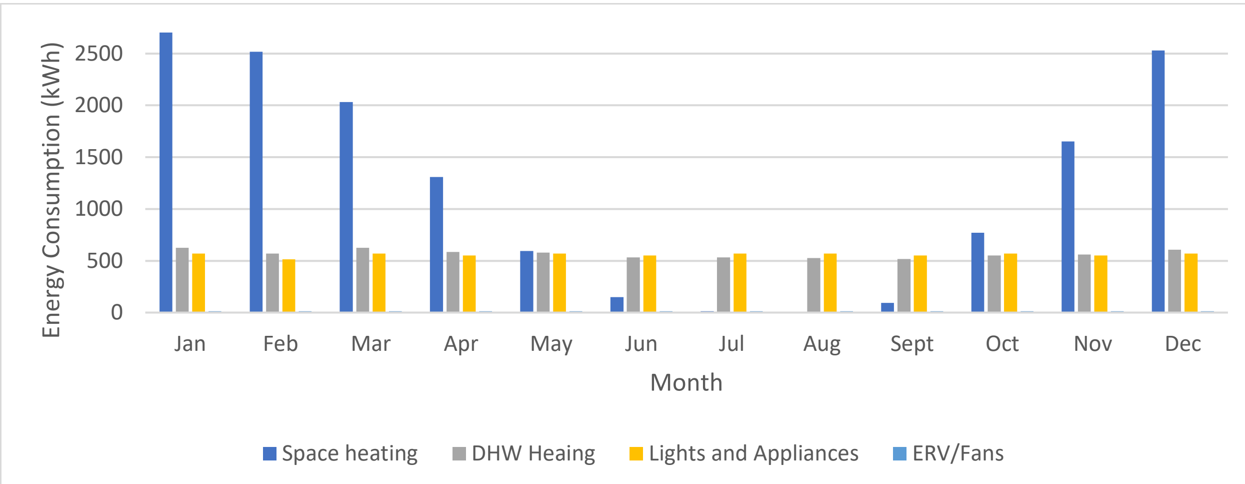


Figure 4: ESNH Annual Energy Consumption by Device

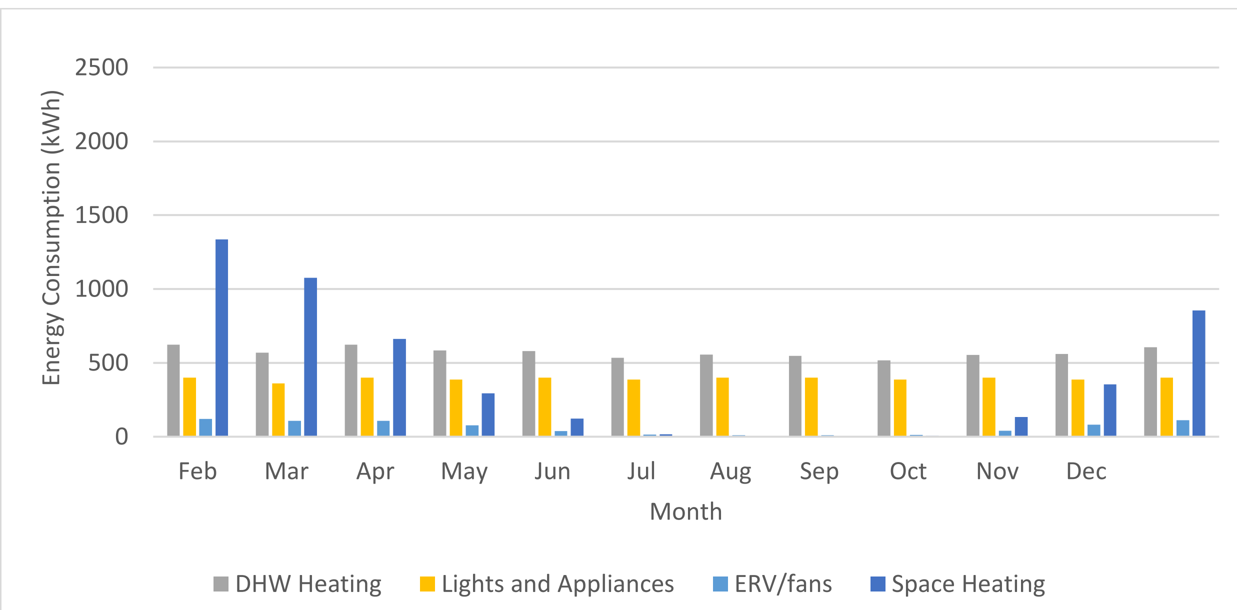


Figure 5: R-2000 Home Annual Energy Use by Device

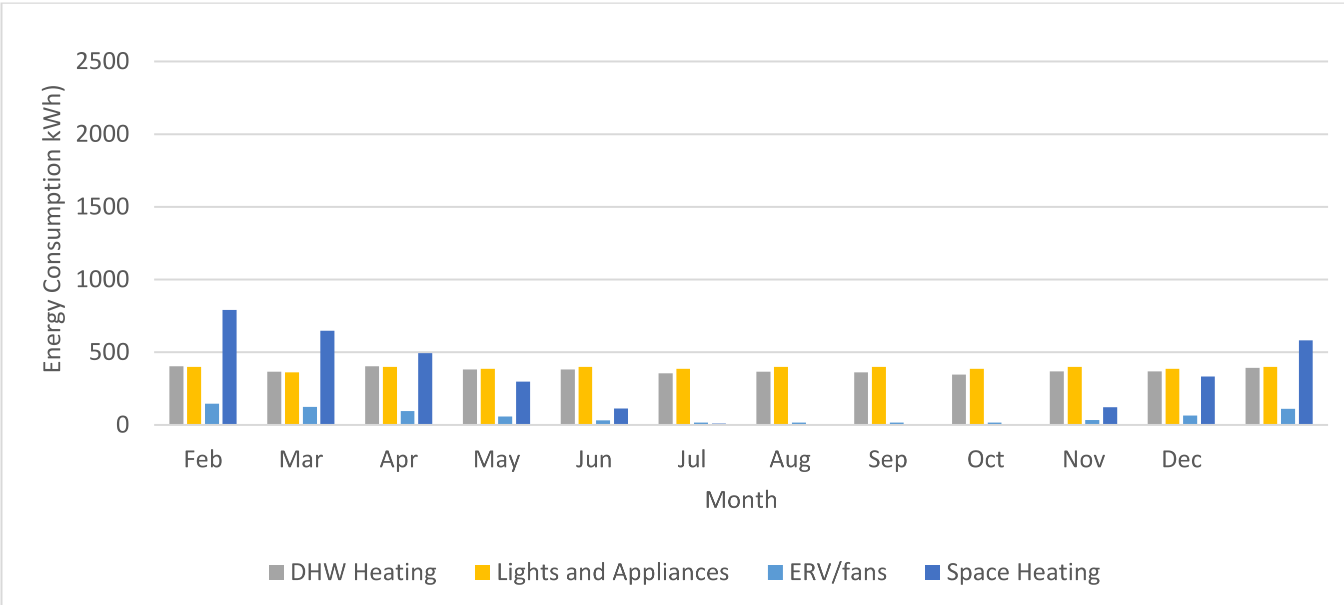
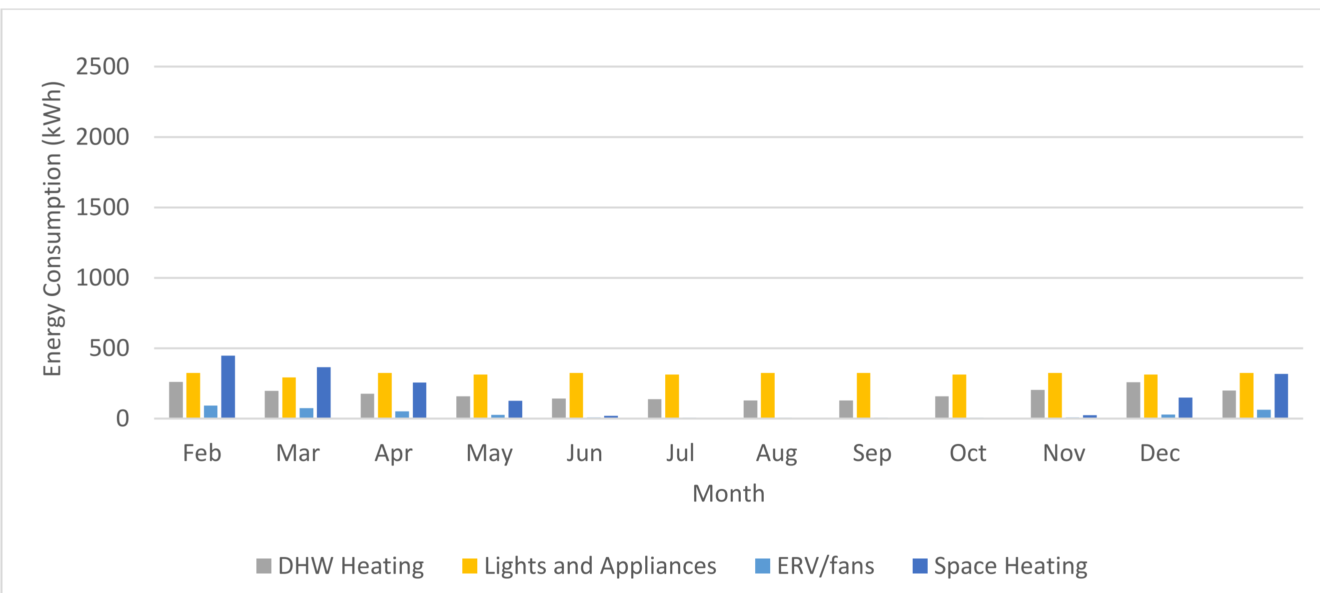


Figure 6: NZR and NZ Home Annual Energy Use by Device

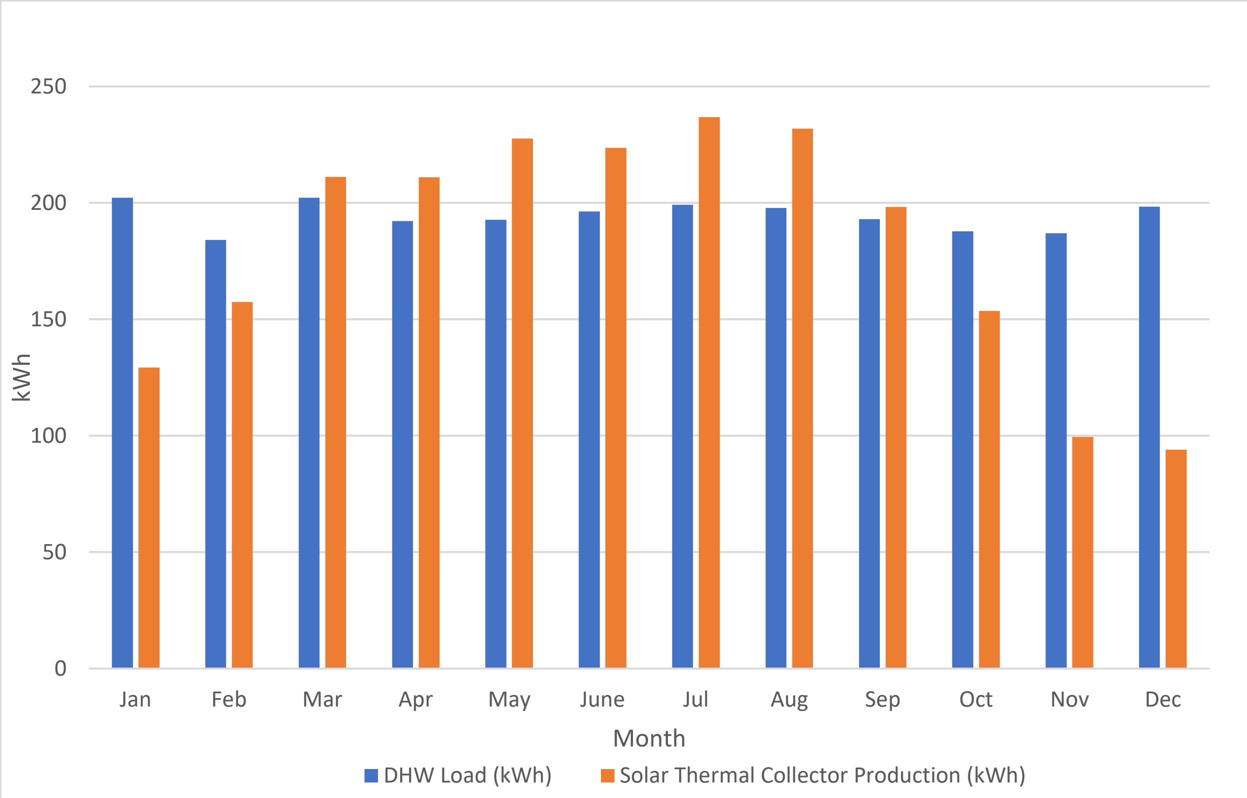


The monthly breakdown of energy consumption for each home in Figures 3 through 6 show a consistent trend in increased space heating energy during the winter months as a result of colder outdoor temperatures. The other categories including lights/appliances, ERV/fans and DHW heating remain relatively consistent throughout the year. Figure 3 highlights the significance of space heating energy consumption in the baseline home as compared to the other categories. Similarly, the high space heating energy use for the baseline home as compared to the space heating energy use for the other homes is highlighted in the consistent scale throughout Figures 3-6. Figures 4-6 highlight the consistently large DHW load in the ESNH, R-2000 and NZR home, as compared to the space heating load which is larger than the DHW load in the winter but negligible in the summer months. Figure 3 shows that the ERV/fans loads are negligible for each month in the baseline home but becomes a more significant proportion of energy use as the homes become more efficient in Figures 4-6 due to the total annual energy use being lower. Similarly, lights and appliances are a consistent load each month but become a significantly larger proportion of the total energy usage as the total annual energy consumption decreases with the more efficient home iterations.

The Net Zero home uses solar thermal collectors for domestic hot water heating and PV modules to supply the electricity required for the home. The Net Zero home has no storage system, and therefore relies on the electricity grid to act as storage, by releasing excess electricity to the grid when the home's load is less than generation and consume electricity from the grid when the home's load is greater than generation. To qualify as net zero, the home must release as much electricity as it consumes to the grid annually (CHBA, 2020a).

The NZ home's annual hot water heating load before drain heat recovery or solar thermal collector input it 3,600 kWh. The drain water heat recovery eliminates 515 kWh of the load, resulting in a total annual load of 3,100 kWh to be supplied by the solar thermal collectors and PV modules. A breakdown of the solar thermal collector's monthly energy production compared to the domestic hot water load is shown in Figure 7.

Figure 7: Monthly DHW Load versus Solar Thermal Collector Production



The 6 m^2 of solar collectors provides 2,170 kWh of energy per year. The remaining 925 kWh of energy for DHW annually is provided by the PV system, which is sized to account for the load that cannot be met by the solar thermal collectors. Figure 7 shows that either the PV modules or electricity grid must provide higher amounts of hot water heating during the winter months when there is less solar availability for the collectors to produce heating energy.

The Net Zero home's 28 m^2 of solar PV modules are designed to provide 7,500 kWh annually. This provides approximately 10% extra production in the case of solar availability variation annually. The predicted monthly PV production as compared to the electrical load and resulting net grid consumption is shown in Figure 8.

Figure 8: Monthly PV Module Production, Electrical Load and Net Grid Consumption

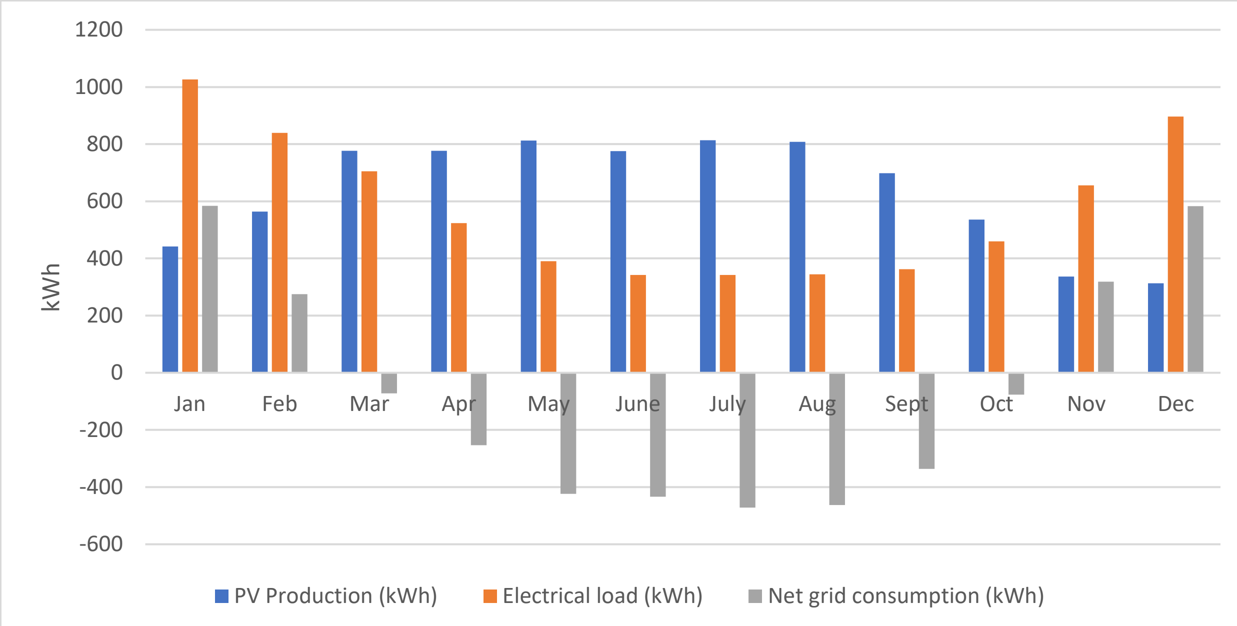


Figure 8 shows the predicted annual interaction between the PV system and electricity grid that allows the home to be considered net zero. During the winter months, when PV production is low and the electrical loads are high, electricity must be consumed from the grid (indicated by positive net grid consumption). During the summer months when solar production is high and the electrical load is low, the PV system sends its excess electricity to the grid (indicated by the negative net grid consumption). This grid can be thought of as a battery, storing the excess summer PV generation until it is needed in the winter months when PV production is low. The annual production of electricity from the PV system is 10% greater than the annual electrical load of the home and therefore can be considered a net zero home according to the CHBA (2020) standard.

The results of the energy modelling section provide the energy use for the operational phase of the home's lifecycle. A breakdown of each home's annual operational energy use by end-use is summarized in Figure 9.

Figure 9: Annual Operational Energy Consumption by End-Use

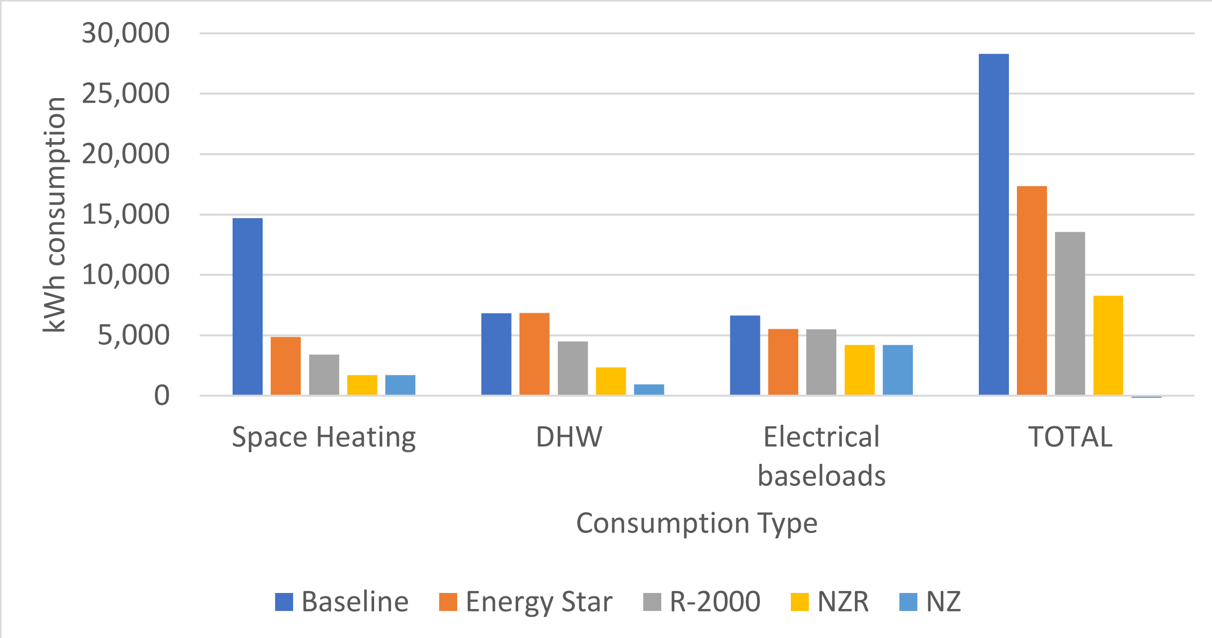


Figure 9 highlights the differences in end-use operational energy for the five home iterations. Notable differences include the approximately 10,000 kWh of additional space heating energy required for the baseline home and the small difference amongst electrical baseloads among all five iterations.

8.0 LCA Modelling Literature Review

Life cycle assessments of all five homes are performed to analyze their cradle-to-grave environmental impacts. Several software are available to perform the assessments, therefore a comparison is performed to determine the most appropriate software tool for this project, and a summary of how the chosen tool works is included in this chapter. The methodology in modelling each home is described but depends primarily on construction specified for each home in the operational energy modelling chapter. The LCA results are presented and compared in terms of environmental impact categories.

8.1 LCA Software Tools

Although it is evident that the operational energy of an NZEB is lower than a traditionally powered home, a holistic approach requires minimizing the "cradle to grave" environmental impact of dwellings through life cycle assessment (LCA). An in-depth understanding of a building's embodied environmental impacts can be developed by performing an LCA. The assessment tool quantifies the impact of an entire building's activities over its lifespan by considering raw material extraction, manufacturing, transportation, building construction, operation, demolition and disposal (Walker et al., 2019). These inputs and outputs are evaluated using the tool's extensive construction material databases and are formed into a dataset that can be used to interpret the effect of specific energy efficiency and renewable/alternative energy measures on a LCA impact category. These categories include global warming, ozone depletion, acidification, smog, eutrophication and non-renewable energy consumption (*Athena Sustainable Materials Institute*, 2021). The results of an LCA help decision-makers make environmentally preferred choices and comparisons, by highlighting products and/or life-cycle stages that are contributing to the environmental impacts of a project.

