TECHNO-ECONOMIC FEASIBILITY OF A NET-ZERO ENERGY RETROFIT FOR A MULTI-UNIT RESIDENTIAL BUILDING IN HALIFAX, NOVA SCOTIA

By

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Dedicated to my mother

Thank you for believing in me

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Abstract

The building sector has a large environmental footprint that contributes to the current global GHG emissions. Implementing energy efficiency measures in the building sector will assist in reducing energy consumption and has the potential for substantial CO_2 reductions. There is an increased interest for net-zero energy buildings to reduce the high energy demands associated with buildings. This project investigates the techno-economic feasibility of implementing a net-zero energy retrofit for a MURB in Halifax, Nova Scotia. A MURB was selected and modeled in its current state using the building performance software OpenStudio. Iterations of energy efficiency modifications were implemented until the total annual energy consumption was reduced to a level that would allow for the building to achieve net zero energy status. The building reached net zero energy operation after the addition of 2,280 solar panels, or 47,400 ft^2 of solar cells. The economic feasibility was determined using the TCC method.

List of Abbreviations Used

ACH – Air Changes per Hour

AHU – Air Handling Unit

ASHRAE – American Society of Heating, Refrigeration and Air-Conditioning Engineers in America

BAPV – Building Applied Photovoltaics

BC – British Columbia

BIPV – Building Integrated Photovoltaics

CEC – California Energy Commission

CHP – Combined Heat and Power

CMHC – Canadian Mortgage and Housing Association

CTF – Conduction Transfer Function

DHW – Domestic Hot Water

EPBD – Energy Performance of Buildings Directive

ERV – Energy Recovery Ventilator

EU – European Union

EUI – Energy Use Intensity

EV – Electric Vehicle

GDP – Gross Domestic Product

GHG – Greenhouse Gas

HRV – Heat Recovery Ventilator

HVAC – Heating Ventilation and Air-Conditioning

IAQ – Indoor Air Quality

IBC – Interdigitated Back Contact

IPCC – International Panel on Climate Change

LED – Light-Emitting Diode

MRL – Machine Room-Less

MURB – Multi-Unit Residential Building

NACM – Non-Residential Calculation Method

nNZEB – Near Net Zero Energy Building

NRCan – Natural Resources Canada

NREL – National Renewable Energy Laboratory

NS – Nova Scotia

NZEB – Net Zero Energy Building

NZR – Net Zero Ready

PTHP – Packaged Terminal Heat Pump

PV – Photovoltaics

TCC – Tolerable Capital Cost

U.S. DOE – United States Department of Energy

UN – United Nations

VVVF – Variable Voltage and Variable Frequency

ZEB – Zero Energy Building

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Chapter 1 Introduction

1.1 Motivation

Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system, and are extremely likely to have been the dominant cause of the observed warming since the mid 20th century (IPCC, 2014).

The building sector has a large environmental footprint that contributes to the current global greenhouse gas (GHG) emissions. In Canada, the energy consumption of the residential sector is approximately 17 %, whereas the GHG emissions are approximately 15 % (NRCan, 2016). Building's effect GHG emissions through various aspects of their design, location, orientation, and use. Implementing energy efficiency measures in the building sector will assist in reducing energy consumption and has the potential for substantial Carbon Dioxide (CO_2) reductions. There is an increased interest for Net Zero Energy Buildings (NZEB) to reduce the high energy demands associated with buildings (Younger *et al.,* 2008). NZEB's are buildings that produce as much energy as it consumes on an annual basis. This is typically achieved by reducing the loads as much as possible through high performance enclosures and efficient mechanical and electrical systems. The balance of energy is then generated through on-site renewable energy such as solar photovoltaics (PV). NZEB's are often grid-tied, meaning that they draw energy from the grid as needed and supply energy back to the grid as it is produced in excess, the balance over the course of the year being zero or net-supply (CMHC, 2011).

NZEB are a radical approach for the mitigation of energy usage in the building sector (Ionesou *et al.,* 2015). However, global energy consumption has been increasing due to the increasing population and gross domestic product (GDP), and the population is expected to grow by two billion people over the next 30 years (UN, 2019). Energy is one of the key commodities required to sustain human existence and advancement, and one of the largest components of the world's economy. It is inevitable that an increased reliance on alternative and/ or renewable energy will be required to meet the energy needs of the future (Ugursal, 2014).

1.2 Defining Net Zero Energy Buildings

1.2.1 General Definition

The topic of zero energy buildings (ZEBs) has received increasing attention in recent years, until becoming part of the energy policy in several countries (Sartori, Napolitano, & Voss, 2011). Significant policy action towards the promotion of energy efficiency and on-site renewable energy in the building sector is under development all around the world, with different levels of intensity and structure (Kapsalaki & Leal, 2011). In the recast of the European Union (EU) directive on Energy Performance of Buildings (EPBD) it is specified that by the end of 2020 all new buildings shall be "nearly zero energy buildings". For the building technologies program of the United States Department of Energy (U.S. DOE), the strategic goal is to achieve "marketable zero energy homes in 2020 and commercial zero energy buildings in 2025" (Sartori et al., 2011). Currently, Canada does not have any mandatory initiatives to implement Net Zero Energy Buildings. However, proposed changes to Canada's energy and building codes will lay the foundation for Canada's Net Zero Energy Ready model code, enabling the provinces and territories to adopt a 'Net Zero Energy Ready' model building code by 2030 (NRCan, 2018a). Voluntary energy-based standards for buildings such as Passive House Canada and Energy Star are implemented at the developer's discretion. However, despite the emphasis on the goals, the definitions remain in most cases generic and are not yet standardized (Sartori et al., 2011).

The literature shows variations with the definition of NZEB. The first major difference being the inclusion of 'net' in the expression, 'zero energy building' or 'net zero energy building'. While the first is a more practical definition, the second is scientifically correct. In terms of substance, the two main differentiating factors were found to be the level of the energy chain at which the balance was made, and the requirement for a high level of energy efficiency.

In 2014, the U.S. DOE Building Technologies Office contracted with the National Institute of Building Sciences to establish definitions, associated nomenclature, and measurement guidelines for zero energy buildings, with the goal of achieving widespread adoption and use by the building industry (U.S. DOE, 2014). In addition to establishing a definition for Zero Energy Buildings (ZEB), it was clear that definitions were needed to accommodate the collections of buildings where renewable resources were shared. In the U.S. DOE definition, the building boundary is considered such that it includes all property premises, and the utility connections and the energy import/export occur at the building boundary (Nikoofard, Ugursal, & Beausoleil-Morrison, 2014). The variations on the ZEB definition are shown below:

Zero Energy Building (ZEB)

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 (U.S. DOE).

Zero Energy Campus

An energy-efficient campus where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy (U.S. DOE, 2014).

Zero Energy Portfolio

An energy-efficient portfolio where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy (U.S. DOE, 2014).

Zero Energy Community

An energy-efficient community where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy.

The second major differentiating factor regarding the definition of NZEB is the inclusion of on-site generation added to a building where significant energy efficeicny measures have been taken, to decrease demand. Having an explicit requirement for the zero balance to be met at a high level of energy efficiency is necessary. Otherwise, the simplest NZEB would be designed 'as usual' (or even very inefficiently) regarding the envelope and the equipment, and simply enough local generation would be added to offset the demand/consumption. However, several authors defend that a high level of energy efficiency should be a requirement for the NZEB label. A formal definition of NZEB needs to be developed and agreed upon to aid in the greater implementation of the concept (Kapsalaki & Leal, 2011).

Attia, (2018) lists several informal and formal definitions of NZEB. The most important definitions are summarized below:

Net Zero Energy Building (NZEB)

A Net Zero Energy Building (NZEB) is a building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is equal to the amount of renewable energy generated on-site, or by renewable energy sources off-site (Attia, 2018).

Nearly Zero Energy Building (nZEB)

A Nearly Zero Energy Building (nZEB) is a building that has a very high energy performance and that produces 30 % or more of its required energy through renewable resources on-site or nearby (Attia, 2018).

Net Zero Ready (NZR)

Buildings that are Net Zero Ready (NZR) are built to a high energy efficient standard but do not incorporate renewable energy to offset the demand. This allows the building owner to incorporate renewable energy generation later and at a lower cost due to a reduced requirement for energy in the building (Efficiency Nova Scotia, 2020).

Net Zero Site Energy

A Net Zero Site Energy Building produces at least as much energy as it uses annually, when accounted for at the site. This definition does not take into account the type of energy used, as long as the energy is produced on-site and equals the amount of energy used on-site over the course of a year (Attia, 2018).

Net Zero Source Energy (Primary Energy)

A Net Zero Source Energy Building produces at least as much energy as it uses annually, when accounted for at the source. Source energy refers to the primary energy required to generate and deliver the energy to the site. Primary energy refers to a form of energy found in nature that has not been subjected to any human engineered conversion process (Attia, 2018).

Net Zero Cost Energy

A Net Zero Cost Building is a building in which the amount of money the building owner pays the power plant or utility for energy services and energy used over a year is at least equal to the amount the energy company pays the building tenant or owner for the energy the building exports to the grid over a year (Attia, 2018).

Life Cycle Zero Energy Building

A Life Cycle Zero Energy Building is a building where the primary energy used during operation and the embodied energy within its constituents' materials and systems, including energy generating components, over the life of the building are equal to or less than, the energy produced by its renewable energy systems within the building over its lifetime (Attia, 2018).

1.3 Objective

The overall objective of this thesis is to investigate the techno-economic feasibility of retrofitting an existing multi-unit residential (MURB) in Halifax, Nova Scotia, into a net zero energy building (NZEB).

A comprehensive review of the literature indicated that while there are numerous studies that focus on single family dwellings, there is no such study for MURBs. Therefore, to realize the overall objective, several sub-objectives need to be achieved, and are listed below:

1. The selection of a modern MURB in Halifax, Nova Scotia, to be used as a case study building,
2. Developing a methodology for the investigation, and,
3. Identify the appropriate tools to carry out the investigation.

It is expected that this work will provide guidance for developers and condominium corporations in Nova Scotia to improve existing MURB's into net-zero energy ready and NZEB status through retrofit.

Chapter 2 Literature Review

2.1 History of Net Zero Energy Buildings

There are four key moments that distinguish the history of building energy efficiency in the 20th century. The "House of Tomorrow" of George F. Keck and "MIT Solar House 1" of Hoyt C. Hottel, built in the 1930s demonstrated the importance of utilizing heat gains from the sun. The thermal design of the components as well as the equipment used, such as solar collectors, were the key features of these buildings. The enhancement of the thermal insulation was becoming a basic rule. The oil crisis of 1973 amplified the interest in building energy efficiency. People became more preoccupied with the air tightness of buildings, super-insulation, and heat recovery in ventilation systems, the use of triple pane windows and passive technologies that were mainly oriented towards utilizing thermal energy from the sun. The first "Passive House Kranichstein" was built in 1991, in Darmstadt, Germany by Wolfgang Feist in collaboration with Bo Adamson. The Passive House concept outlined at the beginning of the 1990s integrated all the valuable theories and algorithms of energy efficient building design. Feist and Adamson went on to found the Passivhaus Institute in 1996, as a means to promote the Passive House Standard and present their new rules for energy-efficient design. In 1992, the first energy autonomous house, designed by the Fraunhofer Institute for Solar Energy in Freiburg Germany, was built. Due to the high levels of insulation and the solar energy technology installed, the house was able to cover its own energy needs without the help of external energy sources (Ionescu *et al*., 2015).

Some of the most essential components of durable and energy efficient homes were introduced in Canada as early as the 70s, with the construction of the Saskatchewan Conservation House (Passipedia, 2015). The Saskatchewan Conservation House used features such as increased air tightness, high levels of insulation and air-to-air heat exchangers. This approach allowed a reduction in the area of required solar collection surface and solar storage, when compared to previous zero-heating installations. Early examples of energy efficient houses, such as the Saskatchewan Conservation House, were influential in current approaches to building design and contributed to the definition and upgrade of building standards and regulatory codes (Hernandez & Kenny, 2009).

The Saskatchewan conservation house influenced the energy-efficient building movement in Canada, including the R-2000 program that began in the 1980s (SRC, 2018). The R-2000 voluntary standard continues to set the standard for leading edge energy-efficient homes in Canada, using the principles of high insulation, good air tightness and heat recovery ventilation systems (Hernandez & Kenny, 2009). The technical requirements of the R-2000 standard include measures for the efficient use of energy, improved indoor air quality and better environmental responsibility in the construction and operation of a house. The R-2000 Standard allows builders to find a balance between increased construction costs (3 % - 6 % above code) and optimized energy efficiency (> 50 % better than code), resulting in the best return on investment for homeowners. The standard applies to residential buildings that are within the scope of Part 9 of the National Building Code of Canada, detached, attached and, semi-attached houses, as well as multi-unit residential buildings (NRCan, 2012).

The R-2000 program resulted in 23 net zero energy homes being built by six builders. This program allowed for the construction of a range of different archetypes, including detached (single family) dwelling, four townhouses and a six-plex multi-unit residential building (NRCan, 2020). In 2017, the Canadian Home Builders Association (CHBA) launched its Net Zero Home labelling program. The program provides the industry and consumers with a clearly defined and rigorous two-tiered technical requirement that recognizes Net Zero and Net Zero Ready homes and identifies qualified builders and renovators (CHBA, 2017). In 2020, the CHBA followed their Net Zero Home Labelling Program with a Net Zero initiative for MURB's, in partnership with Natural Resources Canada. Six builders from British Columbia, Alberta, Saskatchewan, and Ontario, will each build a low-rise MURB for purely residential occupancy. The buildings will consist of a set of separate, stacked units, with each unit having a private entrance either outside the building or from a common hall, lobby, vestibule, or stairway inside the building. They will incorporate a minimum of two vertically stacked units and be a minimum of two storeys above finished grade (CHBA, 2020b). The MURB projects must utilize some pre-fabrication including penalization and modular construction and be optimized for advanced high-performance envelopes designed to address high insulation values, reduce thermal bridging, and improve air tightness, and will also include high-performance windows and mechanical systems in accordance with guidelines from the CHBA Net Zero Home Labelling Program (CHBA, 2020a).

Voluntary standards, such as the CHBA Net Zero Labelling program are a crucial component in reducing emissions, increasing efficiency in homes, and growing the economy. However, it is also important that each step not be regulated until it can be shown to be cost effective. It can be tempting for some to want to make rapid changes, however, sudden jumps in housing prices due to rapid code changes can be devastating for Canadians trying to afford a home. Currently there is a housing crisis on two fronts: affordability and availability of housing supply. The Net Zero MURB Pilot was officially launched with the objective: “To validate the use of panelized/ modular construction and integrated mechanical system technologies, design and construction practices on Net Zero or Net Zero Ready MURBs to optimize energy efficient performance, reduce costs, increase construction productivity and reduce construction schedules. Housing affordability is crucial for Canadian family’s financial future and a healthy economy (Coleman, 2020).

