DEVELOPMENT AND ANALYSIS OF PATHWAYS TO NEW CONSTRUCTION NET-ZERO ENERGY HOUSES IN NOVA SCOTIA

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ABSTRACT

17% of Canadian secondary energy consumption is consumed by the residential sector. Efforts to reduce this energy consumption and the associated emissions include the replacement of traditional housing with net-zero energy house designs. This concept involves decreasing energy use as much as possible through high performance enclosures and high efficiency mechanical and electrical systems as well as offsetting these small loads with on-site renewable energy generation.

An effort has been made to evaluate the techno-economic feasibility of achieving NZEB status for a new construction, detached, single family residence in the province of Nova Scotia. This is achieved using a combination of energy modelling software to estimate energy needs for proposed home designs as well as estimating the prospective monetary costs of proposed home designs. These energy use and cost evaluations are compared to a "base case", an approximation of a current typical new construction four-person home in Nova Scotia.

LIST OF ABBREVIATIONS AND SYMBOLS USED

AC	alternating current
ACH	Air Changes per Hour
AFUE	Annual Fuel Utilization Efficiency
Ar	Argon
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	building energy modelling
BIPV/T	building integrated photovoltaic/thermal
CBRM	Cape Breton Regional Municipality
CDD	cooling degree day
CFL	compact fluorescent lighting
cfm	cubic feet per minute
CHBA	Canadian Home Builders' Association
CHP	combined heat and power
CMHC	Canadian Mortgage and Housing Corporation
c-SI	crystalline silicon
DC	direct current
DHW	domestic hot water
EPS	expanded polystyrene
ERV	energy recovery ventilator
EV	electric vehicle
FIT	Feed-In Tarriff
GEGEA	Green Energy Green Economy Act
HDD	heating degree day
HP	heat pump
HPWH	heat pump water heater
HRM	Halifax Regional Municipality

HRV	heat recovery ventilator
HST	harmonized sales tax
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IESO	Independent Electricity System Operator
LCC	life cycle cost
LED	Light emitting diode
NPV	net present value
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
NSP	Nova Scotia Power
NZEB	Net-Zero Energy Building
NZEH	Net-Zero Energy House
O.C.	outside centres
PCM	phase change material
PV	photovoltaic
PURPA	Public Utility Regulatory Policy Act
RESOP	Renewable Energy Standard Offer Program
StatsCan	Statistics Canada
UN	United Nations
US DOE	U.S. Department of Energy
XPS	extruded polystyrene

CHAPTER 1. INTRODUCTION

1.1 MOTIVATION

A readily available supply of useful energy is required for the processes and services necessary for supporting civilization. As such, energy growth has been linked to increasing prosperity and well-being. Since the industrial revolution, energy used in such processes as transportation, industry and buildings has been primarily sourced from non-renewable energy stores. Although these stores offer high energy density, their finite nature threatens energy independence and security when relied upon exclusively.

Additionally, human energy needs can be expected to increase with both population and quality of life. With the population growing at an annual rate of 1.9% and expected to plateau at approximately 11 billion globally (UN, 2015), and average per capita energy consumption also increasing, it is inevitable that alternative and/or renewable energy sources will be required to meet the energy needs of the future.

The combination of these factors serves to highlight the importance of both the more efficient use of energy as well as the use of less finite and more renewable energy sources.

Of all secondary energy consumed in Canada, approximately 17% is consumed by the residential sector (NRCan 2016a). Efforts to reduce this energy consumption and the associated emissions include the replacement of traditional housing with passive and net-zero/near net-zero energy house designs. These two concepts involve the decreasing of loads as much as possible through high performance enclosures and high efficiency mechanical and electrical systems as well as, in the case of Net-Zero Energy Buildings (NZEBs), offsetting these small loads with their own on-site renewable energy generation.

To accurately describe the practicality of constructing net-zero energy homes, a clear definition of a NZEB must be established. The economic and technical viabilities of achieving this status must then be evaluated for promising technology and design options to achieve this objective.

1.2 DEFINING NET-ZERO ENERGY

Natural Resources Canada (NRCan) defines NZEBs as buildings which "produce as much energy as they consume on an annual basis" (CMHC 2011a). This definition lacks clarity as to how the energy is measured, potentially leading to confusion regarding what constitutes a NZEB. A less ambiguous definition comes from the United States Department of Energy (US DOE) which defines a NZEB as: "an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" (US DOE 2015). This definition further specifies a source energy, which is the total amount of raw energy required to produce the energy needed to operate a building over a year (Deru and Torcellini 2007).

Based on these federally established definitions a common definition for a net-zero energy building can be proposed as "a building which, through a combination of energy efficiency and on-site renewable energy collection, exports as much energy as it consumes over a year on a source energy basis". The additional requirement of offsetting energy used in the construction and demolition of the building would result in a definition for a Life Cycle Net-Zero Energy Building (LC-NZEB) (Hernandez and Kenny 2009).

In addition to the more typically accepted source and site energy based definitions of net-zero energy buildings, net energy can also be defined using energy costs or greenhouse gas emissions (Torcellini et al 2006).

The US DOE divides NZEBs into four different classifications based on the sources of renewable energy:

NZEB:A – based on renewables within the building footprint

NZEB:B – based on renewables within the site boundary

NZEB:C – based on renewables imported from off-site (e.g. biomass)

NZEB:D – based on renewable energy certificates

For the purpose of this thesis, the goal is set as achieving net-zero source energy while making use of energy harvested within the building footprint (NZEB:A).

1.3 OBJECTIVE

Over the course of this thesis, the technical and economic feasibility of achieving NZEB status for a standard design, new construction home in Nova Scotia is investigated for three primary locations. These locations; Halifax, Sydney, and Truro, constitute the primary population centres of the two largest municipalities within the province as well as the most populous individual town respectively as shown in Table 1.1. Their diverse climates also make these locations appropriate for study.

Rank	**Population centre**	**Size group**	**Population in 2016**
1	Halifax Regional Municipality (Halifax)	Municipality	403,131
2	Cape Breton Regional Municipality (Sydney)	Municipality	94,285
3	Truro	Town	12,261

Table 1.1: Population data for Nova Scotia's three largest population centres (Statistics Canada, 2017)

For comparison purposes, an approximation of a typical new construction home is developed to represent the base case. Using data concerning new home construction in the province, this base case is modelled for both construction cost and annual energy use. This design is then modified to develop subsequent models used to investigate the feasibility of potential modifications.

Technology and design modifications made to the base case are implemented in stages with a goal of decreasing net energy use as much as possible while minimizing cost increases. Four primary points of interest are displayed in Figure 1. During design modification and efficiency increases, increased costs from the initial condition (1) is offset by energy savings up to a minimum cost point (2). From this point onward, efficiency increasing measures result in an increase in total costs until a point is reached at which energy savings would reach monetary parity with energy harvested using photovoltaic (PV) cells (3). From this point, the size of PV system can be increased until NZEB status is achieved (4).

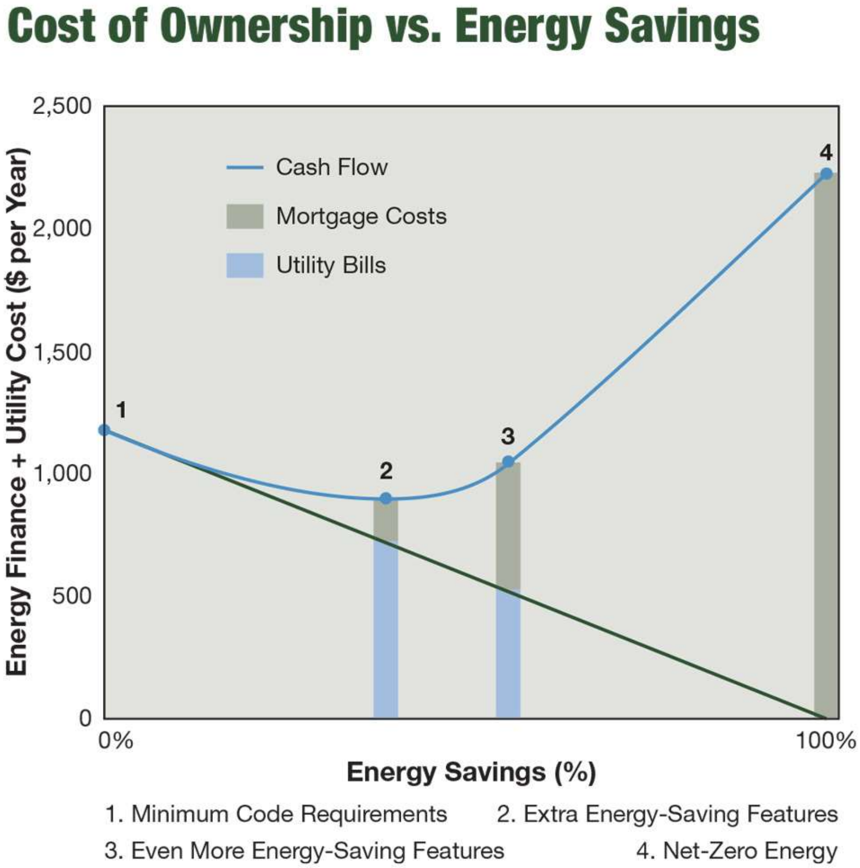

Figure 1.1: Cost of ownership vs energy savings trend towards NZEB (Klingenberg, 2015)

Findings from this work will provide guidance to home builders in the province to design and build homes which meet the minimum cost, net-zero energy ready and NZEB status with confidence in both the energy use and the cost associated with such a construction.

CHAPTER 2. LITERATURE REVIEW

2.1 HISTORICAL DEVELOPMENTS

2.1.1 History of Net Energy as a Concept

The concept of net energy has its roots in papers published by Ukrainian economist Sergei Podolinsky in the late 19th century (Podolinsky 2004). Combining ideas from the Physiocrat movement of the 18th century which posited that all value was derived from land and agriculture with the then recent breakthroughs regarding thermodynamics, Podolinsky hypothesized that all value was in fact derived from energy. This idea was further developed by English chemist Frederick Soddy's suggestion that energy is a more fundamental measure of value than currency (IAEA 1994). The first recorded analyses of the net energy balance of industry processes were conducted in the 1920s by a group of American scientists and engineers known as the "Technical Alliance"(Berndt 1982).

Further development of the concept of net energy would be spurred on by the two "energy crises" of the 1970s. These crises exposed the western world's reliance on foreign oil stocks, prompting an acceleration of research regarding energy sources. The application of the law of entropy to the economic model was a particularly important breakthrough, as it stressed that energy lost in the net energy balance of a process had ceased to be useful (Georgescu-Roegen 1986). The concept of net energy also began to impact government policies, with the American Research and Development Act of 1974 stating "the potential for the production of net energy by the proposed technology at the stage of commercial application shall be analyzed and considered in evaluating proposals".

2.1.2 History of Net-Zero Energy Buildings

The modern movement towards a zero-energy house began with attempts to use solar heat to create a house requiring no outside energy for heating. The earliest example of this can be seen in the Massachusetts Institute of Technology's Solar House I, constructed in 1939. This house, which served to spawn a series of subsequent prototype houses, made use of a large solar collection area and water storage to achieve its heating needs using solar energy (Ionescu et al. 2015)

The earliest development towards NZEBs in Canada was seen in the Saskatchewan Conservation House completed in 1977. Making use of a high insulation envelope, an infiltration rate of 1.3 *Air Changes per Hour at 50Pa* (ACH_{50}) and air-to-air heat exchangers, this building required less solar energy collection and storage area than previous zero-energy heating applications. This house surpassed its objective of reaching a heat loss rate of 81 Watts per degree Celsius difference between outside and inside temperature (Hernandez and Kenny 2009).

Applications of net-zero energy principles have led to the creation of voluntary standards for energy efficiency in homes. These standards include the Canadian R-2000 (NRCan, 2012) and German Passivhaus (Passivhaus Trust, 2012) standards which encourage the use of high-performance insulation, air-tight building envelopes and heat recovery systems to reduce the energy needed for home heating. While not specifically designed for zero energy or zero heating buildings, homes meeting these standards are much more easily retrofitted to meet these criteria.

The R-2000 standard has resulted in tangible goals for Canadian homebuilders to meet with regards to energy efficiency. Natural Resources Canada has begun a pilot program for the construction of net-zero energy homes under the R-2000 program (NRCan, 2018). The most common approach to this goal is currently the use of electricity from the utility grid as both the source and sink for electricity. In this case, the "net energy" refers to the annual difference between that sourced from the grid when the building's demand is not met by on-site renewables and that returned to the grid when on-site renewables exceed demand.

The tracking of energy in the form of electricity to and from the grid is made possible through **net-metering**, in which a single meter is used to track the net electrical energy use, typically either on a monthly or annual basis. Alternatively, separate meters can be used to track energy taken from and returned to the grid, with the energy returned to the grid being purchased under a **feed-in tariff** (FIT). FITs are a policy mechanism enacted to accelerate the adoption of renewable energy technologies. Under FIT programs, renewable energy producers are offered long term contracts guaranteeing that any excess electrical energy returned to the grid is purchased at a pre-determined price, sometimes higher than that charged by the utility provider. These prices are also dictated by the cost of production associated with the renewable energy gathering technology in question.

Net metering as a policy began in the United States in 1983 when both Minnesota and Iowa adopted it at a state level (DSIRE, 2018a). The initial reasoning behind this was to bypass the possibility of the utility buying the energy at a rate of their own choosing, as allowed by the 1978 Public Utility Regulatory Policy Act (PURPA), Section 210 of which states that the customer can sell excess energy back to the utility provider (Stoutenborough and Beverlin 2008). This act is considered a forerunner to the FIT programs of today and was followed in 1991 with Germany's **Electricity Feed-in Law** (IEA, 2013a). This law, unlike PURPA which left the buyback price to the discretion of the individual states, mandated at a federal level that electric energy be bought back at a rate of 65-90% of the retail rate, depending upon both the technology type and the size of the project used. This concept would eventually lead to the development of FIT schemes based on the costs to generate renewable energy, such that efficiently run renewable energy projects could be run at a profit (Couture et al. 2010).

The Canadian province of Ontario's FIT program was established initially in 2006 with the adoption of **Renewable Energy Standard Offer Program** (RESOP) (IEA, 2013b). This program allowed renewable energy producers to enter 20-year contracts in which projects with a capacity smaller than 10MW would earn a fixed price of 11 cents (CDN) per kWh, except for solar PV which earned a fixed price of 42 cents per kWh. By the end of 2008 this project had secured 443 contracts with a total capacity of 1,419MW, 90% of which was wind and solar PV. After 2008 this program was replaced with Ontario's current FIT program.

Due to potential customers experiencing difficulties both connecting to the grid and financing feasibility studies for potential projects, the **Green Energy and Green Economy Act** (GEGEA) was established in Ontario (Sinclair, 2013). One of the most notable features of this act, which attempts to encourage communities to become involved in a more sustainable energy economy, is MicroFIT, a FIT program established for renewable energy projects with a capacity of less than 10kW (Mabee et al. 2012). Contract prices per kWh in this program are given in Table 2.1.

Renewable Fuel	Price ($/kWh)					
	Inception	5 April 2012	26 August 2013	30 September 2014	21 June 2016	1 January 2017
Solar (PV) (rooftop)	$0.802	$0.549	$0.396	$0.384	$0.313 (< 6kW) $0.294 (> 6kW < 10 kW)	$0.313 (< 6kW) $0.288 (> 6kW < 10 kW)
Solar (PV) (non-rooftop)	$0.642	$0.445	$0.291	$0.289	$0.214	$0.210
On-shore wind	$0.135	$0.115		$0.128	$0.128	$0.125
Waterpower	$0.131		$0.148	$0.246	$0.246	$0.241
Renewable biomass	$0.138		$0.156	$0.175	$0.175	$0.172
Biogas	$0.160		$0.164	$0.168	$0.168	$0.165
Landfill gas	$0.111		$0.077	$0.171	$0.171	$0.168

Table 2.1: Contract prices for renewable energy under Ontario's MicroFIT Program (IESO 2017)

The rate paid for energy from rooftop PV systems at the inception of the MicroFIT program played a role in the Independent Electricity System Operator receiving nearly 1200 applications for the program in less than a year (IESO 2009). At nearly eight times the retail price for energy, this rate allowed the Canadian Mortgage and Housing Corporation to retrofit a post-war, 1-1/2 story Ontario home to reach net-zero energy costs as part of the Now House Windsor Five project (CMHC 2011b).

2.2 REDUCTION OF SPACE CONDITIONING ENERGY NEEDS

In Canada, 60% of residential energy use is for space heating purposes, constituting approximately 10% of Canadian secondary energy usage (StatsCan, 2014). Residential energy use in Canada has been increasing in recent years, based largely on the increasing size of Canadian homes. Between 1990 and 2005, for example, the average floorspace of a new home in Canada increased 19% from 126m^2 to 149m^2 (NRCan, 2017). In addition to an increase in the size of homes, Canada's growing population and a reduction in the average number of individuals per household from 2.8 in 1990 to 2.6 in 2005 have resulted in an increase in residential construction (NRCan 2009).

2.2.1 Building Envelope

An increase in both the number of houses as well as the floor space of the average Canadian home yields even greater potential savings from an increase in space heating efficiency. In terms of cost effectiveness, the most viable way to decrease space heating needs in most existing Canadian housing stock is by improving the building envelope performance in terms of air tightness and insulation values. For example, the Canadian Mortgage and Housing Corporation (CMHC) recommends the insulation levels given in Table 2.2 in order to achieve NZEB status.

Component	**Recommended RSI-value (R-value)**
Window	RSI-0.88 (R-5)
Slab	RSI-2.64 (R-15)
Basement Walls	RSI-3.52 (R-20)
Above Grade Walls	RSI-7.04 (R-40)
Ceiling	RSI-10.57 (R-60)

Table 2.2: Suggested R-value to achieve net-zero energy (CMHC 2011A)

In terms of placement, insulation and air tightness, windows present a viable option in improving building envelope performance. Since windows typically have the lowest R-values of building envelope components, relatively small increases in insulation can yield greater energy savings than those seen with the same increases in insulation elsewhere. For example, an increase from R-5 to R-10 will result in twice the energy savings compared to those achieved from an increase from R-10 to R-20. This is a result of the reciprocal relationship between thermal resistance and heat transfer coefficient, with heat loss being linearly related to the heat transfer coefficient.

The thermal resistance of a window is dependent on multiple factors in its construction. These are the number of panes, the spacing between panes, the gas used in the spacing, the emissivity of the material used, the thermal characteristics of the material used, the frame type and the operability of the window. In general, lower emissivity (~>0.20), multiple glazings, greater space between panes and the use of argon for the spaces are among the manufacturing practices associated with high performance windows.

Air tightness can prove to be even more important with regards to containing energy within the building envelope. The USDOE estimates that as much as 40% of heat energy lost by homes is lost due to air leakage (Niemeyer et al. 2011).