8.1.1 Introduction to LCA Tools

Life Cycle Assessments (LCA) are simplified by using software tools with extensive databases to assess the cradle-to-grave environmental effects of a whole building. Using building energy simulation models, the LCA software are able to retrieve environmental impact data from their databases for raw material extraction (the cradle), manufacturing, transportation, construction, operation, demolition and disposal (the grave) of the building (Walker et al., 2019). This creates a holistic model of a home's environmental impact which helps to optimize planning in the design stage.

In this project, LCA will act as a comparison tool for increasingly energy-efficient home constructions to analyze embodied emissions associated with each construction. There are several prevalent software available for Canadians to perform whole building LCAs. Four tools will be compared and discussed for the purpose of this project:

- Athena's Impact Estimator for Buildings is an LCA software that was developed by a Canadian non-profit research group and has a Canadian material database (*Athena Sustainable Materials Institute*, 2021).
- Tally is a United States-based LCA software tool which was created specifically for performing whole-building assessments and focuses on design comparison options (Tally, 2021).
- One Click LCA is a Finland-based technology which relies on environmental product declarations (EPDs) to provide standardized information regarding the cradle-to-grave environmental impact of specific products (One Click LCA® software, 2021).
- SimaPro is one of the most popular LCA tools used worldwide, but it is not commonly used for whole building assessments 2022-10-25 10:24:00 AM.

8.1.2 LCA Tool Descriptions

Athena's Impact Estimator for Buildings is a Canadian developed LCA software capable of completing cradle-to-grave whole-building assessments (Athena Sustainable Materials Institute, 2021). The assessment can be accomplished through manual input of a bill of materials (BOM) within Athena's software, or a BOM can be imported from a building information modelling (BIM) program. Users have the opportunity to use pre-made structural and envelope assembly combinations within the software for preliminary design consideration. The Athena tool uses North American product databases, including their own database and the U.S. Life Cycle Inventory (*Athena Sustainable Materials Institute*, 2021). Impacts from these products including raw material extraction, manufacturing and transportation are included when considering their environmental effects. The whole-building assessment focuses on a limited selection of generic products available in North America to build the structure and building envelope, with no option to input mechanical, piping or finishes such as flooring and appliances. Athena allows users to input a specific Canadian city in which the project is to be performed, allowing the assessment of transportation, construction and end-of-life methods to be regionally specific (Cormick, 2017). The operational electrical energy use must be externally calculated and inputted, and is then multiplied by a local grid emission factor depending on the primary sources of energy and fossil fuel use within that region (Cormick, 2017). A shortcoming of Athena is that it does not disclose how results are developed in the back-end of the software, lacking transparency which could benefit the user's analysis (Schultz et al., 2016). LCA results can be viewed only by life-cycle stage or building component, but not for specific materials (Schultz et al. 2016). However, comparison amongst different models is possible (Schultz et al., 2016).

Tally is a United States-based software tool which is used directly with the Autodesk Revit BIM software to produce LCA results (Tally, 2021). The use of BIM is beneficial for changing materials or plans once the model is built, however it can make it difficult for the user to consider initial designs in the preliminary planning stage of a building. Tally utilizes a U.S. product database, called GaBi (*GaBi Software*, 2021), which produces generic impact information for common building materials (Tally, 2021). Although many products are available through this database, in a study by Cormick (2017), the carbon emissions from the product lifespan phase were 33% higher than the results produced by other LCA tools. This highlights the importance of specifying regionally specific data for materials. Tally has significant limitations as the end-of-life, construction and transportation stages assume U.S. methods. Mechanical or electrical equipment cannot be considered in the product analysis, and default values for each LCA category cannot be changed (Schultz et al., 2016). Maintenance and replacement impacts for individual products are estimated, including construction and transportation effects for replacement parts (Al-Ghamdi & Bilec, 2017). Operational electrical energy must be externally calculated and inputted, which is then multiplied by an emission factor based on average Canadian grid characteristics (Cormick, 2017). Tally has transparent back-end calculations, producing detailed results that allow for an in-depth analysis and identification of specific factors causing particularly high environmental impacts within the model (Cormick, 2017). However, it is difficult to compare design options or various models within Tally (Walker et al., 2019).

One Click LCA is a Finland-based software which relies on environmental product declarations (EPDs) to provide standardized information regarding the cradle-to-grave environmental impact of specific products (One Click LCA® software, 2021). The declarations provide a high level of accuracy regarding the impact of a product and make it possible for users to include all building components in their design, including mechanical and electrical systems (Cormick, 2017). If specific products are not available within their EPD database, they supplement data using generic material databases, such as EcoInvent (One

Click LCA® software, 2021). Since very few North American manufacturers submit EPDs for modelling in Canada, One Click's generic databases have to be heavily relied upon (Cormick, 2017). The building model can be built within the program by manually inputting materials or can be integrated with a BIM program (One Click LCA® software, 2021). The Carbon Designer tool within One Click can be used to create preliminary designs by inputting simple building characteristics like floor area, material type, etc. (Walker et al., 2019). The end-of-life stage for products being used is assumed to be the same lifespan as the building, except for interior finishes, exterior finishes, windows and doors, which are assumed to have a shorter lifespan (Walker et al., 2019). There is a lack of transparency involving the back-end calculations within this tool, as all environmental impact data is within externally-verified EPDs (Cormick, 2017). The operational electricity for the building must be calculated externally and inputted into the program and is then multiplied by an emission factor based on the province's grid profile and fossil fuel use (Cormick, 2017). The impact results produced by One Click can be viewed by life-cycle stage, building component or material (Walker et al., 2019). A variety of comparisons amongst models are possible for evaluation purposes (Cormick, 2017).

SimaPro is a leading LCA tool that has existed for 30 years (SimaPro, 2021). SimaPro uses several databases to provide in-depth environmental impact data of specific products, and so is an advanced tool built for knowledgeable users looking for complex analysis inputs and results (Al-Ghamdi & Bilec, 2017). Although SimaPro is used extensively in academia (SimaPro, 2021), it will not be considered for this project due to its focus on product LCAs, rather than whole building LCAs and extensive training requirements (Cormick, 2017).

8.1.3 LCA Tools Comparison

In-depth comparison studies of different tools have been performed by a number of groups. Cormick (2017) compared three LCA tools including the *Athena Impact Estimator* (*Athena Sustainable Materials Institute*, 2021)*, Tally* (Tally, 2021) and *One-Click LCA* (One Click LCA® software, 2021) by preforming whole building assessments with the purpose of analyzing each tool's benefits in terms of the Canadian construction industry. The findings identified the applicability of tools for different scenarios and found that the outputs from each program were significantly different despite having identical inputs. This highlights the importance of using relevant and accurate databases in each tool to evaluate a project's potential impact. In another study, Al-Ghamdi and Bilec (2017) compared *Athena Impact Estimator, Tally* and *SimaPro* (SimaPro, 2021) by assessing the life cycle impact of a new hospital that was being built in Pittsburgh. This comparison focused on which tool could be used most easily in different design stages and how easily the user could interpret the results in terms of impact categories, life-cycle stages and comparison to other models. In 2019, a UBC sustainability group performed a policy review to improve the implementation of LCA at the university, while providing framework for other groups looking to learn about LCA tools (Walker et al., 2019). The results of their comparison amongst *Athena Impact Estimator, Tally* and *One-Click LCA* indicate the reliability of data sources, the requirement for building information modelling (BIM) and the ability to use preloaded design options for preliminary LCAs (Walker et al., 2019). A summary of each tool's characteristics in terms of the project's priorities is shown in Table 24.

There are several priorities to be considered when choosing an LCA software which will be most beneficial to this project. These priorities include:

1. The tool should have an extensive database with inventory specific to NS, including the climate, regionally specific data regarding manufacturing practices, transportation and electricity grid characteristics will increase the accuracy of the building energy models' embodied emissions.
2. The tool should be able to compare various building models and subcategories within each model. This will allow for a comprehensive comparison of the impact from life-cycle stages and materials amongst the models, allowing in turn for design optimization within each model.
3. The tool should be relatively transparent in its back-end calculations, being capable of highlighting a specific area's impacts through derivation to highlight issues within a design.
4. A tool that collaborates with green-building certifications to assign points towards the certification within the LCA tool would be beneficial in verifying that each model's design qualifies for the desired certification and could be used to optimize each design.

Table 24: LCA Tool Capabilities

	Athena Impact Estimator for Buildings	**Tally**	**One Click LCA**
Database	Athena database, U.S. LCI database[a]	U.S. based GaBi database[d]	Verified EPDs[e]
Regional specificity	Canadian city[a]	Canada [d]	Canadian province[e]
Modelling Method	BOM within software, BIM integration or pre-assembled structures[a]	Must be integrated with BIM software Autodesk Revit [d]	BOM, BIM integration or pre-assembled structures [e]
Model comparison capability	Can compare general results from models[a]	Difficult to compare models [c]	Many comparisons amongst model results possible[b]
Calculation transparency	Poor[b,c]	Good [b]	Fair[b]
Components included in assessment	Structure, envelope [b]	No mechanical or electrical equipment included [c]	Any product with EPD[e]
Results	Building component, life-cycle stage impacts [b]	In-depth impact results with known sources [b,c]	Building component, life-cycle stage, specific material impacts[e]

[a:] (Athena Sustainable Materials Institute, 2021)
[b:] (Cormick, 2017)
[c:] (Al-Ghamdi & Bilec, 2017)
[d:] (Tally, 2021)
[e:] (One Click LCA® software, 2021)

8.1.4 LCA Tool Choice Summary

After comparing the three tools' abilities, it is evident that no one tool is optimal for this project. They all present advantages and disadvantages in certain categories. For example, Tally's main drawbacks involve the steep learning curve required to use the software and associated BIM program as well as its use of U.S. data, resulting in a lack of ability to provide relevant information for NS. The primary issue associated with Athena's software is its inability to account for mechanical equipment, electrical equipment, and other finishes, making it difficult to understand the true impact of upgrading a home to a certain level of energy efficiency. Incorporating these components is essential to comparing the effects and benefits of creating energy efficient homes. One Click's lack of recognition within North America is reason for concern regarding its ability to localize data.

Contrastingly, One Click's major advantage is its ability to incorporate all building components including mechanical equipment, electrical equipment and finishes using their EPD database. Although One Click relies on EPDs, which are not yet common in North America, its EcoInvent backup database is robust and claims to be able to provide data specific for Canada (Zizzo et al., 2017). One Click and Athena both provide tools within the program to manually input a BOM, reducing the time required to perform the LCA compared to the time required to learn a BIM program and allows for modifications to be made simply in the planning stages to optimize a design. Tally's main advantage involves its transparency in back-end calculations, providing the user with useful data for analytical purposes.

Ultimately, Athena is chosen for this project as it has the most regionally specific data for Nova Scotia and provides good comparative results amongst houses, thus providing the most relevant requirements for this project's analysis.

8.2 Athena Transparency

All information in this section comes from Athena's User Manual and Transparency Document – Impact Estimator for Buildings v.5 (Athena Sustainable Materials Institute, 2019).

When additional materials are added to a home with the intention of reducing operating energy, the environmental effects embodied within the additional material is often ignored. Performing LCAs through Athena allows for the consideration of the embodied environmental effects of the whole building, which include the resources use and emissions required to manufacture, transport, build, operate, replace and dispose of all building materials.

Athena Impact Estimator follows ISO14004:2006 (International Organization of Standardization, 2006), which provides guidelines and regulations for properly performing LCAs and reporting associated environmental impacts. The impact categories results reported by Athena are consistent with the U.S. Environmental Protection Agency (EPA) Tool for Reduction and Assessment of Chemicals and other Environmental Impacts (TRACI) methods – the most widely used LCA method in North America (US EPA, 2015). Athena Impact Estimator accounts only for building's structure, ignoring the impact of any mechanical/electrical systems, appliances, and finishes.

Athena provides public access to all of their publications on their website and are listed in Appendix A. There are over 80 publications regarding LCA topics, descriptions of the LCA process, background information regarding the software development, LCA reports for building materials used in the software and reports of Whole Building LCAs performed using Athena. Most notably, the LCA reports for materials used in Athena describe detailed methods of how the values used in the software are derived.

8.2.1 Athena Inputs

Athena's primary input is a complete bill of materials for the building. This can be done through modelling the home in Athena's modelling system or by importing an external bill of materials (BOM).

Other inputs required to perform the LCA include location, expected building life, area, height and building type.

Athena's modelling system quantity estimations of structural materials is performed using a built-in sizing-algorithm based on sizing curves and the user's input of widths, spans and live loads. Athena states that this algorithm has been proven to estimate with 10% margin of error. The bill of material can be manually adjusted by users if the produced BOM is not identical to that of the building. For the purpose of this project – the Athena algorithm is used and the 10% margin of error is accepted for structural material estimation.

Non-structural materials such as insulation, gypsum board and plywood, are calculated based on area of assembly for which it is a part of minus the area of windows and doors. Window area, window glazing (number of panes), and door area are based on user-input. The window hardware is estimated based on the type of window, ie. fixed, slider or hinged. The structural algorithm accounts for the insertion of windows and doors by subtracting the framing quantity in that area and accounting for the addition of studs and headers.

8.2.2 Regional Specificity

The Athena database considers the closest available materials, manufacturing methods for those products, energy mix in the region, transportation distances and transportation modes within the region – Halifax for this project. Rather than using specific manufacturer's data, Athena creates weighted average life cycle inventory and transportation profiles for each product.

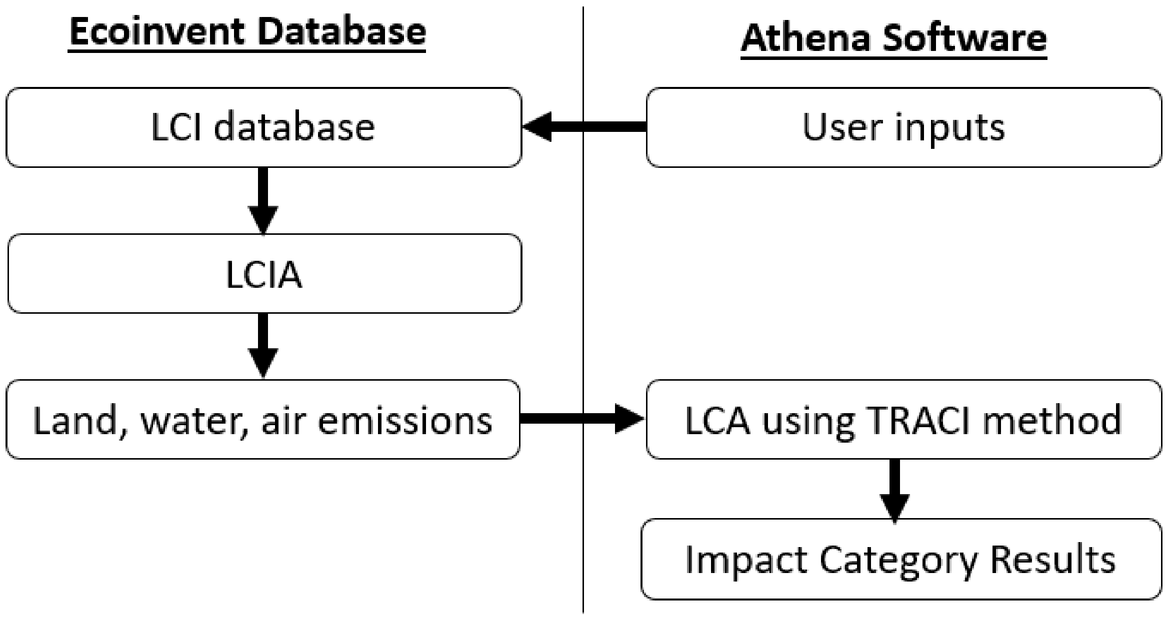
The electricity grid fuel mix is described for each Canadian province using data from Ecoinvent 3.4 (EcoInvent, 2022). The provinces' grid mix is used to calculate the associated environmental impacts of the operational energy use and energy used during construction and maintenance of the building. The energy-associated environmental impacts of manufacturing building materials are calculated using the energy mix of the province in which the material is manufactured. The energy mix used for Nova Scotia is shown in Appendix E.

8.2.3 LCI Database

Athena uses Ecoinvent as a life cycle inventory (LCI) database – one of the two global, leading LCI databases. The database consists of over 18,000 datasets that have been developed to quantify the land, air and water emissions associated with the products/processes in the datasets through a life cycle impact assessment (LCIA). The analysis for each dataset has been performed through supply-chain-tracking, market analysis, manufacturer surveying and academic studies specific to geographic location. If a specific dataset is not available for the specified location, a global average is used.

The methods used to obtain a complete LCA from Athena through the use of the Ecoinvent database is described in Figure 10.

Figure 10: Process Diagram Describing Athena's Interaction with Ecoinvent Database



8.2.4 Impact Categories

Athena Impact Estimator software calculates all life cycle assessment results for North American building materials and is regionally specific to Halifax, NS for the case of this project. The TRACI LCA method calculates quantitative impact category results in terms of local estimations of energy use, transportation, construction methods, replacement requirements, demolition and disposal practices using the LCIA data obtained from Ecoinvent. The LCIA data is characterized in terms of a common unit using a characterization factor. For example, kg of CO_2 is the common unit used to assess global warming potential (Bowick, 2011). Therefore, the characterization factor for the impact of CO_2 is 1. However, methane is 25 times more harmful to GWP and therefore has a characterization factor of 25 to convert it in terms of CO_2 equivalent (Bowick, 2011). Athena states a 15% margin of error for their LCA results. A summary of the sources for all building materials' environmental product declaration or

Athena LCA report are given in Table 3 of the Athena User Manual and Transparency document (Athena Sustainable Materials Institute, 2019).

The LCA impact categories results calculated in Athena using the TRACI method represent the environmental impact of the building. The impact categories are listed below. A detailed description of each impact category is in Appendix B.

- Total primary energy (kWh): All energy encompassed in the building's lifecycle
- Non-renewable Energy (kWh): All fossil fuel and nuclear energy used in the building's lifecycle
- Fossil fuel consumption (kWh): All fossil fuel consumption over the building's lifecycle
- Global warming potential (kg CO_2 eq): Measures the quantity of gases that cause a greenhouse gas effect created by the building throughout its lifecycle
- Acidification potential (kg SO_2 eq.): Measures the quantity of acid created in the air and rain created by the building throughout its lifecycle
- Eutrophication potential (kg N eq.): Measures the abundance of nitrogen created by the building throughout its lifecycle
- Human health (HH) particulate matter ($PM_{2.5}$): Measures the quantity of small airborne particles created by the building throughout its lifecycle
- Ozone depletion potential (kg CFC -11 eq.): Measures the quantity of chemicals released by the building throughout its lifecycle that lead to ozone layer depletion
- Smog potential (kg O_3 eq.): Measures the quantity of ozone-depleting chemicals that get trapped at ground level due to the building throughout its lifecycle

8.2.5 Life Cycle Stages

The analysis of the building's life cycle stages is performed according to EN 15804/15978 (European Standards, 2022) and includes all stages outlined in Table 25 excluding "B1 – installed product in use", "B3 – Repair", "B5 – Refurbishment", "B7 – Operational Water Use" and "C3 – Waste Processing". The "installed product in use phase" is accounted for by inputting the operational building energy. Athena does not account for B2, B3 or C3 stages due to their small magnitude compared to the other lifecycle stages, the lack of sufficient data and the individual case-by-case analysis requirements for proper quantifiability. A detailed description of each lifecycle stage is listed in Table 25.

Table 25: Athena Information Modules as According to EN15804 Regulations (Athena Sustainable Materials Institute, 2019)

Module	Details
A1: Raw Material Supply	Resources required for harvesting and mining materials
A2: Transport	Resources required to transport raw material to manufacturing plants
A3: Manufacturing	Resources used to convert raw materials to manufactured building materials
A4: Transport	Resources required to transport building materials from manufacturing plants to the building construction site
A5: Construction / Installation	Energy-use of construction equipment and construction waste
B2: Maintenance	Resources required to perform maintenance on the building during its life
B4: Replacement	Duplicate materials effects for A1-A5 for new material and C1,C2,C4 for old material
B6: Operational Energy Use	Resources used for energy extraction, production, delivery and use
C1: De-construction Demolition	Energy use of demolition equipment
C2: Transport	Resources required to transport demolished materials to nearest landfill
C4: Disposal	Energy use for disposal equipment and landfill site effects
D: Benefits and loads beyond the system boundary	Carbon sequestration and metals recycling

8.2.6 Construction Phase

The construction phase encompasses transporting manufactured materials to a distribution center and subsequently to the building site as well as all on-site construction activity including equipment use and waste. For example, the environmental impacts of machinery required to lift all envelope materials to the building height is considered. Each material has an associated waste factor based on typical construction methods in the region and considers the transportation required to transport wasted materials to the landfill. Athena does not consider site-preparation environmental impact due to the unique characteristics of each site.

8.2.7 Maintenance and Replacement Phase

The most significant factor effecting the maintenance and replacement phase of the LCA is the building's service life. Each product has its own maintenance schedule from the life cycle inventory database that determines whether it needs to be replaced within the building's service life. The Athena algorithm life cycle inventory assumes more aggressive maintenance and replacement schedules in owner-occupied homes as opposed to rental units. Material service life also varies depending on the building's climate. The total environmental impact of a replacement material is not applied if the building service life ends before the material service life. The materials that are considered for replacement in Athena's algorithm are the roof, cladding, windows and paint.

8.2.8 Operating Energy

Athena does not calculate operating energy. For the purpose of this project, the operating energy of each building is calculated using HOT 2000 and manually entered into Athena. Athena then uses the Ecoinvent 3.4 database to determine the environmental impacts of the operating energy based on the local energy mix.

8.2.9 End of Life Phase

The end-of-life phase considers all building materials to be either recycled, reused or landfilled. All materials except metals that can be recycled or reused in that region are considered to have no positive or negative effect on the impact category results, as they are no longer considered part of the building system. For all material that cannot be recycled or reused, Athena accounts the energy required to demolish the remaining building materials at the end of life, the energy required to transport the materials to the landfill and the energy required to process the mass of building material at the landfill.