There are numerous independent MURB projects throughout Canada. Many of these projects have stated the importance that these buildings are energy efficient while also being affordable, reducing or even eliminating the ‘green premium’ that is often associated with energy efficient builds. These energy conservation goals are not unique to Canada as other countries are on the same trajectory with their building codes (Coleman, 2020).

2.2 Methods for Achieving Net-Zero Energy in Existing Buildings

New construction allows for an integrative design process. It relies on every member of the project team working together to incorporate energy efficiency, renewable energy, and sustainable green design features into as many aspects of the building as possible. The process enables the team to optimize systems and minimize operating and maintenance costs. Greater energy efficiency begins at planning and designing, allowing new construction to offer more opportunities for integrating energy efficiency measures. However, implementing energy retrofits in existing buildings is typically a more expensive proposition. New construction allows for design features such as optimal building orientation and window placement to be implemented, as well as opportunities for increased solar production.

The reuse of existing building stock through building retrofits offers greater environmental savings than demolition and new construction. Building retrofits reduce the volume of new material used, well as the emissions created through its construction.

Retrofits can include minor, major, and deep retrofits. Minor retrofits include modifications that are low-cost, easy to implement and offer good value for the money and effort invested, whereas major retrofits take a more holistic approach to the upgrades. A deep retrofit includes an extensive overhaul of the building's systems. Deep energy retrofits of MURBs can achieve multiple economic, social, and environmental goals. They can reduce overall costs by renewing near-end-of-life systems and extending building lifespan, lower carbon emissions and operational costs, and provide lower energy bills and better health and comfort for residents (NRCan, 2020).

Due to its northerly location and prevalence of single-family housing, in 2003 the residential sector accounted for 17 % of the total energy consumption and 16 % of the total GHG emissions in Canada. Improving the end-use energy efficiency in the residential sector would play a major role in Canadas's commitment to reduce its GHG emissions, and because of this, research tends to focus on single-family housing. There are many energy efficient improvements to be considered to reduce the end use energy consumption the end use energy consumption in the residential sector (Asaee et al., 2019; Guler et al., 2001; Aydinalp-Kolsal & Ugursal, 2006).

However, MURBs can be difficult to upgrade. Building owners want verifiable proof that the retrofit measures will pay off before they take action. The residents may not want the disruptions requiring them to be timed with tenant turnover or other major changes, or, if utilities are included in their rent, may see no benefit in participating. Finally, industry trades may not fully understand all of the factors involved or the benefits to be had.

The steps required to achieve NZE are listed below:

1. Make improvements to the building envelope. This includes increasing the insulation of the exterior walls and roof, air-tightness improvement, upgrading glazing surfaces and adding insulation to balcony decks to reduce the effect of thermal bridging.
2. Reduce the buildings electrical load. Electrical loads include major appliances, water use equipment, receptacle loads, and lighting. Major appliances are upgraded to energy star status, and receptacle loads are reduced by implementing sensors. The lighting load is reduced by replacing bulbs with LEDs, as well as using daylighting and occupancy sensors.
3. Improve the HVAC system. Replace the current space conditioning system with an electrified system with a higher efficiency, such as a heat pump and an energy recovery ventilator.
4. Install renewable energy, such as solar photovoltaics or solar thermal, to offset the energy consumption.

2.3 Reduction of Space Conditioning Energy Needs

2.3.1 Building Envelope

Building envelope modifications include wall, roof and exposed floor insulation upgrades, window replacement, and air-tightness improvement (Asaee *et al*., 2018). Envelope insulation retrofits represent an important starting point for projects seeking to reduce whole house energy consumption to near net zero levels (CMHC, 2012). The building envelope design should help keep the heating and cooling loads to a minimum, while also being practical to build and make sense from a cost and functional standpoint (CMHC, 2012). The Canadian Mortgage and Housing Corporation (CMHC) suggested insulation levels are shown in Table 2.1.

Table 2.1 Suggested R-values to achieve net-zero energy (CMHC 2011A)

Component	Recommended RSI-Value (R-value)
Windows	RSI-0.9 (R-5)
Foundation Slab	RSI-2.6 (R-15)
Below Grade Walls	RSI-3.5 (R-20)
Above Grade Walls	RSI-7.0 (R-40)
Ceiling or Roof	RSI-10.6 (R-60)

For each area there are a number of alternative building envelope retrofit strategies that are feasible as a part of an overall near net zero retrofit, provided that the appropriate control of air, water and vapour are addressed. A summary of insulation materials typical to the Canadian housing market can be found in NRCan's *Keeping the Heat in (2012)* document.

The integration of passive solar design into a building can provide substantial opportunities for reducing energy consumption and GHG emissions in Canada's residential sector. In heating season dominated climates, such as that of Canada, passive solar heating techniques that make use of the direct solar gain through building and window design are commonly used because they are simple and effective approaches for energy conservation. The basic principle is that sunlight is admitted into the living space directly through glazed windows to heat the wall and floors, and thereby the air inside (Radosavljevic et al. 2012). Appropriate passive solar design should consider key building parameters such as building and window orientation, thermal mass, distribution materials and control strategies. Of these parameters, appropriate orientation is the most fundamental and generally most easily addressed aspect of solar design. However, this is only the case for new builds where the building can be designed for optimal orientation. In the event that an existing buildings exposure to the sun is limited there are still retrofit options for passive solar design. Retrofit options include switching out building materials that do a poor job of capturing and storing heat, adding insulation so that it stores heat in the winter and blocks it in the summer, roof overhangs or low-emissivity blinds to keep the sun out in the summer, and installing more windows with a southern orientation (Tierra Concepts, 2012). If only a portion of the building receives sunlight, as is the case in many existing apartment buildings, the captured heat can be redistributed throughout the building by using energy efficient vents and fans.

Windows can represent a major source of heat loss in the winter, as they typically have the lowest insulating value of the building envelope components. One way of achieving better performance with windows is by replacing a single- or double-glazed simple window with a highly insulated one, such as a double- or triple-glazed window with low-emissivity (low-e) coating and argon fill. Use of advanced glazing systems and insulated frames can dramatically improve the energy performance of a residential building. Nikooford *et al*., (2014) found that upgrading all windows to triple glazed with low-e coating (emissivity 0.1) and 13 mm argon-filled gap windows would result in a reduction of 7 % in energy consumption in the housing stock and 8 % in GHG emissions.

Air tightening of the building envelope and ducts to reduce air leakage is a core element of energy efficiency programmes and residential retrofit practices. Current best practices in construction seeks to make homes as airtight as possible (within reasonable costs) and provide controlled ventilation with mechanical systems. In general, the literature suggests an air change rate of less than 1.5 ACH at 50 Pa.

2.3.2 Ventilation Systems

Air tightening techniques can reduce air leakage to the point that contaminants with known health effects are sealed into the house. Natural ventilation, or infiltration is the uncontrolled air movement in and out of the cracks and small holes in a home. In the past, this air leakage usually diluted air pollutants enough to maintain adequate indoor air quality (US Department of Energy, 2020a). With increased air tightening to make our homes more efficient, the addition of mechanical ventilation is required to remove indoor-generated pollutants and excess moisture, and to provide a sufficient supply of outdoor air to ensure acceptable indoor air quality (IAQ). The ASHRAE Standard 62.1, 2019 dictates that a dwelling unit requires an outdoor air supply rate of 5 cfm/person and an additional 0.06 cfm/ft^2.

Exhaust-only systems are a good choice for a simple, relatively inexpensive, and easily installed method of mechanical ventilation, which still remains one of the most widely used systems in Canadian houses. Supply-only systems are also available but are rarely used in Canada as they have issues that impact their ability to be effective in newer, more tightly built homes. In general, the more effective mechanical systems are balanced systems which are calibrated to balance the exhaust and supply air flows. Balanced systems include a basic balanced system (however, these are rarely used due to technical and operating limitations), Heat recovery ventilators (HRV's) and Energy recovery ventilators (ERV's).

Providing mechanical ventilation require electrical energy to operate the mechanical system and thermal energy to condition the ventilation air (Logue *et al*., 2016). To minimize the impact the incoming outdoor air has on indoor conditions, it is recommended that a HRV or an 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 the indoor conditions (US Department of Energy, 2020a).

The main difference between an HRV and a ERV is the way that the exchange of heat works. An ERV transfers both moisture and heat between the air streams, while a HRV only transfers heat. The transfer of some of the moisture from the exhaust air to the usually less humid incoming winter air by the ERV allows for the humidity of the indoor air to stay more consistent. Most ERV's can recover 70 % to 80 % of the heat energy from the exhausted air and are most cost-effective in climates with extreme winters and summers (US Department of Energy, 2020b).

2.3.3 Space Heating Systems

Canada’s cold climate results in space heating accounting for 61.6 % of the energy used in the average Canadian home. As of 2017, 39.2 % of Nova Scotia space heating used heating oil as the energy source, 21.4 % of space heating used electricity (NRCan, 2017). The share of generation from renewable sources has grown from 9 % in 2010 to 30 % in 2020 (Nova Scotia Power, 2021). However, Nova Scotia’s primary source of electricity generation is coal, accounting for more than 60 % of the province’s total generation in 2018. The use of heat pumps has become increasingly more popular. In 2016, there were 767,000 heat pumps installed in Canada, most in Quebec in Ontario. The province of Nova Scotia has seen a steady increase of heat pump installations, from 11,550 units installed in 2000, to 20,470 units installed in 2016 (Canada Energy Regulatory, 2020). In 2017, in Nova Scotia, the majority of space heating energy use in the residential sector was single detached homes, however,10.1 % of space heating energy use was from apartments (NRCan, 2017).

Heat pumps are highly efficient heating and cooling systems that can significantly reduce a home’s energy consumption, while providing year-round climate control. The heat pump cycle is fully reversible, providing home-heating in the winter and cooling and dehumidification control in the summer (NRCan, 2004). An air source heat pump is the most common type of heat pump in Canadian homes.

Ground-source, also called earth-energy, geothermal and geo-exchange heat pumps that draw heat from the ground or ground water are becoming increasingly more popular. The earth, ground water, or both are used as the sources of heat in the winter and as the sink for heat rejection in the summer. Ground-source heat pump units can either be open or closed systems. Open systems take advantage of the heat retained in an underground body of water. Closed loop systems collect heat from the ground by means of a continuous loop of piping underground. These systems have the potential to reduce heating and cooling load associated energy consumption, with 65 % energy savings when compared to standard heating technology (NRCan, 2004).

Co-generation, also referred to as combined heat and power (CHP) is another energy saving heat production opportunity. Co-generation is the simultaneous production of electrical and thermal energy from a single fuel. The heat rejected from one process is used in the production of another. This allows for substantial gains in energy efficeicny, when compared to the independent production of both products (Strickland & Nyboer, 2002).

2.3.4 Other Space Conditioning Requirements

Canada is a heating dominated country, however with hot, humid, sunny days becoming increasingly more common during the summer months, more Canadians are using cooling. While space cooling only accounts for 1.9 % of the energy used in the average Canadian home, this trend has been increasing over the past ten years (NRCan, 2018b). Space cooling equipment commonly used include air-conditioning systems, humidifiers, and de-humidifiers. In 2009, 50 % of Canadian homes reported having some type of air-conditioning unit (Statistics Canada, 2009). The increasing adoption of heat-pumps, specifically reversible heat pumps allow for more Canadians to make use of the cooling features. However, despite the growing presence of these systems, the Canadian climate does not result in a need for space cooling on the same scale as it does for space heating.

2.4 Reduction of Energy Use for Other Equipment

2.4.1 Lighting

Lighting is important from both a practical and aesthetic viewpoint. Incorporating energy efficient lighting is an important step in reducing NZEB demand. Electricity demand for household lighting currently accounts for 3.6 % of the energy used in the average Canadian home (NRCan, 2010).

Energy efficient home design makes the most of natural lighting opportunities through the strategic placement of windows in living areas and task lighting (Zero Energy Project, 2020).

LEDs are the most efficient, longest lasting light source available. The majority of energy that LEDs consume is used to produce visible light, rather than heat. LEDs emit very little infrared and ultraviolet radiation and consume substantially less electricity than other light sources (NRCan, 2019a).

In modern buildings, lighting control systems are installed to maximize the energy-efficiency of the lighting system without affecting the comfort of the occupant (Delaney *et al*., 2009). Dimmers can be used to extend the life of the lamp and reduce the energy consumption. Motion sensors, timers and photocells allow for lights to be switched off when it is not needed, reducing unnecessary lighting energy use. Technical reports from the US DOE show that light control according to users living patterns has the potential to reduce 15 % of the total energy consumption of lights (Jinsung *et al*., 2013)

2.4.2 Major Appliances

ENERGY STAR is a certification awarded to products that meet specifications for energy performance and represent the most energy-efficient products on the market. NZEB should use ENERGY STAR *Most Efficient* designated models, as they have demonstrated superior energy performance. An average set of major household appliances, which include large stationary appliances used for refrigeration (refrigerators and freezers), cooking (ovens) and cleaning (washing machines, clothes dryers, and dishwashers), will consume 2,600 kWh/yr (NRCan, 2019b). Clothes dryers are among the largest energy use appliances, with EnerGuide data estimating annual usages of nearly 1,000 kWh for most models (NRCan, 2019b). The most efficient and energy saving method of clothes drying is not having a clothes dryer, and instead installing an interior and/or outdoor clothes drying rack or line for air drying.

2.4.3 Small Appliances and Plug Loads

NZEB must have low plug loads and process loads compared to conventional buildings. Reducing plug loads is achieved through sub-metering the energy process down to the critical level. This is done through technology such as occupancy sensors, load shedding devices and advanced power strips that prevent electronics from drawing electricity when not in use. These devices also prevent night plug load energy use which is shown to contribute significantly to wasted energy (Attia, 2018, p.26).

Canadian households own 160 % more electronics than they did a decade ago, with these electronics accounting for more than 20 % of electricity use in homes (NRCan, 2019c). Constant connection through electronic devices has revolutionized society, however all of these devices consume electricity. The energy consumption of products is always improving, but the sheer volume of devices used at home and work continue to increase, using more energy. Connected devices are expanding to include products that offer both wired and wireless network functionality such as: smoke detectors, security systems, HVAC, and lighting. These network-enabled devices can draw as much energy in standby as when they are fully activated. Standby power consumption can account for 5 – 10 % of household electricity bills. Reducing energy consumption associated with electronics can be achieved by using smart power bars and unplugging infrequently used items (NRCan, 2019d).