In addition to their air tightness and insulation levels, the placement of windows is important with regards to efficiently maintaining a comfortable temperature in the Canadian climate. This is accomplished through the placement of windows in a southern orientation, facing the sun's position in the northern hemisphere, with a highly thermally massive wall or floor allowing the solar heat allowed through these windows to be stored and dispersed through the day. This is an example of what is known as "Passive Solar

Design”. Passive solar design makes use of awnings or other forms of shade to allow the sun in during the winter season when it is typically lower in the sky than the summer season in which this shade blocks the higher sun, preventing excess heat during the warmer season (Anderson & Michal, 1978).

The remainder of the building envelope, including the walls, slab, ceiling and roof, is much more easily insulated to higher R-values than windows due to most window materials (e.g. glass) having relatively low thermal resistance. A summary of insulation materials typical to the Canadian housing market is provided by NRCan’s Keeping the Heat In (2012) document.

2.2.2 Ventilation Systems

In addition to maintaining a comfortable temperature, a steady supply of fresh, outdoor air is necessary to maintain suitable living conditions. For the case of a dwelling unit, ASHRAE Standard 62.1 dictates an outdoor air supply rate of 5 cfm/person and an additional 0.06 $\mathrm{cfm/ft^2}$ (ASHRAE, 2016).

The amount of energy used to provide this supply of fresh air is dependent largely on the type of ventilation system used and the efficiency of its components. A simple direct exhaust system’s efficiency will be based solely on the efficiency of the motor used, the fan’s design and the placement of the system. A ducted system can result in additional inefficiencies caused by pressure increases in ductwork.

In addition to the energy required to introduce fresh air to the building envelope, ventilation systems can result in an increase in energy requirements for space conditioning due to the addition of unconditioned outside air to the building envelope. To minimize the impact this outdoor air has on indoor conditions, it is recommended that a heat recovery ventilator (HRV) or energy recovery ventilator (ERV) is used. These ventilation systems make use of a heat exchanger between the exhaust and supply air, allowing the incoming air to have more similar properties to indoor conditions.

In the case of an HRV, the heat exchanger used only allows for the transfer of sensible heat energy, changing only the dry-bulb temperature of the air supplied to the space. An ERV, however, allows for the transfer of water vapour as well, providing humidity control. Most ERVs can capture 70% to 80% of heat energy from the exhausted air and are most cost-effective in areas with extreme cold or hot seasons (US DOE, 2018).

2.2.3 Space Heating Systems

In addition to these methods of keeping heat energy within the building envelope, heating energy can be saved using more efficient heat sources. Although 55% of Nova Scotian households used oil burning furnaces as of 2007, the use of heat pumps has become increasingly popular in the province in recent years with a nearly 300% increase from ~5800 in 1990 to 19,800 in 2014 (representing 1.8% and 4.5% of homes respectively). Natural gas has also been increasingly popular with 7900 furnaces in 2014 (1.8% of homes). This is a result of the increasing availability of natural gas and the necessary infrastructure within the province (NRCan 2016b).

Heat pumps import heat energy to the building envelope from multiple sources, such as outside air, water and geothermal heat, by using a refrigeration cycle to reverse the natural high to low temperature transfer of heat. These systems are typically defined by their source (origin of heat energy) and sink (medium being heated) (Howell, Coad & Sauer, 2013):

- **Air-to-Air Heat Pumps**
- **Water-to-Air Heat Pumps**
- **Groundwater heat pumps**
    - ***Surface water heat pumps***
    - ***Solar-assisted heat pumps***
    - ***Wastewater source heat pumps***
- **Water-to-Water Heat Pumps**
- **Ground-Coupled (Geothermal) Heat**

Waste heat, typically lost to the environment, can also be recovered from equipment found in the home. In the case of a net-zero energy home especially, where electricity generation is desired, waste heat from electric generators can be used to provide heat to the home. This process of generating electricity and useful heat at the same time is referred to as **Cogeneration** or, more specifically to home use, **MicroCHP** (Combined Heat and Power) (Manning et al, 2008).

Combined heat and power units commonly make use of Stirling engines, internal combustion engines, or fuel cells to generate electricity, while energy typically lost in the form of waste heat is used to provide space heating. Bianchi et al, 2012, found that, when used in the European market, MicroCHP systems offer a 15-45% energy savings when compared to separate electricity and heat generation.

Heat can be reclaimed from the lubricating system, jacket cooling system, and exhaust in all internal combustion engines, except for small, air-cooled units which lack a jacket cooling system. As shown in Table 2.3, most of the fuel energy is rejected to the jacket water or as exhaust.

Useful Work	33%
Friction and Radiation	7%
Rejected in Jacket Water	30%
Rejected in Exhaust	30%

Table 2.3 Approximate Distribution of Input Fuel Energy for Internal Combustion Engine (Howell et al. 2013)

Neither all jacket heat nor all exhaust heat can be recovered, with a maximum of approximately 70% of each being usable. This amounts to a total of roughly 40% of the input fuel energy being available for space heating purposes (Howell et al. 2013).

Energy required for space heating can also be reduced using more efficient heating methods. These can include changing thermostat setpoints, the integration of "smart" thermostats, changing to a more efficient heating fuel, and the use of more efficient heating equipment.

The use of lower heating setpoints results in a decrease in both heating demand and heat losses. By not requiring a space to be heated more than necessary demand is limited, while limiting the temperature difference between outdoor and indoor air also results in less heat being lost to convection. The extent to which this method can limit heating costs, however, is limited by the need to maintain a comfortable indoor temperature. Indoor temperatures recommended by ASHRAE Standard 55 range from 20.3°C (68.5°F) to 23.9°C (75°F) in the winter, and from 23.9 °C (75°F) to 26.9 °C (80.5°F) in the summer (ASHRAE, 2013).

Recommended comfort temperatures vary based upon both the clothing and activity levels of occupants, which can vary through the day, as can occupancy levels. Additionally, while sleeping, comfort temperatures can be lower than those desired through the day (Song et al. 2015). This change in comfort temperature range over the course of a typical day means heating energy consumption can be reduced by changing thermostat setpoints through the day to match these changing comfort temperatures. Traditionally, this was performed manually as the desired temperature changed. Recently, however, the advent of the programmable “smart” thermostat has allowed these adjustments to be made automatically using both occupancy sensors and manually selected schedules.

Programmable thermostats can change the heating and cooling temperature setpoints for home equipment while the house is unoccupied, as well as while occupants are sleeping, potentially presenting upwards of 25% efficiency savings (Lu et al. 2010).

2.2.4 Other Space Conditioning Requirements

In addition to space heating, spaces can also be conditioned through cooling and humidity control via air-conditioning systems, humidifiers, and de-humidifiers. Although these forms of space conditioning are of a concern in the commercial and industrial sectors, they account for approximately 2% of energy use in the Canadian residential sector (NRCan, 2018). The increasing prevalence of reversible heat pumps, and therefore the ability to provide space cooling may result in an increase of space cooling energy use in Canada. Despite the growing presence of these systems, however, the Canadian climate does not result in a need for space cooling on the same scale as it does for space heating.

2.3 REDUCTION OF ENERGY USE FOR OTHER EQUIPMENT

Beyond space conditioning, residential energy use in Canada also includes water heating, appliances, and lighting. These subcategories use 24.2%, 10.6% and 2.9% of Canadian residential energy usage, respectively. The use of more efficient equipment, as well as less intensive scheduling options can be used to reduce residential energy consumption for these purposes.

2.3.1 Lighting

The use of electricity to provide lighting, both practical and aesthetic, is important for many home owners. Several options exist to reduce the amount of energy used to provide this lighting including the use of daylighting, timed and dimmable lights, more efficient light placement, and more efficient lighting technologies.

Efficient design of spaces for lighting purposes involve the placement of lights in areas which provide lighting as exclusively as possible to necessary spaces. This avoids wasting lighting energy by lighting unused space. Additionally, natural light through windows or daylighting should be maximized, allowing lighting to be provided during daylight hours with minimal energy expenditure.

In addition to design considerations, lighting energy use can also be reduced by taking advantage of technology. Primarily, different forms of electric lighting offer different levels of efficiency. Incandescent lightbulbs, for instance, typically offer efficiencies of less than 5% with standard lightbulbs averaging 2.2% efficiency (Armaroli et al. 2011). Halogen incandescent lightbulbs, which include halogens such as iodine or bromine, offer 28% energy savings over traditional incandescent bulbs in addition to three times longer lives. Compact fluorescent lighting (CFL) offers even greater energy savings with Energy Star certified models using 75% less electrical energy to provide the same amount of lighting as the equivalent incandescent bulb in addition to offering lives up to 8 times longer. The most efficient option available to residential consumers, however, is the use of light emitting diode (LED) lightbulbs which use even less energy than CFL while lasting as much as 25 times as long as incandescent lightbulbs. (NRCan, 2015)

The amount of energy used for lighting can also be reduced using controls on the lights such as timers, dimmers, and motion sensors. Dimmers allow only the desired amount of light to be used, however, energy use benefits associated with dimmers are maximized with the use of LED bulbs which see a linear power use trend as dimmed. (Bierman, 2001) Both timers and motion sensors allow for lights to be automatically switched off when not in use, preventing potential accidental lighting energy use.

2.3.2 Major Appliances

Large appliances constitute large, stationary appliances used for refrigeration (refrigerators and freezers), cooking (ovens), and cleaning (washing machines, clothes dryers, and dishwashers). Appliances sold in Canada are regulated, with tests conducted to evaluate the energy efficiency and estimated annual use being evaluated and made available to consumers through the EnerGuide program (NRCan, 2018). Information provided by this program both on appliances themselves and through a government produced directory allows for estimated energy use for different appliance models to be evaluated by Canadians (NRCan, 2013).

In addition to the use of energy efficiency data provided through EnerGuide and the similar EnergyStar program, it is possible to minimize large appliance energy consumption by minimizing their use. One viable way of eliminating clothes dryer energy use is by maximizing the amount of air drying of clothing and other fabrics. Due to the natural sublimation of water from fabrics to the air, the air drying of clothing is possible in all temperatures allowing for the complete elimination of a clothes dryer if desired. Clothes dryers are among the largest energy use appliances, with EnerGuide data estimating annual usages of nearly 1000kWh for most models.

2.3.3 Small Appliances and Plug Loads

In addition to large appliances, other smaller appliances and electronics can also account for a roughly equal portion of a home's appliance energy use. Many of the appliances and electronics within the home are used only occasionally, meaning that by leaving them plugged in or in stand-by mode can result in "phantom load", electrical power draws even when not in use (Talebi and Way, 2009). Television standby modes, for instance, draw an average of approximately 25W of electricity.

Many electronics allow for settings to be altered to reduce energy usage. Televisions and other screens are often sold set to "showroom" settings which allow the screen to be easily seen in the bright light of a commercial showroom. The brightness necessary for such showrooms far exceeds that for a typical home, with light sensing features resulting in an estimated 30-50% power reduction when brightness is adjusted for watching television with lights turned off (The Guardian, 2014).

Miscellaneous electrical loads account for an estimated 3400 kWh of electrical energy use in the average American household (Hendron and Engebrecht, 2010).

2.3.4 Domestic Hot Water

Heating domestic hot water (DHW) to comfortable temperatures accounts for 18% of Canada's residential energy use. Systems based on electric resistance, fuel-fired, and compression heat pumps can be employed to provide hot water. Additionally, the use of water tanks allows for smaller capacity heaters to provide the energy necessary to heat water to desired temperatures over a longer time. These tanked water heaters have two primary drawbacks with regards to energy efficiency, however:

1. They must be well insulated to avoid losing heat to the surrounding area
2. Water stored in a tank must be heated to approximately 60°C in order to prevent the growth of Legionella bacteria (Levesque et al. 2004)

Tankless water heaters, on the other hand, allow for water to be heated as demanded, minimizing inefficiency. (US DOE, 2012)

The efficiency of different energy sources and heating designs for DHW is like those discussed with regards to space heating.

The simplest manner of reducing DHW energy needs is through reducing the amount of water heating required. This can be accomplished through a combination of reducing water usage through lower flow rate fixtures and appliances and through reducing the temperature demand of water used. Laundry and other forms of cleaning, for example, can be performed with unheated water.

2.4 RENEWABLE ENERGY AND OTHER ON-SITE ENERGY PRODUCTION

In addition to the reduction of annual energy use, achieving net-zero energy status requires energy to be exported from the site to offset any imports.

2.4.1 Solar Photovoltaic Systems

Commercially available PV modules can currently be defined as belonging to one of two categories (Strong 2016):

Thick Crystal Products: make use of crystalline silicon solar cells as either single or poly-crystalline wafers. These products can deliver 150-200 Watts of electricity per m^2 of PV array under full sun.

Thin-film products: make use of very thin layers of photovoltaically active material placed on a glass superstrate or a metal substrate using vacuum deposition to ensure the film is properly adhered. These products can produce 45-60 Watts of electricity per m^2 of array, typically at a lower cost compared thick crystal products due to much lower requirements for active materials as well as energy used in their production.

In terms of the mounting of such systems, options include land on the site as well as the rooftop or other building surfaces. Rooftop mounting systems are especially popular as they allow the systems to occupy otherwise unused space in addition to raising them above potential sources of shade. To maximize their efficiencies, PV systems should be positioned to maximize their exposure to sunlight. In the Northern hemisphere, this entails a southward azimuth orientation at a tilt angle dictated by the location's latitude. This tilt can differ depending on the desired frequency of adjustment, changing the tilt angle of a PV system depending on the sun's position in the sky, especially further from the equator where this varies through the year, can help to maximize a system's efficiency (Parida et al. 2011).

A subcategory of building-mounted PV systems is the Building Integrated Photovoltaic/Thermal (BIPV/T) system which includes a cooling system integrated into the building and PV system, allowing excess heat which can negatively impact the efficiency of panels to be redirected into the building, aiding in space and/or water heating.

In addition to the PV modules, a typical PV system requires a charge controller that controls the electricity transferring into and out of the system if battery storage is used; a battery storage system to allow excess electricity to be stored for later use; power conversion equipment, including and inverter, to convert the PV's DC electrical generation into the AC electricity used in most buildings; and the necessary support and fastening equipment as well as proper wiring and safety disconnects.

As research into the design and manufacture of photovoltaic systems advances, so too has the affordability of such systems. As of 2015, the NREL estimated the cost of photovoltaic systems to be US$3.09 per Watt of capacity installed at a residential level (assuming a 5kW system, the average capacity of such systems in the United States). According to the HRM's Solar City program, however, the average cost of installed PV systems in Halifax in 2019 is $2.55 per Watt. Because of this increasing affordability, there has been rapid growth in the available capacity of PV systems worldwide over the past decade, with a total of nearly 400,000 MW achieved in 2017 compared to just 16,200 MW ten years prior in 2007 (Hill 2017).

This decrease in cost, as well as an increase in availability of knowledgeable technicians in the field of installation and maintenance of PV systems, is making this form of on-site electricity generation more and more practical for homeowners and other building operators (Kanchev et al. 2011).

2.4.2 Solar Thermal Collectors

In addition to the use of solar energy to produce usable electrical energy using the photovoltaic effect, solar energy can be more simply converted to thermal energy to provide both space and water heating. Like photovoltaic systems, solar thermal collectors are often placed on building rooftops and oriented to maximize their exposure to solar radiation. The most commonly seen application of solar heating in the residential sector is solar water heating. (Norton, 2013)

The popularity of solar hot water systems is due to their simplicity. By not requiring the use of complex photovoltaic panels as seen in solar electric systems, as well as requiring water be heated to a relatively low temperature (~55°C), a simple flat plate collector can be employed. Solar water heating has been employed since the 19th century in the form of rooftop mounted water tanks.

2.4.3 Additional On-site Energy Harvesting Options

Along with solar, wind-based electrical generation has experienced exponential growth over the past two decades. Over 20 years, global electrical capacity of wind power increased from just 6.1 GW in 1996 to 486.6 GW in 2016. (GWEC 2012) As a result, wind power now accounts for approximately 4% of global electricity use, including 11.4% in the European Union. (EWEA 2016)

Unlike solar electricity, however, wind-based electrical generation is typically reserved for larger scale turbines which often make up part of a larger wind farm. Although small-scale wind-based electrical generation does exist, it is much less commonly used than PV systems for on-site electrical generation due to the very low efficiency of small (kW) scale wind turbines and unpredictable wind patterns in urban locations.

2.4.4 Exporting and Storing Excess Energy

Excess energy produced on the site of a net-zero energy building must be either stored for later use or exported for off-site use.

The exporting of excess energy away from the site is typically conducted in the form of electricity using the electrical grid. The use of a net metering system allows for electricity to be returned to the grid when on-site systems produce more electrical power than is required by the home. (DSIRE, 2012) Additionally, if the electric charging of an electric vehicle (EV) is conducted on the site, energy used in driving the EV can be considered "exported", contributing towards net-zero energy status (Salpakari et al. 2017).

In locations which make use of district heating systems heat energy can also be exported to be used heating other sites. Such systems are not available for residential customers in Nova Scotia.

On site energy storage can consist of the use of a thermal mass to contain heat energy to be given off later when it is required, as well as the storage of electrical energy in a battery system within the house (Nguyen et al. 2017).

2.5 ISSUES SPECIFIC TO NOVA SCOTIA

In addition to the general issues associated with the design of net-zero energy buildings, developing a model to achieve such a building in Nova Scotia comes with a set of issues specific to the region. These are the area's weather characteristics and existing energy infrastructure.

2.5.1 Weather Characteristics

Nova Scotia is defined by ASHRAE as having a climate zone of 6A (cold, humid) (British Columbia, 2014). Using CFB Shearwater (the closest weather station to Halifax, the provincial capital and largest population centre) as a reference, average monthly and annual high and low temperatures are given in Table 2.5.

Month	**High**	**CDD**	**Low**	**HDD**
January	0	0	-8	681
February	0	0	-8	532
March	4	0	-4	559
April	9	0	1	416
May	14	5	6	231
June	20	27	11	154
July	23	99	14	22
August	23	100	15	16
September	19	29	12	103
October	13	0	6	301
November	8	0	1	413
December	3	0	-4	634
Annual	11	260	4	4062

Table 2.4: Average monthly temperature high and lows for Halifax including heating and cooling degree days

2.5.2 Insolation

Despite its coastal location resulting in an increase in annual precipitation compared to much of the country (annual average of 1468mm for Halifax vs 831mm for Toronto) (Environment Canada, 2018), Halifax receives enough solar radiation to make the use of solar thermal and electricity viable. On average, 43% of annual daylight hours are considered to have bright sunshine, constituting 1962 hours of bright sunshine annually (Environment Canada, 2018). Based on NREL's PVWatts program, a typical PV solar system with a 4kW capacity, 14% losses, southward azimuth and 45° tilt can be expected to produce 5,022kW of electricity annually. Because of Halifax's Northern latitude (~45° N), however, the amount of electricity generated each month is inconsistent as shown in Table 2.6.