The process of metal recycling is modelled within the system boundary of Athena's LCA. Steel recycling is based on the World Steel Organization's North America LCI database cradle-to-gate analysis for the end-of life phase (World Steel Organization, 2021). This means that a complete LCA for the metals were evaluated after the building was demolished. The assessment is performed using an "avoided burden" formula, as shown in equation 8.

$$LCI\ for\ 1kg\ metal\ with\ recycling = X - (RR - S) \times Y \times (Xpr - Xre) \qquad \text{Eq. 8}$$

where:

- LCI = cradle-to-gate value for any given LCI category
- X = cradle-to-gate LCI value of the metal product
- (RR – S) = net amount of scrap produced from the system
- RR = end-of-life recycling rate of the steel product

- S = scrap input to the steelmaking process
- Y = process yield of the electric arc furnace (EAF) (i.e. if >1 kg scrap is required to produce 1 kg steel).
- Xpr = LCI value for 100% primary metal production. This is a theoretical value of slab made in the basic oxygen furnace route, assuming 0% scrap input.
- Xre = LCI for 100% secondary metal production from scrap in the EAF, assuming 100% scrap input.

At the end of the recycled product's life, a credit (negative LCA value) is given by subtracting the LCI value of the scrap metal that was reused – which represents the avoided impact that would come from initially producing the metal. The LCI value for the scrap metal is calculated using the last two terms of equation 8, as shown in equation 9.

$$Scrap\ LCI = Y \times (Xpr - Xre) \qquad \text{Eq.9}$$

The difference in equation 9 represents the savings of primary metal production as a result of inputting recycled metal.

8.3 LCA Studies on Single Family Dwellings

As a reference for the results produced in this project, and to identify the required area of study, a literature review was performed to assess other LCA studies performed on single-family dwellings.

Bowick (2011) performed of life cycle assessments using Athena Impact Estimator on thousands of permutations of Canadian residential buildings with varying material choices, fuel types, locations and efficiency measures. Bowick (2011) found that in terms of location, the electricity grid mix of the province has the largest impact on resulting environmental impact. For example, in Quebec and Alberta, each kWh of electricity produces 4 and 870 grams of CO_2 eq. respectively.

The single-family dwelling studied is comparable to the dwelling modelled in this study – with 3 bedrooms, 2 bathrooms, a full basement, and a garage. Several archetypes of the single-family home were developed, however archetype S8/R8 in Bowick's study is most comparable to this study's home – at 170 m^2 of above-grade floor area. The home assumes cast-in-place concrete foundation walls and wood framing. The S8/R8 archetype modelled in Halifax was upgraded from consuming 163 to 40 kWh/m^2/year through increased energy efficiency measures.

Using a 60-year life cycle, the original and upgraded homes were compared. The results showed that for every tonne of embodied CO_2 eq. that was invested via upgrades, 11 tonnes of CO_2 eq. were saved through the reduction of operating energy consumption. The original home's embodied CO_2 eq. accounted for 11% of the total GWP whereas the upgraded home accounted for 44%. Bowick's analysis focused primarily on GWP and energy consumption. Life cycle stage results showed manufacturing accounts for approximately 60% of embodied GWP while space heating accounts for 45-64% of operating GWP. Of the ten major cities across Canada in which the detached home was modelled, the highest total emissions but lowest percent of embodied emissions occurred in Halifax, NS. This is indicative of the fact that the majority of emissions come from operating energy use and the electricity grid mix in NS produces higher emissions than most other provinces as it is primarily coal based. Heating oil is also a common space heating method in older NS homes, which has high emissions.

Dahlstrøm et al. (2012) performed life cycle assessments on two single family dwellings in Norway with 50-year lifespans. One building was modelled according to the Norwegian building code and the other according to the Norwegian passive house standard NS 3700. Similarly to the baseline home in this project, the home modelled to the building code by Dahlstrøm et al. (2012) has a wooden structure, electric resistance heating and electric water heating. The results of Dahlstrøm et al. (2012)'s LCA for the home built to code are shown in Table 26.

Table 26: Dahlstrøm et al. (2012) LCA Results per m2 of Home with a 50-year Lifespan

Impact Category	**Unit**	**Quantity**
Greenhouse Gas Emissions	kg CO_2 eq.	1657
Ozone Depletion	kg CFC-11 eq	2.37×10^{-4}
Particulate Matter	kg PM_{10} eq	2.77
Acidification Potential	kg SO_2 eq	5.84
Eutrophication Potential	kg N eq	1.47
Fossil Fuel Depletion	kWh	287
Energy Demand	GJ	58

Grygierek & Ferdyn-Grygierek (2022) compared the life cycle environmental impacts of a home built to code and Passivehouse standard in Poland. The standard wood-framed home uses electric resistance heating, assumes a 25-year lifespan. The results found that for both the standard and passive iterations of the home, the operational life cycle stage accounted for 80% of each environmental impact category studied. The operational energy of the Passivehouse is 75% lower than that of the equivalent standard house. The environmental impacts of the standard and Passivehouse shown in Table 27 have been doubled for a more comparable lifespan (50 years) to the lifespan of the homes in this project (60 years).

Table 27: Grygierek & Ferdyn-Grygierek (2022) Life Cycle Assessment Results per m^2 of Floor Area

Impact Category	**Unit**	**Standard House**	**Passivehouse**
Greenhouse Gas Emissions	kg CO_2 eq.	2,020	1,610
Ozone Depletion	kg CFC-11 eq	9.0 $x10^{-5}$	7.2 $x10^{-5}$
Acidification Potential	kg SO_2 eq	11.9	9.2
Eutrophication Potential	kg N eq	4.6	3.5
Primary Energy Demand	kWh	5,280	1,195

Zhang et al. (2014) performed a life cycle assessment using Athena Impact Estimator on a typical single family detached home in Vancouver, BC with a 50-year lifespan. Similar to the houses modelled in this study, the structure is wood framed with a concrete foundation and using electric heating. A cradle-to-grace LCA was performed, however only the embodied and operational energy values are published. The environmental impacts were only published as a proportion relative to other types of dwellings. The lifetime operational energy of the detached home modelled was 15,500 kWh/m^2 (311 kWh/m^2 x 50yrs), whilst the embodied energy accounted for 600 kWh/m^2. Within the embodied energy in terms of life cycle stages, the product stage accounted for 70% of the total embodied energy. Within assembly groups, the walls, foundation, floors, and roofs accounted for 30%, 44%, 12% and 13% of total embodied energy respectively.

9.0 LCA Modelling Methodology

All five homes are modelled with a life expectancy of 60 years and a location of Halifax, NS. Athena is the primary software used to develop whole-building life-cycle assessments and produce life cycle impact results for each home's structure including foundation, walls, windows/doors, floors and roof. The following assemblies and components are included in Athena's LCA modelling:

- Floors: Joists, plywood decking, insulation, ceiling drywall, paint
- Roof: Joists, plywood decking, waterproofing, asphalt shingles
- Foundation footings / garage floor: rebar, concrete, waterproofing
- Foundation walls: concrete, rebar, windows, waterproofing, studs, insulation, drywall, paint
- Exterior main and second floor walls: studs, plywood sheathing, insulation, vinyl siding, gypsum board, paint, doors, windows
- Interior main and second floor walls: studs, plywood sheathing, insulation, gypsum board, paint, doors

The specific materials inputted for the baseline home are based on the HOT 2000 energy modelling. A full Bill of Materials for the baseline home are given in Appendix F.

The Energy Star home primarily has the same structure as the baseline homes. The upgrades made to model the Energy Star home are summarized below and based on the upgrades made in the HOT 2000 energy modelling for the ES home:

- Foundation walls: Additional 25mm of spray foam insulation (51mm total)
- Garage floor: 15 MPa insulating concrete (more lightweight) with 1 inch of spray foam insulation specified
- Exterior doors: Upgraded to fibreglass polystyrene core
- Operational energy: 18,120 kWh/year

A full Bill of Materials for the ES home is given in Appendix F.

The Energy Star home obtains its certification primarily from reduced operational energy though appliances, ventilation system, decreased infiltration, and lower domestic hot water consumption. Therefore, the building materials do not change significantly from the baseline home. Therefore, it is expected that the LCA results in terms of embodied effects will change minimally from the baseline home.

The following are a list of limitations within Athena in terms of modelling the Energy Star Home:

- Windows: The Energy Star home's windows included heat mirrors, which could not be added as a specification for the windows in Athena
- Roof insulation: Unable to add foam layer to roof assembly
- Cellulose insulation in ceiling provides R3.8/in. 340mm (15") of R51 is modelled.
- Fibreglass batt insulation in walls provides R3.2/in. 150 mm (6") of R20 is modelled.

The upgrades made from the ES home to model the R-2000 home include:

- Floor above foundation: Added extra layer of 25 mm spray foam insulation (51mm total)
- First and second floor walls: Fibreglass batt insulation increased to R24 (190 mm) and a 25mm layer of spray foam insulation was added
- Exterior doors: Upgraded to steel
- Garage floor: Upgraded to 8" (200 mm) concrete block with XTPS IV insulation board (40mm)
- Foundation walls: XTPS IV insulation board (60mm) added (51mm of spray foam insulation removed in ES home removed. R12 fibreglass batt insulation remains)
- Operational energy: 14,250 kWh/year

A full Bill of Materials for the R-2000 home is given in Appendix F.
In addition to the limitations listed for the ES home, the R2000 home's two 20mm layers of XTPS IV insulation board under the garage floor had to be modelled as extruded polystyrene.
The modifications required to upgrade the R-2000 home to the NZR home are:

- Garage floor: 2 layers of XTPS IV insulation board (total 80mm)
- Roof: 52mm (2") of spray foam insulation added (76mm total)
- Main and Second Floor walls: 4.9 RSI (R28) fiberglass batt insulation and 76mm (3") spray foam insulation. Framing size increased to 2" x 10" to fit insulation thickness.
- Floor above foundation: 4.2 RSI (R24) fibre batt insulation and an 89 mm (3.5 inch) layer of medium density spray foam
- Operational energy: 8,270 kWh/year

A full Bill of Materials for the NZR home is given in Appendix F. The limitations and assumption made within Athena when modelling the NZR home are the same as for the R-2000 home.

The NZ home is identical to the NZR home for all components and modelled in Athena using the same methods. However, the additional life cycle impacts of PV modules and solar thermal collectors that cause the NZ home's total impact to differ from the NZR home are accounted for in the NZ LCA model. Neither the PV modules nor solar thermal collectors could be modelled in Athena. Therefore, data gathered from a literature review analyzing previous studies' findings regarding the life cycle environmental impacts of PV modules is used to estimate the impacts of PV on the NZ home. Since the materials required to construct the solar thermal collectors are more common, their environmental lifecycle impact is found using the OneClick LCA software. The results found using Athena for the NZR home are used in addition to the impacts for the PV modules and solar thermal collectors to develop a complete LCA model of the NZ home.

9.1 PV Module LCA

The very little operational energy used by PV systems is offset by generated electricity. Therefore, the embodied environmental impact of a PV system is significantly higher than the impact of the operational phase, unlike other energy sources like fossil fuels (Muteri et al., 2020). The most common and efficient type of material used in PV modules is silicon (Muteri et al., 2020). The modules modelled in this project's NZ home are made from mono-crystalline silicone cells. The life-cycle environmental effects of the PV modules and solar thermal collectors are the only difference in the LCA results between the NZR and NZ homes.

` The modelling of environmental impacts of PV modules in this project is based on an average of the data in the four studies listed in Table 28. There is insufficient data available for cradle-to-grave LCA of single-crystalline PV modules manufactured in China and installed in Canada. Performing a full LCA for the PV modules used for the NZ home is not within the scope of the project. Therefore, the studies described in this section will provide an estimate of the modules' life cycle. The differences in the parameters used amongst the four studies are highlighted in Table 28.

Table 28: Differences Among LCA Parameters for Four Studies

Parameter	**Fu et al. (2015)**	**Frischknecht et al. (2015)**	**Santoyo-Castelazo et al. (2021)**	**Stamford & Azapagic, (2018)**
Type of module	mc	sc	sc + mc	sc
System components modelled	Module	Module, inverter, mount	Module, inverter, mount	Module, inverter, mount
Manufacture location	China	Euro/U.S./China	United States	China
Installation location	China	Germany	Mexico	Spain, Germany
Life cycle stages*	Cradle-to-gate	Cradle-to-end of life	Cradle-to-grave	Cradle-to-end of life
Lifespan (years)	25	30	30	30

*Cradle-to-grave includes life cycle stages leading up to installation. Cradle-to-gate includes all life cycle stages other than end-of-life. Cradle-to-grave refers to all life cycle stages (including end-of-life)

The typical lifetime of a PV modules is 30 years (Bowick, 2011). Therefore, for this project, the PV modules will need to be replaced once in the building's 60-year lifespan. The most energy intensive life cycle stage of a crystalline-silicone PV cell is manufacturing – in particular, silicone purification process requires a significant amount of electricity (Muteri et al., 2020). The location where PV modules are manufactured have a large impact on their embodied environmental effects because the primary methods of manufacturing use electricity and is therefore reliant upon the local electricity grid mix. Currently, most PV modules are manufactured in countries with electricity grids that release high quantities of greenhouse gas emissions. In this project, Hanwha Q-cell PV modules are modelled – which are manufactured in South Korea, Malaysia and China (Q CELLS, 2022).

Most LCA studies for PV modules lack sufficient data to model end-of-life stages including decommissioning, transportation, waste management, recycling and reuse (Fu et al., 2015; Santoyo-Castelazo et al., 2021). These methods vary significantly from region to region and since most PV systems installed are still in use today, there is a lack of data regarding typical end-of-life practices.

Muteri et al. (2020) reviewed 39 PV LCA studies, comparing the primary energy use and environmental impacts amongst PV modules of varying materials, manufacturing locations and efficiencies. The investigation of single-crystalline silicon modules found that the manufacturing stage accounts for over 40% of the energy use, acidification potential and eutrophication potential of the PV module. The environmental impacts were found to be highest if produced in countries with electricity grids that use coal as their primary source of electricity.

Fu et al. (2015) used the TRACI LCA method to study the life cycle impacts of a multi-crystalline PV system made in China. Since China's electricity grid is primarily supplied by coal power plants – Fu et al. (2015) was interested in studying the cradle-to-gate (mining materials to end of manufacturing stage) of modules with a 25-year lifespan to analyze the impacts caused by the high electricity use required for manufacturing. The environmental impact categories studied include acidification potential, eutrophication potential, global warming potential (GWP), ozone depletion potential and smog potential. The results of the cradle-to-gate LCA per kWh of solar module manufactured in Bejing, China is presented in Table 29.

Frischknecht et al. (2015) studied the life cycle environmental impacts of PV systems manufactured in Europe, China and the United States that are mounted in Germany. The study analyzed flat-glass single-crystalline silicone PV modules with 16.5% efficiency and a 30-year lifespan including all life cycle stages other than end-of-life (cradle-to-end of life). The results based on an average of the grid mixes across the three manufacturing locations studied are shown in Table 29. Similar to other studies, Frischknecht et al. (2015) found the most significant contributor to all environmental impacts was the manufacturing stage.

Santoyo-Castelazo et al. (2021) performed a comparative LCA for three different PV technologies, including single-crystalline silicone modules, their inverters and mounting systems. Of the literature reviewed by Santoyo-Castelazo et al. (2021) it was found that GWP potential of PV modules have a mean GWP potential of 46 g CO2eq/kWh. Santoyo-Castelazo et al. (2021) modelled a 3 kWp PV system on a 20-degree inclined southern-facing roof in Mexico which generated about 2600 kWh_e annually. The results showed that the life cycles stages that contributed the most to each environmental impact included manufacturing, installation, and end of life (in order from greatest impact to least). The manufacturing of the modules accounted for 64% of environmental impacts associated with manufacturing stage, whilst the fabrication of inverters and mounting system accounted for 27% and 9%, respectively. The results based on an average of the multi and single crystalline silicon are summarized in Table 29.

Stamford & Azapagic (2018) compared the environmental impacts of manufacturing single-crystalline silicone PV modules, inverters and mounting systems in Germany and China, as the market is shifting such that China is manufacturing most PV modules. The analysis considers two installation locations, the UK and Spain. The LCA considers life cycle stages up to operation and maintenance (cradle-to- end of life), excluding end of life stage due to lack of data. The average environmental impacts of the UK and Spain installations for the modules manufactured in China are summarized in Table 29.

The data from each study is averaged for applicable environmental impact categories. The averaged data used for this project is shown in Table 29. Eutrophication values presented in units of kg $PO4_3$ eq./ kWh of generation (gen) have been converted to kg N eq./ kWh of generation using a conversion factor of 2.096 and values presented in kg phosphate eq./ kWh of generation have been converted to kg N eq./kWh of generation using a conversion factor of 8.351 based on characterization factor ratio of the units (Dong et al., 2021).

Table 29: Approximation of Life Cycle Environmental Impacts of Single-Crystalline PV Modules

Environmental Impact	Unit	Study				Average
		Fu et al. (2015)	**Frischknecht et al. (2015)**	**Santoyo-Castelazo et al. (2021)**	**Stamford & Azapagic (2018)**	
Energy Demand	kWh / kWh gen	0.14	0.27	N/A	N/A	0.207
Acidification Potential	kg SO_2 eq./ kWh gen	4.27E-04	5.40E-04	5.01E-04	3.54E-04	4.55E-04
Eutrophication Potential	kg N eq. / kWh gen	8.87E-05	N/A	1.70E-03	2.91E-04	6.92E-04
Global Warming Potential	kg CO2 eq./ kWh gen	0.051	0.080	0.058	0.047	5.90E-02
Ozone Depletion Potential	kg CFC-11 eq./ kWh gen	3.02E-09	N/A	7.04E-09	2.60E-09	4.22E-09
Particulate Matter	kg $PM_{2.5}$ eq./ kWh gen	N/A	1.80E-04	N/A	N/A	1.80E-04

The NZ home in this project produces 7,500 kWh of electricity per year. Therefore, to obtain an estimate of the PV modules' environmental impacts over the 60-year lifespan of the building, considering a PV module lifespan of 30 years, the results from Table 29 are multiplied by 7,500 kWh of generated electricity and doubled for two lifespans of PV modules. The lifecycle environmental impacts of the PV modules over the 60-year lifespan of the NZ home are presented in Table 30.

Table 30: PV Module Environmental Impacts for NZ Home

Environmental Impact	Unit	PV modules' impact	% of total impacts
Total Primary Energy Demand	kWh/kWh gen	3,105	0.14
Fossil Fuel Consumption	kWh/kWh gen	N/A	N/A
Non-Renewable Energy	kWh /kWh gen	N/A	N/A
Acidification Potential	kg SO2 eq. / kWh gen	6.8	0.18
Eutrophication Potential	kg N eq. / kWh gen	10.4	3.25
Global Warming Potential	kg CO2 eq. / kWh gen	885	0.16
Ozone Depletion Potential	kg CFC-11 eq. / kWh gen	0	0
Particulate Matter	kg PM2.5 eq. / kWh gen	2.7	0.62
Smog Potential	kg O3 eq / kWh gen	N/A	N/A

9.2 OneClick Inputs and Results

The solar thermal collectors for the project are modelled using OneClick LCA as Athena does not allow for all materials to be input. The main components of the Thermo Dynamics Ltd. G-32 series solar thermal collectors are:

- Low-iron tempered glass
- Aluminum frame
- Aluminum backing sheet
- Aluminum solar fins bonded to copper tubes
- Copper header
- Fibreglass insulation

The volume of copper, aluminum, glass, and insulation are estimated using dimensions given in the specification sheet for the 6m^2 of G-32 series solar collectors. The final volumes used to model the collectors in OneClick are shown in Table 31.

Table 31: Solar Thermal Collector Quantity Estimation

Material	Quantity Estimate
Copper tubing (m^3)	0.0010
Aluminum (m^3)	0.0114
Glass (m^3)	0.0089
Fibreglass insulation (m^3)	0.1491

The life cycle environmental impacts are found by inputting on the quantities from Table 31 into OneClick LCA and doubling the resulting impacts as the lifecycle of the solar thermal collectors are 30 years, while the lifecycle of the building is 60 years. The total life cycle environmental impacts of the solar thermal collectors are shown in Table 32.

Table 32: Life Cycle Impacts of Solar Thermal Collectors

Environmental Impact	Unit	PV modules impact	% of total impacts
Total Primary Energy Demand	kWh	3,440	0.16%
Fossil Fuel Consumption	kWh	2,742	0.14%
Non-Renewable Energy	kWh	N/A	N/A
Acidification Potential	kg SO2 eq.	1.52	0.040%
Eutrophication Potential	kg N eq.	0.163	0.051%
Global Warming Potential	kg CO2 eq.	287.3	0.052%
Ozone Depletion Potential	kg CFC-11 eq.	0.0000132	0.037%
Particulate Matter	kg PM2.5 eq.	N/A	N/A

10.0 Life Cycle Assessment Results

The results from each home's LCA provide detailed analysis of the life cycle environmental impacts incurred due to all life cycle stages of the home. Additionally, the results of each home's environmental effects are compared according to life cycle stage and assembly group. By comparing the resulting environmental effects of each home, the lifecycle environmental performance of operationally efficient homes can be analyzed.

The life cycle stages presented in the LCA results represent all environmental contributions from manufacturing to beyond building life as follows (Athena Impact Estimator, 2022):

- Product: Raw material supply, manufacturing, transportation
- Construction: Installation, transportation
- Use: Replacement manufacturing, replacement transport, operational energy use
- End of Life: Demolition, transport to landfill, disposal
- Beyond Building Life: Recycling credits for steel products and carbon sequestration

10.1 Baseline Home

10.1.1 Baseline Home Life Cycle Stage Results

The baseline home's results processed in Athena according to life cycle stage are shown in Table 33 in terms of above grade living area. The results are normalized to square meter of above grade living area (176 m^2) for comparison purposes to other studies.