2.4.4 Domestic Hot Water

Canadians use an average of 75L of hot water each at home every day, with water heaters accounting for 19 % of the energy used in the average Canadian home (NRCan, 2019e). Options to reduce domestic hot water (DHW) energy consumption include technology such as heat pump hot water systems, and solar water heaters. Heat pump water heaters use up to 50 % less energy than standard electrical heaters. Heat is not generated directly, but instead moved from one place to another. Heat taken from air in, for example the basement or utility room, and then used to heat the water. Solar water heaters use 60 % less energy than the standard models and can provide up to 60 % of the DHW for an average home, depending on the local climate and average DHW use of the home. Electric water heaters come in a wide range of sizes, are relatively easy to install and need no venting. However, they cannot supply hot water if there is a power outage and they can take a long time to reheat (NRCan, 2019e).

Reducing residential water consumption can be done through installation of a water-saving shower head and faucet aerators that reduce the amount of hot water used (NRCan, 2019f).

2.5 Renewable Energy and Other On-Site Energy Production

2.5.1 Solar Photovoltaic Systems

Photovoltaics (PV) are a technology that converts light into electricity using semi-conducting materials that exhibit the photovoltaic effect. Active solar energy utilization is one of the main strategies used to provide on-site renewable energy to buildings with the intent to achieve net-zero energy designation. PV for building reduces the electricity demand from the electric grid and minimizes the amount of new land required by integrating the technology into the building envelope (Scognamiglo et al., 2014). Solar cell can be made from monocrystalline silicon, polycrystals, amorphous silicon or monocrystalline dye cells, with the best efficiency being achieved by monocrystalline cells of commercial modules, which can reach upwards of 20 % efficiency. PV can be used in a building envelope in two ways: building added PV (BAPV) and building integrated PV (BIPV).

BAPV refers to solar modules that are mounted on the roof or envelope surface; they require support structures (Attia, 2018). The optimal interaction of the PV modules for maximum electrical generation is related to the panel orientation-mounting slope (NRCan

2019g). The solar access is simulated and assessed before installation to avoid any shade on the PV panels. BIPV are solar modules that are part of the building cladding units, such as roof cladding, wall siding, curtain walls, skylights, windows or even roof shingles. These forms of PV are restricted to the building geometry and orientation, which can reduce the overall efficiency (Attia, 2018).

A renewable power system will be compromised of a PV unit, inverters, an electricity meter, a mounting system, and electrical cables. When the PV system produces more electricity than the building requires, excess electricity is exported to the grid. Since the PV system forms a significant portion of the overall cost of the NZEB, sizing and integration of the system should be accomplished after the maximum energy efficiency of the building itself has been achieved (Attia, 2018, p. 205). On site energy storage, such as batteries in connection with advanced controls allows for the covering of an increased amount of the electrical load by time-shifting utilization of the stored energy generated on-site.

2.5.2 Solar Thermal Collectors

Solar thermal collectors absorb solar irradiation energy as heat that is then transferred to a working fluid such as air, water, or oil. Solar thermal energy for heating can be collected and stored in hot water tanks, used for hot water services or to provide space heating (Tian & Zhao, 2013). The two main types of solar thermal collectors are evacuated tube thermal collectors and flat plate collectors (Attia, 2018). In projects with ambitious energy targets or limited available area for installations, solar thermal collectors and PV modules may be competing for the available space on the building roofs and facades

(Good *et al*., 2015). In this situation a hybrid Photovoltaic/ Thermal (PVT) collector can be used, which simultaneously converts solar energy into electricity and heat. A typical PVT collector consists of a PV module and an absorber plate attached on the back. (Tian & Zhao, 2013).

2.5.3 Additional Off-Site Energy Harvesting Options

Building envelope surfaces or surrounding land may not be sufficient to place enough PV required for powering the building, requiring the use of nearby renewable energy. In this scenario there is a need to extend the boundary beyond the building scale (Scognamiglo *et al*., 2014). Off-site options such as shares of wind farms or hydroelectricity would need to be considered for these instances.

2.5.4 Exporting and Storing Excess Energy

Due to the intermittency of most renewable 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.

Net-metering is the process in which homeowners receive credits for excess electricity that is generated by the renewable energy sources installed on their houses, for buildings that do not have on-site renewable energy storage, such as batteries, or has surpassed its maximum capacity of storage (Noguchi *et al*., 2008). Feeding electricity from on-site generation into utility grids is part of a strategy to increase the overall efficiency as well as increasing the share of power generated by renewables (Voss *et al*., 2010). Electric vehicles (EVs) can also be used as a grid storage tool, by using idle EV battery power as a grid storage unit with which to mitigate fluctuations from renewable electric power sources (Alirezae *et al*., 2016).

On site energy storage for NZEB's typically consists of electrical energy stored in a battery system within the building. Integrating batteries into NZEB is not meant to make them energy independent, however, it assists in shifting periods of peak supply to periods of higher demand (Rosen, 2015).

2.6 Issues Specific to Nova Scotia

2.6.1 Weather Characteristics

Nova Scotia is a maritime province of southeastern Canada, whose weather characteristics are heavily influenced by the Atlantic Ocean. ASHRAE classifies Nova Scotia as having a climate zone of 6A, which mean a cold but humid climate. The closest weather station to Halifax, Nova Scotia's capital and largest population center, is a naval base called Shearwater A. The average monthly and annual high and low temperatures, as well as the heating and cooling degree days are given in Table 2.2.

Table 2.2 Average monthly and annual high and low temperatures, and heating and cooling degree days for Shearwater A

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

2.6.2 Insolation

Nova Scotia has the ninth highest potential to produce solar energy in all of Canada, receiving less solar irradiance than most other provinces, except British Columbia and Newfoundland (plus the Northwest and Yukon Territories). According to data from Natural Resources Canada, the average solar energy system in Nova Scotia can produce 1,090 kWh of electricity per kW of solar panels per year (Energy Hub, 2020). In Nova Scotia, solar performance varies by only 7 % from one end of the province to the other (Solar Data NS, 2019). Solar Data NS is a website that is a part of the Community Solar Database, spearheaded by Nova Scotia Community Collage (NSCC), which collects data on solar electricity generation from solar arrays across NS. The amount of electricity generated each month, by a system with an 8.55 kWh capacity (Solar Data NS, 2019), in

Halifax Nova Scotia, is shown in Table 2.3. The Solar array specifications are provided in Appendix A.

Table 2.3 Monthly electrical generation for an 8.55 kWh capacity solar system in Halifax Nova Scotia (Solar Data NS, 2019)

Month	Electricity Produced (kWh)
January	241
February	374
March	681
April	657
May	879
June	1006
July	1173
August	967
September	599
October	429
November	251
December	130
Total	7386

2.6.3 Energy Availability

In Nova Scotian homes and businesses, most of the energy is used for space and water heating (NRCan, 2017), shown in Table 2.4, with the primary energy sources in Nova Scotia being electricity and heating oil (NRCan, 2017), shown in Table 2.5. Electricity is mainly generated from burning coal; however, increased shares are being produced by renewable energy sources, including hydro (Nova Scotia Department of Energy, 2015).

Table 2.4 Nova Scotia residential sector secondary energy use by end use (NRCan, 2017)

Energy End-Use	% Share			
	1990	2015	2016	2017
Space Heating	71.7	68.3	66.1	67.4
Water Heating	15.9	15.6	15.9	15.6
Appliances	9.6	12.6	14.2	13.2
Lighting	2.7	3.1	3.4	3.2
Space Cooling	0.1	0.4	0.4	0.4

Table 2.5 Nova Scotia residential sector secondary energy use by energy source (NRCan, 2017)

Energy Source	% Share			
	1990	2015	2016	2017
Electricity	23.5	34.9	37.7	36.8
Natural Gas	0	0.6	0.6	0.6
Heating Oil	50.3	37.7	33.1	35.1
Other	3.8	1.2	1.2	1.1
Wood (Coal and propane)	22.3	25.6	27.5	26.5

Natural gas is an important source of low-carbon energy. Natural gas has a GHG intensity half that of coal and heavy oils. While natural gas has been used in other parts of Canada for up to 60 years, it is still relatively new to Nova Scotia, putting Nova Scotia at a disadvantage (Energy Nova Scotia, 2020). The pipelines that distribute oil and natural gas from western Canada end in Central Canada, leaving the Maritimes without access to most of Canada's petroleum supplies (CCPA, 2007). Due to the decline of off-shore natural gas from Sable and Deep Panuke and Nova Scotia's moratorium on high-volume hydraulic fracturing, Nova Scotia's sources of locally produced and competitively priced natural gas is dwindling (Heritage Gas, 2018). In the winter, when Nova Scotia's power needs are greatest, the price of natural gas is at it highest, so it is a last-resort fuel source for electricity (Nova Scotia Department of Energy, 2015).

Over the past decade, the average cost of power in Nova Scotia has increased by more than 70 %. Less than a decade ago, more than 85 % of the province's electricity depended on high-carbon fuel – mostly coal. To gain maximum value from intermittent renewable electricity, new ways of managing electricity use are required (Nova Scotia Department of Energy, 2015).

2.7 Energy Use in Multi-Unit Residential Buildings

Multi-unit residential buildings consume a significant amount of energy. For example, In Vancouver, approximately 32 % of residential gas and 50 % of residential electricity is used in mid and high-rise multi-unit buildings. To better understand energy use in MURBs, the Homeowner Protection Office; Branch of BC housing collected energy consumption data from more than 60 mid to high-rise condominium buildings located on the south coast of British Columbia, primarily in Metro Vancouver and Victoria (RDH Building Engineering Ltd., 2012).

The average energy use intensity for the MURBs study was 213 kWh/m^2/yr. On average, 51% of this energy is attributable to the burning of natural gas for make-up air units, hot water, and gas fireplaces, 28 % to electricity used in individual suites for electric heat, lighting, appliances, and miscellaneous plug loads, and 21 % to electricity supplied to common areas for lighting, elevators, fans, pumps, common space heating and other amenities, shown in Figure 2.1 (RDH Building Engineering Ltd., 2012).

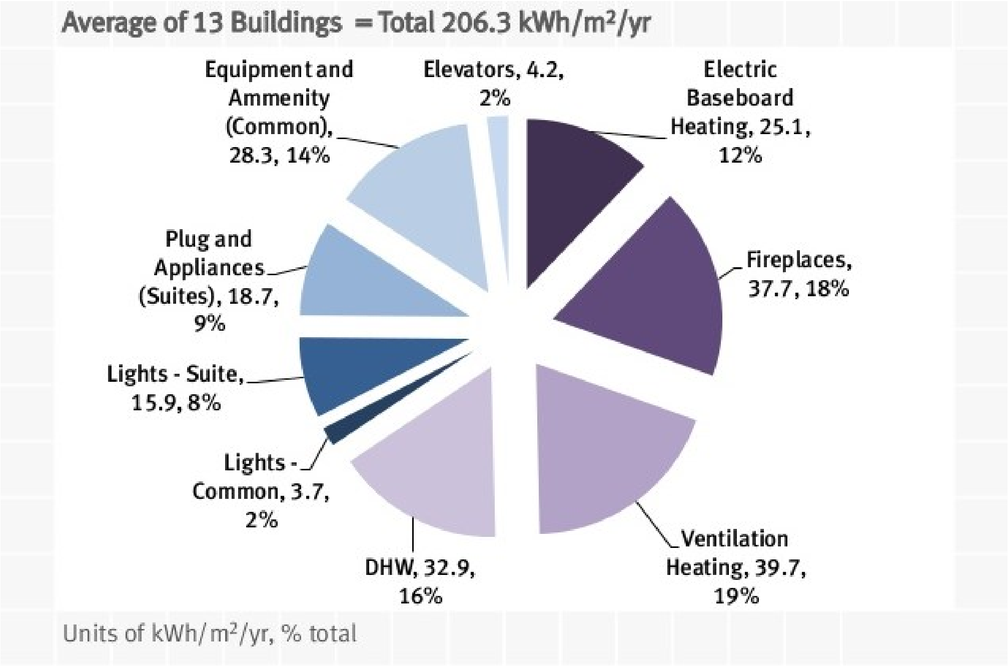

Figure 2.1 Distribution of annual energy consumption in a typical MURB (RDH Building Engineering Ltd., 2012)

Buildings with larger suites can have a higher total energy consumption that is not apparent when looking at it on a per floor area basis. For example, building number 57, despite having a median floor area, shown in Figure 2.2, has the highest energy consumption by far when looking at it on a per suite basis, shown in Figure 2.3. The high energy consumption of building 57 is attributed to the fact that it is a high-end condominium with suites in the 2000+ ft^2 range with full amenities, including air conditioning, in-suite fireplaces, and common area recreation center and a pool (RDH Building Engineering Ltd., 2012).

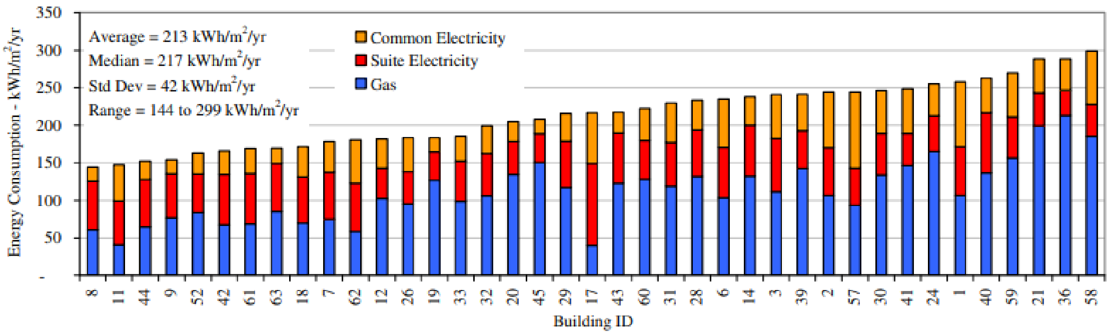

Figure 2.2 Total Energy Usage per Gross Floor Area – Sorted low to High, Split by Electricity (Common & Suite) and Gas (RDH Building Engineering Ltd., 2012)

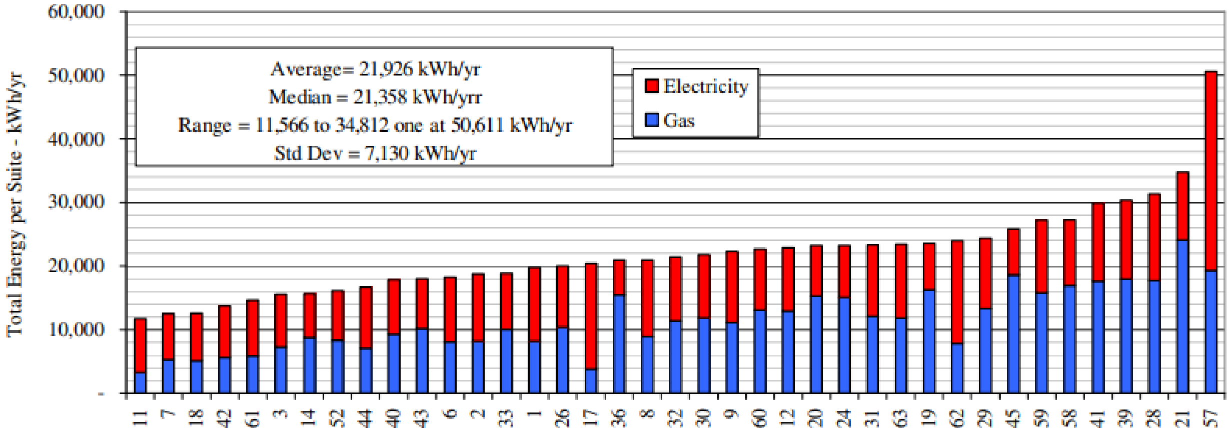

Figure 2.3 Total Building Energy Consumption Normalized by Suite, divided between Total Electricity (Common & Suite) and Gas (RDH Building Engineering Ltd., 2012)

From a 2010 BC hydro internal analysis of 425 high-rise residential condominiums in the city of Vancouver, the average total electricity use per suite is 10,484 kWh/yr. This is distributed into 5,800 kWh/yr of electricity used within the suites and 4,684 kWh/yr of electricity used within the common areas apportioned to each suite. BC Hydro also analyzed data from 314 rental high-rise residential buildings. The total building electricity per suite was 4,673 kWh/yr (approximately 45 % of the condominiums), with the suite consumption accounting for 2,826 kWh/yr and common area 1,848 kWh/yr. The difference in electricity consumption between the condominium and rental unit buildings is significant (RDH Building Engineering Ltd., 2012).