Month	**Electricity (kWh)**
January	324
February	394
March	508
April	447
May	490
June	476
July	490
August	510
September	466
October	397
November	260
December	258
Annual	5022

Table 2.5: Monthly electrical generation for 4kW PV system, CFB Shearwater (Dobos, 2014)

2.5.3 Energy Availability

In terms of access to inexpensive energy, Nova Scotia is at a distinct disadvantage due to the lack of natural gas supply in much of the province. Because of this lack of supply, while most North Americans can access natural gas at a cost of approximately $2-3USD/GJ, Nova Scotians pay an estimated $6-9USD/GJ (Heritage Gas, 2018). Due to both the added expense and resulting lack of infrastructure to supply natural gas to many homes and businesses within Nova Scotia, the use of natural gas for space and water heating, as well as to produce electricity, is underutilized within Nova Scotia (Chronicle Herald, 2017).

In addition to a lack of access to natural gas, Nova Scotia is also subject to increases in electricity costs. In the decade from 2004 to 2014, for instance, residential electricity prices from the province's electrical utility nearly doubled from 8.61 to 14.95c/kWh while also achieving 60% of its electrical output through the burning of solid fossil fuels, primarily in the form of coal (Energy Nova Scotia, 2015).

2.6 INCENTIVES, MANDATES AND PROGRAMS

With many governments both within Canada and abroad having recognized the importance of energy independence and reduction of greenhouse gas emissions, various programs have been established to finance and incentivise the more efficient use of energy. Many of these programs extend to the efficient use of energy within the residential sector. Additionally, many private institutions have established their own standards with regards to energy efficiency.

2.6.1 Halifax Solar City Program

To incentivize the use of solar energy within the city, the Halifax Regional Municipality (HRM) established the Solar City financing program in 2012 as a pilot program before eventually expanding. The Solar City program offers financial assistance as well as evaluation of potential solar electric, hot air, and hot water systems for HRM residents (HRM, 2018).

2.6.2 Efficiency Nova Scotia Rebates

Efficiency Nova Scotia, a non-profit entity devoted to managing Nova Scotia's electricity use from a demand side perspective, offers savings and rebates to residential customers of Nova Scotia Power within the province (EfficiencyNS, 2016).

2.6.3 Natural Resources Canada R-2000

In collaboration with the Canadian Home Builders' Association (CHBA), Natural Resources Canada developed the R-2000 program in 1981 before formalizing it as a standard in 1982 (RDBA, 2018). R-2000 is a voluntary standard which exceeds building code standards for energy efficiency, indoor air quality, and environmental responsibility.

The R-2000 standard is regularly updated to reflect increasing building standards and improving technology. A typical R-2000 home features:

- high insulation levels in walls, ceilings and basements
- high-efficiency windows and doors
- high-efficiency heating
- whole-house mechanical ventilation
- minimal air leaking from the house
- water-conserving fixtures such as taps and showerheads

R-2000 homes are constructed by trained R-2000 homebuilders before being inspected and tested by independent, third party inspectors. This construction and testing procedure is certified by the Government of Canada.

2.6.4 EnerGuide

Acting approximately as an equivalent to the American Energy Star program, Natural Resources Canada has developed the EnerGuide program (NRCan, 2013). This program provides energy efficiency information for appliances and energy consuming products, new and existing homes, and light duty vehicles. The EnerGuide program for products is previously discussed concerning efficient energy use in appliances.

EnerGuide for homes allows for both new ad existing homes to be rated on either a 0 to 100 scale or based on estimated annual energy usage in GJ. The 0 to 100 scale represents improved energy efficiency with increasing values such that:

- 0 represents a house that leaks a lot of air, has no insulation and uses a lot of energy. In other words, a house with poor energy efficiency and high utility costs.
- 100 represents an airtight and well-insulated house where the energy it uses and the energy it generates through renewable sources (such as solar panels or geothermal) are equal, fitting the definition of a NZEB.

2.7 CURRENT APPLICATIONS

As the technologies necessary to achieve net-zero energy status for homes in Canada mature, becoming more practical, more and more homes are beginning to apply them. As a result, several net-zero and near net-zero energy homes already exist in Canada and similar climates.

2.7.1 EQuilibrium Homes

The Canadian government's first program to promote the construction of net-zero energy homes was the Canadian Mortgage and Housing Corporation's (CMHC) EQuilibrium program. Launched in May 2006, the EQuilibrium program allowed homebuilders to submit plans for constructing net-zero, or near net-zero homes, with 20 of these applicants being selected to receive $10,000 to support this design work. Of these applicants, 12 were selected to receive an additional $60,000 in funding in February 2007. A second call for proposals was placed in 2008 resulting in a further four selected applicants. Table 2.7 provides predicted energy consumption and production for the initial 12 designs. (CMHC, 2017)

Home Name	**Location**	**Predicted Annual Consumption**	**Predicted Annual Production**	**Predicted Net Annual Energy**
Abondance le Soleil	Montreal, Quebec	99.5 kWh/m^2	82.3 kWh/m^2	-17.2 kWh/m^2
EcoTerra	Eastman, Quebec	40.84 kWh/m^2	27.96 kWh/m^2	-12.88 kWh/m^2
Avalon Discovery 3	Red Deer, Alberta	54.56 kWh/m^2	56.06 kWh/m^2	+1.49 kWh/m^2
EchoHaven	Calgary, Alberta	45.93 kWh/m^2	40.87 kWh/m^2	-5.07 kWh/m^2
Inspiration – The Minto EcoHome	Ottawa, Ontario	66.6 kWh/m^2	68.6 kWh/m^2	+2.0 kWh/m^2
Now House	Totonto, Ontario	96.94 kWh/m^2	39.36 kWh/m^2	-57.58 kWh/m^2
Riverdale NetZero Project	Edmonton, Alberta	61.51 kWh/m^2	63.01 kWh/m^2	+1.5 kWh/m^2
The Laebon CHESS Project	Red Deer, Alberta	46.2 kWh/m^2	51.6 kWh/m^2	+5.4 kWh/m^2
Urban Ecology	Winnipeg, Manitoba	53.8 kWh/m^2	15.0 kWh/m^2	-38.8 kWh/m^2
Harmony House	Burnaby, British Columbia	33.5 kWh/m^2	38.4 kWh/m^2	+4.9 kWh/m^2
The Green Dream Home	Kamloops, British Columbia	38.84 kWh/m^2	42.47 kWh/m^2	+3.63 kWh/m^2

Table 2.6: Summary of Equilibrium Homes

2.7.2 R-2000 Net-Zero Homes

As of 2013 the Canadian government has transferred the responsibility of establishing net-zero energy housing options from the CMHC to Natural Resources Canada (NRCan, 2017). Specifically, a pilot program for the further construction of net-zero and near net-zero houses has been established under NRCan's R-2000 program. This program resulted in the construction of 23 net-zero energy homes constructed by six different home builders across three provinces (NRCan, 2017). All homes constructed through this pilot program were certified and labelled as zero gigajoule (0 GJ) homes under the EnerGuide Rating System (ERS) version 15 (NRCan, 2017). A further 14 homes constructed as part of this pilot program were rated as being "net-zero energy ready", meaning home energy use was judged to be small enough that on-site energy harvesting could offset it (NRCan, 2017).

2.8 FEASIBILITY

A review of existing and maturing technologies which allow for net-zero energy status to be achieved for a new construction home in Canada in general and in Nova Scotia more specifically is supportive of the hypothesis that such a home can be economically constructed. This hypothesis is further supported by the practical application of many such technologies in homes throughout the province, including a home defined as “Net-Zero Energy Ready” being constructed in Halifax as part of the R-2000 Net Zero Pilot Project. This home, constructed by a local developer, has been verified as requiring only the addition of a solar photovoltaic system to achieve net-zero energy status (Sobchak, 2015).

CHAPTER 3. MODELLING CONCEPTS

3.1 MODEL OVERVIEW

The building modelled is meant to represent a new construction home in the province of Nova Scotia. The initial model, a base case used to identify a baseline for home energy use, is modified incrementally with the impacts of modifications analyzed to assess their viabilities in achieving net-zero energy status.

Modifications to the home are initially based on the building envelope with insulation levels, fenestration model and placement, and air-tightness progressively increased over three stages. An evaluation of both the energy and cost models of these stages is then used to evaluate the most viable building envelope model moving forward.

Once a building envelope design is settled upon, modifications to internal equipment, lighting, and occupant behaviour are evaluated. The first mechanical upgrades implemented are more efficient water heating systems, followed by high-efficiency appliances and lighting. Next a dynamic heating setpoint is implemented followed by more efficient space conditioning systems, the use of phase change thermal mass and finally renewable energy technologies.

All upgrades are selected based on their energy and cost savings potential.

Analysis of both the described simulation model results and those for potential solar photovoltaic (PV) electricity systems is then used to evaluate the PV system required to achieve net-zero or near net-zero status.

3.1.1 Model Geometry

All buildings modelled maintain the same basic geometry except for where modifications are noted. The design used is a two-storey, single-family house with an unfinished, unconditioned basement. Conditioned living space is evenly distributed across both storeys. The dimensions of each storey is 7.3m x 10.7m (24’x35’) for a total of 78m^2 (840ft^2) per storey or 156m^2 (1,680ft^2) total conditioned floor area. Ceilings are 2.4m (8’) in height. The unconditioned basement zone has the same dimensions as the conditioned floors.

The thermal mass of walls, partitions, floors, and ceilings are considered in addition to that of furniture.

Above the second storey is an unconditioned attic zone and roof. The roof is a gable design, initially modelled with a pitch of 6/12.

Windows occupy 26.8m^2 (288ft^2) of wall space evenly distributed across the four outside walls. Two fibreglass exterior doors occupy a total of 3.7m^2 (40ft^2).

The initial model has both conditioned stories modelled as a single thermal zone. The unconditioned basement and attic are modeled as individual thermal zones.

Building orientation is assumed to be true north and the effects of neighbouring buildings and other obstructions (e.g. trees) are ignored.

A three-dimensional rendering of the building geometry described is shown in Figure 3.1.

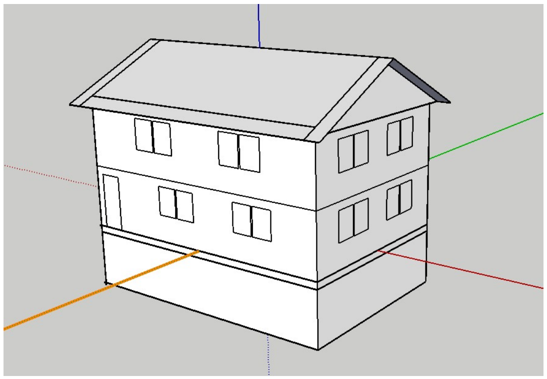

Figure 3.1: Three-dimensional rendering of the building geometry modelled

The first story is treated as a single, 78m^2 space with the second story subdivided as shown in Figure 3.2.

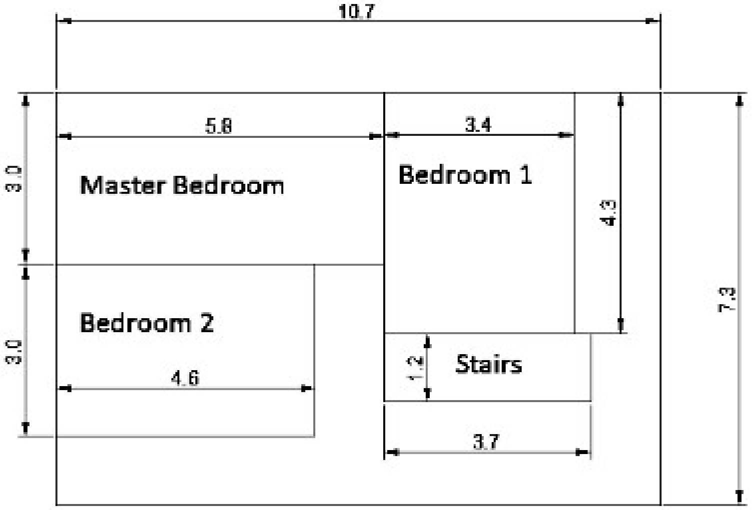

Figure 3.2: Second story floorplan

3.2 BASE CASE AND UPGRADE DESCRIPTIONS

All homes modelled use the same geometry described in the previous section. The first section describes a base case home used as a reference for both cost changes and energy savings. Changes concern upgrades made to the building envelope, mechanical and electrical systems, and the addition of renewable energy technologies. The following sections describe the base case and upgrades tested.

3.2.1 Base Case

The base case is meant to represent a typical new construction home in the province of Nova Scotia. The building envelope and all interior equipment are selected to reflect this.

Building insulation levels and construction techniques are shown in Table 3.1.

Component	**Construction Technique**	**Insulation Type**	**Nominal Insulation Level**
Ceiling	2”x10” joists, 16” outside centres	Loose-fill cellulose	R-30
Above-grade wall	2”x6” framing, 24” outside centres	Fibreglass Batt	R-21
Below-grade wall	20cm (8”) concrete wall	XPS board	R-10
Concrete slab	10cm (4”) concrete slab	None	N/A

Table 3.1: Construction techniques and nominal insulation levels of base case new construction home for Nova Scotia

NRCan's "Keeping the Heat In" (NRCan, 2012) explains that, since most basement heat is lost through the upper part of the basement wall, basement floor slabs are seldom insulated. Therefore, the base case home does not have an insulated slab.

Windows are low-emissivity and double-glazed with a 12.7mm (1/2") air gap on a non-metal frame. This gives them a thermal transmittance of 2.16 W/m^2*K ($0.38Btu/hr*ft^2°F$).

Outdoor air infiltration is based on a rate of 5 ACH at a 50Pa pressure differential. This is a typical air tightness level for a new construction home (Sherman and Walker, 2012).

Mechanical ventilation is provided by a heat recovery ventilation system with a 70% efficient heat exchanger. Ventilation rates conform to ASHRAE Standard 62.2 for single family homes, in this case 20L/s (ASHRAE 2013).

Space heating is provided by a hot air, fuel oil burning furnace. This furnace has a capacity of 11kW, sized based on a design day of January 21 from Shearwater weather data and an 85% annual fuel use efficiency (AFUE). The same system is adequately sized for both Truro and Sydney as well. Oil-burning furnaces are the most commonly used space heating systems in Nova Scotia (StatsCan, 2013).

DHW heating is also provided by a fuel oil burning unit (53.3% of residential water heating energy use in Nova Scotia is consumed in the form of heating oil [StatsCan, 2017]). This unit, with a total annual energy efficiency of 62%, maintains a 150L (40 gallon) tank of water at 52°C (125°F) for domestic use. The total heating capacity of the unit is 26.4kW. Oil fired water heaters are often over sized in this manner to allow for almost instantaneous water heating should the water tank's supply be exhausted (Giant, 2014).

Total power for lighting is 330W. Assuming the average of approximately 25 lightbulbs (Fung and Ugursal, 1997), this equates to 13.2W per lightbulb. This is a typical power rating for an 800 lumen compact fluorescent lamp (CFL) lightbulb.

The refrigerator has a total volume of 0.51m^3 (18 ft^3). The modified volume of this refrigerator, wherein the volume of the top-mounted freezer unit is multiplied by a factor of 1.63 to account for its additional energy consumption, is 0.59m^3 (20.9 ft^3). The modeled power of this unit is much lower than that rated for a similar production model to account for the frequent "on-off" cycling of a residential refrigerator when used with an hourly schedule. This allows the annual energy usage of this refrigerator to match the National Renewable Energy Lab's (NREL) 434 kWh/yr energy usage as prescribed in their House Simulation Protocols (Hendron and Engebrecht, 2010).

Other internal electrical appliances as well as plug loads and their power rating are provided in Table 3.2.

Appliance	**Peak Power (W)**	**Annual Energy Use (kWh)**
Cooking Range	5000	500
Dishwasher	1200	100
Clothes Washer	700	40
Clothes Dryer	5000	1000
Plug Loads	750	2100

Table 3.2: Peak electrical loads and annual electrical energy consumption for base case

A summary of the base case home's features is shown in Table 3.3.

Feature	Component Used
Space Heating	Oil-fired, hot-air furnace
DHW	Oil-fired water heater
Ventilation	HRV (70% efficiency)
Windows	Double-glaze, 12.7mm air gap
Air-tightness	5 ACH_{50}
Lighting	Compact fluorescent
Appliances	Standard efficiency

Table 3.3: Base Case Summary

3.2.2 Envelope Modifications

The first upgrades applied to the home are made to the building envelope. Done in three stages, insulation levels of the ceiling, above-grade walls and below-grade walls are shown in Table 3.4.

Component	Base Case	Stage 1	Stage 2	Stage 3
Ceiling	R-30	R-45	R-60	Same as stage 2
Above-Grade Wall	R-21	R-23	R-45	R-57
Below-Grade Wall	R-10	R-15	R-20	Same as stage 2

Table 3.4: Insulation level modifications

All ceiling designs use the same 2”x10”, 16” O.C. construction technique and loose-fill cellulose insulation. The only factor changed is the amount of insulation used.

Above grade wall designs are progressively changed as shown in Table 3.5.

Model	Framing Construction	Insulation Type
Base Case	2”x6” stud, 16” O.C.	Fibreglass Batt
Stage 1	Same as base case	Open-Cell Sprayfoam
Stage 2	2”x4” double-stud, staggered 24” O.C.	Fibreglass Batt
Stage 3	Same as stage 2	Closed-Cell Sprayfoam

Table 3.5: Above grade wall construction and insulation types

Below grade walls use the same 20cm (8") concrete wall with XPS board insulation. Only the thickness of insulation board used is changed.

The building's air tightness is also increased progressively. Stage 1 modifications decrease infiltration rates to 1.5 ACH_{50}, conforming to NRCan's R-2000 standard. Stage 2 further reduces this to 0.6 ACH_{50}, the level of air tightness prescribed by the Passivhaus standard. Stage 3 maintains air tightness at Passivhaus standard.

Window performance is also increased with envelope modifications. Window upgrades are described in Table 3.6:

Building	**Number of Glazings**	**Gas**	**Thermal Transmittance (u-value: (W/m^{2}K / Btuhr*ft^2°F)**
Base Case	2	Air	2.16/0.38
Stage 1	2	Argon	1.99/0.35
Stage 2	3	Air	1.65/0.29
Stage 3	3	Argon	1.53/0.27

Table 3.6: Window models

In addition to the style of window used, window placements and areas were modified as described in Table 3.7.

Building	**Window Area (m^2/ft^2)**	**Window Distribution**
Base Case	27/290	25% all faces
Stage 1	23/250	Same as Base Case
Stage 2	Same as Stage 1	40% S, 20% all other faces
Stage 3	Same as Stage 2	Same as Stage 2

Table 3.7: Window areas and distributions

In addition to the upgrades made to insulation already existing in the base case, further insulation upgrades were added to stages 2 and 3. The two additional insulation upgrades are the use of fibreglass batt insulation between the first story of the living space and the unfinished basement as well as XPS board insulation on above-grade walls between the framing and siding.

24.1cm (9.5in) of fibreglass batt is placed between the living and basement zones with a nominal insulation level of R-30. The exterior sheathing is given 7.6cm (3in) of XPS board with a nominal insulation level of R-15.

3.2.3 Electric Water Heating Options

Although the base case made use of fuel oil for both space and water heating, most Nova Scotian households make use of electric water heaters (Statistics Canada, 2014). Based on this, a variety of electric water heating options are investigated. These water heaters consist of three models; a high efficiency model with a 150L tank, a tankless model, and a heat pump water heater (HPWH). It is assumed that the DHW unit is situated within the unconditioned basement zone. Specifications of the electric water heater models used are shown in Table 3.8.