Table 33: Baseline Home LCA Results by Life-Cycle Stage

LCA Measures	Unit	Product	Construction	Use (including operational)	End of Life	Beyond Building Life	Total
Global Warming Potential	kg CO2 eq	165	34	9,975	13	-53	10,134
Acidification Potential	kg SO2 eq	0.9	0.4	67.3	0.2	0.0	69
HH Particulate	kg PM2.5 eq	0.2	0.0	7.0	0.0	0.0	7
Eutrophication Potential	kg N eq	0.1	0.0	5.5	0.0	0.0	6
Ozone Depletion Potential	kg CFC-11 eq	4.5E-06	6.2E-07	6.6E-04	5.4E-10	-1.4E-11	6.7E-04
Smog Potential	kg O3 eq	13	10	512	5	0	541
Total Primary Energy	kWh	700	131	37,770	53	10.8	38,662
Non-Renewable Energy	kWh	633	126	35,206	53	11	36,030
Fossil Fuel Consumption	kWh	562	124	34,760	53	23	35,525

The results from Table 33 are used as reference for the environmental effects of the ESNH, R-2000 home, NZR home and NZ home. Bowick (2011) LCA results for a similar home in Halifax show that the 60-year lifespan home consumes approximately 35830 kWh/m^2 of total primary energy. The lifetime energy use is comparable to the energy use per floor area of the baseline home in this project, which uses 8% more energy than Bowick's model. Similarly, the global warming potential for Bowick's model was found to be 8,400 kg CO_2, which is 20% lower than the GWP produced by the baseline home. All other environmental impact category results from Bowick's study are within 20% of the results for this baseline home, justifying the resulting quantities of the baseline home's LCA.

Alternatively, Zhang et al. (2014) performed an LCA on a comparable home that was modelled in Vancouver and consumes a lifetime primary energy use of 16,110 kWh/m^2, which is 59% lower than the energy use of the baseline home in this project. However, due to the use of some energy efficiency measures, a warmer climate in Vancouver, and a shorter lifespan, this difference in results is justifiable.

When comparing the baseline home's results to the LCAs of homes modelled in other countries, including Dahlstrøm et al. (2012) modelled in Norway and Grygierek & Ferdyn-Grygierek (2022) modelled in Poland, the results vary further. For example, the primary energy use of Dahlstrøm et al. (2012) home is 19,330 kWh/m^2, but is built according to the Norwegian Building code, which has higher efficiency standards than most (Dahlstrøm et al., 2012). In terms of global warming potential, for every kWh of primary energy use, 0.008 kg of CO_2 is emitted, unlike the baseline home which emits 0.02 kg CO_2 for every kWh of energy used. This is representative of the electricity grid in Norway using 90% hydro power for their electricity grid while Nova Scotia uses 52% coal (Statistics Norway, 2022).
For context and comparison within the baseline home's results,
Table 34 shows the proportion that each life cycle stage has on a given environmental impact's total lifecycle effects.

Table 34: Life Cycle Stage Results in Terms of Contribution to Total Effects of the Baseline Home

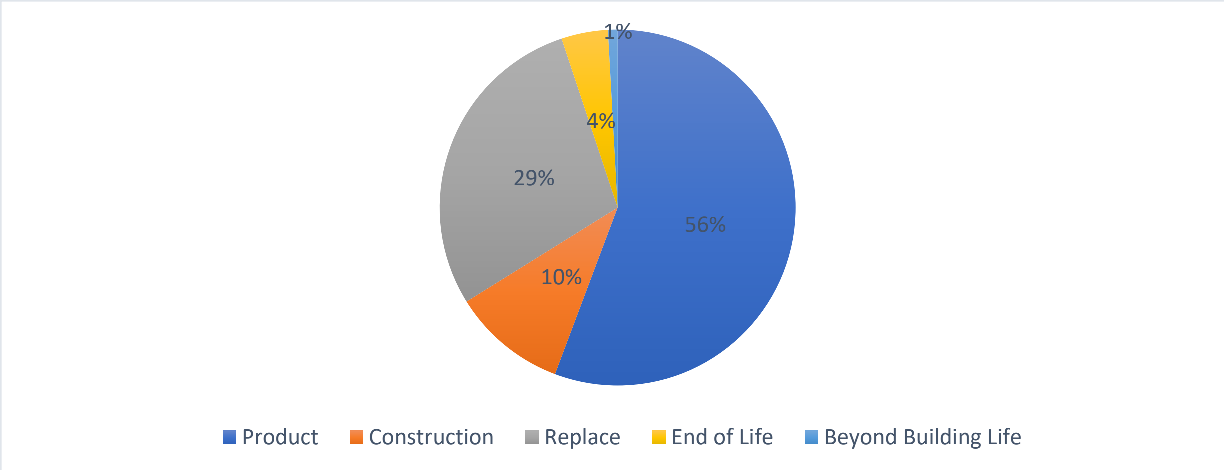
LCA Measures	**Unit**	**Product**	**Construction**	**Use (including operational)**	**End of Life**	**Beyond Building Life**
Global Warming Potential	%	1.6	0.3	98.4	0.1	-0.5
Acidification Potential	%	1.3	0.5	97.9	0.2	0.0
HH Particulate	%	3.4	0.3	96.1	0.1	0.1
Eutrophication Potential	%	1.5	0.4	97.9	0.2	0.0
Ozone Depletion Potential	%	0.7	0.1	99.2	0.0	0.0
Smog Potential	%	2.4	1.8	94.8	1.0	0.0
Total Primary Energy	%	1.8	0.3	97.7	0.1	0.0
Non-Renewable Energy	%	1.8	0.3	97.7	0.1	0.0
Fossil Fuel Consumption	%	1.6	0.3	97.9	0.1	0.1

The results in
Table 34 show that the environmental impacts of the Use phase, which represent the operational energy and material replacement effects, dominate the home's total lifecycle impacts. For all environmental impacts, the use phase constitutes between 94% and 99% of the total lifecycle impact.

The operational energy associated with the baseline home accounts for the majority of the impacts incurred because of the sixty-year lifespan of the building. The product phase is the second largest contributor to each environmental impact, but only accounts for 0.7-3.4% of the total impact amongst all impact categories. Although the resources required to source raw materials, manufacture and transport a product are high, they are small compared to the repeated annual resource consumption in the use phase. The construction and end of life phases have very low environmental impacts in terms of the total life cycle impacts, accounting for less than 1% in all impact categories other than smog potential. Smog potential accounts for 1.8% and 1.0% of the Construction and End of Life phases respectively, due to the exhaust from machinery and transportation vehicles required for these phases. The Beyond Building Life stage uses recycling methods to reuse some materials in the home, which results in a negative 0.5% of the total life cycle CO_2 emissions. This value is negative because it eliminates the CO_2 emissions that would have been produced had a new product been built rather than using the recycled baseline home materials.

The embodied environmental impacts consider all phases excluding operational. Within the embodied effects, the product stage, which includes manufacturing and transportation, accounts the largest proportion of impact category. In terms of global warming potential, the product category accounts for 83% of the impact, construction 17% and replacement 19%. However, 26% of the global warming potential is eliminated in the beyond building life stage as materials are recycled. The impacts associated with replacement also account for a substantial proportion of each impact category, as many products must be remanufactured and transported to the home. The replacement stage accounts for between 8% and 38% of the total life cycle impacts for all categories, the highest proportion occurring with HH particulate and the lowest with eutrophication potential. In contrast, the construction stage accounts for only 4% of HH particulate but 19% of eutrophication. The construction stage's highest environmental impact occurs in smog potential at 32%, due to the equipment and transportation required to perform construction. The construction stage contributes to approximately one fifth of the total global warming potential, acidification potential and eutrophication potential. The beyond building life stage contributes the lowest proportion to each impact category, with all categories being under 2%. In terms of embodied primary energy consumption, which is closely aligned with fossil fuel consumption, 56% of the energy is used within the product stage and 30% in the replacement stage, meaning the majority of embodied energy comes from manufacturing products. Figure 11 breaks down the total embodied primary energy use in the baseline home.

Figure 11: Embodied Primary Energy Use of Baseline Home



10.1.2 Baseline Home Assembly Group Impact Results

The life cycle assessment results are broken down into assembly groups to analyze which assemblies and materials contribute most significantly to the environmental impact categories. Table 35 shows the LCA results per square meter of floor area for each impact category according to assembly group.

Table 35: Baseline home LCA Results by Assembly Group per Square Meter of Floor Area

LCA Measures	Unit	Foundations	Walls	Roof	Floors
Global Warming Potential	kg CO2 eq	94	88	13	3
Acidification Potential	kg SO2 eq	0.5	0.9	0.2	0.2
HH Particulate	kg PM2.5 eq	0.1	0.2	0.1	0.1
Eutrophication Potential	kg N eq	0.0	0.1	0.0	0.0
Ozone Depletion Potential	kg CFC-11 eq	0.0	0.0	0.0	0.0
Smog Potential	kg O3 eq	9.1	14.6	1.9	5.6
Total Primary Energy	kWh	273	486	357	141
Non-Renewable Energy	kWh	260	449	352	121
Fossil Fuel Consumption	kWh	224	429	349	117

The total assembly group results are much lower than the life cycle stage results as operational energy is not included. Figure 12 shows the effects of each assembly group in terms of total impact for each impact category.

Figure 12: Baseline Home LCA Results by Assembly Group

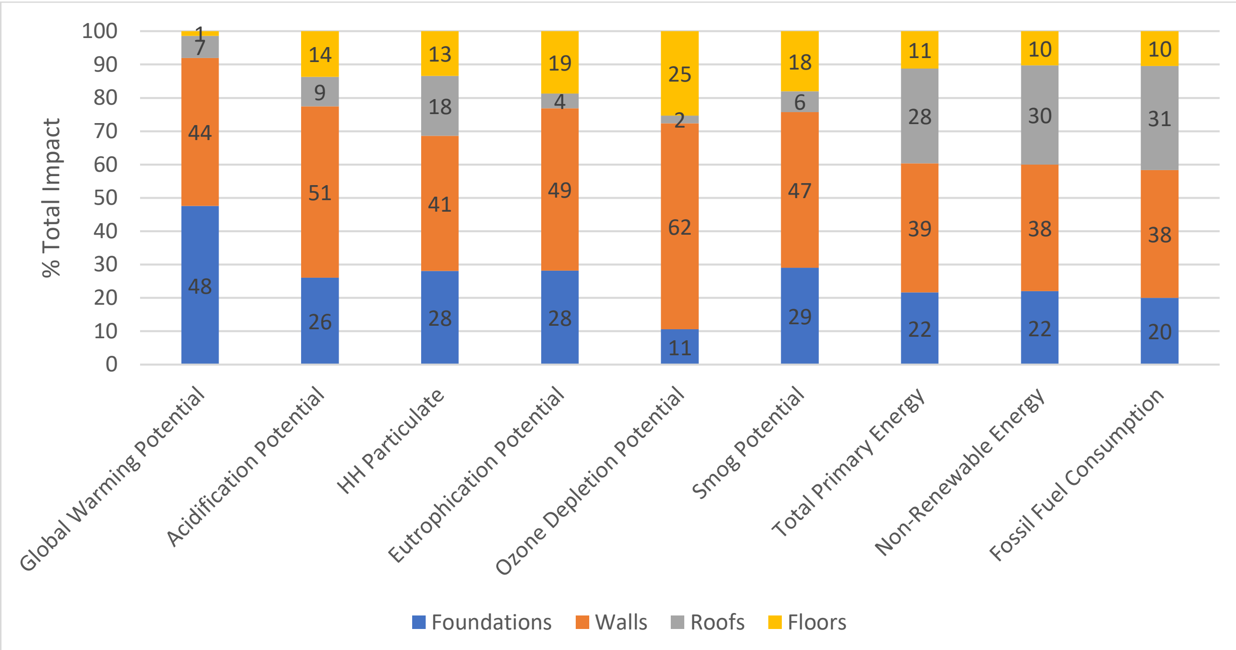


Figure 12 shows that the walls and foundation contribute most significantly to each impact category, except for global warming potential. The foundation contributes to 47% of global warming potential and walls contribute to 44%. This is due to the high embodied carbon associated with concrete. The walls, foundation and roof contribute to 90% of primary energy use and fossil fuel consumption. The floors contribute to only 1% of global warming potential for the home but contribute to one quarter of the total ozone depletion potential, due to chemicals released in the manufacturing process. The walls contribute 48% of the eutrophication potential, likely because of application of fertilizers with high nitrate content being applied to the trees as they are grown for the wall's lumber.

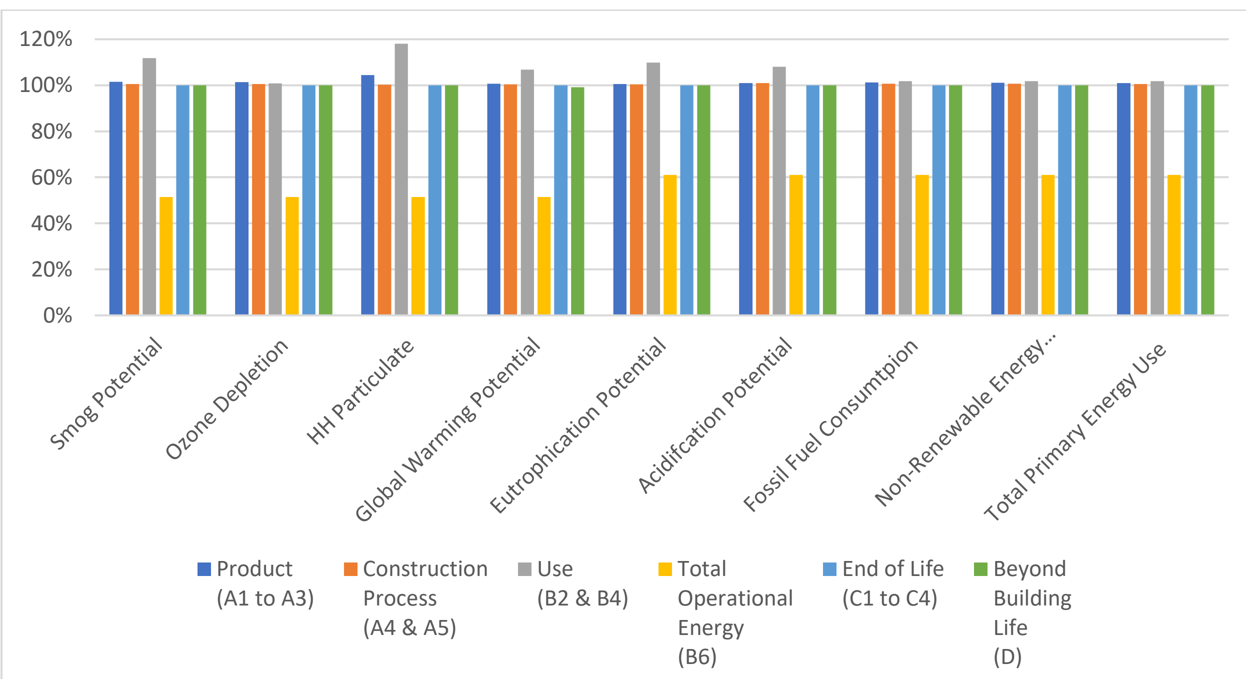
Some individual materials including insulation, windows, wood, siding and paint are analyzed to observe their contribution to the total embodied environmental effects. Concrete contributed most significantly to all environmental impact categories, other than ozone depletion potential. Most notably, concrete accounted for 96% of the embodied global warming potential for the building, but only 1.5% of the total global warming potential for the building, which includes operational impacts. Concrete accounts for between 47% and 63% of other embodied impacts other than ozone depletion, for which it only accounts for 21%. The most significant contributor to embodied ozone depletion are windows, which account for 52% of the embodied ozone depletion potential. However, windows are replaced once within the lifetime of the building, therefore doubling the impacts associated with manufacturing and transportation. Insulation accounts for another 10% of embodied ozone depletion, but less than 5% of all other impact categories. Wood is the primary material that is recycled and decreases embodied global warming potential by 12%. However, it contributes to 22% of embodied smog potential and 17% of acidification potential. Otherwise, wood contributes to less than 11% of all impact categories. Similarly, siding and paint account for less than 14% and 6% of all impact categories respectively.

10.2 Energy Star Home

10.2.1 Energy Star Home Life Cycle Stage Impact Results

The Energy Star home's results per life cycle stage as a percentage of the baseline home results from Table 33 are presented in Figure 13. The use stage of the ES results shown in Figure 13 only includes stages B2 and B4 (maintenance and replacement). Operational energy use is analyzed as a separate category.

Figure 13: ES Home LCA Results by Lifecycle Stage as a Percentage of Baseline Home Results in Table 36



The lifecycle stage results for the ES home vary minimally from those of baseline home in all life cycle stages apart from operational energy use, as shown by Figure 13. The product, construction, end of life and beyond building life categories varied less than 4% in every category from the corresponding baseline home. These negligible differences are a result of space heating improvements through additional insulation, heat pump installation and home orientation being the significant contributions to Energy Star Certification. Since Athena LCA focuses primarily on house structure and envelope, the space heating system, ie. heat pump was not evaluated. Therefore, the improvements made to the ES home are most evident in the reduction of operational energy use effects. Since the electricity grid for the ES home and baseline home are the same, all operational energy environmental effects all decrease by the same amount according to the decrease in operational energy, which is 39% compared to the baseline home. Due to the increase in insulation and heat-mirrored windows, the environmental effects of the use phase, which includes replacement and maintenance increased between 2% and 18% of the baseline home results.

Table 36 provides a comparison of the contribution of each life cycle stage to the total environmental impacts of the ES home.

Table 36: Life Cycle Stage Results in Terms of Contribution to Total Effects of the ES Home

LCA Measures	**Unit**	**Product**	**Construction**	**Use (including operational)**	**End of Life**	**Beyond Building Life**
Global Warming Potential	%	2.6	0.5	97.4	0.2	-0.8
Acidification Potential	%	2.2	0.8	96.6	0.4	0.0
HH Particulate	%	5.5	0.4	93.7	0.1	0.2
Eutrophication Potential	%	2.4	0.7	96.6	0.3	0.0
Ozone Depletion Potential	%	1.1	0.2	98.7	0.0	0.0
Smog Potential	%	3.8	2.9	91.7	1.6	0.1
Total Primary Energy	%	2.9	0.5	96.3	0.2	0.0
Non-Renewable Energy	%	2.8	0.6	96.3	0.2	0.0
Fossil Fuel Consumption	%	2.6	0.6	96.5	0.2	0.1

Table 36 shows that the use phase, which includes operational energy, accounts for over 91% of each environmental impact category. However, the use phase's environmental impacts account for 1-3% less than each of the baseline home's impact categories. This is representative of the embodied impacts between the baseline home and ES home being very similar (within 2% difference in each category), but the operational energy decreasing.

10.2.2 Energy Star Home Assembly Group Impact Results

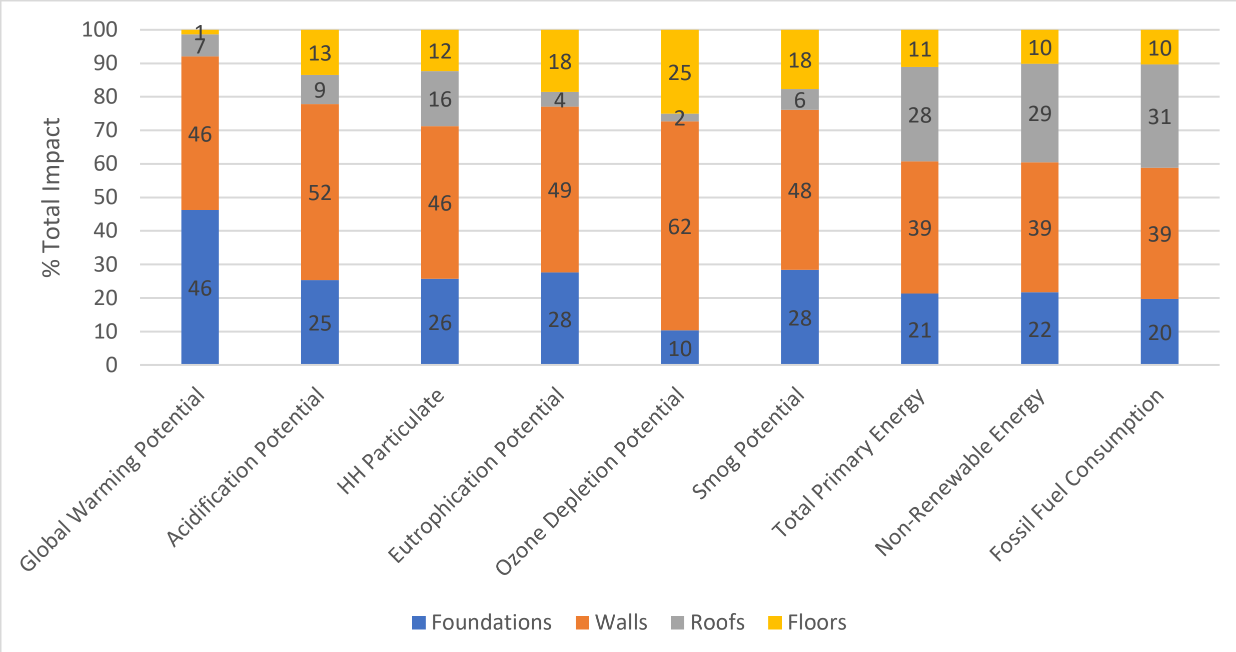
Table 37 shows the LCA results for each impact category according to the assembly group as a percentage of the baseline home's corresponding results from Table 33.

Table 37: ES Home LCA Results by Assembly Group as a Percentage of Baseline Home Results

LCA Measures	**Unit**	**Foundations**	**Walls**	**Roof**	**Floors**	**Total**
Global Warming Potential	kg CO2 eq	99%	106%	101%	100%	**102%**
Acidification Potential	kg SO2 eq	100%	104%	101%	100%	**102%**
HH Particulate	kg PM2.5 eq	100%	123%	100%	100%	**109%**
Eutrophication Potential	kg N eq	99%	103%	101%	100%	**101%**
Ozone Depletion Potential	kg CFC-11 eq	99%	102%	101%	100%	**101%**
Smog Potential	kg O3 eq	100%	104%	102%	100%	**102%**
Total Primary Energy	kWh	100%	103%	100%	100%	**101%**
Non-Renewable Energy	kWh	100%	103%	100%	100%	**101%**
Fossil Fuel Consumption	kWh	100%	104%	100%	100%	**101%**

Based on Table 37's results, the assembly group results from the ES home as compared to the baseline home's assembly group results vary minorly. The only assembly group that saw notably higher environmental effects are the walls. However, all walls in the baseline and ES home are identical, other than the windows and doors. In particular, the doors in the ES home are modelled as fiberglass core to increase thermal resistance, but in contrast increases the wall's HH particulate matter impact by 23% compared to the baseline home. Figure 14 shows the effects of each assembly group in terms of total impact for each impact category.

Figure 14: ES Home LCA Results by Assembly Group



The results shown in Figure 14 show the contribution of each assembly group towards the total environmental impact category. Due to the increased impact of the walls in most categories, the contribution of the walls towards the total impact in each category has increased, while the foundation's proportion has decreased in each category. The impacts of the roof and floors have changed minorly compared to the baseline home.