From the same sample set of buildings, BC hydro showed that the total energy consumption intensity increased in newer buildings, particularly those constructed from 1990 to 2000. The reason for the increase can be attributed to a combination of factors, including amenities in newer buildings (pools, hot tubs, gyms, etc.), building size, and architectural expression (glazing areas, balconies, etc.) (RDH Building Engineering Ltd., 2012).

In a MURB, ventilation is provided by the make-up air unit and a pressurized corridor to distribute to the suites. Heated make-up air already constitutes a significant portion of a building's energy consumption, and the data would suggest that even more natural gas for ventilation heat if the industry continues to rely on a pressurized corridor approach for ventilation. A more energy efficient and effective ventilation strategy is to compartmentalize suites and provide heating and ventilation directly to each suite (RDH Building Engineering Ltd., 2012).

While many general conclusions can be drawn from these studies, they do not necessarily apply to all MURBs. Each building has unique features and location and therefore its energy use characteristics are also unique.

2.8 OpenStudio

OpenStudio is an open-source analysis platform that facilitates integrated whole-building energy analysis. OpenStudio leverages the EnergyPlus and the Radiance simulation engines and provides a framework for conducting integrated whole building energy analysis. A plug-in for Google Sketch Up enables users to create building geometry and a variety of other input data objects required by EnergyPlus and Radiance. The OpenStudio application is a fully featured graphical interface that includes building envelope, loads, schedules, and HVAC systems. A results view enables browsing, plotting, and comparing of simulation output data. The parametric analysis tool enables users to study the impact of applying multiple combinations of OpenStudio Measures to a base model building. All the building geometry and simulation parameters are stored in a single coordinated building model, an OpenStudio Model (.osm) (OpenStudio, 2022). The workflow followed when using OpenStudio is shown in Figure 2.4.

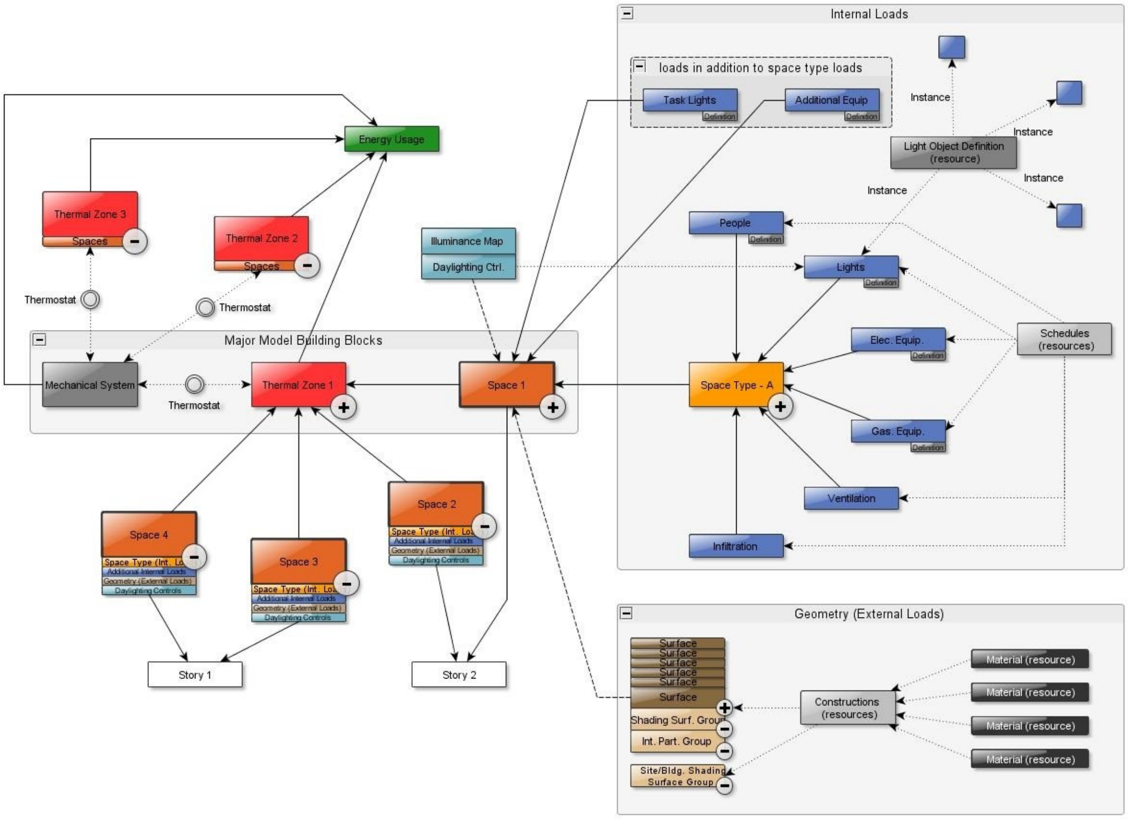

Figure 2.4 OpenStudio workflow (OpenStudio, 2022)

EnergyPlus is a console-based program that reads input and writes output to text files. EnergyPlus uses a number of utilities including IDF-Editor for creating input files using a simple spreadsheet-like interface, EP-Launch for managing input and output files and performing batch simulations, and EP-Compare for graphically comparing the results of two or more simulations. The US DOE releases major updates to EnergyPlus twice annually, version 9.5.0 was available at the time of this research (EnergyPlus, 2022a). Some notable features and capabilities of EnergyPlus include:

- Integrated, simultaneous solution of thermal zone conditions and HVAC system response that does not assume that the HVAC system can meet zone loads and can simulate un-conditioned and under-conditioned spaces.
- Heat balance-based solution of radiant and convective effects that produce surface temperatures, thermal comfort, and condensation calculations.
- Sub-hourly, user-definable time steps for interaction between thermal zones and the environment; with automatically varied time steps for interactions between thermal zones and HVAC systems. These allow EnergyPlus to model systems with fast dynamics while also trading off simulation speed for precision.
- Combined heat and mass transfer model that accounts for air movement between zones.
- Advanced fenestration models including controllable window blinds, electrochromic glazing's, and layer-by layer heat balances that calculate solar energy absorbed by windowpanes.
- Illuminance and glare calculations for reporting visual comfort and driving lighting controls.
- Component -based HVAC that supports both standard and novel system configurations.
- A large number of built-in HVAC and lighting control strategies and an extensible runtime scripting system for user-defined control.
- Functional Mock-up Interface import and export for co-simulation with other engines.

- Standard summary and detailed output reports as well as user definable reports with selectable time-resolution from annual to sub-hourly, all with energy source multipliers.

The EnergyPlus program is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources, as shown in Figure 2.5 (EnergyPlus, 2022b). It does this by simulating the building and associated energy systems when they are exposed to different environmental and operating conditions. The core of the simulation is a model of the building that is based on fundamental heat balance principles, which are described in the Engineering Reference document (EnergyPlus, 2022b).

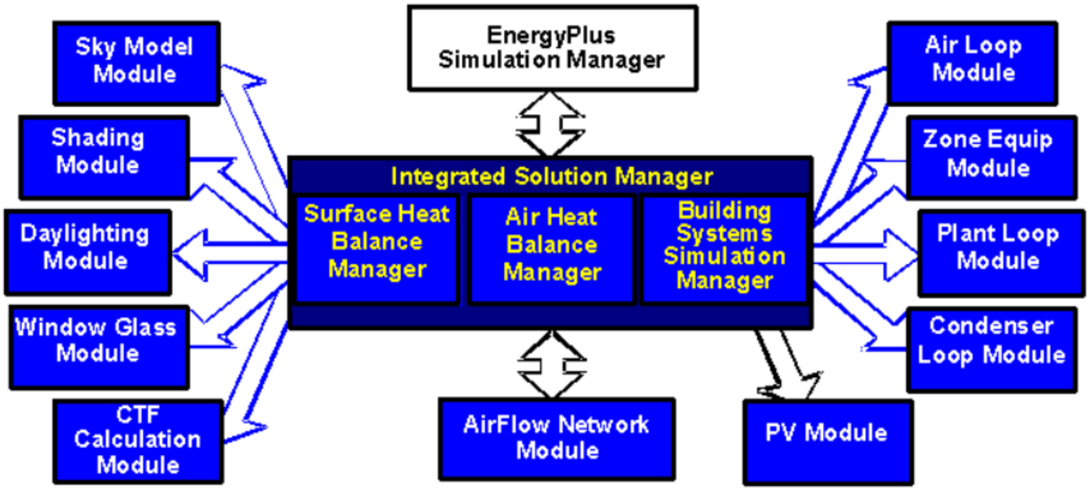

Figure 2.5 EnergyPlus Program Schematic

EnergyPlus is an integrated simulation in which all three of the major parts of a building, building zones, system, and plant, are solved simultaneously rather than sequentially to account for the feedback from each part onto the other parts. To obtain a simulation that is physically realistic, the elements (zone, system and plant) are linked in a simultaneous solution scheme that are represented as a series of functional elements connected by fluid loops divided into supply and demand sides. The solution scheme generally on successive substitution iteration to reconcile supply and demand using the Gauss-Seidell philosophy of continuous updating. The various individual functions of the integrated solution are discussed in detail in the 1,771 pages of the Engineering Reference of EnergyPlus (EnergyPlus, 2022b). To provide a glimpse of the magnitude of detail of the simulation methodology of EnergyPlus, the basis for the zone and air system integration and the calculation of conduction through walls are summarized below from the Engineering Reference (EnergyPlus, 2022b).

1. Zone and air system integration

Zone and air system integration the basis for the zone and air system integration is to formulate energy and moisture balances for the zone air and solve the resulting ordinary differential equations using a predictor-corrector approach. The formulation of the solution scheme starts with a heat balance on the zone air, shown in Equation 1:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \tag{1}$$

Where:

$\sum_{i=1}^{N_{sl}} \dot{Q}i$ = sum of the convection internal loads

$\sum_{i=1}^{N_{surfaces}} h_i\, A_i(T_{si} - T_z)$ = convective heat transfer from the zone surfaces

$\sum_{i=1}^{N_{zones}} \dot{m}_i\, C_p(T_{zi} - T_z)$ = heat transfer due to interzone air mixing

$\dot{m}_{inf} C_p(T_\infty - T_z) + \dot{Q}_{sys}$ = heat transfer due to infiltration of outside air

$C_z \frac{dT_z}{dt}$ = energy stored in zone air

$C_z = \rho_{air} C_p C_T$

ρ_{air} = zone air density

C_p= zone air specific heat

C_T= sensible heat capacity multiplier

Since air systems provide hot or cold air to the zones to meet heating or cooling loads, the system energy provided to the zone, $\dot{Q}_{sys}$ is formulated from the difference between the supply air enthalpy and the enthalpy of the air leaving the zone. As a result, the heat balance equation, shown in Equation 1, becomes Equation 2, shown below.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}i + \sum_{i=1}^{N_{surfaces}} h_i\, A_i(T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i\, C_p(T_{zi} - T_z) + \dot{m}_{inf} C_p(T_\infty - T_z) + \dot{m}_{sys} C_p\left(T_{sup} - T_z\right) \tag{2}$$

The sum of zone loads and air system output now equals the change in energy stored in the zone. Typically, the capacitance C_z is that of the zone air only. However, thermal masses assumed to be in equilibrium with the zone air can be included in this term.

EnergyPlus provides three different solution algorithms to solve the zone air energy and moisture balance equations: 3rd Order Backward Difference, Euler Method and Analytical Solution. The first two methods use the finite difference approximation while the third uses an analytical solution.

The finite difference approximation used to calculate the derivative term with respect to time is of the form of the Euler formula, shown in Equation 3.

$$\frac{dT}{dt} = (\delta t)^{-1}\left(T_z^t - T_z^{t-\delta t}\right) + O(\delta t) \tag{3}$$

The use of numerical integration in a long time simulation is a cause for concern due to the potential build-up of truncation error over many time steps. In this case, the finite difference approximation is of low order that further aggravates the problem. However, the cyclic nature of building energy simulations should cause truncation errors to cancel over each daily cycle so that no net accumulation of error occurs, even over many days of simulation. Replacing the Euler formula to replace the derivative term in the energy balance Equation 2, and with further mathematical manipulation, an energy balance equation that includes the effects of zone capacitance is obtained, as shown in Equation 4.

$$T_z^t = \frac{\sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{inf} C_p T_\infty + \dot{m}_{sys} C_p T_{supply}}{\left(\frac{11}{6}\right)\frac{C_z}{\delta t} + \sum_{i=1}^{N_{surfaces}} h_i A + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C} - \frac{\left(\frac{C_z}{\delta t}\right)\left(-3T_z^{t-\delta t} + \frac{3}{2}T_z^{t-2\delta t} - \frac{1}{23}T_z^{t-3\delta t}\right)}{\left(\frac{11}{6}\right)\frac{C_z}{\delta t} + \sum_{i=1}^{N_{surfaces}} h_i A + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C} \tag{4}$$

This is the form used in the ZoneAirHeatBalanceAlgorithm object which requires zone air temperatures at three previous time steps and uses constant temperature coefficients.