Type	**Tank Size (L)**	**Installed Annual Energy Efficiency**	**Electrical Power Input (kW)**	**COP**
Electric Premium	189	95%	5.5	N/A
Electric Tankless	N/A	95%	24.0	N/A
Heat Pump Water Heater	189	N/A	4.5	2.8

Table 3.8: Electric Water Heater Models

3.2.4 Appliance Modifications

Following modifications to the building envelope, an upgrade to high-efficiency appliances is applied. The refrigerator is switched for a model with an annual energy usage of 348kWh. Other appliances are upgraded to higher efficiency models with power and energy usages shown in Table 3.9. The 20% reduction in cooking range energy use is attributed to both a better insulated oven and more efficient use of stovetop (Hendron and Engerbrecht, 2014).

Appliance	**Power (W)**	**Annual Energy Use (kWh)**
Cooking Range	4000	400
Dishwasher	1000	93
Clothes Washer	400	25
Clothes Dryer	4000	800
Plug Loads	550	1550

Table 3.9: High efficiency appliance peak electrical load and annual energy usage

The clothes dryer is eliminated completely in favor of year-round line drying. This reflects the energy conscious operation expected to correspond to the energy efficient construction and components of the upgraded house.

3.2.5 Lighting Modifications

The number of lights and their scheduling remain unchanged. All models assume approximately 25 lightbulbs and 2.74 hours of usage per lightbulb per day (Fung and Ugursal, 1997). By changing the lightbulb model used from a 13W CFL to a 9W LED, both 800 lumens (equivalent to a 60W incandescent), lighting energy is reduced by approximately 30%.

3.2.6 Dynamic Heating Setpoint

Heating setpoints are initially set statically at 22.2°C (72°F). Though this is a comfortable living temperature, typical living arrangements make maintaining this temperature at all hours inefficient. Setpoints should instead be dynamically altered to account only for the comfort needs at any given time.

Space heating energy can be saved by using lower temperature heating setpoints (setbacks) during periods where typical comfort temperatures are not required. It is obvious that maintaining comfortable temperatures is not necessary when the home is not occupied. Leaving the home completely unconditioned during this time, however, could result in an unreasonably cold home upon return. Based on this, a setback temperature of 18.3°C (65°F) was selected. This setback temperature is employed from 0900hrs to 1700hrs during weekdays, approximating a typical working schedule.

In addition to working hours, the setback temperature setpoint is applied overnight from 2300hrs to 0600hrs throughout the week. This is based on typical sleeping patterns where lower temperatures are considered comfortable when the body is in its resting state (Chen et al. 2014).

Additionally, the temperature during awake occupancy is lowered slightly to 21.7°C (71°F), approximately as low as can be assumed to be comfortable for typical occupants.

3.2.7 Phase Change Material Thermal Mass

The use of increased thermal mass for the storage of heat energy to be dispersed later is a major factor of passive solar design. Thermal mass is increased using phase change materials (PCMs) in interior walls on the south-facing side of the home.

The PCM drywall used is based on examples described in existing literature (Bland et al. 2017) as being commercially viable. Specific enthalpies at specific temperatures are shown in Table 3.10.

Temperature (°C)	Enthalpy (J/kg)
-60	0.001
21.9	17,155
23.6	37,508
63.6	45,882

Table 3.10: Specific enthalpies of PCM drywall

This equates to PCM drywall having a quarter of the thermal mass of typical drywall outside of the phase change temperatures (21.9°C to 23.6°C), but approximately 10 times that within those temperatures.

3.2.8 Electric Resistance Space Heating

Electric resistance heating offers a 100% efficient source of space heating for a relatively low initial cost. The size and number of baseboard heaters is also highly alterable to allow for sizing to meet the low heating demands of highly insulated, air-tight homes.

After building envelope upgrades are applied, electric resistance heating replaces the oil-fired furnace. This system is sized for the modified home.

3.2.9 Air Source Heat Pump for Space Heating

A variety of air source heat pump models exist on the Nova Scotia market. Ground source heat pumps are not considered as Nova Scotia's mild climate makes them cost prohibitive. For the purpose of this thesis, three models are considered. These three models are described briefly in Table 3.11.

Model	**Type**	**SEER**	**Maximum Number of Indoor Units**	**Capacity (cooling/heating)/ indoor unit (W)**
Fujitsu RLS3Y	Ductless	33	1	2600/3500
Fujitsu ARU12RLF	Ducted	14.7	1	3500/4700
Daikin 4MXS36RMVJU	Ductless	17.7	4	2600/2600

Table 3.11: Space heat pump models

The Fujitsu RLS3Y is only able to support a single indoor unit. Therefore, it is assumed one will be used to heat the first-floor thermal zone and heating of the second floor will be provided by several potential heating technologies:

- Electric resistance heating
- 1 Fujitsu ARU12RLF ducted air source heat pump
- 3 additional Fujitsu RLS3Y

The Fujitsu ARU12RLF ducted air source heat pump allows for multiple spaces to be conditioned using a single unit at the cost of a lower SEER.

A single RLS3Y heat pump is also placed in the master bedroom with other spaces in the upstairs zone being heated only using electric resistance baseboard heating.

The Daikin 4MXS36RMVJU can support four indoor units which can be spread out across spaces within the home. Therefore, it is assumed that just a single indoor unit can provide heating for the first floor (open living room and kitchen) with the remaining three spread through the upstairs zone (bedrooms).

3.2.10 Rooftop Solar Energy Collection

In addition to the use of passive solar energy transmitted through windows providing a portion of the building's heating, solar radiation can be actively harvested for use as both thermal and electrical energy by solar thermal collectors and photovoltaic systems, respectively.

Two sizes of system are used, a 3.72m^2 (40 ft^2) collector with 230L (60-gallon) tank and a 5.95m^2 (64 ft^2) unit with a 360L (96-gallon) tank. Both tanks are insulated with an R-10 insulation jacket.

The final addition made to the home is a photovoltaic system sized to offset energy use. The cells used for this system are crystalline silicon (C-Si) models with efficiency based on the Sandia performance model (King et al. 2004). This system is connected to the electrical grid using an inverter of 96% efficiency.

3.3 ENERGY MODELLING

To estimate the annual energy usage of the base case and upgraded houses energy models were developed. A building energy model (BEM) is a physics-based software simulation which uses inputs based on a building's geometry, weather data, construction materials, equipment, controls and scheduling to output expected energy use. BEM programs are capable of simulating energy use at hourly or smaller timesteps over the course of a year taking into consideration the complex interactions between all relevant input parameters. Figure 3.3 shows an example of energy flow paths in a typical building.

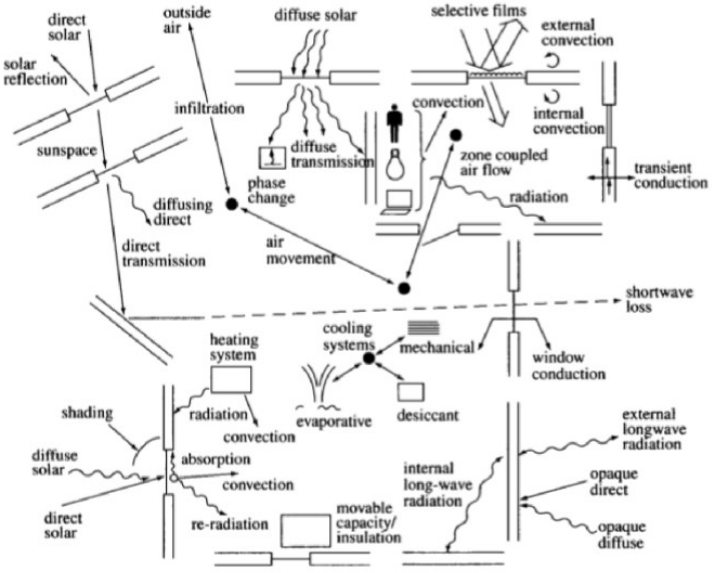

Figure 3.3: Energy flow paths in a typical building (Clarke, 2001)

The BEM software employed in this research is EnergyPlus (v8.8) with the user interface BEOpt (v2.8).

EnergyPlus is a sub hourly energy simulation program developed by the United States Department of Energy as an evolution of the earlier, hourly BLAST and DOE-2 programs.

In addition to offering variable, sub-hourly time steps, EnergyPlus improves upon previous energy simulation programs by using an integrated solution technique. At each time step, load calculations are passed on to the building simulation module for the same time step. The building simulation module calculates heating and cooling, plant, and electrical system response. Feedback from any loads not met by the building simulation module is then reflected in the next step of the load calculations in adjusted space temperatures if necessary.

The use of such an integrated simulation solves the most serious deficiency of previous, sequential simulation software; inaccurate space temperature predication due to a lack of feedback from the HVAC model to the load calculations. Accurate space temperature simulations are critical to energy efficient system engineering with system size and occupant comfort relying on space temperature (Crawley et al. 2000).

EnergyPlus has been tested and validated using a variety of methods including:

- Analytical tests
    - HVAC tests
    - Building fabric tests
- Comparative tests
    - ANSI/ASHRAE standard 140-2011
    - International Energy Agency Solar Heating and Cooling Programme (IEA SHC) BESTest (Building Energy Simulation Test)
    - HVAC component comparative tests
    - Global heat balance tests
- Release and executable tests (EnergyPlus, 2018)

3.4 ECONOMIC ANALYSIS METHODOLOGY

A base Life Cycle Cost (LCC) analysis time period of 30 years is considered. LCC analyses with a period greater than 30 years are not recommended. This is due to both interest rates and energy escalation rates being very difficult to predict with any certainty.

The economic analysis of upgrades is based on energy savings and cost increases in comparison to the base case. Two metrics are used to assess the economic viability of upgrades, the cost of energy savings ($/kWh) and the payback period.

Due to the difficulty of estimating the interest and fuel escalation rates over the thirty-year life cycle, as well as the similarities in current energy escalation rates and interest rates in Nova Scotia, simple payback is used as the measure of economic feasibility. A simple payback period is the increase in capital cost divided by the annual operational savings. This model ignores changes in both the value of money and the cost of energy. The impact of changes of energy costs on the payback period for a net-zero energy home are presented in the form of sensitivity analyses in appendix C.9.

Costs are based on both the Means Square Foot Contractors Pricing Guide (RSMeans, 2007) to determine the necessary components. Updated component costs are retrieved from the RSMeans cost catalog (RSMeans, 2016) which includes labour, material, and equipment costs. Costs of land are ignored as they are highly variable depending on location and irrelevant to the research.

By including the costs associated with equipment replacement, the possibility of artificially inflating the total cost with replacement costs accrued near the end of the period is presented. In order to prevent this, salvage values are associated with the materials. Salvage values are based on a linear depreciation method using the current Bank of Canada interest rate.

Since non-energy related operation costs are assumed to be the same regardless of upgrades, energy costs are the only operation costs investigated.

Operational electricity costs can be calculated using either an equivalent annual billing rate or a breakdown of electricity fees as specified from the utility. Since the objective is an evaluation of energy operation costs over an annual period, an equivalent annual billing rate is used. Costs of oil for models using oil burning space and water heating equipment are also based on an equivalent annual billing rate.

Energy cost savings are calculated using both the energy model results and energy costs for all three locations. Electricity costs are retrieved from Nova Scotia Power while average fuel oil costs are recorded by Statistics Canada.

All costs include 15% HST.

3.4.1 Material Costs

The initial costs are based on the sum of costs of the components detailed in the following section. A more detailed breakdown of components and cost data is given in Appendix B.

3.4.1.1 Land Preparation and Basement

Costs associated with land preparation, excavation, and preparing concrete for the basement are sourced from RSMeans Residential Square Foot Costs (2007) and RSMeans cost data (2016) with components necessary sourced from residential construction data and up to date cost data for those components sourced from RSMeans cost data.

3.4.1.2 Building Envelope

Framing costs are based on the cost models described by Residential Square Foot Costs (2007) with the component material, labour, and equipment costs sourced from more recent RSMeans data (2016).

Wall framing is based on two primary construction plans: single and double studded walls. Single studded walls are built using 2x6" studs while double studded walls use 2x4" studs spaced on 2x10" top plates. Cost data is only supplied for single stud construction, however a conversation with a local developer expressed similar costs for both framing constructions. A sensitivity analysis is performed to investigate the impact of potential cost increases associated with the construction of a double studded wall in Appendix C.

The floor framing is constructed using 2" x 10" joists, 16" O.C (on-centre spacing).

Roof framing is based on two separate models depending on the pitch used. Though modelled with 6/12 and 9/12 pitches, design costs were approximated using cost models for 4/12 and 8/12 pitches, respectively.

Interior partition walls are modelled as 2" x 4", 16" O.C. stud framing.

Insulation costs are based on RSMeans cost data for the insulation material prescribed by each model as well as insulation thickness used in the BEM. Insulation values are based on RSMeans data for the insulation materials utilized:

- Fibreglass batt
- Loose fill cellulose
- Extruded Polystyrene Insulation (XPS) rigid board

- Spray foam (Open-cell and closed-cell)

The air-tightness of a home is dependent upon the precision of the builder, making it a difficult cost to quantify. Costs associated with improved air tightness are not quantified by RSMeans and must be sourced from elsewhere.

Bucking (2013) details an estimate of costs associated with increasing the air-tightness of a 2500 ft^2 home from 3ACH$_{50}$ (air-tightness possible without special materials or additional labour) to 1.5ACH$_{50}$ and 0.6ACH$_{50}$, meeting R-2000 and Passivhaus standards respectively. This estimate was provided by the director of Habitat Studio, a participant in the Net-Zero Energy Home Coalition.

Costs of achieving the described air-tightnesses for a 2500ft^2 home are shown in Table 3.12.

Air-Tightness (ACH @ 50Pa)	Incremental Cost ($)
>3.0	0
1.5	3200
0.6	4000

Table 3.12: Costs of achieving air tightness levels modelled for a 2500ft^2 house

These values are normalized by floor area as shown in Table 3.13.

Air-Tightness (ACH @ 50Pa)	Incremental Cost ($/m^2 FA)
>3.0	0
1.5	13.80
0.6	17.20

Table 3.13: Cost per m^2 floor area to achieve air tightness levels modelled

Exterior walls are finished with 8” vinyl clapboard siding.

Also accounted for in exterior walls are windows and exterior doors.

Windows are priced based on the cost associated with the construction of 3’ x 4’, double hung, plastic clad wood windows.

Window costs are modified as new window models are implemented. Costs associated with additional glazings and argon fills are sourced from RSMeans.

The exterior door is a colonial, 6 panel, 3’ x 6’8” wood model.

The roofing system consists of class A asphalt roof shingles with rake trim and gutters included. The design and components are based on RSMeans Square Foot Residential Costs Data (2008), Individual component cost data is gathered from an updated RSmeans catalog (2016).

The cost of roofing is modified by multiplying by the ratio of roof surface of the roof pitch used in comparison to the 4/12 pitch used in this cost model.

The interior walls are finished with ½” drywall, taped and finished. The interior ceiling is finished with ½” taped and finished sheetrock. Interior doors are hollow core, flush, lauan doors.

Stairs are costed as prefabricated and basement stair systems with 14 risers each.

3.4.1.3 Mechanical Systems

The components necessary for an oil-fire hot-air furnace are sourced from RSMeans Residential Square Foot Data (2008) with a more recent RSMeans catalog (2016) being used to provide updated costs for each component.

Costs of heat pumps are based on quotes provided by suppliers and installers in the Halifax Regional Municipality. It is assumed materials and labour associated with heat pump installation are constant for all locations tested.

Costs associated with electric baseboard heaters paired with mini-split heat pumps are sourced from RSMeans (2016).

Costs associated with DHW systems are sourced from RSMeans data with the cost of models available through retailers servicing the HRM used to modify costs for specific models.

All models make use of the same heat recovery ventilator (HRV) model, the cost of which is sourced from RSMeans (2016).

Costs associated with solar thermal collectors for water heating are sourced from RSMeans (2016).

Costs associated with the photovoltaic system are based on listed costs of available PV systems as well as quotes for installation services. Both wholesale and local supply options are considered, leading to variability of costs. As a result of this, a sensitivity analysis is conducted regarding the impacts of different PV costs.

3.4.1.4 Appliances and Devices

Costs of standard and high efficiency appliances and electronic devices are based on retailers serving the HRM. Costs associated with shipping and installation are ignored with only the material cost of the appliances considered.

3.4.2 Location Cost Multiplier

In order to accurately estimate construction costs as modelled using RSMeans, location cost multipliers are provided. Modifiers for each category and location are applied when developing cost models.

Location multipliers for the three locations tested are included in appendix D. Individual multipliers are included for each set of building components.

CHAPTER 4. RESULTS AND ANALYSIS

4.1 GOAL DESCRIPTION

The purpose of this research is to develop an economically viable pathway towards achieving a net-zero energy new construction home in Nova Scotia. This pathway begins with a base case home to which upgrades are applied until net-zero annual energy use is achieved.

4.1.1 Methodology

As described in Chapter 3, a variety of potential upgrades are evaluated. Some of these upgrades are mutually exclusive (e.g. different water heater models). Mutually exclusive upgrades must be compared directly to select the most viable option. Upgrades are selected based on both energy use and construction costs. Upgrades delivering greater energy savings in comparison to cost increases are the most viable and are selected for use in subsequent models.

Energy saving upgrades are:

- More efficient domestic hot water systems
- High-efficiency appliances
- More efficient use of appliances and hot water systems
- LED lighting
- Dynamic heating setpoint
- Internal thermal mass
- More efficient space conditioning systems
- Solar domestic hot water systems

A detailed description of the upgrades used is found in Chapter 3.

An upgrade is applied if the energy saving cost (dollars spent per annual kWh saved) is less than the cost of annual electrical generation from a PV system. A simple PV system is considered to establish a baseline cost for comparison.

Upgrades are evaluated for use in all three locations tested.

4.1.2 Photovoltaic System Results

A 1kW capacity PV system is simulated using EnergyPlus in order to evaluate the annual electrical generation at various tilt angles. Annual electricity generation both before and after losses due to inverter inefficiencies for Halifax are shown in Table 4.1. All results are based on an azimuth facing South.

Roof Pitch (pitch/degrees)	**Annual Electricity (Before Inverter) (kWh)**	**Annual Electricity (After Inverter) (kWh)**
6:12/26.6	1,150	1,090
7:12/30.3	1,160	1,100
8:12/33.7	1,170	1,110
9:12/36.4	1,170	1,110
10:12/39.8	1,170	1,110

Table 4.1: Annual electricity generation for 1kW PV system in Halifax by roof pitch

Based on the similar latitude of locations of interest in this work (Halifax, Truro, Sydney) it is assumed that all locations will follow the same trends regarding tilt angle’s impact on PV performance. Roof slope has minimal impact on annual electricity generation.