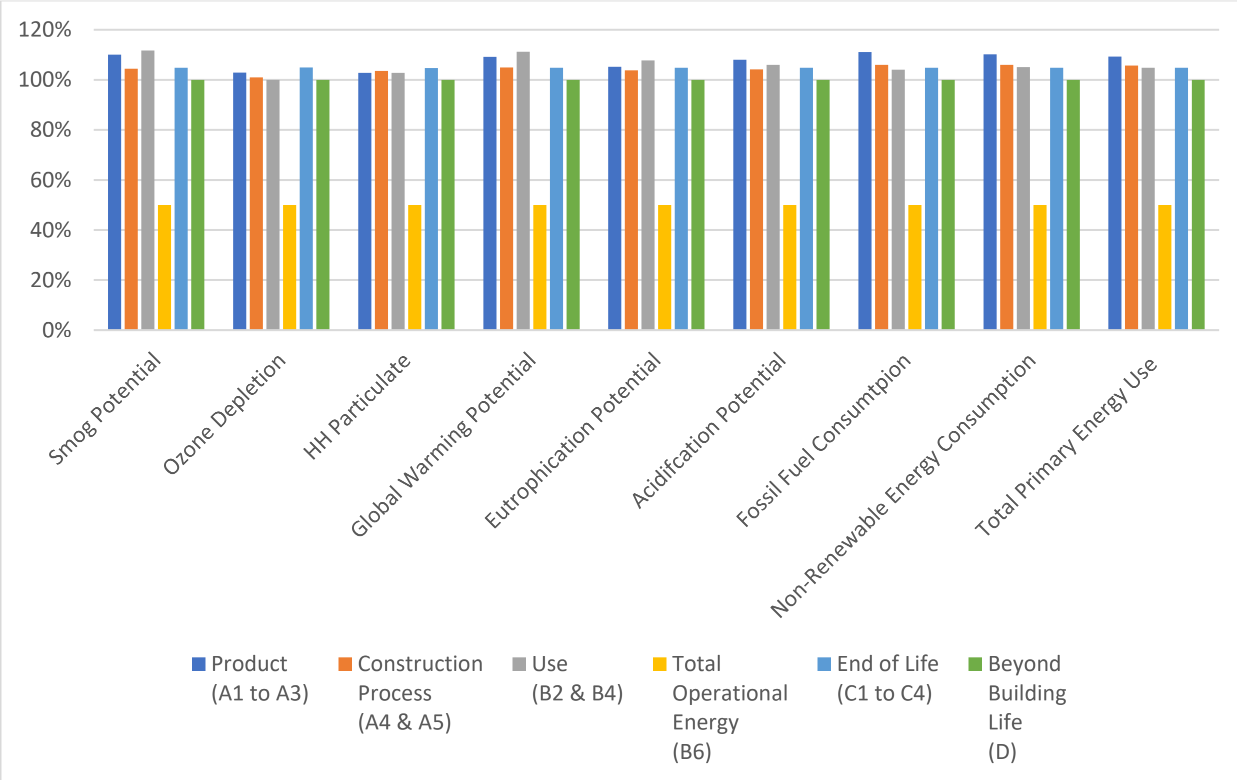
Similarly to the baseline home, concrete accounts for 95% of the embodied global warming potential for the building, but increased by 1.1% to 2.4% of the total global warming potential for the building, due the lower operating impacts. Concrete accounts for between 47% and 63% of other embodied impacts other than ozone depletion, for which it only accounts for 21%. These results are the same as the baseline home. The notable difference in embodied effects comes from the impact of the insulation, as additional polystyrene foam insulation was added to the ES home, increasing all embodied environmental impacts due to insulation by an average of 6% (range of 1-11%).

10.3 R-2000 Home LCA Results

10.3.1 R-2000 Home Life Cycle Stage Impact Results

The R-2000 home's results per life cycle stage as a percentage of the baseline home results from Table 33 are presented in Figure 15.

Figure 15: R-2000 Home LCA Results by Lifecycle Stage as a Percentage of Baseline Home Results in Table 36



The total operational phase of the R-2000 home accounts for 50% of each environmental impact category compared to baseline home. This is a result of the operational energy being 50% of the baseline home's energy and both homes being modelled with the NS electricity grid. Due to the decrease in operational energy, the embodied environmental effects become a larger proportion of the total environmental effects of the R-2000 home. Whereas the ES home's impacts in all categories other than use and operation only increased by less than 5% compared to the baseline home, the R-2000 home's impacts vary more significantly due a difference in material usage and lower total environmental effects. For example, the average environmental impacts of the product stage and use phase (replacement/maintenance) are 8% and 6% higher than the baseline home's impacts respectively due to the increased material required. The construction stage only increases its environmental effects by an average of 4% more than the baseline, while the beyond building life stage's differences in effects were negligible compared to the baseline. The major difference in LCA modelling for the R-2000 home includes the change in operational energy, increase in insulation quantity and increase in concrete quantity. For perspective, Table 38 shows the contribution of each life cycle stage towards the R-2000 home's total impact category results.

Table 38: R-2000 Home's Life Cycle Stage Results in Terms of Total Lifespan Effect on a Given Impact Category

LCA Measures	Unit	Product	Construction	Use	End of Life	Beyond Building Life
Global Warming Potential	%	3.5	0.7	96.7	0.3	-1.1
Acidification Potential	%	2.8	1.0	95.7	0.5	0.0
HH Particulate	%	6.5	0.5	92.7	0.2	0.1
Eutrophication Potential	%	3.0	0.9	95.7	0.4	0.0
Ozone Depletion Potential	%	1.4	0.2	98.4	0.0	0.0
Smog Potential	%	4.9	3.6	89.6	1.9	0.0
Total Primary Energy	%	3.8	0.7	95.2	0.3	0.0
Non-Renewable Energy	%	3.7	0.7	95.3	0.3	0.0
Fossil Fuel Consumption	%	3.4	0.7	95.6	0.3	0.1

The use phase, which includes operational energy, accounts for the majority of each impact category. However, the use category's impacts are 1-5% lower than then equivalent baseline home's contributions. The product category's impacts are 2% higher on average than those of the baseline home's, due to the additional material usage required to each lower operational energy efficiency. The remaining categories account for the smallest proportion of impacts and their proportions to the total impacts have changed minimally compared to the baseline home.

10.3.2 R-2000 Home Assembly Group Impact Results

Table 39 shows the LCA results for each impact category according to the assembly group as a percentage of the baseline home's corresponding results from Table 33.

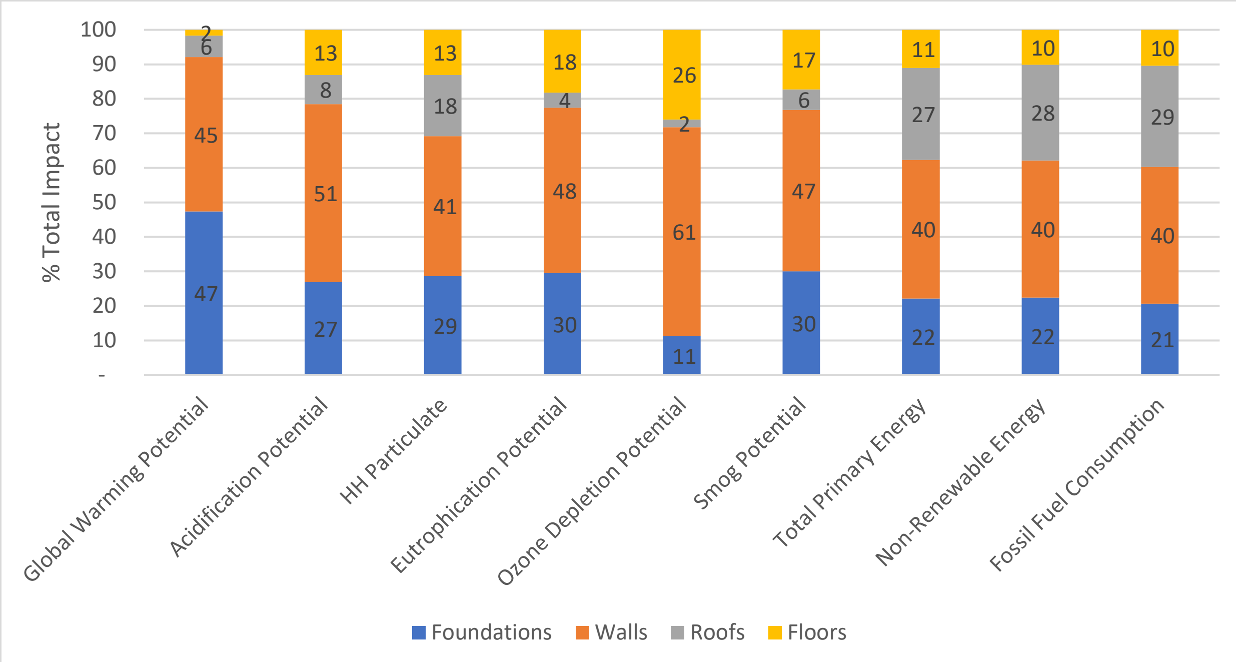
Table 39: R-2000 Home LCA Results by Assembly Group as a Percentage of Baseline Home Results

Effect	Unit	Foundation	Walls	Floors	Roof
Smog Potential	kg O3 eq	111%	107%	103%	102%
Ozone Depletion	kg CFC-11 eq	108%	100%	105%	101%
HH Particulate	kg PM2.5 eq	103%	102%	99%	100%
Global Warming Potential	kg CO2 eq	109%	110%	110%	101%
Eutrophication Potential	kg N eq	109%	103%	102%	101%
Acidification Potential	kg SO2 eq	110%	106%	101%	101%
Fossil Fuel Consumption	kWh	110%	110%	106%	100%
Non-Renewable Energy Consumption	kWh	109%	112%	106%	100%
Total Primary Energy Use	kWh	109%	111%	106%	100%

The R-2000 home's assembly group results vary most significantly from the baseline home results in the foundation group, as an additional 64mm layer of XTPS insulation board was added as exterior insulation for the foundation. On average, this addition increases all impact categories by 8-11%, apart from HH particulate, which only increases by 3%. The additional insulation added to the floor above the foundation increases the global warming potential and energy consumption by 10% and 6% respectively compared to the baseline home. Similarly, the spray foam insulation added to the main and second floor walls increases the lifetime global warming potential and energy consumption by 10% and 11% respectively.

Figure 16 shows the effects of each assembly group in terms of total impact for each impact category.

Figure 16: R-2000 Home LCA Results by Assembly Group



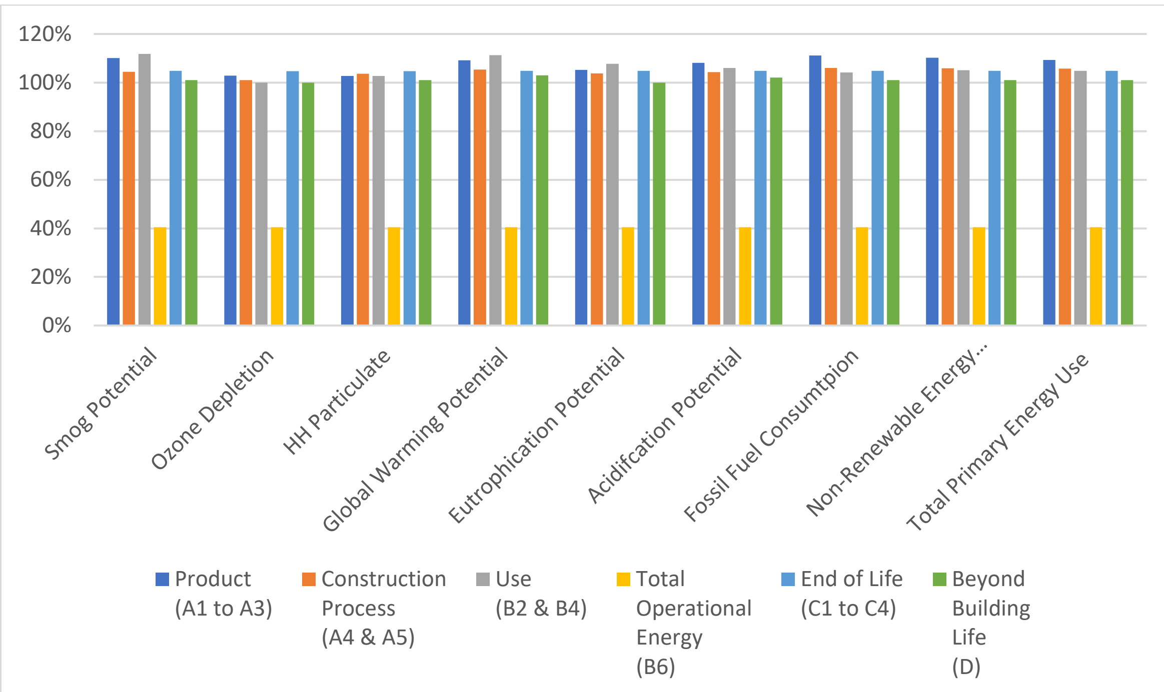
The contribution of each assembly group towards the total environmental impacts vary insignificantly between the baseline and R-2000 home results. The primary contributors to each impact group are the foundation and walls. Although the walls and foundations in the R-2000 project utilize additional insulation material, these groups' contributions only increase by 1-5%. When analysing the individual materials, insulation in the home accounts for 20% of the total embodied energy use and 12% of the global warming potential. The majority of the insulation's impacts come from the product stage. Due to the increased impact of insulation materials, the concrete's contributions to the total impacts decreased for the R-2000 home by an average of 11% compared to the baseline home. Most notably, the concrete only accounts for 81% of global warming potential and 38% of primary energy in the R-2000 home's embodied effects, as opposed to the 96% of GWP and 47% of primary energy use of the baseline home's embodied effects.

10.4 NZR Home LCA Results

10.4.1 NZR Home Life Cycle Stage Impact Results

The NZR home's results per life cycle stage as a percentage of the baseline home results from Table 33 are presented in Figure 17. The use stage of the NZR results in Figure 8 only includes stages B2 and B4 (maintenance and replacement). Operational energy use is analyzed as a separate category.

Figure 17: NZR LCA Results by Lifecycle Stage as a Percentage of Baseline Home Results in Table 36



The total operational energy of the NZR home is 60% less than the baseline home. Therefore, the NZR home's environmental impacts are all 60% lower than those of the baseline home as a result of both homes being modelled with the NS electricity grid. Due to the decrease in operational energy, the embodied environmental effects become a larger proportion of the total environmental effects of the NZR home. The results in the other stages as compared to the baseline home are similar to the ES home, with the average environmental impacts of the product stage and use phase (replacement/maintenance) being 8% and 6% higher than the baseline home's impacts respectively due to the increased material required. The end-of-life stage increases to 5% higher than the baseline home's impacts in all categories. The major difference in LCA modelling for the NZR home includes the change in operational energy, increase in insulation quantity and increased stud size. For perspective,

Table 40 shows the contribution of each life cycle stage towards the NZR home's total impact category results.

Table 40: NZR LCA Life Cycle Stage Results in Terms of Total Lifespan Effect on a Given Impact Category

LCA Measures	**Unit**	**Product**	**Construction**	**Use**	**End of Life**	**Beyond Building Life**
Global Warming Potential	%	6.0	1.2	94.1	0.4	-1.9
Acidification Potential	%	4.7	1.8	92.5	0.8	0.0
HH Particulate	%	10.2	0.9	87.9	0.3	0.2
Eutrophication Potential	%	5.1	1.4	89.6	0.6	0.0
Ozone Depletion Potential	%	2.6	0.3	97.1	0.0	0.0
Smog Potential	%	8.3	5.8	82.8	3.1	0.0
Total Primary Energy	%	6.7	1.2	91.5	0.5	0.0
Non-Renewable Energy	%	6.5	1.2	91.7	0.5	0.0
Fossil Fuel Consumption	%	6.0	1.2	92.2	0.5	0.1

As with the previous house models, the use phase, which includes operational energy, accounts for the majority of each impact category. However, the use category's impacts are on average 7% lower than the baseline home's use phase contributions to each category, while the NZR home's product category has an average of 6% higher environmental effects than the baseline homes This is due to the increase in material usage and decrease in operational energy. Hence, the embodied effects are accounting for a larger proportion of the total environmental effects since the large decrease in operational energy decreases the total environmental effects for the home's lifespan. The remaining life cycle stages account less than 3% of any given impact category. The beyond building life stage decreases to -1.9% of the baseline home's global warming potential due to the increased quantity of wood that can be recycled.

10.4.2 Assembly Group Impact Results

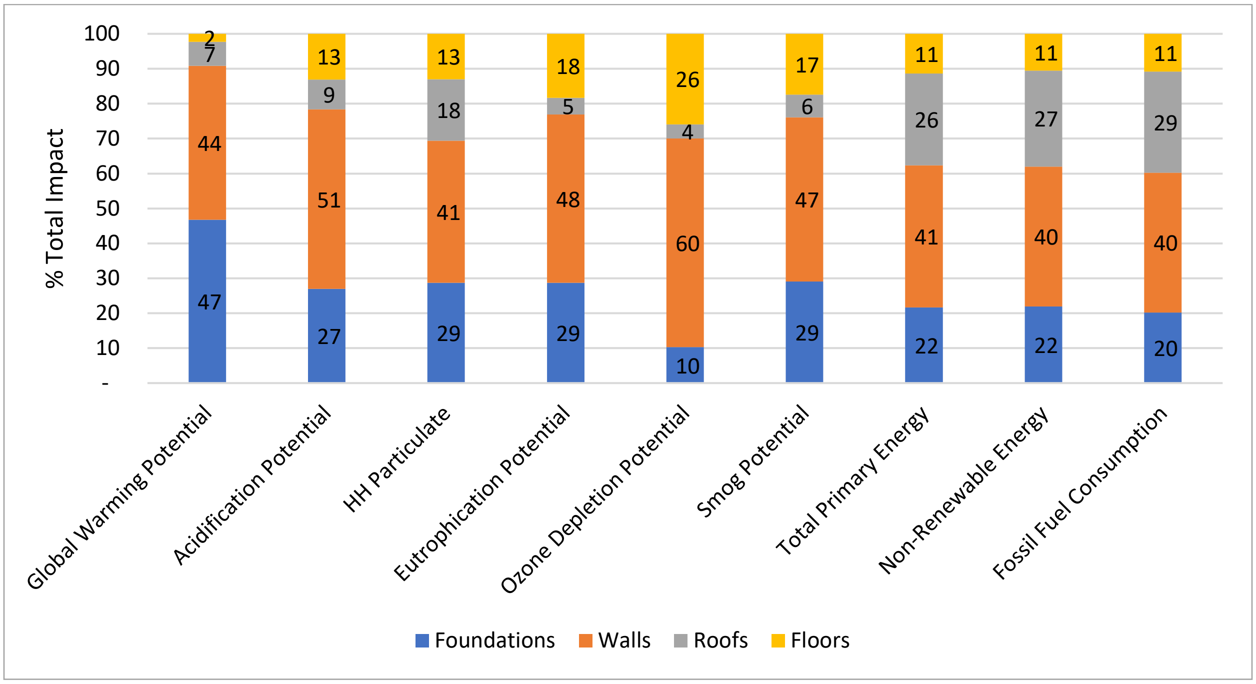
Table 41 shows the LCA results for each impact category according to the assembly group as a percentage of the baseline home's corresponding results from Table 33.

Table 41: NZR Home LCA Results by Assembly Group as a Percentage of Baseline Home Results

Effect	**Unit**	**Foundation**	**Walls**	**Floors**	**Roof**
Smog Potential	kg O3 eq	112%	113%	108%	117%
Ozone Depletion	kg CFC-11 eq	108%	108%	114%	116%
HH Particulate	kg PM2.5 eq	103%	102%	99%	100%
Global Warming Potential	kg CO2 eq	110%	111%	120%	114%
Eutrophication Potential	kg N eq	110%	107%	106%	116%
Acidification Potential	kg SO2 eq	111%	108%	103%	104%
Fossil Fuel Consumption	kWh	114%	117%	116%	104%
Non-Renewable Energy Consumption	kWh	112%	119%	116%	104%
Total Primary Energy Use	kWh	112%	118%	113%	104%

The NZR home's assembly group results vary significantly from the baseline home due to the additional insulation, window thickness and stud thickness. On average, the foundation environmental impacts increase by 10% and the wall's impacts by 8%, the floor's impacts by 11% and the roof's impacts by 9% compared to the baseline home. The addition of spray foam insulation, R28 batt insulation and additional wood in the walls increased the global warming potential and energy consumption by 20% and 13% respectively compared to the baseline home. Figure 18 shows the effects of each assembly group in terms of total impact for each impact category.

Figure 18: NZR LCA Results by Assembly Group



The contribution of each assembly group towards the total environmental impacts vary insignificantly between the baseline and NZR home results. This proportion of environmental impacts per assembly group has been a consistent trend throughout all the home iterations.

When analysing the individual materials, the insulation's contribution towards the total life cycle environmental impacts increases as compared to the other models due to the addition of spray foam and increased thickness of fibreglass batt insulation. Most significantly, insulation accounts for 27% of primary embodied energy use, 16% of embodied global warming potential and 19% of embodied ozone depletion potential. The majority of the insulation's impacts come from the product stage. Due to the increased impact of in insulation materials, the concrete's contributions to the total impacts decreases by an average of 15% compared to the baseline home, accounting for 76% of embodied global warming potential, 46% of acidification potential and 36% of primary embodied energy use. Wood accounts for negative 22% of the global warming potential for the home as it can be recycled. However, the wood also accounts for 20% of embodied acidification potential, 26% of embodied ozone depletion potential and 12% of total primary energy.

10.5 NZ Home LCA Results

The results of the whole-building LCA are not divided into impact by life cycle stage as the impacts of the solar PV modules and solar thermal collectors are not modelled in this detail. Therefore, their impacts are added to the NZR Athena's total life cycle results and considered their own assembly group when analyzing the impact of each assembly group.

10.5.1 NZ Home Assembly Group Impact Results

Table 42 shows the LCA results for each impact category according to the assembly group. The "Renewables" group represents the combined impact of the PV modules and solar thermal collectors. Due to the inability to model the solar thermal collectors and PV modules in Athena, some impact categories could not be analyzed, as indicated by "N/A" in Table 42.