The Analytical Solution algorithm provides a possible way to obtain solutions without truncation errors and independent of time step length. In addition, the algorithm only requires the zone air temperature for one previous time step, instead of three previous time steps as required by the 3rd Order Backward Difference algorithm. The integrated (analytical) solution for Equation 4 may be expressed as shown in Equation 5.

$$T_z^t = \left(T_z^{t-\delta t} - \frac{\sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{inf} C_p T_\infty + \dot{m}_{sys} C_p T_{supply}}{\sum_{i=1}^{N_{surfaces}} h_i A + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p}\right) *$$

$$exp\left(-\frac{\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p}{C_z} \delta t\right) + \qquad (5)$$

$$\frac{\sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{inf} C_p T_\infty + \dot{m}_{sys} C_p T_{sup}}{\sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p}$$

Since the load on the zone drives the entire process, that load is used as a starting point to give a demand to the air system. Then a simulation of the air system provides the actual supply capability and the zone temperature is adjusted if necessary. This process in EnergyPlus is referred to as a Predictor/Corrector process.

2. Conduction through the walls

The most basic time series solution is the response factor equation which relates the flux at one surface of an element to an infinite series of temperature histories at both sides as shown by Equation 6.

$$q''_{ko}(t) = \sum_{j=0}^{\infty} X_j T_{o,t-j\delta} - \sum_{j=0}^{\infty} Y_j T_{i,t-j\delta} \tag{6}$$

Where q'' is heat flux, T is temperature, i signifies the inside of the building element, o signifies the outside of the building element, t represents the current time step, and X and Y are the response factors.

While in most cases the terms in the series decay fairly rapidly, the infinite number of terms needed for an exact response factor solution makes it less than desirable. Fortunately, the similarity of higher order terms can be used to replace them with flux history terms. The new solution contains elements that are called conduction transfer functions (CTFs). The basic form of a conduction transfer function solution for the inside heat flux is shown by Equation 7.

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} - Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j \, q''_{ki,t-j\delta} \tag{7}$$

The basic form of a conduction transfer function solution for the outside heat flux is shown by Equation 8.

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} - X_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j \, q''_{ko,t-j\delta} \tag{8}$$

where:

X_j = Outside CTF coefficient, $j = 0,1,\ldots nz$.

Y_j = Cross CTF coefficient, $j = 0,1,\ldots nz$.

Z_j = Inside CTF coefficient, $j = 0,1,\ldots nz$.

Φ_j= Flux CTF coefficient, $j = 1,2,\ldots nq$.

T_i= Inside face temperature

T_o = Outside face temperature

$q"_{ko}$ = Conduction heat flux on outside face

$q"$ = Conduction heat flux on inside face

These equations state that the heat flux at either face of the surface of any generic building element is linearly related to the current and some of the previous temperatures at both the interior and exterior surface as well as some of the previous flux values at the interior surface.

The final CTF solution form reveals why it is so elegant and powerful. With a single, relatively simple, linear equation with constant coefficients, the conduction heat transfer through an element can be calculated. The coefficients (CTFs) in the equation are constants that only need to be determined once for each construction type. The only storage of data required are the CTFs themselves and a limited number of temperature and flux terms. The formulation is valid for any surface type and does not require the calculation or storage of element interior temperatures. The method used in the calculation of the CTFs is the state space method is described in the Engineering Reference (EnergyPlus, 2022b).

EnergyPlus undergoes testing using industry standard methods, as major builds are completed, with the objective of reducing the number of bugs in the software (EnergyPlus, 2022c). The three major types of tests currently conducted are:

- Analytical tests
    - HVAC tests, based on ASHRAE Research Project 865 (NREL, 2016)
    - Building fabric tests, based on ASHRAE Research Project 1052 (Whitte, Henninger, and Crawley, 2004)
- Comparative tests
    - ANSI/ASHRAE Standard 140-2011 (Design Builder, 2014)
    - International Energy Agency Solar Heating and Cooling Programme (IEA SHC) BESTest (Building Energy Simulation Test) methods not yet in Standard 140 (EnergyPlus, 2004)
    - EnergyPlus HVAC component Comparative tests (EnergyPlus, 2004)
    - EnergyPlus Global Heat Balance tests (EnergyPlus, 2004)
- Release and executable tests

Radiance is a suite of programs for the analysis and visualization of lighting in building design. Input files specify the scene geometry, materials, luminaires, time, date, and sky conditions. The calculated values include spectral radiance, irradiance, and glare indices. The primary advantage of radiance over simpler lighting calculation and rendering tools is that there are few limitations on the geometry or the materials that may be simulated.

Radiance is used to predict the light levels and appearance of a space prior to construction (Radiance, 2022).

The Sketch-up OpenStudio Plug-in is the graphical application used by OpenStudio and allows users to create the geometry necessary for EnergyPlus. The Plug-in includes templates for rapidly populating the model with valid mechanical systems, constructions, and schedules. The Plug-in supports new OpenStudio objects as they are added to the model (OpenStudio, 2022).

2.9 Tolerable Capital Cost

Energy users must determine if it is worthwhile to invest in an energy efficiency or renewable energy upgrade based on the economic feasibility of the upgrade. To evaluate the economic feasibility of energy efficiency or renewable energy upgrades, a variety of tests are used such as payback period, cost-benefit ratio, and return on investment. To reach a conclusion, these tests consider the capital cost of the upgrade. However, it is not always possible to reliably estimate the capital cost of a potential energy upgrade. This could be due to a number of reasons, including the rapidly changing price of technology, the development stage of the upgrade technology, the fluidity of the market, and regional price differences. In these situations, an alternative approach that involves the calculation of a tolerable capital cost (TCC) of the upgrade can be used (Nikoofard et al., 2014).

The TCC is the capital cost that one is able to pay for an energy upgrade based on the number of years considered acceptable for payback, the annual savings, and the applicable annual interest and the fuel cost escalation rates. By applying the TCC method, an owner or decision maker can determine at what price an energy efficiency or renewable energy technology retrofit will be economically feasible. This type of analysis can also help policy makers if they wish to promote energy efficiency or renewable energy upgrades, by allowing them to determine the magnitude of incentive necessary to promote a certain technology so that the actual cost of the technology to be borne by the buyer can be reduced to a level acceptable to the buyer (Nikoofard et al., 2014).

To estimate the tolerable capital cost of an energy upgrade, a reverse payback analysis is conducted as follows:

1. Based on the estimated energy performance improvement, calculate the annual energy savings, including any quantifiable monetary benefits due to reductions in greenhouse gas emissions and/or other environmental impacts.
2. Determine the cost of capital (interest rate) applicable.
3. Estimate the energy price escalation rate for the energy saved.
4. Determine the acceptable payback period.
5. Conduct a reverse payback analysis to determine the tolerable capital cost of the upgrade that will result in the acceptable payback period using Equations 9 and 10, shown below.

$$TCC = ACS \times \left[\frac{1-(1+e)^{n}(1+i)^{-n}}{i-e}\right] \quad for\ i \neq e \tag{9}$$

$$TCC = ACS \times n(1+i)^{-1} \quad for\ i = e \tag{10}$$

Where: TCC = tolerable capital cost of the upgrade (\$); n = acceptable payback period (year); i = interest rate (decimal); e = energy cost escalation rate (decimal); and

ACS = net annual cost savings due to the energy upgrade ($). TCC is the value of the initial investment which is equivalent to a geometric gradient series representing the net annual cost savings due to the energy upgrade ACS, adjusted for interest rate, i, and energy cost escalation rate, e, over an acceptable payback period, n (Nikoofard et al., 2014).

2.10 Feasibility

A review of existing technologies that are commonly used to achieve net zero energy status for existing or new construction residential buildings in Canada, and Nova Scotia more specifically, is supportive of the hypothesis that a net zero energy retrofit for a multi-unit residential building in Halifax, Nova Scotia is technically feasible. This hypothesis is further supported by the practical application of many such technologies in MURBs throughout the province, as well as large scale solar arrays, such as the IKEA Dartmouth solar PV system with an array capacity of 838 kW DC (IKEA, 2021).

Chapter 3 Methodology

Since it is not possible to carry out an experimental study, this work relies on simulations conducted using a building energy performance simulation software. The methodology used is outlined below.

The first step was to identify a modern MURB in Halifax that could be used as a case study building. Taking into consideration the trend in the MURBs in Halifax, the case study building should be a relatively new mid-rise residential building. Mid-rise residential buildings are taller, with approximately five to twelve stories. Limiting the search to mid-rise residential buildings allows for a building with at least 10 stories and approximately 100 units to be selected. The building should be built with some energy efficient designs and systems that have already been implemented. Finally, it should be possible to gain access to a set of engineering drawings. The building selected meets these criteria. The case study building is described in Section 4.2.1.

Successful building energy analysis relies on considering as many of the physical factors influencing building loads and equipment performance as possible. Requirements for high-quality results include: the range and timing of weather conditions, the hourly and daily variation in internal load, the dynamic nature of building heat transfer, and the response and performance of HVAC equipment. Detailed multiple measure methods perform energy calculations on an hour-by hour basis, and as a result they have the potential to satisfy all the requirements listed previously, for a higher quality of energy analysis results (Pegues, 2002). It was determined that an hour-by-hour simulation software would be selected due to the complexity of modeling a multi-story building.

Examples of building performance software that run hour-by-hour simulations include EnergyPlus, ESP-r, Carrier Hourly Analysis Program (HAP), and OpenStudio. EnergyPlus is a whole building energy simulation program, used to model both energy consumption and water use in buildings. EnergyPlus is a console-based program that reads input and writes output to text files. Several comprehensive graphical interfaces for EnergyPlus are also available (BEST Directory, 2018). ESP-r is a whole building energy simulation program for integrated modelling of building energy performance. ESP-r calculates building performance values based on a finite volume approach where it solves a set of conservation equations (BEST Directory, 2018). Carrier HAP is program used for designing systems and sizing system components as well as modeling annual energy performance and energy costs. HAP's energy analysis module performs an hour-by-hour simulation of building loads and equipment operation for all 8760 hours in a year (BEST Directory, 2018). Finally, OpenStudio is an open-source software development kit (SDK) for building energy simulation. OpenStudio also includes a suite of graphical applications, that include a plug-in for Trimble SketchUp for creating 3D geometry (BEST Directory, 2018). All four programs were extensively validated.

The building performance software selected was OpenStudio because the software provides a large library of common helper functions for creating, querying, and transforming energy models, running simulations, and working with results. A unique feature of OpenStudio is that its application programming interface (API) is accessible via a variety of scripting languages, including Ruby and Python, and OpenStudio itself can execute scripts written in these languages. The scripting facility allows OpenStudio to be customized and extended in flexible ways. The most common use of scripting is to automate energy conservation measures that can be applied to existing models. OpenStudio measures as well as static simulation content such has HVAC components, constructions and weather files are stored in the Building Component Library (BEST Directory, 2018). OpenStudio leverages the EnergyPlus and the Radiance simulation engines and provides a framework for conducting integrated whole building energy analysis. EnergyPlus. EnergyPlus conducts mathematical analysis using a third order finite difference approximation, as well as analytical solutions that follow an integration approach.

To evaluate the economic feasibility of the energy efficiency and renewable energy upgrades, a variety of evaluation methods were investigated. Commonly used tests to evaluate the economic feasibility of energy upgrades include pay-back period, cost-benefit ratio, and return on investment. These tests consider the capital cost of the upgrade. In situations where it is difficult to estimate a realistic capital cost of an energy efficiency or renewable energy upgrade, the commonly used approach to assess economic feasibility is to conduct a sensitivity analysis using a probable range of capital costs and calculates range of probable payback periods, cost-benefit ratios, or return on investment values. An alternative approach is to calculate the tolerable capital cost (TCC) of the upgrade. TCC is the capital cost that one is able to pay for an energy upgrade based on the number of years considered acceptable for payback, the annual savings, and the applicable annual interest and fuel cost escalation rates (Nikoofard et al., 2014). The TCC method was selected to determine the economic feasibility of the building modifications because, due to the complexity of the building, it is not possible to estimate the capital cost of the energy upgrades considered.

A thorough investigation of potential energy efficient retrofits suitable for the MURB, that will reduce its energy consumption to a level that will allow net-zero operation with the addition of a solar PV array, was conducted. The categories for energy upgrade retrofits are building envelope, electrical loads, and HVAC systems. Modifications to the building envelope include increased insulation and the installation of more efficient windows. To reduce electrical loads, replacing major appliances, installing smart sensors, and upgrading lights to LEDs was considered. Lastly retrofit options for the HVAC systems include replacing existing systems with high efficiency versions and more complex systems such as ground source heat pumps.

Once all possible retrofit options were listed, the MURB was simulated under its current condition, to obtain its baseline energy consumption. The baseline building is described in Section 4.2.

Low cost and low disruption energy efficiency improvements were made to the baseline building. These improvements included upgrading major appliances, daylighting and plug load sensors, and the installation of packaged terminal heat pumps. However, the modifications did not reduce the energy consumption to a level that would allow for net zero energy status to be met with the addition of solar PV. The first iteration of energy efficiency modifications is outlined in Section 4.3.

A second iteration of energy efficiency upgrades was applied, using more aggressive modifications. This iteration did not consider retrofit cost or potential disruptions to current occupants, but instead focused on reducing the energy consumption as much as possible. The energy improvements of the second iteration allowed for the building to reach an energy consumption that would allow for net zero energy status, reaching net zero energy operation through the addition of a PV array. The second iteration of energy efficiency improvements are given in Section 4.4.

Once the building reached net zero status, a PV system was designed using National Renewable Energy Laboratory's (NREL) PVWatts Calculator (NREL,2022) A current PV module with a high efficiency was selected (Sunpower M-Series 420-440 W Residential AC Module – given in Appendix B). To run the PV Watt's Calculator, the user inputs data such as building location, panel tilt and orientation, system losses and array type. Using weather data for the building's approximate location from NREL's database (Halifax) and selecting a panel orientation of 180°that would optimize energy production year-round, the number of PV panels required in the array to reach net zero energy operation was determined. The number of panels that would be installed on the roof, and the number of remaining panels that would be installed either on-site or nearby was also calculated. The PV array is described in Section 4.5.

The final energy consumption of the net zero energy building was determined, and by comparing it to the energy consumption of the baseline building, the associated energy cost savings were determined. The energy consumption of the building in its current state, after the first iteration of energy efficiency modifications, and once the building reached net zero energy status, are included in Sections 5.1, 5.2, and 5.3.

An economic analysis was conducted using the economic evaluation method selected. The economic feasibility is shown in Section 5.4.

The final step of the analysis was to provide a summary of the findings from the net zero energy analysis and the resulting conclusion. The conclusion is provided in Chapter 6.