The cost for each kW of installed, grid-tied capacity PV in Nova Scotia is estimated at $2,950 before financial rebates based on communication with Halifax’s “Solar City” office. Rebates and other incentives are ignored in this financial analysis due to their long-term unpredictability. Combining the annual electrical generation and costs of a PV system in Halifax for a system at a 9/12 pitch gives a cost of annual energy savings 2.70$/kWh as the point at which PV becomes the most financially viable upgrade.

Annual electricity generations after inverter for Truro and Sydney are 1,070kWh and 1,110kWh respectively. A system at a 9/12 pitch gives a cost of annual energy savings 2.80$/kWh and 2.70$/kWh as the point at which PV becomes the most financially viable upgrade for Truro and Sydney, respectively.

4.2 RESULTS AND UPGRADE SELECTION

Based on the metrics described in the previous sections, a series of homes are modelled and evaluated on both energy and cost metrics. First, the annual energy use and cost of the base case home is analyzed. Next, upgrades are considered and selected on a case-by-case basis. This process is conducted for all three locations.

4.3 HALIFAX

4.3.1 Base Case

Energy use for the base case home design described in Chapter 3 in Halifax totals 122.9GJ. This total can be further divided into 23.7GJ (6,580kWh) of electricity and 99.2GJ (2,560L) of fuel oil. This is validated by the average energy use for a 4-person household in Canada, which was 127GJ in 2011 (StatsCan, 2013).

The construction cost of the base case home is $242,000. This is within the predicted price range for a Canadian new construction home of the size modelled (Altus, 2017).

4.3.2 Envelope Modifications

The first upgrades tested are the envelope modifications described in Section 3.2.2. Annual energy uses and construction costs with these upgrades applied are shown in Table 4.2. Energy savings and cost increases are compared to the base case home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Base Case	23.7/6,580	99.2/2,560	242,000	N/A	N/A	N/A
Stage 1	23.6/6,560	78.7/2,030	254,700	12,700	20.6/5,720	2.22
Stage 2	22.5/6,250	43.8/1,130	264,900	22,900	56.6/15,720	1.46
Stage 3	22.5/6,250	41.5/1,070	279,800	37,800	58.9/16,360	2.31

Table 4.2: Envelope modification energy use and construction costs (Halifax)

Stage 2 envelope upgrades provide the most cost-effective energy savings option. This, combined with minimal additional energy savings associated with the more expensive Stage 3 upgrades, make Stage 2 envelope upgrades the building envelope selected for subsequent models.

4.3.3 Electric Water Heating

The electric water heating upgrades described in Section 3.2.3 are added to the Stage 2 home model. The energy use and costs for each of these are shown in Table 4.3. Energy savings and cost increases are compared to the Stage 2 envelope upgrade home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Stage 2	22.5/6,560	43.8/1,130	264,900	N/A	N/A	N/A
Premium	32.7/9,080	26.1/670	265,700	800	7.5/2080	0.38
Tankless	32.6/9,050	26.1/670	265,900	1,000	7.6/2,110	0.47
Heat Pump	31.2/8,670	26.5/680	266,700	1,800	8.6/2390	0.75

Table 4.3: Electric water heating energy use and construction costs (Halifax)

Compared to oil water heating, a premium electric water heater provides energy savings at minimal increase in construction costs. Both a heat pump electric water heater and a tankless electric water heater provide even greater energy savings but at a cost increase compared to a premium electric water heater that makes those savings not cost effective. Based on these results, a premium electric water heater is selected for use in subsequent models.

4.3.4 Appliance Upgrades and Lighting

Annual energy use for a home with high efficiency appliance upgrades as described in Section 3.2.4 is 26GJ (7,220kWh) of electricity and 27.6GJ (710L) of fuel oil, before clothes dryer removal. After the clothes dryer removal, the annual energy use totals 22.6GJ (6,280kWh) of electricity and 28.3GJ (730L) of fuel oil. Removal of the clothes dryer reduces the construction cost by $800.

LED lighting also replaces the CFL lighting initially used as described in Section 3.2.5. LED lights are assumed to be at cost parity with their CFL equivalent. Results and costs of these upgrades are shown in Table 4.4. Energy savings and cost increases are compared to the tankless electric water heater home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Premium Water Heater	32.7/9,080	26.1/670	265,700	N/A	N/A	N/A
Interior Equipment Upgrades	22.3/6,190	28.3/730	266,500	800	8.2/2,280	0.35

Table 4.4: Interior equipment energy use and construction costs (Halifax)

High efficiency appliances with clothes dryer removal and LED lighting is selected for all subsequent homes.

4.3.5 Dynamic Heating Setpoint

Energy savings related to the dynamic heating setpoint described in Section 3.2.6 total 4.9GJ (180L) of fuel oil with negligible impact on electricity use. This gives a total annual energy use of 22.3GJ (6,190kWh) of electricity and 23.4GJ (600L) of fuel oil. Costs are unimpacted by the change in setpoint schedule, meaning the 4.9GJ in annual energy savings have a cost of 0$/kWh. This setpoint schedule is used in all subsequent homes.

Energy use and costs for the dynamic heating setpoint upgrade are shown in Table 4.5. Energy savings and cost increases are compared to the high efficiency appliances with clothes dryer removal and LED lighting home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
LED Lighting	22.3/6,190	28.3/730	266,500	N/A	N/A	N/A
Dynamic Heating Setpoint	22.3/6,190	23.4/600	266,500	0	4.9/1,360	0

Table 4.5: Dynamic heating setpoint energy use and construction cost (Halifax)

4.3.6 Internal Thermal Mass

The addition of the PCM thermal mass described in Section 3.2.7 to the home results in an annual energy use of 22.3GJ (6,190kWh) of electricity and 20GJ (520L) of fuel oil. The installation cost of a PCM thermal mass system is approximately $5000 (Solar UK 2019). Energy use and costs for the PCM thermal mass upgrade are shown in Table 4.6. Energy savings and cost increases are compared to the dynamic heating setpoint home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Dynamic Heating Setpoint	22.3/6,190	23.4/600	266,500	N/A	N/A	N/A
PCM Thermal Mass	22.3/6,190	20.0/520	271,500	5,000	3.4/940	5.32

Table 4.6: PCM thermal mass energy use and construction cost (Halifax)

Energy saving cost of PCM thermal mass exceeds that of the PV system described in Section 4.1.2. This upgrade is not used in subsequent homes.

4.3.7 Electric Resistance Heating

Replacing the oil-burning furnace with the electric baseboard system described in Section 3.2.8 eliminates the need for fuel oil. All energy used is supplied in the form of electricity. A 4kW system is calculated to be the appropriate size to heat the home. This capacity is assumed to be evenly distributed among eight 500W electric baseboard heaters.

Energy use with electric baseboard heating totals 42.7GJ (11,860kWh) of electricity. This is a 3.0GJ (830kWh) decrease in total energy use when compared to the same model using an oil-burning furnace. Additionally, the construction costs are reduced to $255,300.

Energy use and costs for the electric resistance heating upgrade are shown in Table 4.7. Energy savings and cost increases are compared to the dynamic heating setpoint home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Dynamic Heating Setpoint	22.3/6,190	23.4/600	266,500	N/A	N/A	N/A
Electric Resistance Heating	42.7/11,860	N/A	255,300	-11,200	3.0/830	-13.49

Table 4.7: Electric resistance heating energy use and construction costs (Halifax)

Electric resistance heating offers savings in both energy use and construction cost. The same electric resistance heating system is used as supplemental heating in the heat pump heated models described in Section 4.3.7.

4.3.8 Heat Pump Space Heating

Five space conditioning heat pump layouts are described in Section 3.2.9. Annual energy uses, energy savings, construction costs, and energy savings costs for these layouts are shown in Table 4.8. Incremental values are compared to the electric resistance heated home.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Electric Resistance Heating	42.7/11,860	255,300	N/A	N/A	N/A
1 RLS3Y Heat Pump	36.5/10,140	259,900	4,600	6.2/1,720	2.67
1 RLS3Y Heat Pump and 1 ARU12RLF Heat Pump	31.8/8,830	267,600	12,300	10.9/3,030	4.06
2 RSL3Y Heat Pumps	34.6/9,610	264,300	9,000	8.1/2,250	4.00
4 RSL3Y Heat Pumps	28.5/7,920	273,200	17,900	14.2/3,940	4.54
1 4MXS36RMVJU with 4 indoor units	30.0/8,330	267,900	12,600	12.7/3,550	3.55

Table 4.8: Air source heat pump energy use and construction costs (Halifax)

The least expensive energy saving option among space conditioning heat pumps is the single RSL3Y heat pump to condition the first story living zone with electric resistance heating used upstairs. This system is also the only one to offer energy savings at a cost on par with the addition of PV.

Because it offers the most energy savings of the financially viable options, a RLS3Y heat pump is selected for space conditioning in the first-floor zone for subsequent upgrades. The upstairs zone is heated solely by electric baseboard heaters.

4.3.9 Solar Domestic Hot Water

The two sizes of solar domestic hot water (SDHW) systems described in Section 3.2.10 are the final additions to the house before the PV system. Annual energy uses with these systems are 34.2GJ (9,500kWh) and 32.4GJ (9,000kWh) for the 40 and 64 sq ft models respectively. Energy use and construction costs for SDHW systems with respect to the heat pump space conditioned model is shown in Table 4.9.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Annual Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
1 RLS3Y Heat Pump	36.5/10,140	259,900	N/A	N/A	N/A
40 Ft^2 SDHW	34.2/9,500	266,300	7,400	2.3/640	11.56
64 Ft^2 SDHW	32.4/9,000	269,700	9,800	4.1/1,140	8.60

Table 4.9: Solar domestic hot water energy use and construction costs (Halifax)

Energy saving costs for both SDHW systems exceed those of a PV system. As a result, SDHW systems are not used in subsequent models.

4.3.10 Photovoltaic System

After applying all financially viable upgrades, annual energy use of the house is reduced to 36.5GJ (10,140kWh). Section 4.1.2 shows the annual net electricity production of a 1kW capacity PV system to be 1,110kWh. A 9.2kW capacity PV system achieves net-positive energy use with an annual energy surplus of 70kWh. This system is estimated to cost $27,100, bringing total construction costs to $287,000.

Energy use and construction costs for PV systems with respect to the heat pump space conditioned model is shown in Table 4.10.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Annual Energy Savings (GJ/kWh)	Annual Cost of Energy Saving ($/kWh)
1 RLS3Y Heat Pump	36.5/10,140	259,900	N/A	N/A	N/A
Net-Zero PV System	-0.3/-70	287,000	27,100	36.8/10,210	2.65

Table 4.10: Photovoltaic system energy use and construction costs (Halifax)

4.3.11 Net-Zero Energy Home Pathway

Figure 4.1 displays the pathway to achieving a net-zero energy home for Halifax with points labelled as:

1. Base case home
2. Stage 2 building envelope upgrades
3. Premium electric water heater
4. High efficiency appliances
5. Clothes dryer removal
6. LED lighting
7. Dynamic heating setpoint
8. Electric Resistance heating
9. Heat pump space conditioning

10. Net-zero PV system

Each point is cumulative, meaning all previous upgrades are included.

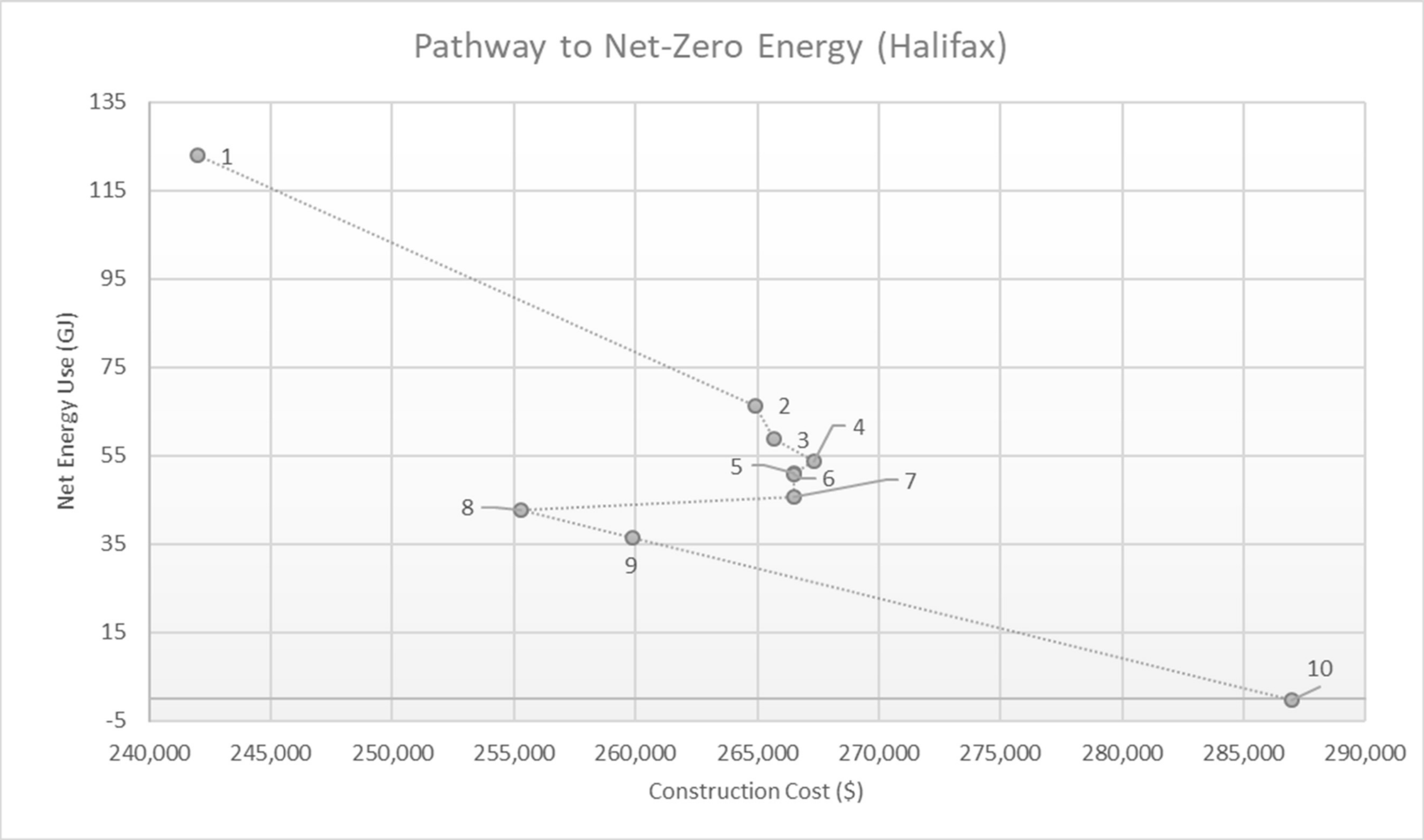

Figure 4.1: Pathway to net-zero energy (Halifax)

The base case and ten upgrade cases which lead to net-zero energy are summarized in Table 4.11. Payback periods are calculated with respect to the base case.

Home Model	Annual Net Electricity Use (GJ/kWh/$)	Annual Fuel Oil Use (GJ/L/$)	Construction Cost ($)	Incremental Cost ($)	Annual Savings ($/year)	Payback Period (years)
Base Case	23.7/6,580/1,180	99.2/2,560/2,640	242,000	N/A	N/A	N/A
Stage 2 Envelope Modifications	22.5/6,250/1,130	43.8/1,130/1,160	264,900	22,900	1,530	14.97
Premium Electric Water Heater	32.7/9,080/1,630	26.1/670/690	265,700	23,700	1,500	15.80
High Efficiency Appliances	26.0/7,220/1,300	27.6/710/730	267,300	25,300	1,790	14.13
Clothes Dryer Removal	22.6/6,280/1,130	28.3/730/750	266,500	24,500	1,940	12.63
LED Lighting	22.3/6,190/1,120	28.3/730/750	266,500	24,500	1,950	12.56
Dynamic Heating Setpoint	22.3/6,190/1,120	23.4/600/620	266,500	24,500	2,080	11.78
Electric Resistance Heating	42.7/11,860/2,130	N/A	255,300	13,300	1,690	7.87
Heat Pump Space Conditioning	36.5/10,140/1,830	N/A	259,900	17,900	1,990	8.99
Net-Zero Energy PV	-0.3/-70/-10	N/A	287,000	45,000	3,830	11.75

Table 4.11: Summary of pathway to net-zero energy home with payback periods (Halifax)

The point at which electric resistance heating is added provides the shortest payback period. All points along the pathway provide a payback within 20 years.

4.4 TRURO

4.4.1 Base Case

Energy use for the base case home design described in chapter three in Truro totals 130.6GJ. This total can be further divided into 23.8GJ (6610kWh) of electricity and 106.8GJ (2,760L) of fuel oil. This is validated by the average energy use for a 4-person household in Canada, which was 127GJ in 2011 (StatsCan, 2013).

The construction cost of the base case home is $230,100. This is within the predicted price range for a Canadian new construction home of the size modelled (Altus, 2017).

4.4.2 Envelope Modifications

The first upgrades tested are the envelope modifications described in Section 3.2.2. Annual energy uses and construction costs with these upgrades applied are shown in Table 4.12. Energy savings and cost increases are compared to the base case home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Base Case	23.8/6,610	106.8/2,750	230,100	N/A	N/A	N/A
Stage 1	23.7/6,580	84.5/2,180	242,300	12,200	22.4/6,220	1.96
Stage 2	22.6/6,280	47.3/1,220	251,200	21,100	60.7/16,860	1.25
Stage 3	22.6/6,280	44.5/1,150	265,100	35,000	63.5/17,640	1.98

Table 4.12: Envelope modification energy use and construction costs (Truro)

Stage 2 envelope uprades provide the most cost-effective energy savings option. This, combined with minimal additional energy savings associated with the more expensive

Stage 3 upgrades, make Stage 2 envelope upgrades the building envelope selected for subsequent models.

4.4.3 Electric Water Heating

The electric water heating upgrades described in Section 3.2.3 are added to the Stage 2 home model. The energy use and costs for each of these are shown in Table 4.13. Energy savings and cost increases are compared to the Stage 2 envelope upgrade home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Stage 2	22.6/6,280	47.3/1,220	251,200	N/A	N/A	N/A
Premium	33.0/9,170	30.1/780	252,000	800	6.8/1,890	0.42
Tankless	33.0/9,170	30.1/780	252,200	1,000	6.8/1,890	0.53
Heat Pump	31.3/8,690	30.4/780	253,000	1,800	8.2/2,280	0.79

Table 4.13: Electric water heating energy use and construction costs (Truro)

Compared to oil water heating, a premium electric water heater provides energy savings at minimal increase in construction costs. Both a heat pump electric water heater and a tankless electric water heater provide even greater energy savings but at a cost increase compared to a premium electric water heater that makes those savings not cost effective. Based on these results, a premium electric water heater is selected for use in subsequent models.

4.4.4 Appliance Upgrades and Lighting

Annual energy use for a home with high efficiency appliance upgrades as described in section 3.2.4 is 26.3GJ (7,310kWh) of electricity and 30.7GJ (790L) of fuel oil, before clothes dryer removal. After the clothes dryer removal, annual energy use totals 22.8GJ (6,330kWh) of electricity and 31.5GJ (810L) of fuel oil. Removal of the clothes dryer reduces the construction cost by $800.