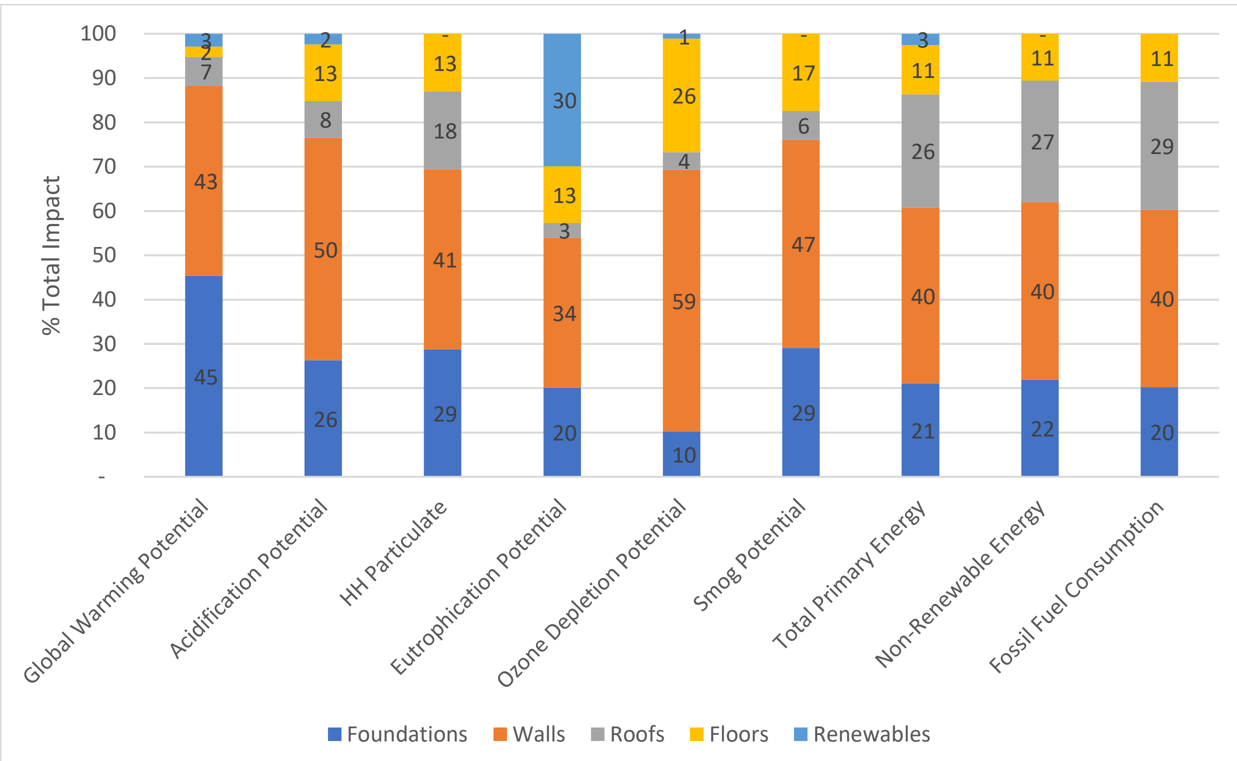
Table 42: NZ Home Life Cycle Environmental Impacts by Assembly Group

LCA Measures	Unit	Foundations	Walls	Roofs	Floors	Renewables	Total
Global Warming Potential	kg CO2 eq	18,290	17,270	2,660	920	1,170	40,310
Acidification Potential	kg SO2 eq	90	180	30	40	8	348
HH Particulate	kg PM2.5 eq	20	30	10	10	N/A	80
Eutrophication Potential	kg N eq	7	11	1	4	11	34
Ozone Depletion Potential	kg CFC-11 eq	0	0	0	0	0	0
Smog Potential	kg O3 eq	1,790	2,900	400	1,070	N/A	6,160
Total Primary Energy	kWh	53,611	100,917	65,222	28,222	6,528	254,500
Non-Renewable Energy	kWh	51,306	93,917	64,306	24,667	N/A	234,194
Fossil Fuel Consumption	kWh	44,694	88,389	63,806	23,944	N/A	220,833

Of the total embodied environmental effects, the renewables only account for 3% of global warming potential, and 3% of primary energy use. However, they do account for 30% of eutrophication potential. The addition of the renewables causes minimal variation in total lifecycle environmental effects, as they increase by less than 3% for all impact categories other than eutrophication, which increases by 42%.

The reliability of this result is low as the value was estimated based on the average of four studies. However, others have found that nitrogen emissions can be high during the production stage due to a the use of NF_3 used as a reactor cleaner during manufacturing (Fthenakis et al., 2010). There are additional nitrous oxide compounds used in manufacturing the panels, wafers and cells (Santoyo-Castelazo et al., 2021). Figure 19 shows the contributions by each assembly group in terms of total impact for each impact category.

Figure 19: NZ LCA Results by Assembly Group



The only notable difference in Figure 19 between the NZR home and NZ home is the 30% eutrophication caused by the renewables. Otherwise, the contributions of the other categories are altered insignificantly as a result of the renewables.

11.0 Discussion

Through operational energy modelling in HOT 2000 and complete life cycle assessment analysis in Athena LCA, it is possible to compare the life cycle environmental impacts of traditionally and energy efficient houses. Since all energy efficiency standards used to model efficient homes in this project focus on decreasing operational energy, life cycle assessment is introduced in this project as a tool to broaden the scope of environmental impact analysis by considering the embodied impacts associated with the measures taken to decrease operational energy.

The LCA results show that despite the increased material quantity required reduce operational energy, the environmental impacts in each category decrease as the homes become more efficient. The operational energy accounts for the majority of each impact, as demonstrated in Figure 20, which shows the total environmental impacts of each home as a percentage of the baseline home's impacts.

Figure 20: Total Environmental Impacts of each Home as a Percentage of the Baseline Home

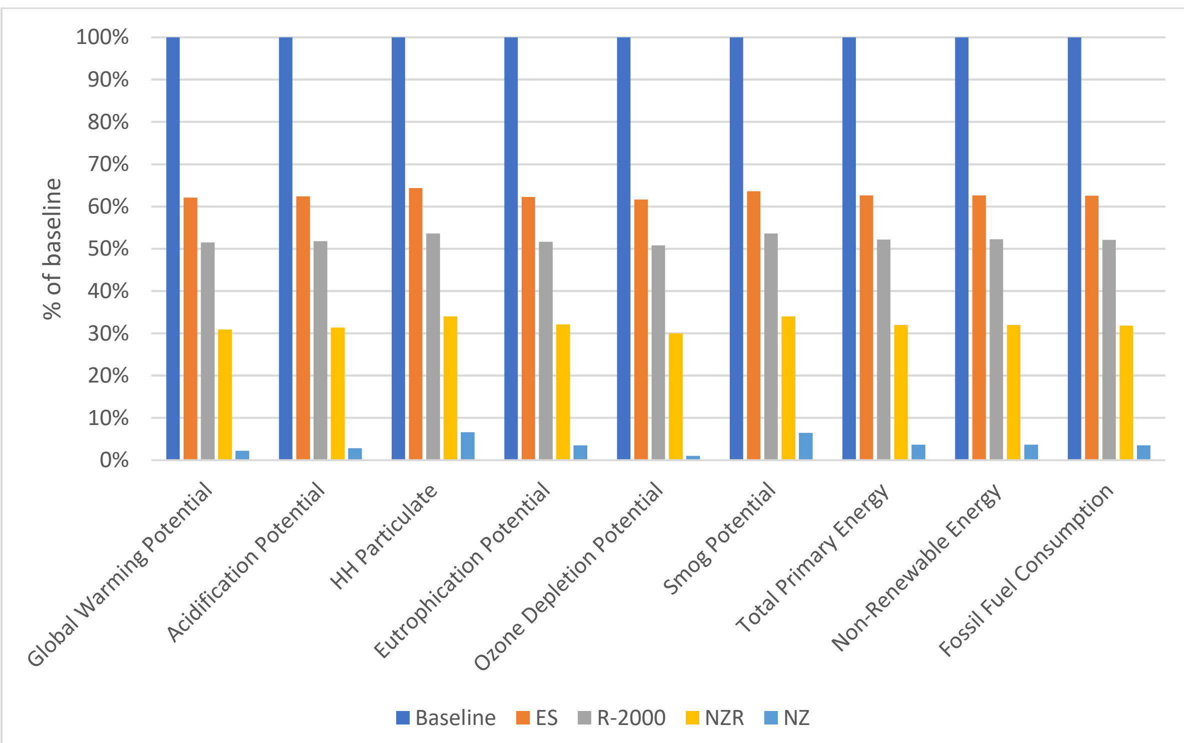


Figure 20 highlights the impact that decreasing operational energy has on environmental impacts. These results signify the high environmental impacts associated with electricity obtained from the grid, which is a result of the energy mix used in NS. The NZ home, which has no associated operational energy impacts and therefore represents only embodied impacts has on average 96% lower lifetime environmental impacts than the baseline home.

In contrast, when analysing the proportion of each home's total impacts attributable to embodied emissions, the trend increases with energy efficiency due to the use of additional materials. Figure 21 shows the embodied impacts as a percentage of the baseline's embodied impacts.

Figure 21: Embodied Impact Results as a Percentage of the Baseline Home's Embodied Impacts

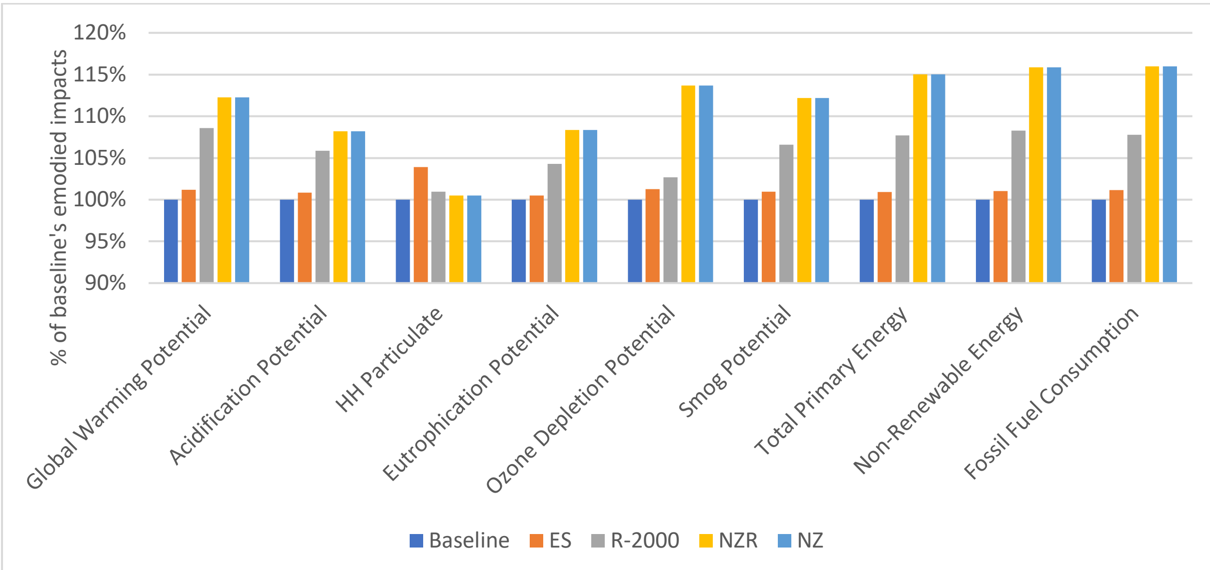


Figure 21 highlights the increase in embodied impacts associated with building efficiently. These impacts primarily come from increased insulation, increased framing size, increased thermal resistance in windows and increase in thermal resistance in doors. The ES home varies minimally in embodied impacts as compared to the baseline home, at only 1-4% differences in all categories. The R-2000 home utilizes significantly more insulation which increases embodied environmental impacts 1-9% compared to the baseline home. The renewables associated with the NZ home make minimal difference in the total embodied impacts and therefore both the NZR and NZ homes vary 1-16% from the baseline home's embodied impacts.

The material that contributes most significantly to the embodied environmental effects is concrete. However, as the homes became more efficient, the insulation has more impact due to the additional quantity used. For example, the baseline home's insulation only accounts for 3% of embodied GWP, while in the ES home, R-2000 home and NZR home, insulation accounts for 8%, 12% and 16% of embodied GWP respectively. Wood removes 12% of the baseline, ES and R-2000 home's GWP and 22% of the NZR and NZ home's GWP as the end-of-life stage for wood assumes 10% recycling. As noted in the

NZ LCA results, the impacts of the solar thermal collectors and PV modules are minimal on the total embodied emissions. Based on these results, the reduction in impacts associated with the operational energy from the grid when these technologies are installed far out-weigh their embodied impacts.

However, embodied impacts only account for under 20% of total impacts (including operational) for all homes other than the NZ home. The NZ home uses no operational energy annually, and therefore all impacts are attributable to embodied impacts. The breakdown of what percentage of each total impact is attributable to embodied impact is shown in Figure 22.

Figure 22: Embodied Impacts as % of Total Impacts

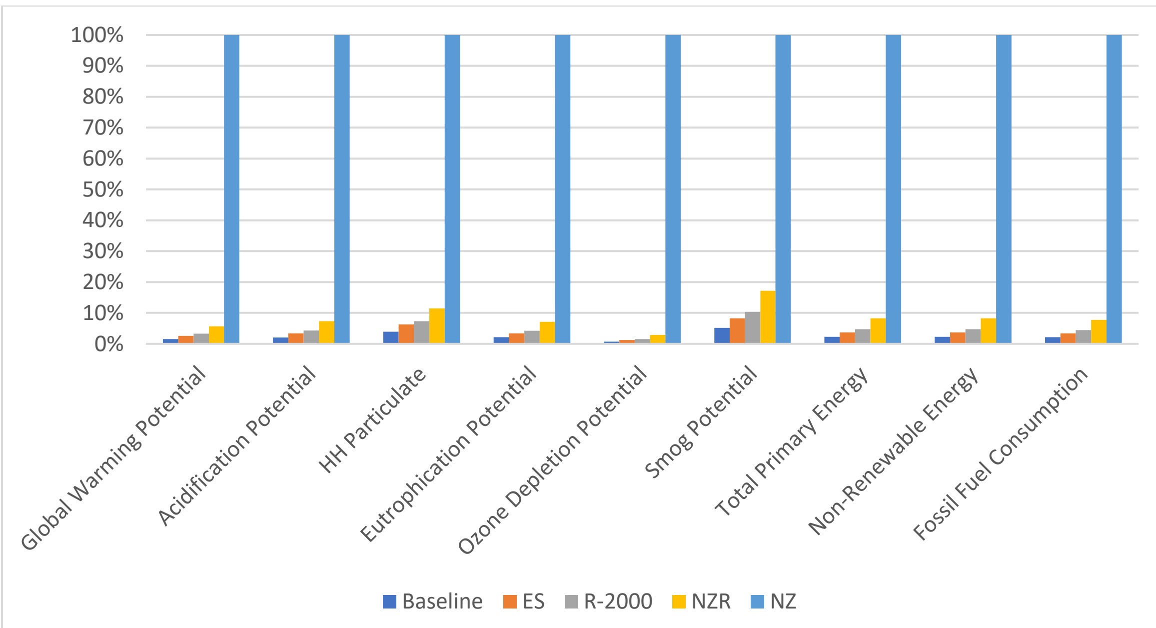


Figure 22 highlights the small contribution of embodied impacts to total impacts for the less efficient homes. For example, the baseline's embodied impacts account for 1-5% of total impacts and the ES home for 1-8%. However, as the material usage increases, the R-2000 home's embodied impacts account for 2-10% and the NZR home for 3-17%. Therefore, when building efficiently, accounting for embodied impacts becomes a consideration if attempting to reduce lifecycle impacts. However, decreasing operational energy has a larger impact on reducing environmental impacts then reducing material associated with embodied effects. Putting into perspective the small contribution of embodied effects for the less efficient homes, the baseline home will operationally produce the same amount of CO2 eq. as the total embodied CO2 eq. in 1.2 years, whereas the NZR home will take three times as long to operationally match the embodied CO2 eq. produced.

12.0 Conclusion

The operational energy usage of single family dwellings is an important step towards reduction in environmental impacts and future energy reduction goals in Nova Scotia and Canada. Although much research has been performed on reducing operational energy in homes, there is a gap in research that considers both operational and environmental impacts, which can be considered using LCA technology. This project analyzes the complete lifecycle environmental impacts amongst five Nova Scotia single family dwellings with varying operational energy efficiencies. The effects of increasing operational efficiency on operational impacts and embodied impacts are compared using the five home iterations as models, with the least efficient home being built to CNBC and the most efficient home being a NZ home.

Detailed operational energy modelling for each home is performed using HOT 2000 to represent the environmental impacts incurred due to the use of grid electricity required to provide energy to the home during its operational lifecycle phase. The operational phase is the most environmentally impactful stage for all homes except the NZ home due to its length of time and the electricity grid mix of Nova Scotia using coal as its primary source. Through efficiency upgrades in each home, the operational energy decreases and therefore the operational phase accounts for a smaller percentage of the total lifecycle environmental impacts.

The lifecycle environmental impacts of all lifecycle stages are studied using Athena LCA software, which sources data from the Ecoinvent Database. The results show that the embodied environmental impacts associated with more energy efficient buildings are insignificant compared to the operational energy savings created. The most efficient home in this project, which produces electricity using PV modules has on average 96% lower environmental impacts than the baseline home. However, when considering only the embodied impacts, the NZ home has 11% higher embodied impacts than the baseline home amongst the nine impact groups. Comparatively, the NZR home, which mimics the NZ home, but does not have any generation capabilities has on average 68% lower environmental impacts than the baseline home and 11% higher embodied impacts on average. Therefore, implementing operational energy efficiency upgrades rather than reducing embodied impacts is the most effective pathway to reducing lifecycle environmental impacts when building single family dwellings in Nova Scotia.

The most significant limitation to this study surrounded the LCA software. Athena LCA was unable to include mechanical systems, electrical systems and finishes, which could have altered the embodied impacts of the results. Additionally, Athena was limited in its backend transparency in terms of data sourcing from Ecoinvent and allowing users to see results by material. However, the alternative whole-building LCA software available are not localized to Nova Scotia.

In the future, it could be beneficial to compliment the results of this study with further research in the following topics:

- Alternative building types – compare the operational and embodied impacts of different types of buildings, rather than the same building with varying efficiency measures.
- Alternative heating systems - compare the LCAs of homes in NS with different heating types
- Retrofits – analyze the LCA impacts of retrofitting a home with operational energy upgrades rather than building new.
- Alterative locations – perform an LCA for the same home, but in several different provinces to evaluate how the electrical grid mixture in that province and access to materials changes results.
- Mechanical and electrical systems- Perform a more detailed LCA for a house that includes mechanical systems, electrical systems and finishes.
- Alternative electricity generation methods – compare the LCA of NZ homes in NS with alternative electricity generation systems

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Appendix A: HOT 2000 Technical Modelling Features Manual (Natural Resources Canada, 2022)

Note: The following information is copied directly from the HOT 2000 Help Topics manual within the software.

HOT2000 conducts a monthly energy balance on a house design to determine potential energy (space heating, water heating, appliances, and lighting) requirements. The monthly energy balance includes monthly and hourly bin analyses of specific building components and mechanical systems. HOT2000 contains the following technical modelling features.

A1: Above-Grade Envelope Components

The above-grade envelope components support the following technical modelling features:

l. Areas and insulation thermal resistance values can be entered for individual building components (such as walls, floors, and ceilings). The effective thermal resistance of the assembly is calculated by the program from the construction details the user enters through pop-up lists. It takes into account thermal bridging and compression of insulation in the attic along the eaves.

2. Up to 32 entries per building component are permitted.

3. The building main wall and roof components include the solar surface heating effect of sunshine.

4. The monthly heat loss for each component is based on the area, effective insulation, and a temperature bin analysis that uses the setpoint temperature, the average monthly temperature, and the standard deviation of temperature.

A2: Window Components

The window components support the following technical modelling features:

l. East, west, north, south, southeast, southwest, northeast, and northwest window orientations can be entered for passive solar gain calculations.

2. Based on the entry of a 6 digit code which defines the glazing type, coatings, gas fill, window type, spacer, and frame material, overall thermal resistance values and solar heat gain coefficients are calculated for each window.

3. Overhang geometry information is used to determine the window shading effect on passive solar gains for individual windows.

4. Shutters on individual windows on each orientation are modelled using empirically derived shutter closure periods based on latitude and solar position.

5. The window rotation feature reorients all windows by entering a new orientation for the south-facing windows. All other windows are automatically rotated to reflect the reorientation.

6. The window exchange feature exchanges all of the windows on two or more orientations without affecting the windows on the remaining orientations.

7. The total incident solar radiation is calculated on planar, glazed surfaces (windows and skylights) in the 8 cardinal directions and for any upward-facing tilt angle between a horizontal inclination (0°) and a vertical inclination (90°).

8. Monthly passive solar contribution and utilization are calculated on the basis of available solar gains, internal building mass, interior temperatures and temperature swings, house heating loads, and building mass heat storage parameters.

A3: Foundation and Below-Grade Building Components

The foundation and below-grade building components support the following technical modelling features:

1. The heat loss model is a regression-based algorithm which expresses both above-grade and below-grade time-dependent heat losses. It calculates the heat loss as a function of the foundation's thermal and geometrical properties (insulation resistance, height, depth, width, length) and site conditions (soil conductivity, water-table depth and weather).

2. A heat balance is performed bin by bin on the basement , crawl space and walkout foundations taking into account heat exchange (with the main floor, ground and outside), internal gains and air infiltration.

3. Open, closed (sealed), and ventilated crawl spaces are modelled.

4. Slab on grade foundations are modelled, taking into account above and below slab insulation, horizontal and vertical skirts, insulation around the edge of the slab and the connection between the slab and the wall.

5. Basements are modelled, taking into account interior and/or exterior insulation on the walls, below slab insulation, thermal break between the slab and the wall and the connection between the foundation wall and the first storey wall.

6. Houses with multiple foundations (e.g. a basement and a crawl space) can be modelled.

7. Supports non-rectangular floor plans.

8. Supports custom foundations modelled in the BASECALC program.

A4: Infiltration and Ventilation Heat Losses

The infiltration and ventilation heat losses support the following technical modelling features:

1. Natural air infiltration rate can be determined in one of two ways; either based on fan depressurization test results or by choosing from a list of four air tightness types (Loose, Average, Present, Energy Tight).

2. A monthly wind-induced infiltration rate and temperature-induced infiltration rate is calculated, based on the exposure of the house to winds, wind speed, airtightness and leakage areas, and temperatures.