Chapter 4 Modeling of the Building, the Energy Efficient Measures Implemented and the PV System

4.1 Modeling of The Building and Building Systems

The base case building, and the building after the first and second iteration of energy efficiency modifications was designed using ScketchUp Pro 2019 (SketchUp, 2021), OpenStudio v1.2.0 (OpenStudio, 2021) and GLHEPro 5.0 (IGSHPA, 2021). The building was first sketched in SketchUp Pro 2019, using an OpenStudio plug-in. The building geometry was then imported into the OpenStudio main user interface. Using the OpenStudio user interface, detailed information regarding the building envelope, schedules, electric and water loads, thermal zones, and HVAC systems were inputted for the building in its current state, as well as after energy efficiency modifications. Each simulation was run, and the total energy consumption of each iteration of energy efficiency measures was calculated. The energy consumption was broken up into end use categories: heating, interior equipment, interior lighting, water systems, cooling, fans, and pumps. The heating loads from the net zero energy model were exported and then imported into GLHEPro 5.0. The information regarding the design of the vertical ground heat exchanger was inputted and then using the heating loads, the software determined the necessary size of the ground source heat exchanger. The PV system design and analysis was completed using Microsoft Excel.

4.2 Existing Building

4.2.1 Building Geometry

The building is a 12-storey condominium building with two additional floors of unconditioned, underground parking. The total floor area is 267,100 ft^2, with 262,530 ft^2 being conditioned floor space. Unconditioned spaces include the elevators, stairwells and the parking garage levels. The dimensions of the above ground floors are 65 ft by 280 ft, and the dimensions of the underground levels are 130 ft by 280 ft. All ceilings are 9 ft 7 in in height. Exterior walls have a net area of 60,000 ft^2, and the roof has a net area of 38,000 ft^2. Windows and glass exterior doors occupy 14,500 ft^2 of wall space. Two metal exterior doors occupy a total of 40 ft^2. There are a total of 145 balconies, with various dimensions, attached to the exterior of the building. The thermal mass of walls, interior partitions, floors, ceilings, and some of the thermal mass of the furniture and parked cars are considered.

Each of the underground parking levels, and all of the spaces they encompass are modelled as individual thermal zones. The above ground spaces are broken up so that each apartment has its own thermal zone. Each of the underground floors are identical. The first above ground floor has a unique floor plan. Floors 2 through 12 are identical.

The long axis of the building, that includes the buildings main entrance, is approximately oriented north. The shading effects of the balconies and a neighbouring condominium building are included in the analysis.

A three-dimensional rendering of the building geometry described is shown in Figure 4.1.

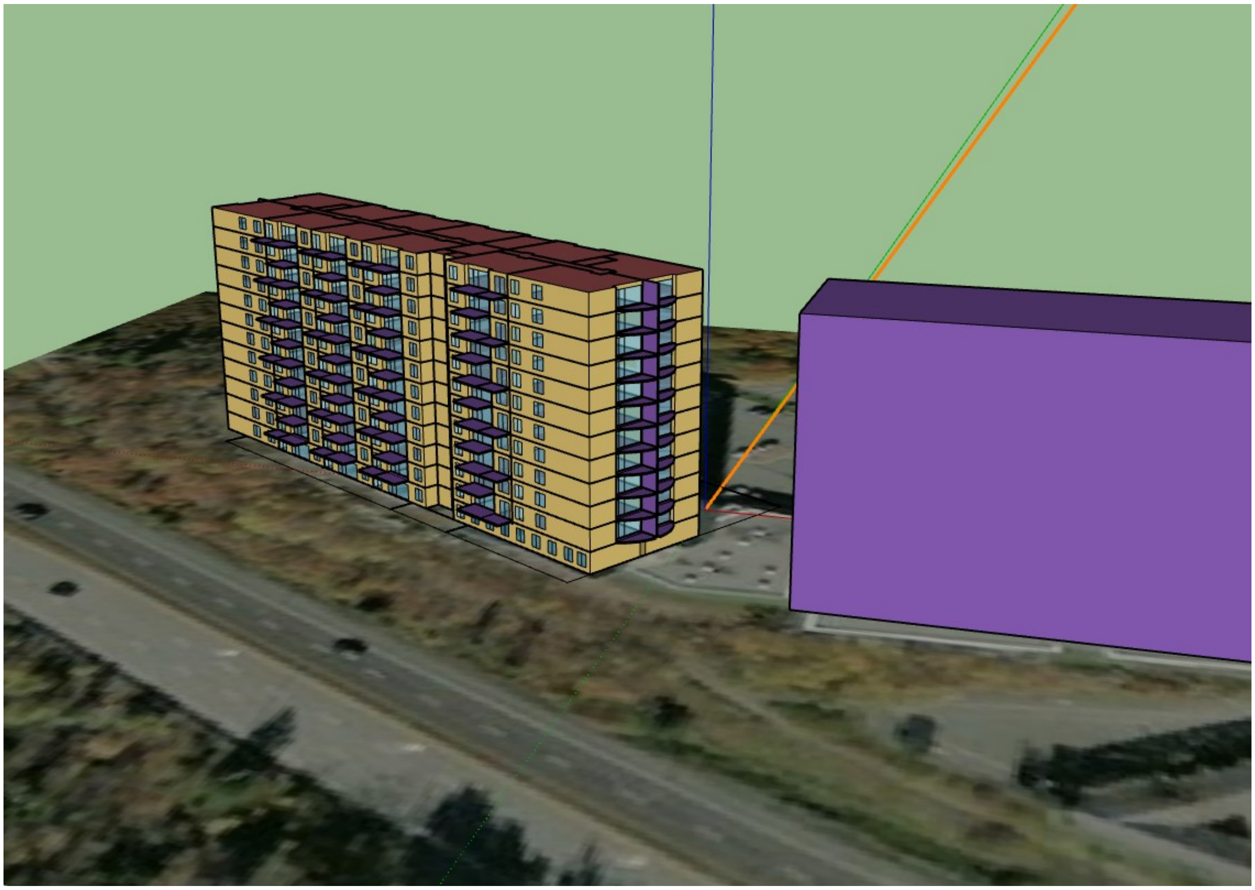

Figure 4.1 Three-dimensional rendering of the building geometry, using Sketch Up Pro 2019 and OpenStudio

The underground levels are primarily parking, with the remaining space being dedicated to storage, garbage rooms, mechanical equipment, and the elevator shafts. A two-dimensional rendering of the floor plan for the building's underground levels is shown in Figure 4.2.

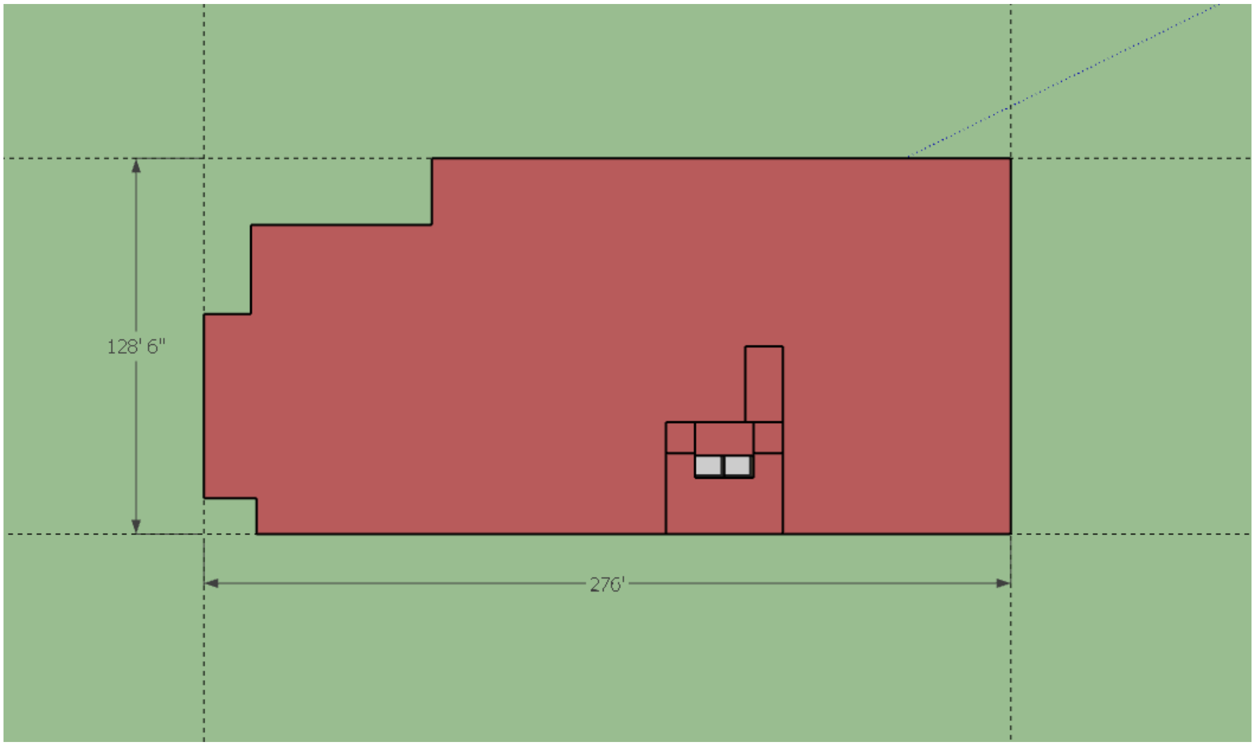

Figure 4.2 Two-dimensional rendering of the floor plan for the building's underground levels, using SketchUp Pro 2019 and OpenStudio

The ground floor contains apartments as well as some common living spaces such as the main lobby and the lounge. A two-dimensional rendering of the floor plan for the building's ground floor, is shown in Figure 4.3.

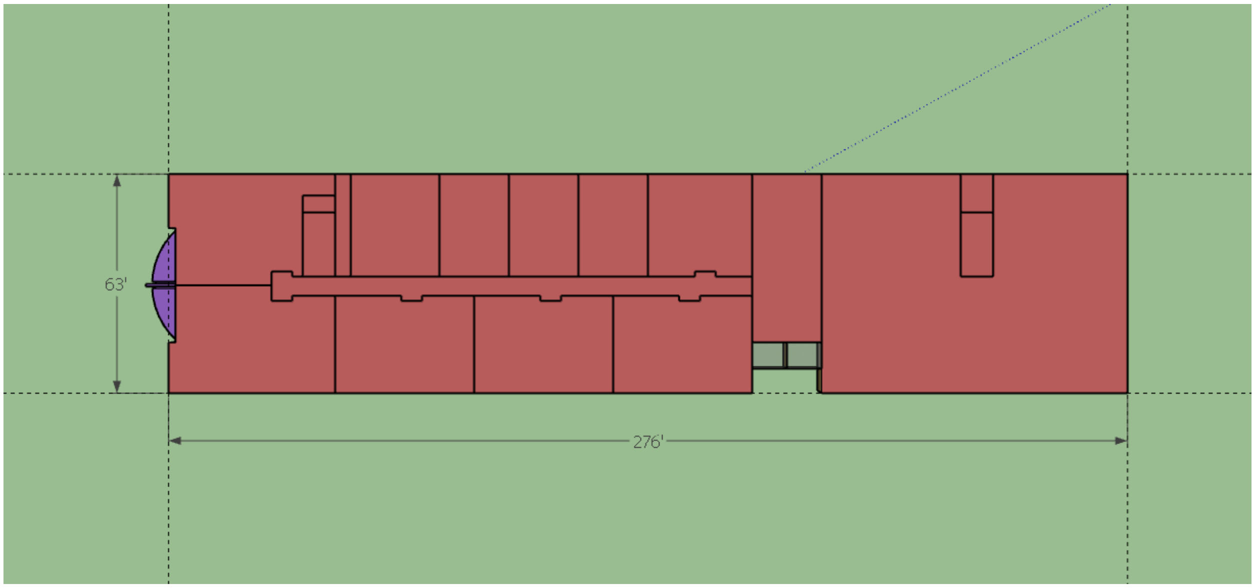

Figure 4.3 A two-dimensional rendering of the floor plan for the building's ground floor, using SketchUp Pro 2019 and OpenStudio

The remaining floors, floors 2 through 12, are identical and consist of only apartments. A two-dimensional rendering of the floor plan for the building's upper levels, is shown in Figure 4.4.

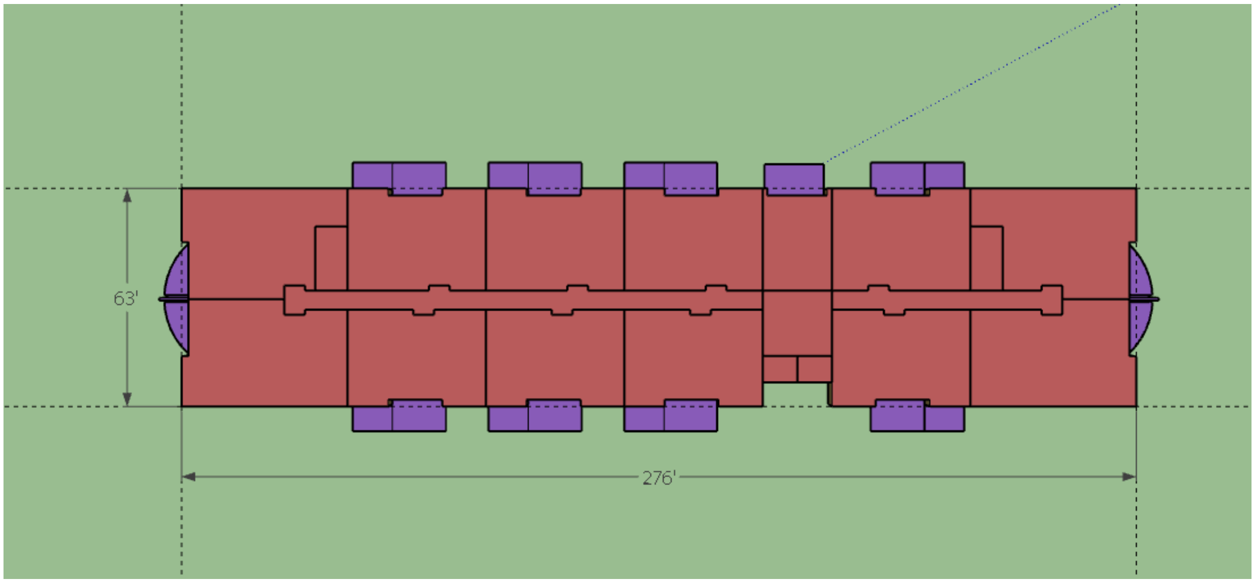

Figure 4.4 A two-dimensional rendering of the floor plan for the building's upper levels, using SketchUp Pro 2019 and OpenStudio

4.2.2 Site

Weather data is downloaded from EnergyPlus, with the closest weather station to the building being Shearwater, Nova Scotia. The weather file location information summary is provided in Table 4.1.