LED lighting also replaces the CFL bulbs as described in Section 3.2.5. LED lights are assumed to be at cost parity with their CFL equivalent. Results and costs of these upgrades are shown in Table 4.14. Energy savings and cost increases are compared to the tankless electric water heater home.

Upgrade	**Annual Electricity Use (GJ/kWh)**	**Annual Fuel Oil Use (GJ/L)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Annual Total Energy Savings (GJ/kWh)**	**Cost of Annual Energy Savings ($/kWh)**
Premium Water Heater	33.0/9,170	30.1/780	252,000	N/A	N/A	N/A
Interior Equipment Upgrades	22.5/6,250	31.5/810	252,800	800	9.1/2,530	0.32

Table 4.14: Interior equipment energy use and construction costs (Truro)

High efficiency appliances with clothes dryer removal and LED lighting is selected for all subsequent homes.

4.4.5 Dynamic Heating Setpoint

Energy savings related to the dynamic heating setpoint described in section 3.2.6 total 5.1GJ (130L) of fuel oil with negligible impact on electricity use. This gives a total annual energy use of 22.5GJ (6,250kWh) of electricity and 26.4GJ (680L) of fuel oil. Costs are unimpacted by the change in setpoint schedule, meaning the 5.1GJ in annual energy savings have a cost of 0$/kWh. This setpoint schedule is used in all subsequent models.

Energy use and costs for the dynamic heating setpoint upgrade are shown in Table 4.15. Energy savings and cost increases are compared to the high efficiency appliances with clothes dryer removal and LED lighting home.

Upgrade	**Annual Electricity Use (GJ/kWh)**	**Annual Fuel Oil Use (GJ/L)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Total Energy Savings (GJ/kWh)**	**Cost of Annual Energy Savings ($/kWh)**
LED Lighting	22.5/6,250	31.5/810	252,800	N/A	N/A	N/A
Dynamic Heating Setpoint	22.5/6,250	26.4/680	252,800	0	5.1/1,420	0

Table 4.15: Dynamic heating setpoint energy use and construction cost (Truro)

4.4.6 Internal Thermal Mass

The addition of the PCM thermal mass described in section 3.2.7 to the home results in an annual energy use of 22.5GJ (6250kWh) of electricity and 22.6GJ (580L) of fuel oil. The installed cost of a PCM thermal mass system is approximately $5,000 (Solar UK, 2019). Energy use and costs for the PCM thermal mass upgrade are shown in Table 4.16. Energy savings and cost increases are compared to the dynamic heating setpoint home.

Upgrade	**Annual Electricity Use (GJ/kWh)**	**Annual Fuel Oil Use (GJ/L)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Total Energy Savings (GJ/kWh)**	**Cost of Annual Energy Savings ($/kWh)**
Dynamic Heating Setpoint	22.5/6,250	26.4/680	252,800	N/A	N/A	N/A
PCM Thermal Mass	22.5/6,250	22.6/580	257,800	5000	3.8/1,060	4.72

Table 4.16: PCM thermal mass energy use and construction cost (Truro)

Energy saving cost of PCM thermal mass exceeds that of the PV system described in Section 4.1.2. This upgrade is not used in subsequent homes.

4.4.7 Electric Resistance Heating

Replacing the oil-burning furnace with the electric baseboard system described in Section 3.2.8 eliminates the need for fuel oil. All energy used is supplied in the form of electricity. A 4kW system is calculated to be the appropriate size to heat the home. This capacity is assumed to be evenly distributed among eight 500W electric baseboard heaters, the same system used for the Halifax home.

Energy use with electric baseboard heating totals 45.6GJ (12,670kWh) of electricity. This is a 3.3GJ (920kWh) decrease in total energy use when compared to the same model using an oil-burning furnace. Additionally, the construction costs are reduced to $249,300.

Energy use and costs for the electric resistance heating upgrade are shown in Table 4.17. Energy savings and cost increases are compared to the dynamic heating setpoint home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Dynamic Heating Setpoint	22.5/6,190	26.4/680	252,800	N/A	N/A	N/A
Electric Resistance Heating	45.6/11,860	N/A	241,800	-11,000	3.3/920	-11.96

Table 4.17: Electric resistance heating energy use and construction costs (Truro)

Electric resistance heating offers savings in both energy use and construction cost. The same electric resistance heating system is used as supplemental heating in the heat pump heated models described in Section 4.3.7.

4.4.8 Heat Pump Space Heating

Five space conditioning heat pump layouts are described in Section 3.2.9. Annual energy uses, energy savings, construction costs, and energy savings costs for these layouts are shown in Table 4.18. Incremental values are compared to the electric resistance heated home.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Electric Resistance Heating	45.6/12,670	241,800	N/A	N/A	N/A
1 RLS3Y Heat Pump	38.9/10,800	246,400	4,600	6.7/1,870	2.47
1 RLS3Y Heat Pump and 1 ARU12RLF Heat Pump	33.4/9,280	254,100	12,300	12.2/3,390	3.63
2 RSL3Y Heat Pumps	35.5/9,860	250,800	9,000	10.1/2,810	3.20
4 RSL3Y Heat Pumps	28.6/7,940	259,700	17,900	17.0/4,730	3.78
1 4MXS36RMVJU with 4 indoor units	33.1/9,190	254,400	12,600	12.5/3,480	3.62

Table 4.18: Air source heat pump energy use and construction costs (Truro)

The least expensive energy saving option among space conditioning heat pumps is the single RSL3Y heat pump to condition the first story living zone with electric resistance heating used upstairs. This system is also the only one to offer less expensive energy savings than the addition of PV.

4.4.9 Solar Domestic Hot Water

The two sizes of solar domestic hot water (SDHW) systems described in Section 3.2.10 are the final additions to the house before the PV system. Annual energy uses with these systems are 35.0GJ (9,720kWh) and 33.2GJ (9,220kWh) for the 40 and 64 sq ft models respectively. Energy use and construction costs for SDHW systems with respect to the heat pump space conditioned model is shown in Table 4.19.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Annual Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
1 RLS3Y Heat Pump	38.9/10,800	246,400	N/A	N/A	N/A
40 Ft^2 SDHW	35.0/9,720	254,000	7,600	3.9/1,080	7.04
64 Ft^2 SDHW	33.2/9,220	256,500	10,100	5.7/1,580	6.39

Table 4.19: Solar domestic hot water energy use and construction costs (Truro)

Energy saving costs for both SDHW systems exceed those of a PV system. As a result, SDHW systems are not used in subsequent models.

4.4.10 Photovoltaic System

After applying all financially viable upgrades, annual energy use of the house is reduced to 38.9GJ (10,810kWh). Section 4.1.2 shows the annual net electricity production of a 1kW capacity PV system to be 1,070kWh in Truro. A 10kW capacity PV system achieves a net energy use of 80kWh. This is approximately net-zero. This system is estimated to cost $29,500, bringing total construction costs to $285,900. Energy use and construction costs for PV systems with respect to the heat pump space conditioned model is shown in Table 4.20.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Annual Energy Savings (GJ/kWh)	Annual Cost of Energy Saving ($/kWh)
1 RLS3Y Heat Pump	38.9/10,810	246,400	N/A	N/A	N/A
Net-Zero PV System	0.3/80	285,900	29,500	38.6/10,730	2.75

Table 4.20: Photovoltaic system energy use and construction costs (Truro)

4.4.11 Net-Zero Energy Home Pathway

Figure 4.2 displays the pathway to achieving a net-zero energy home for Truro with points labelled as:

1. Base case home
2. Stage 2 building envelope upgrades
3. Premium electric water heater
4. High efficiency appliances
5. Clothes dryer removal
6. LED lighting
7. Dynamic heating setpoint
8. Electric Resistance heating
9. Heat pump space conditioning
10. Net-zero PV system

Each point is cumulative, meaning all previous upgrades are included.

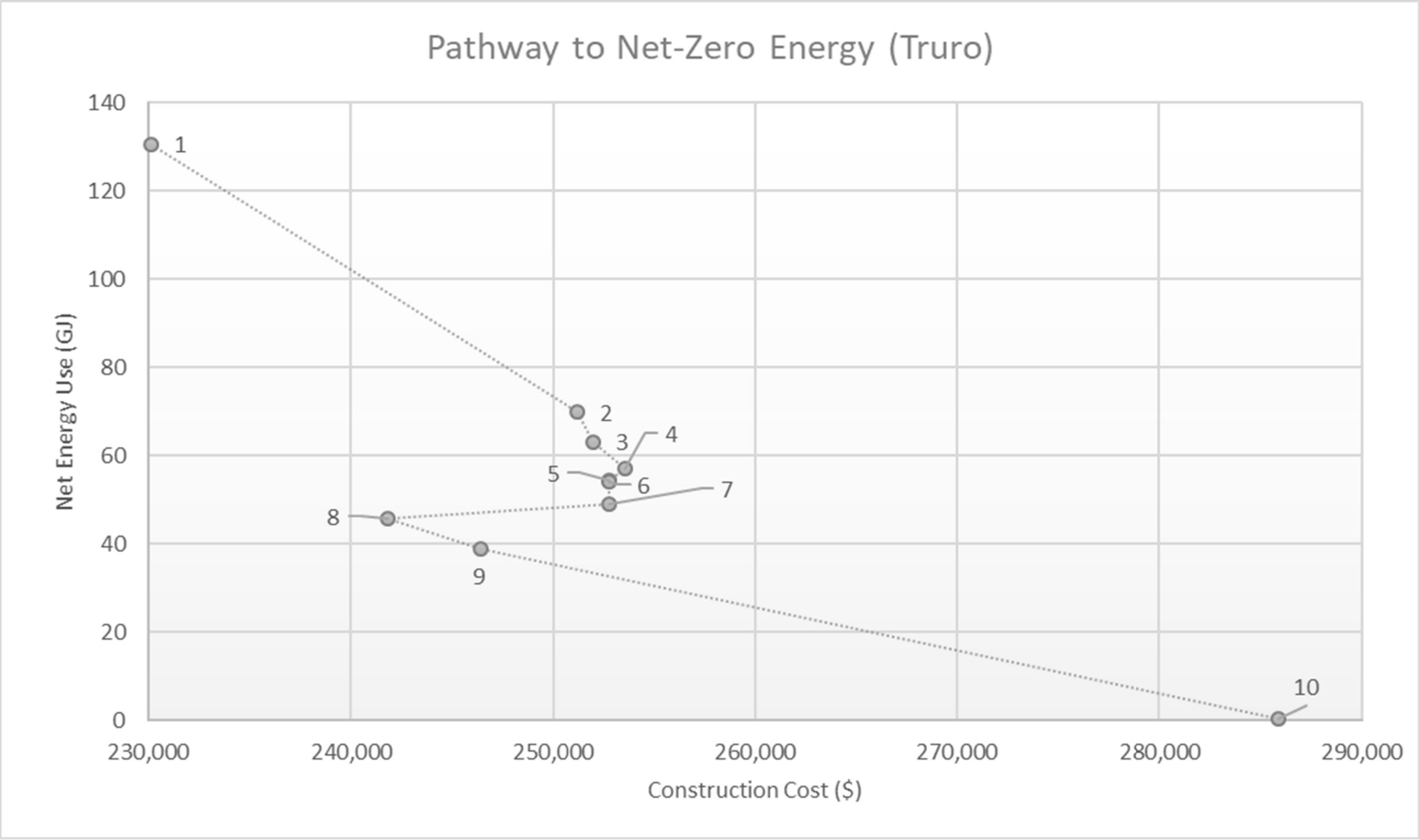

Figure 4.2: Pathway to net-zero energy (Truro)

The base case and nine upgrade cases which lead to net-zero energy are summarized in Table 4.21. Payback periods are calculated with respect to the base case.

Home Model	**Annual Net Electricity Use (GJ/kWh/$)**	**Annual Fuel Oil Use (GJ/L/$)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Annual Savings ($/year)**	**Payback Period (years)**
Base Case	23.8/6,610/1,190	106.8/2,750/2,830	230,100	N/A	N/A	N/A
Stage 2 Envelope Modifications	22.6/6,280/1,130	47.3/1,220/1,260	251,200	21,100	1,630	12.94
Premium Electric Water Heater	33.0/9,170/1,650	30.1/780/800	252,000	21,900	1,570	13.95
High Efficiency Appliances	26.3/7,310/1,320	30.7/790/810	253,600	23,500	1,890	12.43
Clothes Dryer Removal	22.8/6,330/1,140	31.5/810/830	252,800	22,700	2,050	11.07
LED Lighting	22.5/6,2501,130	31.5/810/830	252,800	22,700	2,060	11.02
Dynamic Heating Setpoint	22.5/6,250/1,130	26.4/680/700	252,800	22,700	2,190	10.37
Electric Resistance Heating	45.6/11,860/2,130	N/A	241,800	11,700	1,890	6.19
Heat Pump Space Conditioning	38.9/10,800/1,940	N/A	246,400	16,300	2,080	7.84
Net-Zero PV System	0.3/80/10	N/A	285,900	55,800	4,010	13.92

Table 4.21: Summary of pathway to net-zero energy home with payback periods (Truro)

The addition of electric resistance space heating has the shortest payback period. All points along the pathway provide payback within 15 years.

4.5 SYDNEY

4.5.1 Base Case

Energy use for the base case home design described in Chapter 3 in Sydney totals 142.8GJ. This total can be further divided into 24GJ (6,670kWh) of electricity and 118.8GJ (3,060L) of fuel oil. This is validated by the average energy use for a 4-person household in Canada, which was 127GJ in 2011 (StatsCan, 2013).

The construction cost of the base case home is $246,000. This is within the predicted price range for a Canadian new construction home of the size modelled (Altus, 2017).

4.5.2 Envelope Modifications

The first upgrades tested are the envelope modifications described in Section 3.2.2. Annual energy uses and construction costs with these upgrades applied are shown in Table 4.22. Energy savings and cost increases are compared to the base case home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Base Case	24.0/6,670	118.8/3,060	246,000	N/A	N/A	N/A
Stage 1	23.8/6,610	91.8/2,360	259,800	13,800	27.2/7,560	1.83
Stage 2	22.7/6,310	50.8/1,310	269,400	23,400	69.3/19,250	1.22
Stage 3	22.7/6,310	47.5/1,220	286,500	40,500	72.6/20,170	2.01

Table 4.22: Envelope modification energy use and construction costs (Sydney)

Stage 2 envelope upgrades provide the most cost-effective energy savings option. This, combined with minimal additional energy savings associated with the more expensive

Stage 3 upgrades, make Stage 2 envelope upgrades the building envelope selected for subsequent models.

4.5.3 Electric Water Heating

The electric water heating upgrades described in Section 3.2.3 are added to the Stage 2 home model. The energy use and costs for each of these are shown in Table 4.23. Energy savings and cost increases are compared to the Stage 2 envelope upgrade home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Annual Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Stage 2	22.7/6,310	50.8/1,310	269,400	N/A	N/A	N/A
Premium	33.0/9,170	33.5/860	270,200	800	7.0/1,940	0.41
Tankless	33.0/9,170	33.5/860	270,400	1,000	7.0/1,940	0.52
Heat Pump	31.7/8,810	33.8/870	271,200	1,800	8.0/2,220	0.81

Table 4.23: Electric water heating energy use and construction costs (Sydney)

Compared to oil water heating, a premium electric water heater provides energy savings at minimal increase in construction costs. Both a heat pump electric water heater and a tankless electric water heater provide even greater energy savings but at a cost increase compared to a premium electric water heater that makes those savings not cost effective. Based on these results, a premium electric water heater is selected for use in subsequent models.

4.5.4 Appliance Upgrades and Lighting

Annual energy use for a home with high efficiency appliance upgrades as described in Section 3.2.4 is 26.4GJ (7,330kWh) of electricity and 34.1GJ (880L) of fuel oil, before clothes dryer removal. After the clothes dryer removal, the annual energy use totals 23GJ (6,390kWh) of electricity and 35GJ (900L) of fuel oil. Removal of the clothes dryer reduces the construction cost by $800.

LED lighting also replaces the CFL lighting initially used as described in Section 3.2.5. LED lights are assumed to be at cost parity with their CFL equivalent. Results and costs of these upgrades are shown in Table 4.24. Energy savings and cost increases are compared to the tankless electric water heater home.

Upgrade	**Annual Electricity Use (GJ/kWh)**	**Annual Fuel Oil Use (GJ/L)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Annual Total Energy Savings (GJ/kWh)**	**Cost of Annual Energy Savings ($/kWh)**
Premium	33.0/9,170	33.5/860	270,200	N/A	N/A	N/A
Interior Equipment Upgrades	22.7/6,310	35.0/900	271,000	800	8.8/2,440	0.33

Table 4.24: Interior equipment energy use and construction costs (Sydney)

High efficiency appliances with clothes dryer removal and LED lighting is selected for all subsequent homes.

4.5.5 Dynamic Heating Setpoint

Energy savings related to the dynamic heating setpoint described in Section 3.2.6 total 5.8GJ (150L) of fuel oil with negligible impact on electricity use. This gives a total annual energy use of 22.7GJ (6,310kWh) of electricity and 29.2 GJ (750L) of fuel oil. Costs are unimpacted by the change in setpoint schedule, meaning the 5.8GJ in annual energy savings have a cost of 0$/kWh. This setpoint schedule is used in all subsequent homes.

Energy use and costs for the dynamic heating setpoint upgrade are shown in Table 4.25. Energy savings and cost increases are compared to the high efficiency appliances with clothes dryer removal and LED lighting home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
LED Lighting	22.7/6,310	35.0/900	271,000	N/A	N/A	N/A
Dynamic Heating Setpoint	22.7/6,310	29.2/750	271,000	0	5.8/1,610	0

Table 4.25: Dynamic heating setpoint energy use and construction cost (Sydney)

4.5.6 Internal Thermal Mass

The addition of the PCM thermal mass described in Section 3.2.7 to the home results in an annual energy use of 22.7GJ (6,310kWh) of electricity and 24.8GJ (600L) of fuel oil. The installation cost of a PCM thermal mass system is approximately $5000 (Solar UK 2019). Energy use and costs for the PCM thermal mass upgrade are shown in Table 4.26. Energy savings and cost increases are compared to the dynamic heating setpoint home.

Upgrade	Annual Electricity Use (GJ/kWh)	Annual Fuel Oil Use (GJ/L)	Construction Cost ($)	Incremental Cost ($)	Total Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Dynamic Heating Setpoint	22.7/6,310	29.2/750	271,000	N/A	N/A	N/A
PCM Thermal Mass	22.7/6,310	24.8/600	276,000	5000	4.4/1,220	4.10

Table 4.26: PCM thermal mass energy use and construction cost (Sydney)

Energy saving cost of PCM thermal mass exceeds that of the PV system described in Section 4.1.2. This upgrade is not used in subsequent homes.

4.5.7 Electric Resistance Heating

Replacing the oil-burning furnace with the electric baseboard system described in Section 3.2.8 eliminates the need for fuel oil. All energy used is supplied in the form of electricity. A 4kW system is calculated to be the appropriate size to heat the home. This capacity is assumed to be evenly distributed among eight 500W electric baseboard heaters.