3. Minimum continuous ventilation rates are either derived using the R-2000 ventilation guidelines, which are based on the Canadian Standards Association Preliminary Standard F326.1, *Residential Mechanical Ventilation Requirements*, or entered directly.

4. Heat recovery ventilator efficiencies are modelled using sensible heat recovery test data at 0°C and -25°C (32°F and -13°F).

5. The heat recovery ventilator (HRV) model derives an efficiency-to-temperature curve based on the test data, and derives a monthly weighted efficiency using an hourly bin analysis of temperatures against the efficiency profile curve. The effect of direct heat transfer on HRV effectiveness is accounted for.

6. Fan and pre-heater energy consumptions are derived using a normalized temperature distribution to determine fan energy above and below the indoor setpoint temperature, so that the contribution to heating and cooling loads can be determined.

7. The supply and exhaust ducts between the exterior of the house and the HRV are modelled to take into account the effect of heat transfer and air leakage from the duct to the space.

A5: Space Heating Systems

The space heating systems support the following technical modelling features:

1. HOT2000 contains default steady-state efficiencies for various types of space heating systems and calculates both monthly and seasonal efficiencies for the selected space heating system. Heating System type, fuel type, capacity, efficiency, and pilot light energy consumption may be specified by the user.

2. Either seasonal efficiencies or steady state efficiencies may be entered into the HOT2000 program. HOT2000 contains correlations for converting seasonal efficiencies into steady state efficiencies for furnaces/boilers and heat pumps.

3. HOT2000 calculates a design heat loss for the January 2 1/2 % temperature condition to size a heating system with or without the impact of a heat recovery ventilator (based on the National Building Code of Canada).

4. Space heating heat pumps (air, water, or ground source) are modelled using an hourly temperature and heat loss bin distribution. HOT2000 determines the heat pump capacity, coefficient of performance, and energy consumption for each hourly bin, as well as the load and part-load capacities, cycling times, and energy consumption for backup space heating systems for each hourly bin.

5. The space heating heat pump model considers various heat pump control strategies (temperature-restricted operation, unrestricted operation, or full heating load balanced operation).

A6: Space Cooling Systems

The space cooling systems support the following technical modelling features:

l. Space cooling (air conditioning) systems are modelled using an hourly temperature and heat loss bin distribution.

2. HOT2000 models the following central air conditioning systems: Split system, Single package system and mini-split ductless.

3. For the purpose of determining the air conditioning size required for a house, HOT2000 can estimate the required rated capacity, indoor fan flow rate, and fan power.

4. Sensible cooling load modelling includes the effects of thermal storage and of changes due to the opening and closing of windows.

5. Latent load modelling includes the effects of outside humidity on the inside latent load.

6. Variations in the air conditioner capacity and coefficient of performance (COP) with outdoor temperature is modelled.

7. Dehumidification by the air conditioning system is modelled.

8. Loss of efficiency due to part-load operation is modelled.

9. Either the seasonal energy efficiency ratio (SEER) or the steady state efficiency may be entered into the HOT2000 program. HOT2000 contains correlations for converting the SEER into a steady state efficiency for air conditioners and heat pumps.

A7: Domestic Hot Water Heating Systems

The domestic hot water (DHW) heating systems support the following technical modelling features:

I. HOT2000 calculates the contribution of a solar domestic water heating system from test data using the CSA Standard F379 "Solar Domestic Hot Water Systems" rating. For older systems, the Canadian Solar Industries Association annual rating can be used.

2. Primary and secondary water heating system combinations are modelled.

3. Standby losses, flue loss, hot water temperature, intake temperature, room temperature, location, and occupancy are accounted for in estimating DHW energy consumption.

A8: Internal Heat Gains

The internal heat gains support the following technical modelling features:

I. Internal heat gain modelling includes standby losses for domestic water heating systems, interior electrical usage, pre-heater energy, and occupant heat energy.

2. A monthly internal gain utilization is derived, based on available gains, heating loads, temperatures, and utilization parameters.

Appendix B: House Heat Balance Calculations (Barakat & Sander, 1986)

Note: The following information is copied directly from the Barakat & Sander (1986) – a Natural Resources Canada publication outlining the development of internal heat gains calculations.

B1: Utilization Factor Concept

The concept of a utilization factor to account for the usable portion of internal and solar gains is summarized below (Barakat & Sander, 1982).

The instantaneous (hourly) heat balance is given by:
H = 1t + 1a + 1b – gi - gs

where :
h = instantaneous heating required,
It = instantaneous heat loss due to transmission through exterior walls, windows, ceilings, etc.,
1a, = instantaneous heat loss due to air exchange with outdoors (infiltration plus ventilation)
1b = instantaneous below-grade heat loss,
gi = instantaneous heat gain from internal sources (lights, equipment, people, etc.),
gs = instantaneous solar heat gain through windows.

When gains exceed losses, the excess heat is stored in the mass of the room and the room temperature rises. To prevent the room temperature from rising above an acceptable limit, the excess heat must be removed by opening windows or by operating a ventilation or air-conditioning system. A portion of the stored heat becomes available when the room temperature drops to the thermostat setting. The remainder will have been lost in the form of increased transmission losses due to rise in room temperature.

B2: Seasonal Heat Balance

The heat balance equation may be written for a longer time peiod, a month or a season, by including utilization factors to account for the usable portion of internal and solar gains, that is,

H = Lt + La + Lb – niGi - nsGs

Where
H = total heating required for season,
Lt = seasonal total of heat losses due to transmission through exterior walls, windows, ceilings, etc.
La = seasonal total of heat losses due to indoor-outdoor air exchange (infiltration plus ventilation),
Lb = seasonal total below-grade heat loss,
GI = seasonal total of heat gains from internal sources lights, equipment, people, etc.),
Gs = seasonal total of solar heat gains through windows,
ni = utilization factor for internal gains,
ns = utilization factor for solar gains.

B3: Utilization Factor for Solar Gain

The solar utilization factor, qs, was correlated to two normalized parameters, one of which is the gain-load ratio (GLR) defined as

$$GLR = Gs/Qn \quad (3)$$

The net heating load, Qn, is the amount of heating energy required, in the absence of solar gains, to maintain room temperature at the heating thermostat setting, or

$$Qn = Lt + La + Lb - niGi$$

The determination of Qn therefore, requires an estimate of the utilization factor for internal gains, qi.

B4: Utilization Factor for Internal Gain

The fraction of internal gains that are useful in offsetting heat losses depends upon the magnitude of the internal gains, the profile or variation of these gains with time, the heat losses, the thermal storage characteristics of the building, and the temperature rise that is allowed before excess heat is dumped. In the same manner as for the solar utilization factor, the internal gain utilization factor can be expressed as a function of two normalized parameters, the internal gain-loss ratio (IGLR) and the mass-internal gain ratio (MIGR). The internal gain-loss ratio is defined as the ratio of the internal gains to the building heat loss (calculated at the thermostat setting)

$$IGLR = Gi / (Lt + La + Lb)$$

For Canada, a house built to pre-1975 standards would typically have an IGLR of less than 0.1; a super insulated house would have an IGLR of 0.3 to 0.4. The mass-internal gain ratio is defined as the ratio of the thermal capacity of the building interior, C, (MJ/K) to the average hourly internal gain over the season, gi, (MJ/h), that is:

$$MIGR = C / gi$$

Thermal capacity, C, is the effective mass of the building multiplied by its specific heat. Typical houses of lightweight construction have a MIGR of approximately 1.5 h/K.

Utilization factors for internal gains were derived using an hour-by-hour computer simulation with actual weather data for 11 Canadian locations. These utilization factors are expressed as a function of the ratio of seasonal total internal gains to seasonal total reference loss for three daily profiles of internal gain and four levels of thermal storage. Curves are presented for conditions of constant room temperature and for allowable temperature rises of 2.75 and 5.5 degrees Celsius. The following conclusions can be drawn:

1. For houses with a ratio of internal gains to reference heat loss of less than 0.4, all internal gains can be utilized to offset thermal losses.
2. For buildings with a "constant" or a "house" internal gain profile, increasing the thermal storage mass or the allowable temperature swing has a negligible effect on the utilization of internal gains.
3. For practical purposes, the following equation can be used to calculate the seasonal internal gain utilization factor for houses:

$$ni = (1.0 + 0.054\ IGLR^{3.19}) / (1.0 + 0.24\ IGLR^{3.06}) \quad \text{for } IGLR < 2.2$$

$$ni = 1/ IGLR \quad \text{for } IGLR > 2.2$$

Appendix C: Canadian National Building Code Details

The requirements from CNBC that were used in modelling the baseline home are summarized in Table D1.

Table 46: CNBC base home characteristics (CNBC, 2015)

Characteristic	Specification	CNBC section reference
Concrete	R class Max aggregate size: 19mm	9.3.3.1.
Lumber Grades	Table 9.3.2.1.	9.3.2.2.
Lumber Treatment	Pressure-treated with chemical toxic to termites if in contact with ground.	9.3.2.9.
	Pressure-treated with preservative if exposed to moisture or less than 150mm above ground level. See 9.3.2.9. Part 5 for categories.	9.3.2.9.
Foundation termite protection	Plastic or metal barrier installed through foundation insulation	9.3.2.9.
Ceiling Height	Table 9.5.3.1.	9.5.5.1.
Hallway width	At least 860mm if only one exit. At least 710mm if only used for bedrooms and bathrooms and exit present at both ends.	9.5.5.1.
Door sizes	Exterior entrances, stairway entrances, utility room entrances: Width = 810mm, Height = 1980mm	9.5.5.1.
	Walk-in closets, bathrooms, rooms off of 710mm wide hallways: Width = 610mm, Height = 1980mm	9.5.5.1.
	All other rooms not previously mentioned: Width = 760mm, Height = 1980mm	9.5.5.1.
Max Window Area	Table 9.6.1.3.-B according to type and thickness of glass[1,2,3]	9.6.1.3.
Window and Door thermal performance	Max U-value = 2.0 W/(m^2-K) [4] Min temperature index (I) = 68 [4] Minimum performance level: Performance Class R	9.7.3.3. , 9.7.4.3.
Stair characteristics	Stair type: straight flights	9.8.3.1.
	Max flight height: 3.7 m	
	Min flights width: 860 mm	9.8.2.1.
	Height over stairs: 1950 mm	9.8.2.2.
	Rise per step: 125 mm to 200 mm	9.8.4.1.
	Run per step: 255 mm to 355 mm	9.8.4.2.
Landing requirements	Landing at top and bottom of each flight of stairs	9.8.6.2.
	At least as wide as long as the width of connecting stair flight.	9.8.6.3.
Handrails	Required on one side of stairs [5]	9.8.7.1.
	Height: 865mm to 1070mm	9.8.7.4.
Fire separation	Each exit must be protected by a 12.7mm thick gypsum board on both sides of wall and on underside of floor-ceiling framing separating exit from building.	9.9.4.2.
Bedroom windows	At least one 0.35m^2 window or door with no dimension smaller than 380mm.	9.9.10.1.
Window Spacing	Windows in same room must be spaced 2m apart horizontally and vertically	9.10.15.5.
Max area of unprotected	12% of total exposing building face area [6]	9.10.14.4.

openings on exposing building face area		
Construction requirements for exposing building face area	1hr fire resistance	9.10.14.5.
	Non-combustible cladding required	9.10.14.5.
Max area of glazed openings	12% of total exposing building face area [6]	
Fire Block requirements	Required to block off uninsulated concealed spaces in wall assemblies.	9.10.16.1.
	Materials: 0.38 mm sheet steel 12.7 mm gypsum board 12.5 mm plywood, OSB or waferboard, with joints having continuous supports, 2 layers of 19 mm lumber with joints staggered, or 38 mm lumber.	9.10.16.3.
Garage floor	Dampproofing: Polyethylene sheet installed under garage floor according to CAN/CGSB-51.34-M, not less than 0.15mm.	9.13.2.2.
	Vapour resistant coating applied to top of floor	9.13.2.2.
Waterproofing	Waterproofing material for roof according to 9.13.3.2.	9.13.3.2.
	Membrane waterproofing between 2 layers of 75mm thick concrete required for basement floor.	9.13.3.5.
Soil Gas Control	On-ground floors should have a rough-in for subfloor depressurization including a gas-permeable layer	9.13.4.3.
Drainage	The bottom of foundation walls must have drainage tile or pipe not less than 100mm diameter. See section 9.14.3.1. for tile and material details. Must be covered by at least 150mm of crushed rock.	9.14.3.3.
Concrete forms	Permanent forms for foundation walls are to be made of Type 2, 3 or 4 polystyrene	9.15.4.1.
Masonry	Material requirements according to section 9.20.2.1.	9.20.2.1.
	Flashing materials according to Table 9.20.13.1.	9.20.13.6.
Fasteners	Common steel wire nails or common spiral nails for lumber	9.23.3.1.
	Wood screws according to ASME B18.6.1	9.23.3.1.
	Sheathing and subfloor fasteners according to Table 9.23.3.5.-A.	9.23.3.5.
Wood Framing	Max joist, rafter and beam spans according to Tables 9.23.4.2.-A to 9.23.4.2.-G.	9.23.4.2.
	Wall stud sizing according to Table 9.23.10.1	9.3.10.
	Braced wall band spacing and dimensions according to Table 9.23.13.5.[8] and material according to Table 9.23.13.6.	9.23.13.5.
	Subflooring material and thickness according to Sections 9.23.15.2. and 9.23.15.5. respectively.	9.23.15.2.
Sheathing	Roof sheathing material according to section 9.23.16.2. Thickness according to Table 9.23.16.7.-A.	9.23.16.
	Wall sheathing material and thickness according to Table 9.23.17.2.-A.	9.23.17.
Insulation	All walls, ceilings and floors separating conditioned space from unconditioned space, the exterior air or the ground shall have insulation of material according to section 9.25.2.2.	9.25.2.2.
Air barrier	Wall, ceiling and floor assemblies separating conditioned space from unconditioned space or from the ground shall be constructed so as to include an air barrier system that will provide a continuous barrier to air leakage.	9.25.3.1.

Vapour barrier	Thermally insulated wall, ceiling and floor assemblies require a vapour barrier of a material according to section 9.25.4.2. to be installed	9.25.4.2.
Building envelope leakage	Sheet and panel assemblies must have air leakage less than 0.1L/(s·m2) at 75Pa and a water vapour permeance less than 60ng/(Pa·s·m2)	9.25.5.1.
	Minimum Ratio of Total Thermal Resistance Outboard of Material's Inner Surface to Total Thermal Resistance Inboard of Material's Inner Surface is 0.2 [9]	9.25.5.2.
	Door area to gross wall area ratio: 0.4 [9]	**3.2.1.4 NCEB**
Roofing	Materials according to Table 9.26.2.1.-B	9.26.2.2.
	Minimum slope for asphalt shingles: 1 in 3	9.26.3.1.
	Underlay: No. 15 plain or perforated asphalt-saturated felt.	9.26.6.1.
	Coverage: not less than 2 thicknesses of shingle over the entire roof	9.26.7.1.
Cladding	First protection plane: cladding with appropriate trim, accessory pieces and fasteners	9.27.2.3.
	Second protection plane: effectively dissipate any rain or snow that gets past first plant to the exterior	9.27.2.3.
	Sheathing must consist of 14.3 mm lumber, 7.5 mm plywood, 7.5 mm OSB or waferboard.	9.27.5.1.
	Vinyl siding, including flashing according to CAN/CGSB-41.24	9.27.12.1.
Interior walls	Gypsum board supporting insulation shall be not less than 12.7 mm thick.	9.29.5.4.
	Minimum plywood thickness: 4.7mm	9.29.6.1.
Flooring	Membrane required under flooring in bathrooms, kitchen, laundry area	9.30.1.2.
	Underlay required under floor laid over lumber subfloor must be at least 6mm thick.	9.30.2.1.
	Wood floor of thickness 7.9mm required [10]	9.30.3.1.
	Resilient flooring made of asphalt, rubber, vinyl-asbestos, unbacked vinyl or vinyl with an inorganic type backing shall be attached to the base with a suitable waterproof and alkali-resistant adhesive.	9.30.5.1.
	Ceramic tile shall be set in a mortar bed or applied to a sound smooth base with a suitable adhesive.	9.30.6.1.
Ventilation	Exhaust duct for dryer discharged to outdoors	9.32.1.3.
	Normal Operating Exhaust Capacity of Principal Ventilation Fan (the exhaust fan of the HRV) must be between 22L/s and 32L/s [11]	9.32.3.3.
	Maximum outdoor airflow for mixed temperature of 5degC or 55 L/s [12]	9.32.3.4.
Thermal Transmittance	Maximum Overall thermal transmittance in W/ (m^2·K)+++++++++++ [9]: Wall: 0.278 or 0.379 if in contact with ground Roof: 0.183 or 0.379 if in contact with ground Floor: 0.183 or 0.757 if in contact with ground Overall fenestration: 2.2 Doors: 2.2	**3.2.2.2.- 3.2.2.4.** **NCEB**
Air Duct System	Ducts, duct connectors, associated fittings and plenums shall be constructed of steel, aluminum alloy, copper, clay, asbestos-cement or similar non-combustible material.	9.33.6.2.
	The return-air system shall be designed to handle the entire air supply.	9.33.6.13.
	Piping shall be made from materials designed to withstand the effects of temperatures and pressures that may occur in the system.	9.33.8.1.
	Insulation and coverings on pipes shall be composed of material suitable for the operating temperature of the system to withstand deterioration from softening, melting, mildew and mould.	9.33.8.2.

Electrical	Optical fibre cables and electrical wires and cables installed in buildings permitted to be of combustible construction shall not convey flame or continue to burn for more than 1 min and be located in a masonry wall or an enclosed non-combustible raceway	9.34.1.5.
Energy Efficiency	Where mechanical ducts, plumbing pipes, conduits for electrical services or communication cables are placed within the insulated portion of a floor or ceiling assembly, the effective thermal resistance of the assembly at the projected area of the ducts, pipes, conduits or cables shall be not less than 2.78 (m2·K)/W.	9.36.2.5.
	Thermal Resistance (RSI), (m2·K)/W: [9,11] Ceilings below attics: 8.67 Walls: 2.97 Floors over unheated spaces: 4.67 Foundation walls below grade: 2.98 Unheated floors below frost line: no insulation Below grade heated floors: 2.32	Table 9.36.2.6.-B Table 9.36.2.8.-B
	Fenestration and door minimum energy rating (ER): 25 Fenestration and door maximum U-value: 1.60 W/(m2·K)	Table 9.36.2.7.-A
	Site built windows and glazed-door portion options (not storm doors/windows): 1. Non-metallic frame, triple glazed with a 12.7mm spacer 2. Non-metallic frame, double-glazed argon filled, with at least one pane with low e-coating value <0.1, and non-metallic spacer 3. Thermally broken metallic frame, triple-glazed, with two panes with low e-coating value <0.2 and a 23.7mm spacer.	Table 9.36.2.7.-C
Air Leakage	Building assembly with air leakage rate less than 0.2 L/(s·m^2) at a pressure differential of 75 Pa.	9.36.2.9.
	Air barrier system must be continuous across joints, materials, assemblies and around penetrations	9.36.2.9.
	Flexible sheet air barrier system shall be lapped not less than 50mm, sealed and structurally supported[13]	9.36.2.10.
HVAC	Ducts and plenums carrying conditioned air and located outside the plane of insulation shall have all joints sealed against air infiltration and exfiltration with sealants or gaskets made from liquids, mastics or heat-applied materials.	9.36.3.2.
	Every duct or opening intended to discharge air to the outdoors shall be equipped with a motorized damper, or a gravity- or spring-operated backflow damper.	9.36.3.3.
	All piping forming part of a heating or air-conditioning system shall be located inside the plane of insulation.	9.36.3.4.
	The supply of heating and cooling energy to each common space shall be controlled by thermostatic controls that activate the when the temperature in a conditioned space fluctuates ±0.5°C from the set-point temperature.	9.36.3.6.
	HRV efficiency of at least 60% at an outside air test temperature of 0°C and at least 55% at an outside air test temperature of –25°C.	9.36.3.9.
Water Heating System	Water heater storage tank performance requirement of standby loss less than 35W on top inlet and 40W on bottom inlet [14]	Table 9.36.4.2
	Upstream and first 2m of downstream piping of storage tank should be insulated with at least 12mm thick insulation	9.36.4.4.
	Storage tanks shall be equipped with automatic temperature controls capable of adjustment between the minimum and maximum temperature settings.	9.36.4.5.
Energy performance Compliance	The energy model calculations shall account for annual energy consumption of systems and equipment required for space heating, ventilation, service water heating, and space cooling.	9.36.5.4.

Internal heat gain loads for every hour in a typical day	Table 9.36.5.4.
Temperature setpoints: 21°C in living spaces 19°C in basements	9.36.5.4.
The proposed and reference houses shall both be modeled using the same approach and assumptions, except where building components or energy efficiency features are permitted by this Subsection to be different.	9.36.5.4.
The energy model calculations shall take into account the service water heating use schedule presented in Table 9.36.5.8. using a load of 225 L/ day for houses.	9.36.5.8.
Exterior walls, roofs and exposed floors shall have a solar absorptance of 0.4.	9.36.5.10.
The airtightness value used in the energy model calculations for the proposed house shall be 2.5 air changes per hour at 50 Pa pressure differential[13].	9.36.5.10.
The reference house should have a set value of 0.26 for the solar heat gain coefficient of fenestration.	9.36.5.14.
The area and orientation of fenestration and doors of the reference house shall be modeled as being equally distributed on all sides of the house.	9.36.5.14.
Except as required in Sentence 9.36.3.8.(1), the reference house shall be modeled without a heat-recovery ventilator.	9.36.5.15.
The ventilation system shall be modeled as operating 8 hours a day.	9.36.5.15.
The energy model calculations shall assume all ventilation and circulation fans required to be modeled in the reference house are equipped with permanent-split capacitor (PSC) motors.	9.36.5.15.