Table 4.1 Weather Summary

Parameter	Value
Weather File	Shearwater NS CAN WYEC2-B-14633 WMO#=716010
Latitude	44.63
Longitude	-63.5
Elevation	167 ft
Time Zone	-4.0
North Axis Angle	359.56
ASHRAE Climate Zone	6B

Many components of the building are run using a sizing simulation, which automatically sizes equipment based on the design day. Design day files are imported from EnergyPlus, with the nearest weather station being Shearwater, Nova Scotia. The sizing period design day values are shown in Table 4.2.

Table 4.2 Sizing Period Design Days

	Maximum Dry Bulb (F)	**Daily Temperature Range (F)**	**Humidity Value**	**Humidity Type**	**Wind Speed (mph)**	**Wind Direction (Deg from North)**
SHEARWATER ANN CLG .4% CONDNS DB=>MWB	78.8	13.14	66.92	Wetbulb [F]	9.4	200
SHEARWATER ANN CLG .4% CONDNS DP=>MDB	71.6	13.14	68.18	Dewpoint [F]	9.4	200
SHEARWATER ANN CLG .4% CONDNS ENTH=>MDB	74.66	13.14	26.18	Enthalpy [Btu/Ib]	9.4	200
SHEARWATER ANN CLG .4% CONDNS WB=>MDB	74.48	13.14	69.8	Wetbulb [F]	9.4	200
SHEARWATER ANN HTG 99.6% CONDNS DB	1.4	0.0	1.4	Wetbulb [F]	10.74	340
SHEARWATER ANN HTG WIND 99.6% CONDNS WS=>MCDB	30.92	0.0	30.92	Wetbulb [F]	32.66	340
SHEARWATER ANN HUM_N 99.6% CONDNS DP=>MCDB	2.48	0.0	-7.42	Dewpoint [F]	10.74	340

Surfaces with outside boundary conditions automatically have wind and sun exposure applied. Surfaces with a ground boundary condition interact with the ground temperatures provided through the imported weather file.

4.2.3 Schedules

ANSI/ ASHRAE/ IES Standard 90.1-2016 Performance Rating Method Reference Manual states that if no schedules are present, defaults based on the NACM (Non-Residential Calculation Method) issued by the CEC (California Energy Commission), on the building area type or space type may be used. The NACM issued by the CEC 2016 describes the schedules in Appendix 4.5B Space Uses, in which they are specified separately for each building type (NACM, 2016). Schedules are provided in three formats: fractional, temperature, and on/ off. For this building, schedules from the building types parking, residential common and residential living were used. Schedule sets used include occupancy, lights, receptacle, HVAC available, service hot water, heating set point, cooling set point, infiltration, and water heating setpoint. The schedule set for the elevator was taken from the residential common building type. Hourly data points as well as different schedules for weekdays versus Saturday and Sunday were included. Schedule sets are shown in Table 4.3.

Table 4.3 Schedule Sets

Schedule Set Name	Number of People	People Activity	Lighting	Electric Equipment	Hot Water Equipment	Infiltration
Apartment	Residential living occupancy	Residential living activity level	Residential living lights	Residential living receptacle, Residential living appliances	Residential living service hot water	Residential living infiltration
Corridor	n/a	n/a	Residential common lights	n/a	n/a	Residential common infiltration
Elevator Lobby	n/a	n/a	Residential common lights	n/a	n/a	Residential common infiltration
Elevator Shaft	n/a	n/a	Residential common lights	Residential common elevator	n/a	Residential common infiltration
Elevator Vestibule	n/a	n/a	Parking lights	n/a	n/a	Parking infiltration
Garbage	n/a	n/a	Parking lights	n/a	n/a	Parking infiltration
Lobby	Residential common occupancy	Residential common activity level	Residential common lights	Residential common receptacle	n/a	Residential common infiltration
Lounge	Residential common occupancy	Residential common activity level	Residential common lights	Residential common receptacle	Residential common service hot water	Residential common infiltration
Parking	n/a	n/a	Parking lights	n/a	n/a	Parking infiltration
Stairs	n/a	n/a	Residential common lights	n/a	n/a	Residential common infiltration
Stairs Vestibule	n/a	n/a	Residential common lights	n/a	n/a	Residential common infiltration
Storage	n/a	n/a	Parking lights	n/a	n/a	Parking infiltration

4.2.4 Envelope

The building envelope constructions were provided in the engineering drawings of the building. Table 4.4 lists the construction techniques and nominal insulation levels.

Table 4.4 Construction techniques and nominal insulation levels of base case multi-unit residential building in Halifax, Nova Scotia

Component	Construction (listed outside to inside layer)	Thermal Resistance (ft^2*h*F/Btu)
Above-Grade Wall	6 in heavyweight concrete, 4 in steel framed studs, 1 in air space, 3 in polyurethane spray applied insulation, 5/8 in gypsum board	R-20
Exterior Roof	2/5 in roof membrane, 3 in polyurethane spray applied insulation, 8 in heavyweight concrete, 5/8 in gypsum board	R-25
Below-Grade Wall	6 in heavyweight concrete	R-1.35
Concrete Slab	6 in normal weight concrete floor	R-1.23

Base case windows and exterior glass doors are double glazed with no coating and no gas fill. Glazing is separated by a ¼ in. air space and surrounded by vinyl frames with a thermal break.

Interior doors are constructed from 1 in. Douglas Fir – Larch. Exterior doors are constructed from two layers of surface metal, with 25 mm insulation board between them.

The construction of the balconies is 6 in. normal weight concrete floor. The balconies bridge the insulation provided by the exterior wall insulation, which increases heat transfer between the conditioned spaces and the exterior. This can result in cold interior surface temperatures and condensation or fungal growth during the winter. In order to account for the fin effect caused by the balconies, the insulation R-value of exterior walls that contain a balcony is reduced by 42 % (Finch et al., 2014).

Outdoor air infiltration is based on a rate of flow per exterior surface area equal to 0.045 ft^3/min per ft^2, at a 50 Pa pressure differential.

4.2.5 Appliance, Occupancy, Water Use Equipment and Lighting Loads

The occupancy of the building was not included in the engineering drawings, therefore external resources were used to estimate the occupancy loads. The 2014 Building American House Simulation protocol states that occupancy of a multifamily dwelling can be determined using Equation 11 (NREL, 2014).

$$\#\ of\ occupants = 0.92\ x\ N_{br} + 0.63 \tag{11}$$

$$N_{br} = Number\ of\ bedrooms$$

The Occupancy loads were split into three definitions: residential common, residential living and elevator. Using Equation 3 to estimate the occupancy load for the residential living people definition, a value of 0.00263 people per space floor area (people/ft^2) was used.

A lighting definition was created for each space type. The assumption was made that the building would already have LED lights installed. The lighting loads were taken from the ASHRAE 90.1-2019 standards user manual (ASHRAE, 2019). Lighting definitions are shown in Table 4.5.

Table 4.5 Lighting definitions for each space type

Space Type	**Watts Per Space Floor Area (W/ft^2)**
Apartment	0.68
Corridor	0.41
Lounge	0.59
Lobby	0.84
Parking	0.49
Elevator Lobby	0.65
Elevator	0.65
Elevator Vestibule	0.65
Garbage	0.51
Storage	0.51

The building contains three categories of electric loads: receptacle loads, residential appliances, and the elevator. Each of the three categories is assigned a schedule for the equipment's use. Spaces that contain receptacle loads, and their power draw are shown in Table 4.6. Receptacle loads include electric equipment such as TVs, computers, gaming systems, etc.

Table 4.6 Receptacle loads (Pratus, 2018)

Space Type	**Power (W)**
Apartment	100
Lobby	80
Lounge	100

Annual appliance loads for MURBs with in-suite laundry were determined using typical appliances and assuming an average suite size. It was assumed that each apartment would have the same suite of appliances, despite their varying sizes. The appliances include a refrigerator, standard clothes washer, electric clothes dryer, standard dishwasher, and an electric range. None of the appliances in the building's current state have an Energy Star rating. The annual appliance load for the base case building was 2,370 kWh/yr.

The elevator used is described in Table 4.7. The Elevator in the base case building has two cabs that service 14 floors, 2 of which are the underground parking levels. A geared elevator with a motor generator (MG) was used in the base case building as they are the most common form of elevator used in MURBs. The annual energy consumption of the two elevators for the base line model is 25,400 kWh/yr (ThyssenKrupp, 2021).

Table 4.7 Elevator specifications (ThysseenKrupp, 2021)

Parameter	Value
Application	Geared
Drive Type	MG
Number of elevators	2
Capacity (Ibs)	3500
Speed (fpm)	50
Cab lighting	Fluorescent
Auto light shut-off	Off
Auto exhaust fan shut-off	Off
Number of movements per hour per day	47/759

Water use equipment is located in each apartment of the building. The water use equipment was modeled with an average peak flow rate of 12 gal/min (North Star, 2009) and a daily DHW usage of 75 L/person. Since OpenStudio uses the annual average water temperature to calculate the total annual energy consumption for DHW heating, the monthly energy consumption for DHW heating was calculated from the annual energy consumption using the monthly municipal water temperatures for Halifax, Nova Scotia (Halifax Water, 2022).

4.2.6 Space Types

The building has 10 space types. The space types are listed in Table 4.8. Space types were created and used to reduce the amount of work to model the large-scale multi-unit residential building. It allowed schedule sets, constructions and loads to be assigned once to a space type, and then each individual space was assigned a space type.

Table 4.8 Space Types

Space Type Name	Default Schedule Set	Space Infiltration Design Flow Rates (ft^3/min per ft^2)	Loads	Number of each space type
Apartment	Apartment	0.045	People, lights, receptacle, appliances, water use equipment	153
Corridor	Corridor	0.045	Lights	23
Elevator Lobby	Elevator	0.045	Lights	13
Elevator Shaft	Elevator	0.045	Lights, elevator	2
Elevator Vestibule	Elevator	0.045	Lights	4
Garbage	Garbage	0.045	Lights	2
Lobby	Lobby	0.12	Lights, receptacle	1
Lounge	Lounge	0.12	People, lights, receptacle, water use equipment	1
Parking	Parking	0.12	Lights	2
Stairs	Stairs	0.045	Lights	24

Stairs Vestibule	Stairs	0.045	Lights	2
Storage	Storage	0.045	Lights	2

4.2.7 Thermal Zones

The building has 174 thermal zones. There are six types of thermal zones and they are described in Table 4.9. Common thermal zones encompass the corridors as well as the elevator lobby/ main lobby on each floor. Common thermal zones are heated using electric baseboard heaters and receive ventilation air through a diffuser, which is connected to the floor air loop. The lounge thermal zone includes the large open space that residents are able to use at their leisure, as well as offices, storage rooms and washrooms. The lounge is heated by electric baseboard heaters, receives ventilation through a diffuser, which is connected to the floor air loop, and has an exhaust fan in the washroom. The maximum flow rate of the bathroom exhaust fans is 25 cfm, with an efficiency of 60 %. The parking thermal zones include all of the spaces on each below grade floor. There is a separate thermal zone for each underground parking level. The parking levels are unheated and exhaust air from vehicles is removed using a large zone exhaust fan. The exhaust fans in the parking thermal zones have a maximum flow rate of 1,125 cfm, and an efficiency of 60 %. They are controlled by a carbon dioxide sensor. There are two stairwells in the building, that run from floor 1 through to floor 12. There is no zone equipment in these thermal zones, and they are unheated. The stair thermal zones also include the stair vestibules located on the first floor. Each elevator shaft has its own thermal zone and contain a zone exhaust fan. The elevators exhaust fans have a maximum flow rate of 100 cfm and an efficiency of 60 %. Lastly, each apartment in the building has its own thermal zone that contains a zone exhaust fan in the kitchen and each bathroom, with a maximum flow rate of 25 cfm and a fan efficiency of 60 %. Electric baseboards are used for heating and a diffuser is connected to the floor air loop for ventilation. All electric baseboards have 100 % efficiency and a nominal capacity that is auto sized according to the design day profile, and the maximum air flow rate of each diffuser is auto sized. Zone equipment, heating thermostat setpoint, and air loops are all assigned under the thermal zones.

Table 4.9 Thermal Zones

Thermal Zone Type	Zone Equipment	Heating Thermostat Setpoint (˚F)	Thermal Zone Type Count
Apartment	Zone exhaust fan, electric baseboard, diffuser	71	155
Common	Electric baseboard, diffuser	71	12
Lounge	Zone exhaust fan, electric baseboard, diffuser	71	1
Parking	Zone exhaust fan	N/A	2
Stairs	None	N/A	2
Elevator	Zone exhaust fan	N/A	2

4.2.8 HVAC Systems

Heating for the base case building is supplied through electric baseboards. Any required cooling is done so by opening windows or balcony doors. Ventilation requirements are achieved through the use of centralized air handling units (AHU), shown in Figure 4.5. Each floor has its own AHU with ducted supply and return to each apartment, common, and lounge thermal zone.

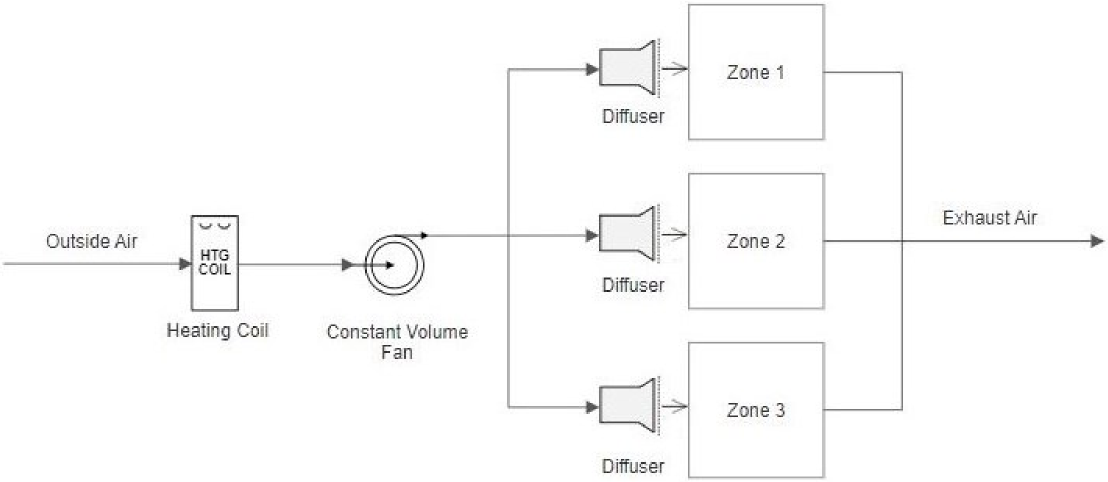

Figure 4.5 Example centralized air handling unit, shown including 3 thermal zones

The AHU system includes a constant volume fan, a heating coil, and a diffuser in each zone. No economizer is included in the HVAC system because the building does not undergo cooling, and an economizer has no effect on the heating of the building. The constant volume fan has a total fan efficiency of 70 %, a pressure rise of 1 inH_2O, a motor efficiency of 0.9 and a maximum flow rate of 1,500 cfm. The fan size allows each unit and each common area to receive the required 100 cfm of outdoor air. The rated total heating capacity and the rated air flow rate of the heating coil are both auto sized. The heating coil is set to increase the temperature of the air to 55°F.