Energy use with electric baseboard heating totals 46.5GJ (12,920kWh) of electricity. This is a 5.4GJ (1,500kWh) decrease in total energy use when compared to the same model using an oil-burning furnace. Additionally, the construction costs are reduced to $254,100.

Energy use and costs for the electric resistance heating upgrade are shown in Table 4.27. Energy savings and cost increases are compared to the dynamic heating setpoint home.

Upgrade	**Annual Electricity Use (GJ/kWh)**	**Annual Fuel Oil Use (GJ/L)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Energy Savings (GJ/kWh)**	**Cost of Annual Energy Savings ($/kWh)**
Dynamic Heating Setpoint	22.7/6,310	29.2/600	271,000	N/A	N/A	N/A
Electric Resistance Heating	46.5/12,920	N/A	259,400	-11,600	5.4/1,500	-7.73

Table 4.27: Electric resistance heating energy use and construction costs (Sydney)

Electric resistance heating offers savings in both energy use and construction cost. The same electric resistance heating system is used as supplemental heating in the heat pump heated models described in Section 4.3.7.

4.5.8 Heat Pump Space Heating

Five space conditioning heat pump layouts are described in Section 3.2.9. Annual energy uses, energy savings, construction costs, and energy savings costs for these layouts are shown in Table 4.28. Incremental values are compared to the electric resistance heated home.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
Electric Resistance Heating	46.5/12,920	259,400	N/A	N/A	N/A
1 RLS3Y Heat Pump	40.3/11,190	263,900	4,500	6.2/1,720	2.62
1 RLS3Y Heat Pump and 1 ARU12RLF Heat Pump	34.6/9,610	271,700	12,300	11.9/3,310	3.71
2 RSL3Y Heat Pumps	36.8/10,220	269,400	9,000	9.7/2,690	3.35
4 RSL3Y Heat Pumps	28.9/8,030	277,300	17,900	17.6/4,890	3.66
1 4MXS36RMVJU with 4 indoor units	33.7/9,360	270,800	11,400	12.8/3,560	3.20

Table 4.28: Air source heat pump energy use and construction costs (Sydney)

The least expensive energy saving option among space conditioning heat pumps is the single RSL3Y heat pump to condition the first story living zone with electric resistance heating used upstairs. It is also the only system with an energy saving cost less than that of a PV system.

Because it is the only financially viable options, a RLS3Y heat pump is selected for subsequent upgrades.

4.5.9 Solar Domestic Hot Water

The two sizes of solar domestic hot water (SDHW) systems described in Section 3.2.10 are the final additions to the house before the PV system. Annual energy uses with these systems are 36.5GJ (10,130kWh) and 34.7GJ (9,630kWh) for the 40 and 64 sq ft models respectively. Energy use and construction costs for SDHW systems with respect to the heat pump space conditioned model is shown in Table 4.29.

Upgrade	Annual Electricity Use (GJ/kWh)	Construction Cost ($)	Incremental Cost ($)	Annual Energy Savings (GJ/kWh)	Cost of Annual Energy Savings ($/kWh)
1 RLS3Y Heat Pump	40.3/11,190	263,900	N/A	N/A	N/A
40 Ft^2 SDHW	36.5/10,130	271,400	7,500	3.8/1,060	7.08
64 Ft^2 SDHW	34.7/9,630	273,800	9,900	5.6/1,560	6.35

Table 4.29: Solar domestic hot water energy use and construction costs (Sydney)

Energy saving costs for both SDHW systems exceed those of a PV system. As a result, SDHW systems are not used in subsequent models.

4.5.10 Photovoltaic System

After applying all financially viable upgrades, annual energy use of the house is reduced to 40.3GJ (11,190kWh). Section 4.1.2 shows the annual net electricity production of a 1kW capacity PV system to be 1,110kWh. A 10kW capacity PV system achieves near net-zero energy use with an annual net energy use of 90kWh. Annual energy use of less than 100kWh is considered net-zero energy for this case. This system is estimated to cost $29,500, bringing total construction costs to $293,400.

Energy use and construction costs for PV systems with respect to the heat pump space conditioned model is shown in Table 4.30.

Upgrade	**Annual Electricity Use (GJ/kWh)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Annual Energy Savings (GJ/kWh)**	**Annual Cost of Energy Saving ($/kWh)**
1 RLS3Y Heat Pump	40.3/11,190	263,900	N/A	N/A	N/A
Net-Zero PV System	0.3/90	293,400	29,500	34.0/11,100	2.66

Table 4.30: Photovoltaic system energy use and construction costs (Sydney)

4.5.11 Net-Zero Energy Home Pathway

Figure 4.3 displays the pathway to achieving a net-zero energy home for Sydney with points labelled as:

1. Base case home
2. Stage 2 building envelope upgrades
3. Tankless electric water heater
4. High efficiency appliances
5. Clothes dryer removal
6. LED lighting
7. Dynamic heating setpoint
8. Electric Resistance heating
9. Heat pump space conditioning

10. Net-positive PV system

All points are cumulative, meaning all previous upgrades are included.

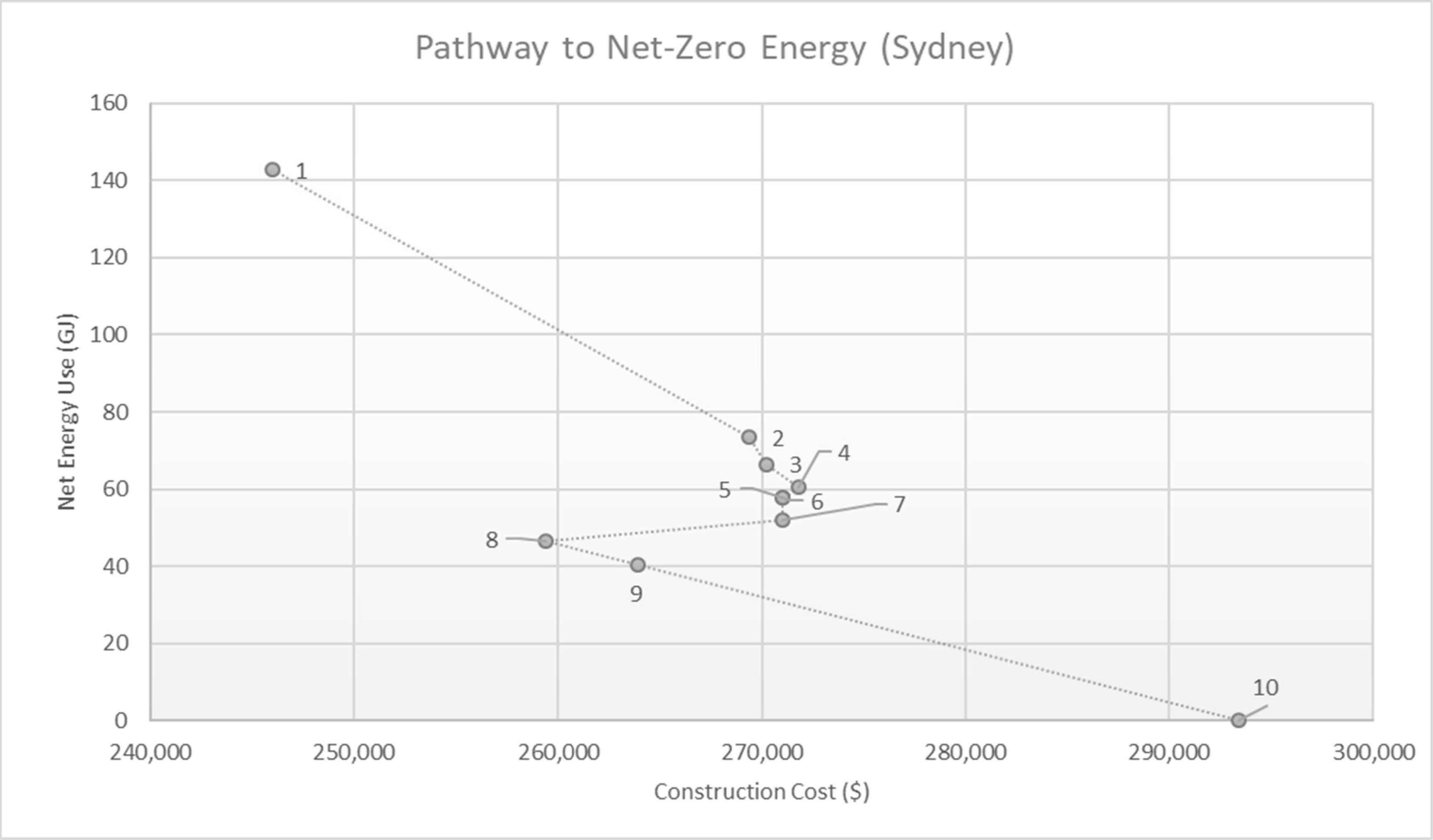

Figure 4.3: Pathway to net-zero energy (Sydney)

The base case and ten upgrade cases which lead to net-zero energy are summarized in Table 4.31. Payback periods are calculated with respect to the base case.

Home Model	**Annual Net Electricity Use (GJ/kWh/$)**	**Annual Fuel Oil Use (GJ/L/$)**	**Construction Cost ($)**	**Incremental Cost ($)**	**Annual Savings ($/year)**	**Payback Period (years)**
Base Case	24.0/6,670/1,200	118.8/3,060/3,150	246,000	N/A	N/A	N/A
Stage 2 Envelope Modifications	22.7/6,310/1,140	50.8/1,310/1,350	269,400	23,400	1,860	12.58
Premium Electric Water Heater	33.0/9,170/1,650	33.5/860/890	270,200	24,200	1,810	13.37
High Efficiency Appliances	26.4/7,330/1,320	34.1/880/910	271,800	25,800	2,120	12.17
Clothes Dryer Removal	23.0/6,390/1,150	35.0/900/930	271,000	25,000	2,270	11.01
LED Lighting	22.7/6,310/1,140	35.0/900/930	271,000	25,000	2,280	10.96
Dynamic Heating Setpoint	22.7/6,310/1,140	29.2/750/770	271,000	25,000	2,440	10.25
Electric Resistance Heating	46.5/12,920/2,330	N/A	259,400	13,400	2,020	6.63
Heat Pump Space Conditioning	40.3/11,190/2,010	N/A	263,900	19,900	2,340	8.50
Net-Positive PV System	0.3/90/20	N/A	293,400	47,400	4,330	10.95

Table 4.31: Summary of pathway to net-zero energy home with payback periods (Sydney)

The point at which electric resistance heating is added provides the shortest payback period. All points along the pathway provide a payback within 15 years.

CHAPTER 5. CONCLUSION

5.1 SUMMARY

Increases in both energy prices and consumers' concerns regarding their energy use are making more energy efficient homes an enticing option for many homeowners. Net-zero energy homes appeal to the desire to offset any energy use through on-site production. Additionally, a properly sized energy storage system could allow net-zero energy homes to exist "off-grid".

This research provides a pathway towards the design and construction of a net-zero energy home for three locations in Nova Scotia. It combines a review of potential technologies and construction techniques with energy model results and estimated costs of homes using these upgrades. These results allow the most viable upgrades to be selected until annual net-zero energy use is achieved.

Chapter 1 describes the motivations and overall goals of the research. A goal of achieving net-zero annual source energy consumption is selected.

In Chapter 2, historical developments of efficient energy use in homes are reviewed before describing technologies and incentives related to home energy efficiency. Environmental features of Nova Scotia are also described.

Chapter 3 provides a description of the home geometry, base case, and upgrades to be tested. The energy simulation software used (EnergyPlus) is also described, along with the methodology of economic analysis.

Chapter 4 describes energy and cost results of models used in developing a pathway to a net-zero energy home for all three locations tested (Halifax, Truro, and Sydney). The base case home energy and cost results are validated by statistics regarding typical Canadian homes. All upgrades applied are based on commercially available equipment and construction techniques.

All three locations achieve net-zero annual energy use with a PV system with a capacity of 10kW or less, a reasonable capacity for a residential rooftop system. The additional cost premium of a net-zero energy home compared to a typical new construction home is found to be approximately $45,000 for all three locations for the home design used. This constitutes a ~20% increase in cost. This increase in cost is estimated to be paid back in roughly 15 years.

Selected upgrades were based on their cost effectiveness in energy saving. Some upgrades, such as electric resistance space heating, resulted in decreased energy use and initial cost. Other upgrades, such as dynamic heating setpoints and LED lighting, provide energy savings at no additional cost.

Cost effective upgrades which increase initial costs while reducing annual energy use include building envelope upgrades, space conditioning heat pumps, and high efficiency appliances. Solar domestic hot water system and PCM thermal mass upgrades were found not to be cost effective when compared to the addition of a rooftop PV system.

By achieving a net-zero energy home design with a reasonable payback period using upgrades available to consumers, this research can be considered a practical guide to developing net-zero or low energy use new construction homes in Nova Scotia.

5.2 SUGGESTED FUTURE RESEARCH

Further areas of potential research towards net-zero energy homes in Nova Scotia include:

- **Inclusion of natural gas where available:** This research ignores natural gas as a potential energy source as it is not widely available throughout Nova Scotia. Some areas, primarily within the HRM, have access to natural gas lines. Systems using these lines could be modelled for areas where they are available.
- **Evaluation of off-grid potential:** In addition to analyzing energy use and costs using the existing energy grid as a sink for excess electricity, home designs can be developed for battery storage. Based on this, the viability and cost of a home capable of sustaining its occupants without connection to an energy grid can be assessed**.**
- **Alternative building geometry and occupancy:** All homes tested use the same basic dimensions and building geometry. While the geometry used is a reasonable home design, it does not describe all new homes constructed in Nova Scotia. Additionally, only a 4-person occupancy schedule is used. In order to more accurately describe new construction homes for Nova Scotia, it will be useful to evaluate a greater variety of home designs and occupancies.

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APPENDIX A: INTERIOR EQUIPMENT SCHEDULES (HENDRON AND ENGEBRECHT, 2014)

This appendix presents the hourly schedules used for interior equipment used in energy models. All values represent a fraction of the peak load as described in section 3.2 over the course of the given hour. These schedules are based on the National Renewable Energy Laboratory's Building America House Simulation Protocols (2014).

A.1 Bathroom Exhaust Fan (All Days)

Hour	Fraction
1	0
2	0
3	0
4	0
5	0
6	0
7	1
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0

A.2 Clothes Dryer

Hour	Fraction (Week)	Fraction (Weekend)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	1
12	0	1
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0

A.3 Clothes Washer

Hour	Fraction (Week)	Fraction (Weekend)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	1
11	0	0.5
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0

A.4 Cooking Range (All Days)

Hour	Fraction (Week)
1	0
2	0
3	0
4	0
5	0
6	0
7	0.14
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0.14
19	0
20	0
21	0
22	0
23	0
24	0

A.5 Lighting (January-June)

Hour	Fraction (Jan)	Fraction (Feb)	Fraction (Mar)	Fraction (Apr)	Fraction (May)	Fraction (Jun)
1	0.08	0.08	0.08	0.08	0.08	0.08
2	0.04	0.04	0.04	0.04	0.04	0.04
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0.04	0.04	0.04	0.04	0.04	0.04
7	0.08	0.08	0.04	0.04	0.04	0.04
8	0.16	0.12	0.08	0.08	0.04	0.04
9	0.12	0.12	0.08	0.08	0.04	0.04
10	0.08	0.04	0.04	0.04	0.04	0.04
11	0.04	0.04	0.04	0.04	0	0
12	0.04	0.04	0	0	0	0
13	0.04	0.04	0	0	0	0
14	0.04	0.04	0.04	0.04	0	0
15	0.04	0.04	0.04	0.04	0	0
16	0.08	0.04	0.04	0.04	0.04	0.04
17	0.12	0.08	0.04	0.04	0.04	0.04
18	0.24	0.16	0.08	0.04	0.04	0.04
19	0.32	0.24	0.16	0.08	0.08	0.08
20	0.32	0.32	0.24	0.12	0.08	0.08
21	0.28	0.28	0.28	0.20	0.16	0.12
22	0.24	0.24	0.24	0.24	0.24	0.20
23	0.16	0.16	0.16	0.16	0.16	0.16
24	0.12	0.12	0.12	0.12	0.12	0.12

A.6 Lighting (July-December)

Hour	Fraction (Jul)	Fraction (Aug)	Fraction (Sep)	Fraction (Oct)	Fraction (Nov)	Fraction (Dec)
1	0.08	0.08	0.08	0.08	0.08	0.08
2	0.04	0.04	0.04	0.04	0.04	0.04
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0.04	0.04	0.04	0.04	0.04	0.04
7	0.04	0.04	0.04	0.08	0.04	0.08
8	0.04	0.08	0.08	0.12	0.12	0.16
9	0.04	0.04	0.08	0.12	0.12	0.12
10	0.04	0.04	0.04	0.04	0.04	0.08
11	0	0.04	0.04	0.04	0.04	0.04
12	0	0.04	0.04	0.04	0.04	0.04
13	0	0.04	0.04	0.04	0.04	0.04
14	0	0.04	0.04	0.04	0.04	0.04
15	0	0.04	0.04	0.04	0.04	0.08
16	0	0.04	0.04	0.04	0.08	0.08
17	0.04	0.04	0.04	0.04	0.16	0.16
18	0.04	0.04	0.04	0.08	0.24	0.28
19	0.04	0.04	0.08	0.16	0.32	0.32
20	0.08	0.08	0.16	0.24	0.28	0.32
21	0.12	0.16	0.24	0.28	0.28	0.28
22	0.20	0.20	0.24	0.24	0.24	0.24
23	0.16	0.16	0.16	0.16	0.16	0.16
24	0.12	0.12	0.12	0.12	0.12	0.12

A.7 Miscellaneous Electric Loads (January-June)

Hour	Fraction (Jan)	Fraction (Feb)	Fraction (Mar)	Fraction (Apr)	Fraction (May)	Fraction (Jun)
1	0.56	0.56	0.45	0.44	0.45	0.37
2	0.52	0.52	0.41	0.41	0.41	0.34
3	0.52	0.52	0.41	0.41	0.41	0.34
4	0.50	0.51	0.40	0.40	0.40	0.33
5	0.46	0.46	0.37	0.37	0.37	0.30
6	0.50	0.51	0.40	0.40	0.40	0.33
7	0.60	0.61	0.48	0.48	0.48	0.40
8	0.66	0.66	0.52	0.52	0.52	0.43
9	0.48	0.48	0.38	0.38	0.38	0.31
10	0.32	0.32	0.26	0.25	0.26	0.21
11	0.34	0.34	0.27	0.27	0.27	0.22
12	0.35	0.35	0.28	0.28	0.28	0.23
13	0.34	0.34	0.27	0.27	0.27	0.22
14	0.39	0.39	0.31	0.31	0.31	0.26
15	0.43	0.44	0.34	0.34	0.34	0.29
16	0.45	0.45	0.36	0.35	0.36	0.29
17	0.55	0.55	0.43	0.43	0.43	0.36
18	0.74	0.75	0.59	0.59	0.59	0.49
19	0.88	0.89	0.70	0.70	0.70	0.58
20	0.94	0.94	0.75	0.74	0.75	0.62
21	0.99	1.00	0.79	0.79	0.79	0.65
22	0.96	0.97	0.77	0.76	0.77	0.63
23	0.83	0.83	0.66	0.65	0.66	0.46
24	0.70	0.70	0.56	0.55	0.56	0.12