Assumptions made:

1. Home is in a built-up area and is more than 120m away from open terrain.
2. Home is not on top of a hill.
3. 1-in-50 Hourly Wind Pressure (HWP) is less than 0.75 kPa
4. January design temperature is between -15 deg C and -30 deg C
5. Assuming stairs are <1100mm wide
6. Based on exposed building face area of ~16m^2, assuming 56ft wide and 30ft high and limiting distance of 2m.
7. Between 10% and 25% max area of unprotected openings permitted
8. Seismic spectral response acceleration, Sa(0.2), is not more than 0.70 and the 1-in-50 hourly wind pressure is less than 0.80 kPa
9. Assuming Halifax has 4000-4999 heating degree days.
10. Assuming hardwood, with subfloor.
11. Assuming HRV is used (Health Canada, 2018) as ventilation for non-heating and heating season.
12. Based on HRV Guide for Homes (Energy Save News West, 2020)
13. Air barrier consists of polyethylene sheet, ie. a flexible sheet material (EcoHome, 2013)
14. Less than 12kW water heater because capacity is 189 L.

Appendix D: Home Floorplans

Figure 23: Basement Floor Plan (Collins Homes & Renovations Ltd, 2021)

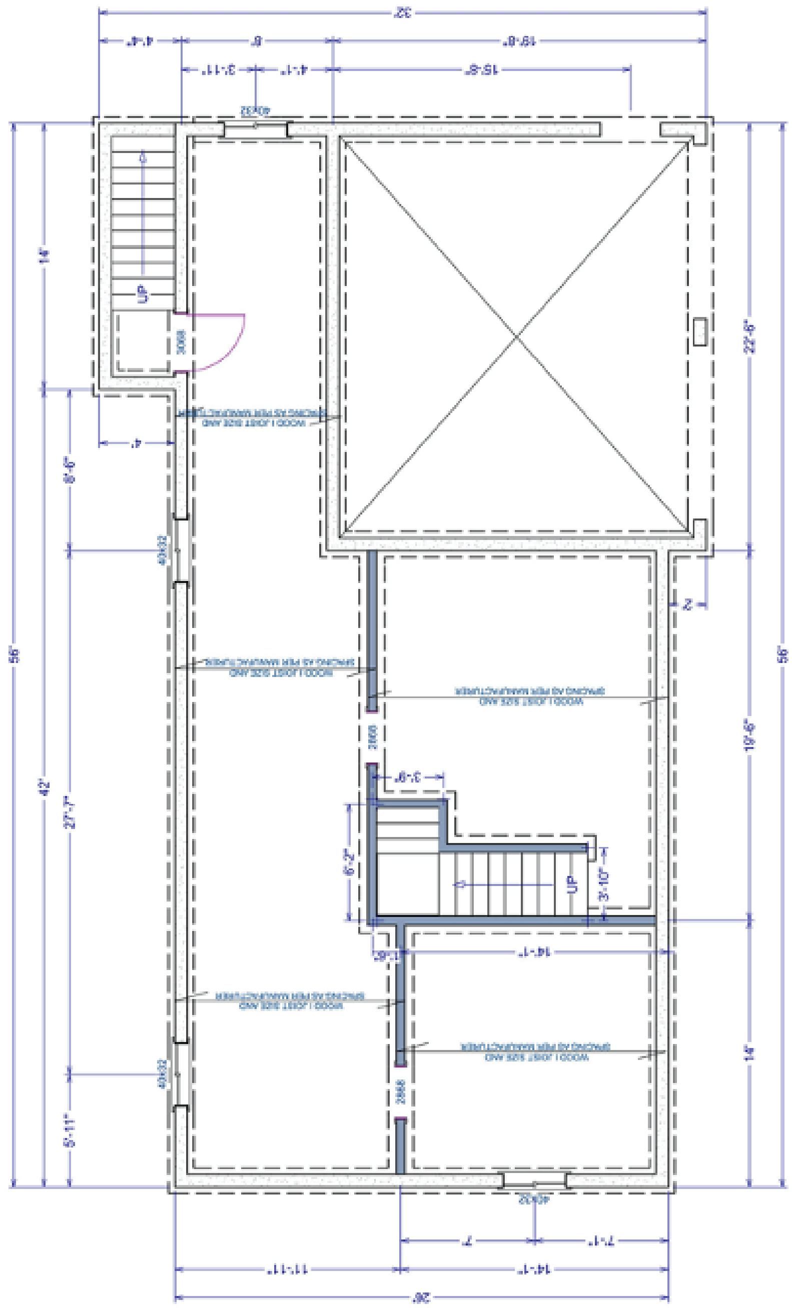


Figure 24: Main Floor Floor-Plan (Collins Homes & Renovations Ltd, 2021)

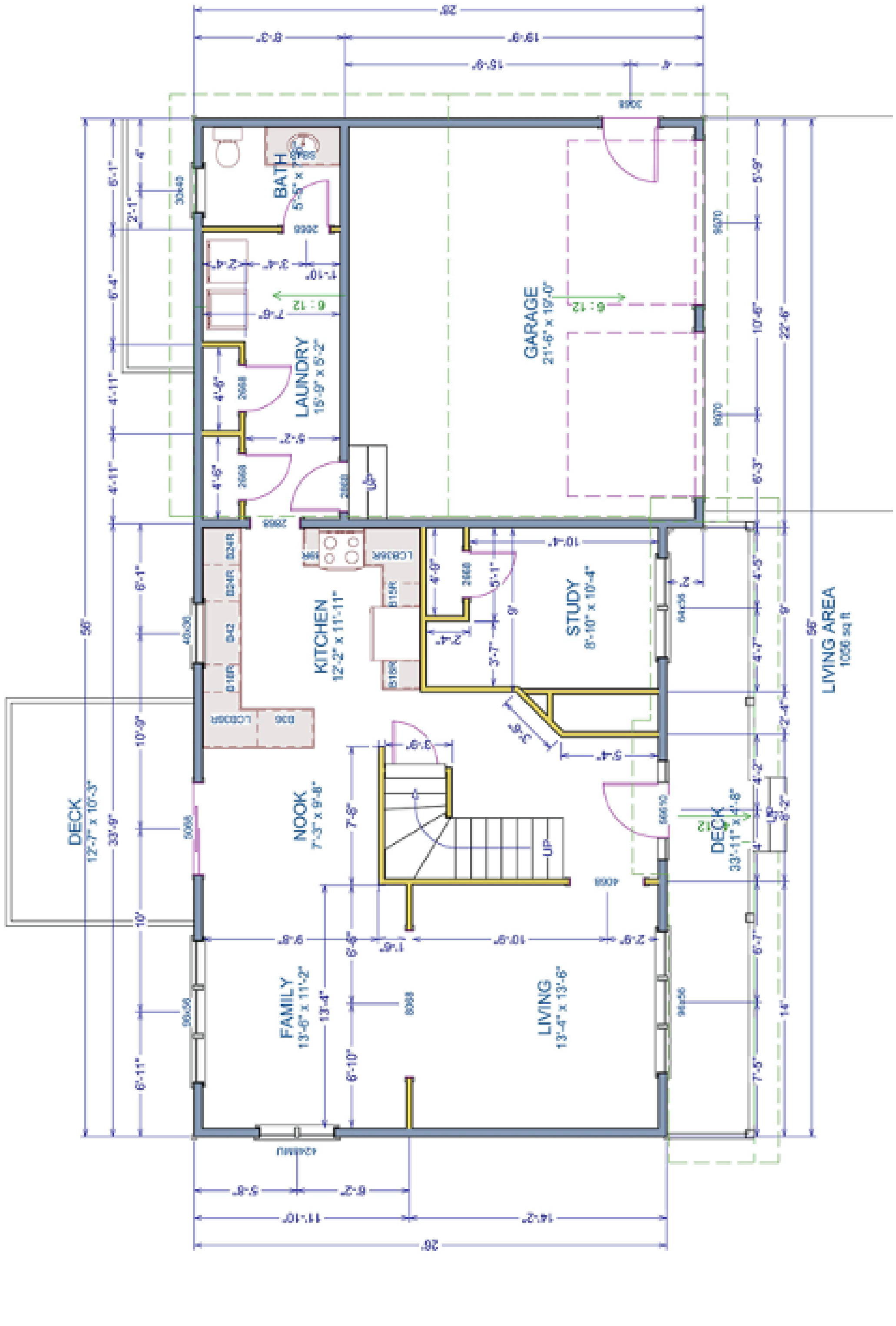
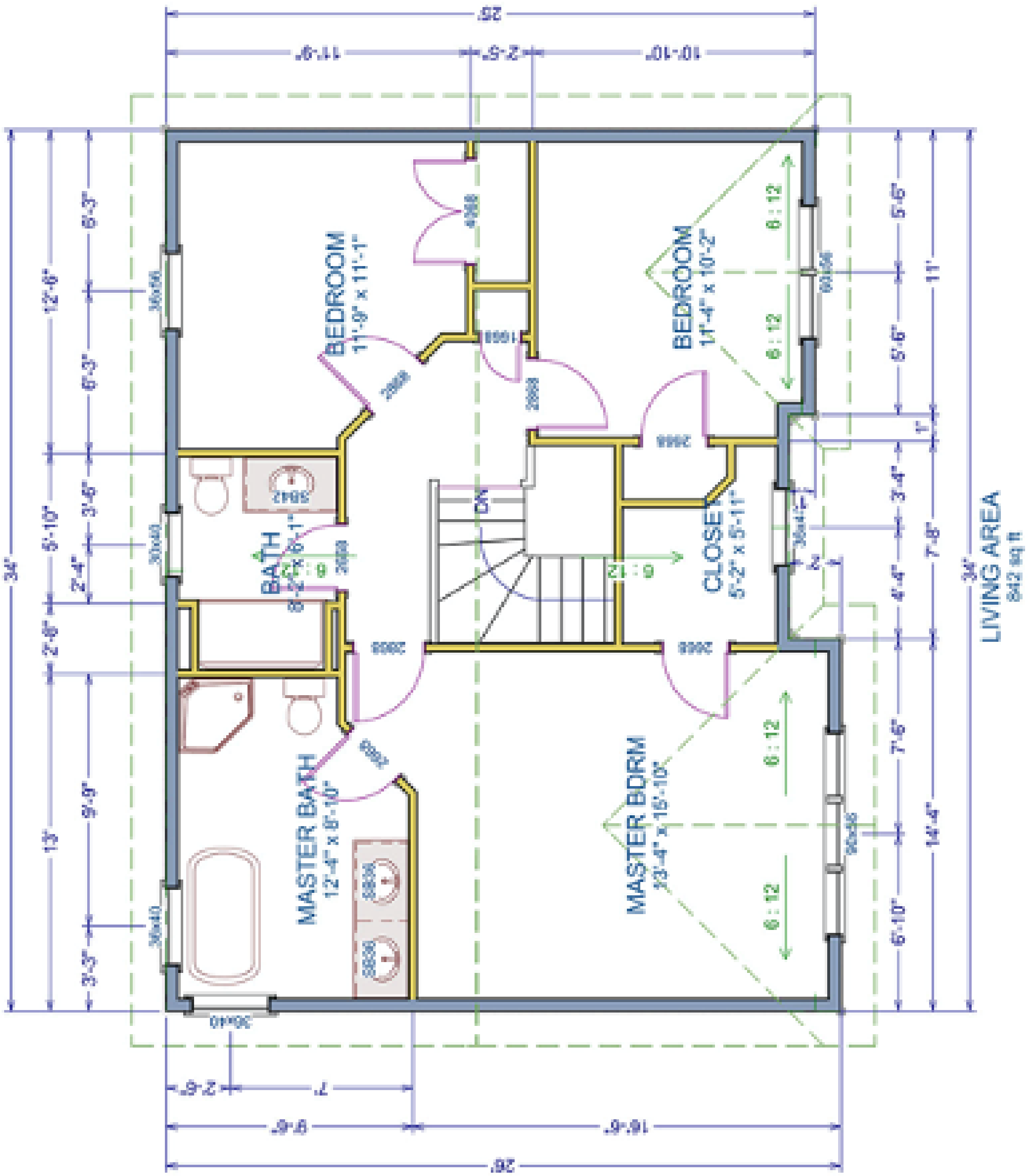


Figure 25: Second Floor Floor-Plan (Collins Homes & Renovations Ltd, 2021)



Appendix E: Electricity Grid Mix used for Nova Scotia in Athena

Table 47 shows the electricity grid mix used for Nova Scotia in Athena.

Table 47: Electricity Grid Mix used for Nova Scotia in Athena

Energy Type	Electricity Energy Percentage (%)
Bituminous Coal (Electricity)	45.3
Petroleum (DFO) (Electricity)	5.2
Natural Gas (Electricity)	19.7
Hydroelectric (Electricity)	7.5
Nuclear (Electricity)	0.3
Subbituminous Coal (Electricity)	1.6
Lignite coal (Electricity)	0.02
Solid Renewable Fuels (Biomass) (Electricity)	1.6
Liquid Renewable Fuels (Biomass) (Electricity)	0.007
Gaseous Renewable Fuels (Biomass) (Electricity)	0.003
Wind (Electricity)	6.9
Solar (Electricity)	0.0005
Petroleum (RFO) (Electricity)	0.0007
Petroleum (Other Fossil) (Electricity)	11.5
Other Gases (Electricity)	0.003
Other Fuels (Electricity)	0.007
Tidal (Electricity)	0.2

Appendix F: Bill of Materials

Table 48: Baseline Home BOM

Material	Unit	Total Quantity	Floors	Foundations	Roofs	Walls
#15 Organic Felt	m^2	1,259	0	0	547	712
1/2" Glass Mat Gypsum Panel	m^2	830	326	0	0	504
3 mil Polyethylene	m^2	214	0	0	85	129
6 mil Polyethylene	m^2	187	0	187	0	0
Air Barrier	m^2	221	0	0	0	221
Ballast (aggregate stone)	kg	4,582	0	0	4,582	0
Blown Cellulose	m^2(25mm)	1,209	83	0	1,125	0
Concrete Benchmark CAN 25 MPa	m^3	65	0	40	0	25
Double Glazed Hard Coated Argon	m^2	71	0	0	0	71
FG Batt R11-15	m^2 (25mm)	435	0	0	0	435
FG Batt R20	m^2 (25mm)	1,958	774	0	0	1,184
Large Dimension Softwood Lumber, kiln-dried	m^3	7	7	0	0	0
Nails	Tonnes	0.3	0.06	0	0.05	0.2
Polyiso Foam Board (unfaced)	m^2(25mm)	271	143	0	0	128
PVC Window Frame	kg	999	0	0	0	999
Rebar, Rod, Light Sections	Tonnes	4	0	3	0	1
Roofing Asphalt	kg	3,076	0	0	3,076	0
Small Dimension Softwood Lumber, kiln-dried	m^3	13	0	0	2	11
Softwood Plywood	m^2 (9mm)	1,263	491	0	133	640
Type III Glass Felt	m^2	1,094	0	0	1,094	0
Vinyl Siding	m^2	392	0	0	0	392

Table 49: ES Home BOM

Material	Unit	Total Quantity	Floors	Foundations	Roofs	Walls
#15 Organic Felt	m^2	1,259.1	0.0	0.0	547.2	711.8
½” Glass Mat Gypsum Panel	m^2	829.6	325.6	0.0	0.0	504.0
3 mil Polyethylene	m^2	214.0	0.0	0.0	84.9	129.1
6 mil Polyethylene	m^2	186.6	0.0	186.6	0.0	0.0
Air Barrier	m^2	220.8	0.0	0.0	0.0	220.8
Ballast (aggregate stone)	kg	4,581.8	0.0	0.0	4,581.8	0.0
Blown Cellulose	m^2(25mm)	1,427.0	83.3	0.0	1,343.7	0.0
Concrete Benchmark CAN 15 Mpa	m^3	4.3	0.0	4.3	0.0	0.0
Concrete Benchmark CAN 25 Mpa	m^3	61.2	0.0	35.7	0.0	25.5
Double Glazed Hard Coated Argon	m^2	71.3	0.0	0.0	0.0	71.3
Expanded Polystyrene	m^2 (25mm)	12.4	0.0	0.0	0.0	12.4
FG Batt R11-15	m^2 (25mm)	435.3	0.0	0.0	0.0	435.3
FG Batt R20	m^2 (25mm)	1,958.2	773.9	0.0	0.0	1,184.3
Galvanized Sheet	Tonnes	0.2	0.1	0.0	0.1	0.0
Glass Fibre	kg	157.5	0.0	0.0	0.0	157.5
Glazing Panel	kh	200	0.0	0.0	0.0	200
Laminated Veneer Lumber	m^3	0.2	0.0	0.0	0.0	0.2
Large Dimension Softwood Lumber, kiln-dried	m^3	6.9	6.9	0.0	0.0	0.0
Nails	Tonnes	0.3	0.1	0.0	0.0	0.2
Polyiso Foam Board (unfaced)	m^2 (25mm)	399.7	142.9	0.0	0.0	256.8
PVC Window Frame	kg	999.4	0.0	0.0	0.0	999.4
Rebar, Rod, Light Sections	Tonnes	3.6	0.0	3.0	0.0	0.7
Roofing Asphalt	kg	3,075.5	0.0	0.0	3,075.5	0.0
Small Dimension Softwood Lumber, kiln-dried	m^3	12.3	0.0	0.0	1.7	10.6
Softwood Plywood	m^2 (9mm)	1,263.2	490.7	0.0	132.6	639.9
Solvent Based Alkyd Paint	L	1.4	0.0	0.0	0.0	1.4
Type III Glass Felt	m^2	1,094.4	0.0	0.0	1,094.4	0.0
Vinyl Siding	m^2	392.5	0.0	0.0	0.0	392.5

Table 50: R-2000 Home BOM

Material	Unit	Total Quantity	Floors	Foundations	Roofs	Walls
#15 Organic Felt	m^2	1,259.1	0.0	0.0	547.2	711.8
½” Glass Mat Gypsum Panel	m^2	829.6	325.6	0.0	0.0	504.0
3 mil Polyethylene	m^2	214.0	0.0	0.0	84.9	129.1
6 mil Polyethylene	m^2	186.6	0.0	186.6	0.0	0.0
Air Barrier	m^2	220.8	0.0	0.0	0.0	220.8
Ballast (aggregate stone)	kg	4,581.8	0.0	0.0	4,581.8	0.0
Blown Cellulose	m^2 (25mm)	1,427.0	83.3	0.0	1,343.7	0.0
Concrete Benchmark CAN 15 Mpa	m^3	8.6	0.0	8.6	0.0	0.0
Concrete Benchmark CAN 25 Mpa	m^3	61.2	0.0	35.7	0.0	25.5
Double Glazed Hard Coated Argon	m^2	71.3	0.0	0.0	0.0	71.3
Expanded Polystyrene	m^2 (25mm)	24.4	0.0	0.0	0.0	24.4
Extruded Polystyrene	m^2 (25mm)	386.0	0.0	66.9	0.0	319.1
FG Batt R11-15	m^2 (25mm)	435.3	0.0	0.0	0.0	435.3
FG Batt R20	m^2 (25mm)	773.9	773.9	0.0	0.0	0.0
FG Batt R30	m^2 (25mm)	1,607.3	0.0	0.0	0.0	1,607.3
Galvanized Sheet	Tonnes	0.7	0.1	0.0	0.1	0.5
Large Dimension Softwood Lumber, kiln-dried	m^3	6.9	6.9	0.0	0.0	0.0
Nails	Tonnes	0.4	0.1	0.0	0.0	0.2
Polyiso Foam Board (unfaced)	m^2 (25mm)	407.6	284.1	0.0	0.0	123.5
PVC Window Frame	kg	999.4	0.0	0.0	0.0	999.4
Rebar, Rod, Light Sections	Tonnes	3.6	0.0	3.0	0.0	0.7
Roofing Asphalt	kg	3,075.5	0.0	0.0	3,075.5	0.0
Small Dimension Softwood Lumber, kiln-dried	m^3	12.1	0.0	0.0	1.7	10.4
Softwood Plywood	m^2 (9mm)	1,263.2	490.7	0.0	132.6	639.9
Solvent Based Alkyd Paint	L	2.2	0.0	0.0	0.0	2.2
Type III Glass Felt	m^2	1,094.4	0.0	0.0	1,094.4	0.0
Vinyl Siding	m^2	392.5	0.0	0.0	0.0	392.5

Table 51: NZR Home BOM

Material	Unit	Total Quantity	Floors	Foundations	Roofs	Walls
#15 Organic Felt	m^2	1,259.1	0.0	0.0	547.2	711.8
1/2" Glass Mat Gypsum Panel	m^2	829.6	325.6	0.0	0.0	504.0
3 mil Polyethylene	m^2	214.0	0.0	0.0	84.9	129.1
6 mil Polyethylene	m^2	186.6	0.0	186.6	0.0	0.0
Air Barrier	m^2	220.8	0.0	0.0	0.0	220.8
Ballast (aggregate stone)	kg	4,581.8	0.0	0.0	4,581.8	0.0
Blown Cellulose	m^2 (25mm)	1,343.7	0.0	0.0	1,343.7	0.0
Concrete Benchmark CAN 15 MPa	m^3	8.6	0.0	8.6	0.0	0.0
Concrete Benchmark CAN 25 MPa	m^3	61.2	0.0	35.7	0.0	25.5
Double Glazed Hard Coated Argon	m^2	71.3	0.0	0.0	0.0	71.3
Expanded Polystyrene	m^2 (25mm)	24.4	0.0	0.0	0.0	24.4
Extruded Polystyrene	m^2 (25mm)	452.9	0.0	133.7	0.0	319.1
FG Batt R11-15	m^2 (25mm)	435.3	0.0	0.0	0.0	435.3
FG Batt R20	m^2 (25mm)	1,050.3	1,050.3	0.0	0.0	0.0
FG Batt R30	m^2 (25mm)	1,731.5	0.0	0.0	0.0	1,731.5
Galvanized Sheet	Tonnes	0.7	0.1	0.0	0.1	0.5
Large Dimension Softwood Lumber, kiln-dried	m^3	6.9	6.9	0.0	0.0	0.0
Nails	Tonnes	0.4	0.1	0.0	0.1	0.2
Polyiso Foam Board (unfaced)	m^2 (25mm)	1,406.6	500.7	0.0	251.5	654.4
PVC Window Frame	kg	999.4	0.0	0.0	0.0	999.4
Rebar, Rod, Light Sections	Tonnes	3.6	0.0	3.0	0.0	0.7
Roofing Asphalt	kg	3,075.5	0.0	0.0	3,075.5	0.0
Small Dimension Softwood Lumber, kiln-dried	m^3	13.7	0.0	0.0	1.7	11.9
Softwood Plywood	m^2 (9mm)	1,263.2	490.7	0.0	132.6	639.9
Solvent Based Alkyd Paint	L	2.2	0.0	0.0	0.0	2.2
Type III Glass Felt	m^2	1,094.4	0.0	0.0	1,094.4	0.0
Vinyl Siding	m^2	392.5	0.0	0.0	0.0	392.5