A.8 Miscellaneous Electric Loads (July-December)

Hour	Fraction (Jul)	Fraction (Aug)	Fraction (Sep)	Fraction (Oct)	Fraction (Nov)	Fraction (Dec)
1	0.37	0.37	0.37	0.44	0.44	0.56
2	0.34	0.34	0.34	0.41	0.41	0.52
3	0.34	0.34	0.34	0.41	0.41	0.52
4	0.33	0.33	0.33	0.40	0.40	0.50
5	0.30	0.30	0.31	0.37	0.36	0.46
6	0.33	0.33	0.33	0.40	0.40	0.50
7	0.40	0.40	0.40	0.48	0.48	0.60
8	0.43	0.43	0.44	0.52	0.52	0.66
9	0.31	0.31	0.32	0.38	0.38	0.48
10	0.21	0.21	0.21	0.26	0.25	0.32
11	0.22	0.22	0.22	0.27	0.27	0.34
12	0.23	0.23	0.23	0.28	0.28	0.35
13	0.22	0.22	0.22	0.27	0.27	0.34
14	0.26	0.26	0.26	0.31	0.31	0.39
15	0.29	0.29	0.29	0.34	0.34	0.43
16	0.29	0.29	0.30	0.35	0.35	0.45
17	0.36	0.36	0.36	0.43	0.43	0.55
18	0.49	0.49	0.49	0.59	0.59	0.74
19	0.58	0.58	0.58	0.70	0.70	0.88
20	0.62	0.62	0.62	0.74	0.74	0.94
21	0.65	0.65	0.66	0.79	0.79	0.99
22	0.63	0.63	0.64	0.77	0.76	0.96
23	0.54	0.54	0.55	0.65	0.65	0.83
24	0.46	0.46	0.46	0.55	0.55	0.70

A.9 Occupancy (All Days)

Hour	Fraction
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	0.75
9	0.5
10	0.25
11	0
12	0
13	0
14	0
15	0
16	0
17	0.25
18	0.5
19	0.75
20	1
21	1
22	1
23	1
24	1

A.10 Dishwasher (Only Operated Wednesday, Thursday and Friday)

Hour	Fraction (Wed)	Fraction (Thurs)	Fraction (Fri)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0.5	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	1	1

APPENDIX B: COST DATA OF COMPONENTS (BEFORE TAX) (RSMEANS 2007, 2016)

Item Number	**Item**	**Unit**	**Cost**		
			Halifax	**Truro**	**Sydney**
B.1	Basement Excavation	N/A	5070	5060	5060
B.2	Concrete Footing	Linear Foot	23.30	22.60	23.10
B.3	Concrete Wall	Square Foot	28.10	26.70	27.10
B.4	Concrete Slab	Square Foot	59.60	58.30	59.60
B.5	Wall Framing	Square Foot	4.90	4.60	5.10
B.6	Floor Framing	Square Foot	7.30	6.80	8.00
B.7	4/12 Pitch Truss Roof Framing	Square Foot	8.40	8.00	9.40
B.8	8/12 Pitch Truss Roof Framing	Square Foot	9.70	9.20	10.80
B.9	Interior Partition Wall Framing	Square Foot	11.50	10.70	11.90
B.10	Exterior Wall Siding	Square Foot	6.50	5.90	6.80
B.11	Double Hung Window	12 Square Feet	460	430	460
B.12	Exterior Door	N/A	1160	1080	1160
B.13	Roofing Finish	Square Foot	3.60	3.30	3.90
B.14	Interior Wall Finish	Square Foot	3.40	3.00	3.20
B.15	Interior Ceiling Finish	Square Foot	2.40	2.20	2.30
B.16	Interior Door	N/A	610	540	570
B.17	Oil-Burning Hot-Air Furnace	N/A	10,710	11,050	11,130

B.1 Basement Excavation

Component	Quantity	Unit
Clear and grub, dozer, medium brush, 30’ from building	0.19	Acre
Excavate, track loader, 1-1/2 C.Y. bucket	550	C.Y.
Backfill, dozer, 8” lifts, no compaction	180	C.Y.
Rough grade, dozer, 30’ form building	1	Ea.

B.2 One Linear Foot of Concrete Footing

Component	Quantity	Unit
Concrete, 3000psi	0.04	C.Y.
Place concrete, direct chute	0.04	C.Y.
Forms, footing, 4 uses	1.33	SFCA
Reinforcing, ½”, bevelled, 4 uses	0.03	CLF
Keyway, 2x4, bevelled, 4 uses	1	L.F.
Dowels, ½” diameter bars, 2’ long, 6’ O.C.	0.166	Ea

B.3 One Square Foot of Concrete Wall

Component	Quantity	Unit
Concrete, 8” thick, 3000psi	0.025	C.Y.
Forms, prefabricated plywood, 4 uses	2	SFCA
Reinforcing, light	0.000335	Lb
Placing concrete, direct chute	0.025	C.Y.
Dampproofing, brushed on, 2 coats	1	S.F.
`Anchor bolts, ½” diameter, 12” long, 4’ O.C.	0.06	Ea.
Sill plates, 2x4, treated	0.25	L.F.

B.4 One Square Foot of Concrete Slab

Component	Quantity	Unit
Concrete, 4” thick, 3000psi	0.012	C.Y.
Place concrete, direct chute	0.012	C.Y.
Bank run gravel, 4” deep	0.111	S.F.
Polyethylene vapour barrier, .006” thick	0.01	S.F.
Edge forms, expansion material	0.1	L.F.
Welded wire fabric, 6x6, 10/10 (W1.4/W1.4)	1.1	CSF
Steel trowel finish	1	S.F.

B.5 One Square Foot of Above-Grade Wall Framing

Component	Quantity	Unit
2” x 6” studs, 16” O.C.	1.000	L.F.
Plates, 2” x 6”, double top, single bottom	0.375	L.F.
Corner Bracing, let-in, 1” x 6”	0.063	L.F.
Sheathing, ½” plywood, CDX	1.000	S.F.

B.6 One Square Foot of Floor Framing

Component	Quantity	Unit
Wood joists, 2” x 10”, 16” O.C.	1.000	L.F.
Bridging, 1” x 3”, 6’ O.C.	0.080	Pr.
Box Sills, 2” x 10”	0.150	L.F.
Girder, built up form three 2” x 10”	0.125	L.F.
Sheathing, plywood, subfloor, 5/8” CDX	1.000	S.F.
Furring, 1” x 3”, 16” O.C.	1.000	L.F.

B.7 One Square Foot of 4/12 Pitch Truss Roof Framing

Component	Quantity	Unit
Truss, 40# loading, 24” O.C., 4/12 pitch, 26’ span	0.020	Ea.
Fascia board, 2” x 6”	0.100	L.F.
Sheathing, exterior, plywood, CDX, ½” thick	1.170	S.F.
Furring, 1” x 3”, 16” O.C.	1.000	L.F.

B.8 One Square Foot of 8/12 Pitch Truss Roof Framing

Component	Quantity	Unit
Truss, 40# loading, 24” O.C., 8/12 pitch, 26’ span	0.020	Ea.
Fascia board, 2” x 6”	0.100	L.F.
Sheathing, exterior, plywood, CDX, ½” thick	1.330	S.F.
Furring, 1” x 3”, 16” O.C.	1.000	L.F.

B.9 One Square Foot of Interior Partition Wall Framing

Component	Quantity	Unit
2” x 4” studs, #2 or better, 16” O.C.	1.000	L.F.
Plates, double top, single bottom	0.375	L.F.
Cross bracing, let-in, 1” x 6”	0.080	L.F.

B.10 One Square Foot of Exterior Wall Siding

Component	Quantity	Unit
PVC horizontal siding, 8” clapboard	1.000	S.F.
Backer, insulation board	1.000	S.F.
Trim, vinyl	0.600	L.F.
Building wrap, spunbonded polypropylene	1.100	S.F.

B.11 One 3’X4’ Double-Hung Window

Component	Quantity	Unit
Window, plastic clad, premium, 3’ x 4’, insulating glass	1.000	Ea.
Trim, interior casing	15.000	L.F.
Paint, interior, primer & 2 coats	1.000	Face
Caulking	14.000	L.F.
Snap-in grill	1.000	Set

B.12 One Exterior Door

Component	Quantity	Unit
Door, 3’ x 6’8” x 1 ¾” thick, pine, 6 panel colonial	1.000	Ea.
Frame, 5-13/16” deep, incl. exterior casing and drip cap	17.000	L.F.
Interior casing, 2-1/2” wide	18.000	L.F.
Sill, 8/4 x 8” deep	3.000	L.F.
Butt hinges, brass, 4-1/2” x 4-1/2”	1.5000	Pr.
Lockset	1.000	Ea.
Weather-stripping, metal, spring type, bronze	1.000	Set
Paint, interior and exterior, primer & 2 coats	2.000	Face

B.13 One Square Foot of Roofing System

Component	Quantity	Unit
Shingles, inorganic class A, 210-235 lb./sq., 4/12 pitch	1.160	S.F.
Drip edge, metal 5” wide	0.150	L.F.
Building paper, #15 felt	1.300	S.F.
Ridge shingles, cedar	0.042	L.F.
Soffit & fascia, white painted aluminum, 1’ overhang	0.083	L.F.
Rake trim, 1” x 6”	0.040	L.F.
Rake trim, prime and paint	0.040	L.F.
Gutter, seamless, aluminum, painted	0.083	L.F.
Downspouts, aluminum painted	0.035	L.F.

B.14 One Square Foot of Interior Wall Finishing

Component	Quantity	Unit
Gypsum wall board, ½” thick, standard	1.000	S.F.
Finish, taped & finished joints	1.000	S.F.
Corners, taped & finished, 32 L.F. per 12’ x 12’ room	0.083	L.F.
Painting, primer & 2 coats	1.000	S.F.
Paint trim, to 6” wide, primer & 1 coat enamel	0.125	L.F.
Trim, baseboard	0.125	L.F.

B.15 One Square Foot of Interior Ceiling Finishing

Component	Quantity	Unit
Gypsum wall board, ½” thick, standard	1.000	S.F.
Finish, taped & finished joints	1.000	S.F.
Corners, taped & finished, 12’ x 12’ room	0.333	L.F.
Painting, primer & 2 coats	1.000	S.F.

B.16 One Interior Door

Component	Quantity	Unit
Door, flush, lauan, hollow core, 2’-8” wide x 6’8” high	1.000	Ea.
Frame, pine, 4-5/8” jamb	17.000	L.F.
Trim, stock pine, 11/16” x 2-1/2”	34.000	L.F.
Paint trim, to 6” wide, primer + 1 coat enamel	34.000	L.F.
Butt hinges, chrome, 3-1/2” x 3-1/2”	1.5000	Pr.
Lockset, passage	1.000	Ea.
Prime door & frame, oil, brushwork	2.000	Face
Paint door & frame, oil, 2 coats	2.000	Face

B.17 One Oil-Burning Hot-Air Furnace

Component	Quantity	Unit
Furnace, oil-fired, atomizing gun type burner	1.000	Ea.
3/8” diameter copper supply pipe	1.000	Ea.
Shut off valve	1.000	Ea.
Oil tank, 275 gallon, on legs	1.000	Ea.
Supply duct, rigid fibreglass	176.000	S.F.
Return duct, sheet metal, galvanized	158.000	Lb.
Lateral ducts, 6” flexible fibreglass	144.000	L.F.
Register elbows	12.000	Ea.
Floor register, enameled steel	12.000	Ea.
Floor grille, return air	2.000	Ea.
Thermostat	1.000	Ea.

APPENDIX C: COST MODEL SENSITIVITY ANALYSIS

This appendix presents sensitivity analyses for 10 components of the cost model described in section 3.3. The construction cost for net-zero (near net-zero for Halifax, net-positive for Truro and Sydney) energy homes compared to the high-efficiency reference home is shown for each variable in tables C.1 to C.8. Table C.9 shows the impact of energy costs on payback period.

Item Number	**Variable**	**Units**	**Minimum**	**Maximum**	**Number of Steps**
C.1	Framing cost multiplier	Fraction	0.8	1.2	8
C.2	Roofing cost multiplier	Fraction	0.8	1.2	8
C.3	Concrete cost multiplier	Fraction	0.8	1.2	8
C.4	Excavation cost multiplier	Fraction	0.8	1.2	8
C.5	Insulation cost multiplier	Fraction	0.8	1.2	8
C.6	Space heating cost multiplier	Fraction	0.8	1.2	8
C.7	Water heating cost multiplier	Fraction	0.8	1.2	8
C.8	Photovoltaic system cost multiplier	Fraction	0.8	1.2	8
C.9	Energy cost multiplier	Fraction	0.8	1.2	8

C.1 Framing Cost Multiplier

	0.80	**0.85**	**0.90**	**0.95**	**1.00**	**1.05**	**1.10**	**1.15**	**1.20**
Halifax	$275,800	$278,600	$281,400	$284,200	$287,000	$289,800	$292,600	$295,400	$298,200
Truro	$274,700	$277,500	$280,300	$283,100	$285,900	$288,700	$291,500	$294,300	$297,100
Sydney	$282,200	$285,000	$287,800	$290,600	$293,400	$296,200	$299,000	$301,800	$304,600

C.2 Roofing Cost Multiplier

	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
Halifax	$286,200	$286,400	$286,600	$286,800	$287,000	$287,200	$287,400	$287,600	$287,800
Truro	$285,100	$285,300	$285,500	$285,700	$285,900	$286,100	$286,300	$286,500	$286,700
Sydney	$292,600	$292,800	$293,000	$293,200	$293,400	$293,600	$293,800	$294,000	$294,200

C.3 Concrete Cost Multiplier

	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
Halifax	$269,400	$273,800	$278,200	$282,600	$287,000	$291,400	$295,800	$300,200	$304,600
Truro	$268,300	$272,700	$277,100	$281,500	$285,900	$290,300	$294,700	$299,100	$303,500
Sydney	$275,800	$280,200	$284,600	$289,000	$293,400	$297,800	$302,200	$306,600	$311,000

C.4 Excavation Cost Multiplier

	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
Halifax	$285,800	$286,100	$286,400	$286,700	$287,000	$287,300	$287,600	$287,900	$288,200
Truro	$284,700	$285,000	$285,300	$285,600	$285,900	$286,200	$286,500	$286,800	$287,100
Sydney	$292,200	$292,500	$292,800	$293,100	$293,400	$293,700	$294,000	$294,300	$294,600

C.5 Insulation Cost Multiplier

	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
Halifax	$283,400	$284,300	$285,200	$286,100	$287,000	$287,900	$288,800	$289,700	$290,600
Truro	$282,300	$283,200	$284,100	$285,000	$285,900	$286,800	$287,700	$288,600	$287,500
Sydney	$289,400	$290,400	$291,400	$292,400	$293,400	$294,400	$295,400	$296,400	$297,400

C.6 Space Heating Cost Multiplier

	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
Halifax	$285,800	$286,100	$286,400	$286,700	$287,000	$287,300	$287,600	$287,900	$288,200
Truro	$284,700	$285,000	$285,300	$285,600	$285,900	$286,200	$286,500	$286,800	$287,100
Sydney	$292,200	$292,500	$292,800	$293,100	$293,400	$293,700	$294,000	$294,300	$294,600

C.7 Water Heating Cost Multiplier

	0.80	**0.85**	**0.90**	**0.95**	**1.00**	**1.05**	**1.10**	**1.15**	**1.20**
Halifax	$286,600	$286,700	$286,800	$286,900	$287,000	$287,100	$287,200	$287,300	$287,400
Truro	$285,500	$285,600	$285,700	$285,800	$285,900	$286,000	$286,100	$286,200	$286,300
Sydney	$293,000	$293,100	$293,200	$293,300	$293,400	$293,500	$293,600	$293,700	$293,800

C.8 Photovoltaic System Cost Multiplier

	0.80	**0.85**	**0.90**	**0.95**	**1.00**	**1.05**	**1.10**	**1.15**	**1.20**
Halifax	$286,500	$286,600	$286,700	$286,900	$287,000	$287,100	$287,300	$287,400	$287,500
Truro	$285,300	$285,500	$285,600	$285,800	$285,900	$286,000	$286,200	$286,300	$286,500
Sydney	$292,800	$293,000	$293,100	$293,300	$293,400	$293,500	$293,700	$293,800	$294,000

C.9 Energy Cost Multiplier vs Payback Period (Years)

	0.80	**0.85**	**0.90**	**0.95**	**1.00**	**1.05**	**1.10**	**1.15**	**1.20**
Halifax	14.69	13.82	13.06	12.37	11.75	11.19	10.68	10.22	9.79
Truro	17.40	16.38	15.47	14.65	15.6	13.26	12.65	12.10	11.60
Sydney	13.69	12.88	12.17	11.53	10.95	10.43	9.95	9.52	9.13

APPENDIX D: CONSTRUCTION COST LOCATION MULTIPLIERS (RSMEANS, 2016)

This appendix collects the location cost multipliers for components used in estimating construction costs for the homes as described in Section 3.3.

D.1 Contractor Equipment Location Multipliers

	Mat.	**Inst.**	**Total**
Halifax	N/A	1.014	1.014
Truro	N/A	1.014	1.014
Sydney	N/A	1.014	1.014

D.2 Site and Infrastructure Location Multipliers

	Mat.	**Inst.**	**Total**
Halifax	1.082	0.977	1.007
Truro	1.042	0.975	0.994
Sydney	1.188	0.975	1.037

D.3 Concrete Location Multipliers

	Mat.	Inst.	Total
Halifax	1.278	0.759	1.026
Truro	1.382	0.666	1.034
Sydney	1.440	0.666	1.064

D.4 Wood, Plastics, and Composites Location Multipliers

	Mat.	**Inst.**	**Total**
Halifax	0.963	0.752	0.845
Truro	0.923	0.686	0.791
Sydney	1.179	0.686	0.905

D.5 Thermal and Moisture Protection Location Multipliers

	Mat.	Inst.	Total
Halifax	1.206	0.777	1.027
Truro	1.118	0.685	0.937
Sydney	1.434	0.685	1.120

D.6 Openings Location Multipliers

	Mat.	Inst.	Total
Halifax	0.939	0.703	0.884
Truro	0.875	0.630	0.818
Sydney	0.956	0.630	0.880

D.7 Finishes Location Multipliers

	Mat.	Inst.	Total
Halifax	1.151	0.874	0.990
Truro	1.063	0.682	0.852
Sydney	1.185	0.682	0.902

D.8 Plumbing and HVAC Location Multipliers

	Mat.	Inst.	Total
Halifax	1.049	0.768	0.930
Truro	1.036	0.835	0.951
Sydney	1.037	0.835	0.951

D.9 Electrical Location Multipliers

	Mat.	Inst.	Total
Halifax	1.052	0.806	0.928
Truro	1.087	0.639	0.860
Sydney	1.141	0.639	0.887