Each apartment in the baseline building has its own hot water tank. Every hot water tank has a 45-gallon capacity and a heater thermal efficiency of 90 %. The water is heated using electricity. The system is set to 140 ˚F. The domestic hot water system is shown in Figure 4.6.

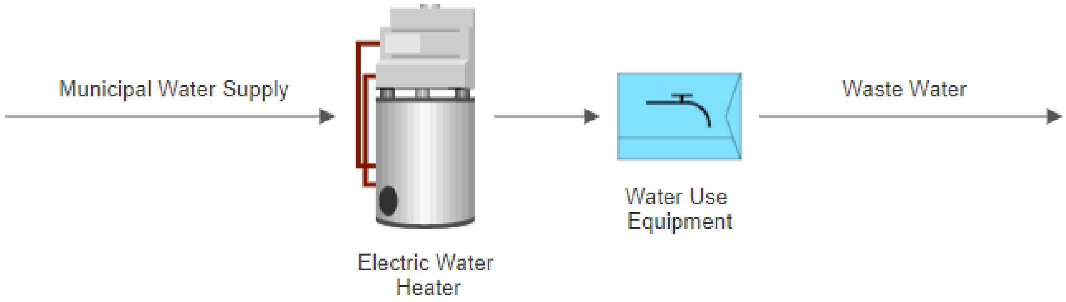

Figure 4.6 Example domestic hot water system

4.3 First Iteration of Energy Efficiency Modifications

The first iteration of energy efficiency modifications represents a low cost, low disruption retrofit for a multi-unit residential building. Low cost, low disruptions means that any modifications would not be drastic, therefore no modifications were made to the building envelope. Modifications include changing the heating supply, adding heat recovery to the ventilation systems, and improving the efficiency of electric loads. All changes are listed in the following sections, all other aspects of the simulation remain the same as the base case building.

4.3.1 Appliance and Lighting Loads

The main structure of the elevator was not changed; however, the fluorescent lights were upgraded to LEDs, auto light shut off was turned on, and auto exhaust fan was turned on. Energy consumption of the elevator with these modifications is 22,100 kWh/yr

All of the appliances in the apartments were upgraded to be Energy Star rated, resulting in an annual energy consumption of 2,130 kWh/yr, per apartment (Pratus, 2018).

Other electric equipment such as computers or gaming systems were not upgraded to Energy Star rated, however controls to reduce nighttime plug loads, as well as the overall electric load were added. The nighttime electric load sensor was set to start at 10 pm and end at 6 am. The plug load controls reduce the receptacle load by 4 %.

The lights were already LEDs in the base case, therefore modifications made were to lighting controls. Lighting controls include controls for daylighting, which has a daylighting setpoint of 45 footcandles. A nighttime lighting load sensor was also added, which was set to start at 11 pm and end at 5 pm.

Water equipment energy use was reduced to 10 gal/min through the installation of low flow shower heads and faucet aerators.

4.3.2 HVAC Systems

All electric baseboard heaters in the base case building were upgraded to packaged terminal heat pumps (PTHP). The rated coefficient of performance of the heat pump is 2.5 (PickHVAC, 2021), the total fan efficiency is 70 % and the motor efficiency is 90 %. The installed PTHP only provides heating.

The overall design of the buildings ventilation system was kept the same, however modifications were made to reduce the energy consumption of the system. A sensible and latent, air-to-air heat exchanger was added to the system, and is shown in Figure 4.7. The nominal air supply flow rate is auto sized. The sensible and latent effectiveness at 100 % heating air flow is 76 % and 68 % respectively.

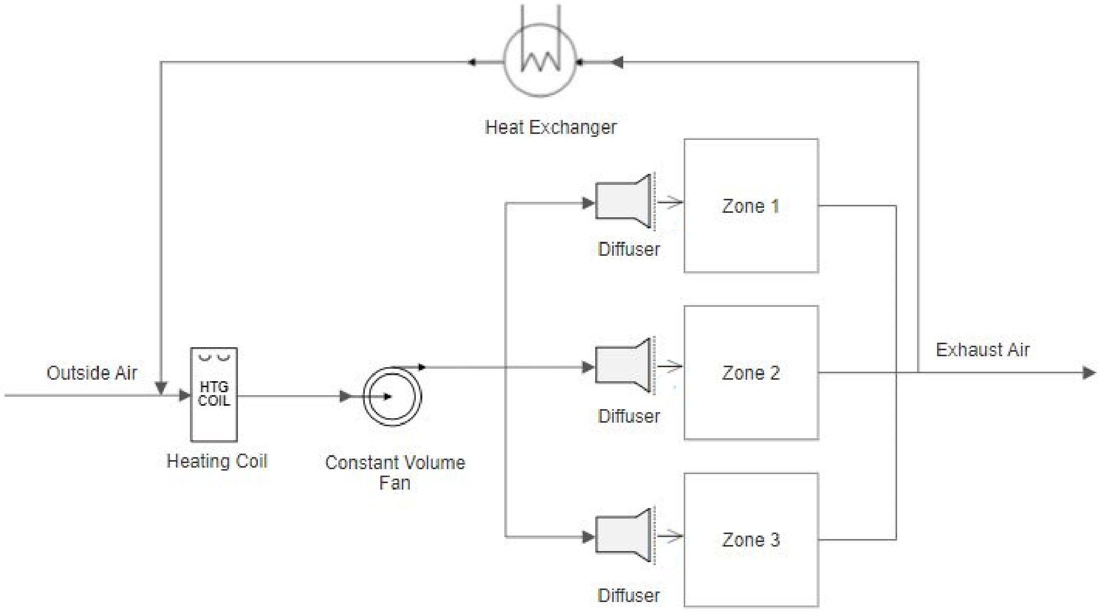

Figure 4.7 Centralized AHU with ERV

4.4 Second Iteration of Energy Efficiecny Modifications

The second iteration of energy efficiency modifications represent aggressive modifications made to the building, in order to reach near net zero energy status. The energy consumption is reduced as much as possible, without concern for cost or potential disruptions. Improvements include increased insulation, more advanced heating, and ventilation systems, and replacing the elevators.

4.4.1 Envelope

Additional insulation was added to all exterior walls and the roof, as shown in Table 4.10. The additional insulation allowed the construction of the exterior walls to reach a total R-value of R-40, and the construction of the roof to reach a total R-value of R-60.

Table 4.10 Increased insulation R-value results

Component	Base Case Thermal Resistance (ft^2*h*F/Btu)	New Construction Thermal Resistance (ft^2*h*F/Btu)
Exterior Wall	R-20	R-40
Roof	R-25	R-60

All windows and exterior glass doors were upgraded to triple glazed with low-e coating (emissivity of 0.1) and ½ in argon-filled gap. The frames of the windows and glass doors were insulated. The resulting R-value is R-5

The air tightness of the building and air ducts was increased by reducing the space infiltration by 30 %.

All balcony surfaces were insulated with 2 in rigid insulation, to minimize balcony heat loss due to the thermal bridge.

4.4.2 Appliance and Lighting Loads

Both elevators were replaced with traction machine room less (MRL) variable voltage and variable frequency (VVVF) regenerative drive elevators. The advantage of changing the elevators are increased system efficiency, reduced energy consumption, and improved power quality. The annual energy consumption of the two elevators is 9,077 kWh/yr (ThyssenKrupp, 2021). The elevator specifications are provided in Table 4.11.

Table 4.11 Improved efficiency elevator specifications (ThyssenKrupp, 2021)

Parameter	Value
Application	Traction MRL
Drive Type	VVVF regen
Number of elevators	2
Capacity (Ibs)	3500
Speed (fpm)	50
Cab lighting	LED
Auto light shut-off	On
Auto exhaust fan shut-off	On
Number of movements per hour per day	47/759

4.4.3 HVAC Systems

For the second iteration of energy efficiency modifications, all packaged terminal heat pumps from the first iteration were upgraded to water-to-air heat pumps with electric backup. The coefficient of performance of the water to air heat pump is 3.5. The rated water flow rate and rated heating capacity were both auto sized based on the design degree day profile. The efficiency of the electric backup coil is 100 %.

The heating coil from the ventilation system of the first iteration was replaced with a water-to-air heat exchanger. The water-to-air heat exchanger has a maximum water flow rate and rated capacity that are both auto sized. The design of the ventilation system used in the second iteration of energy efficiency modifications is shown in Figure 4.8.

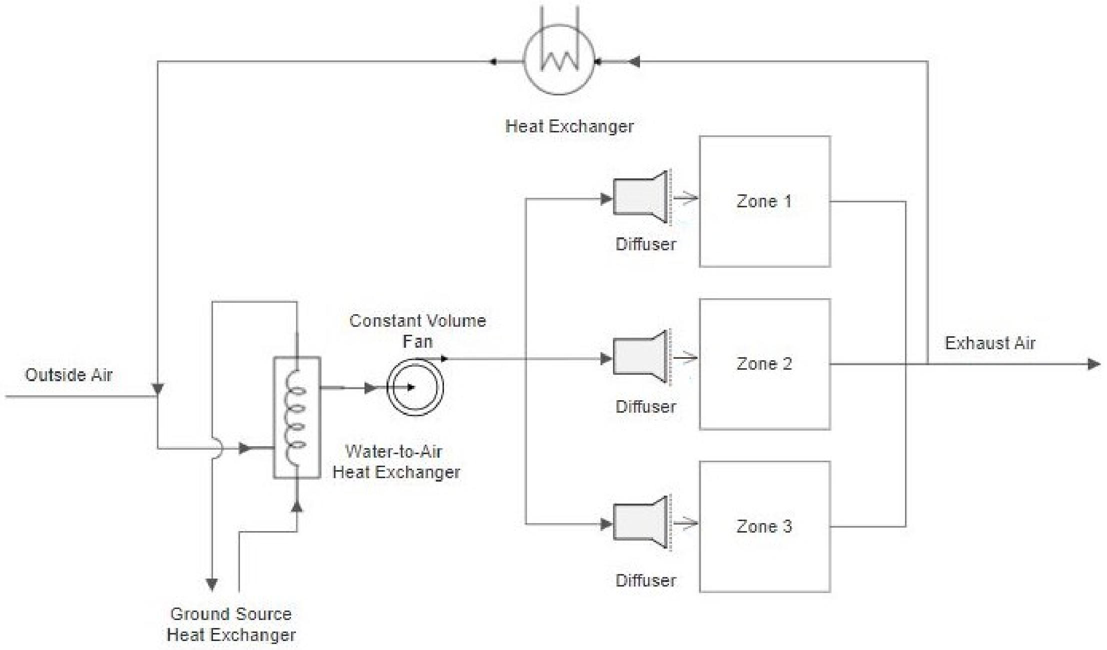

Figure 4.8 Centralized AHU with ERV and water-to-air heat exchanger

4.4.4 Ground Source Heat Exchanger

The water-to-air heat pumps and the water-to-air heat exchangers, for heating ventilation air, are connected to a single plant loop with a vertical ground heat exchanger. The vertical ground heat exchanger consists of a constant speed pump and a vertical bore field. The rated flow rate and the rated power consumption of the constant speed pump is auto sized. The constant speed pump has a motor efficiency of 90 %. The vertical ground heat exchanger is shown in Figure 4.9.

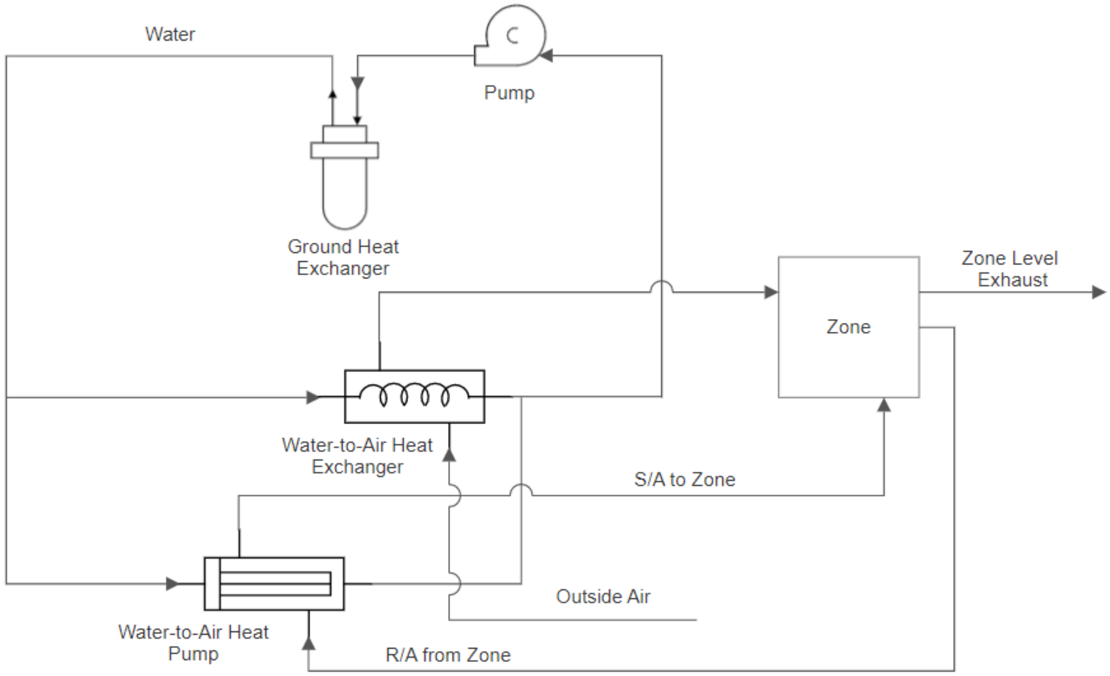

Figure 4.9 Vertical ground heat exchanger plant loop

The vertical ground heat exchanger was designed to meet 80 % of the maximum heating load, with a total of 40 bore holes in a 4 x 10 configuration. Each bore hole reaches a depth of 300 ft. A typical bore hole cross-section is shown in Figure 4.10.

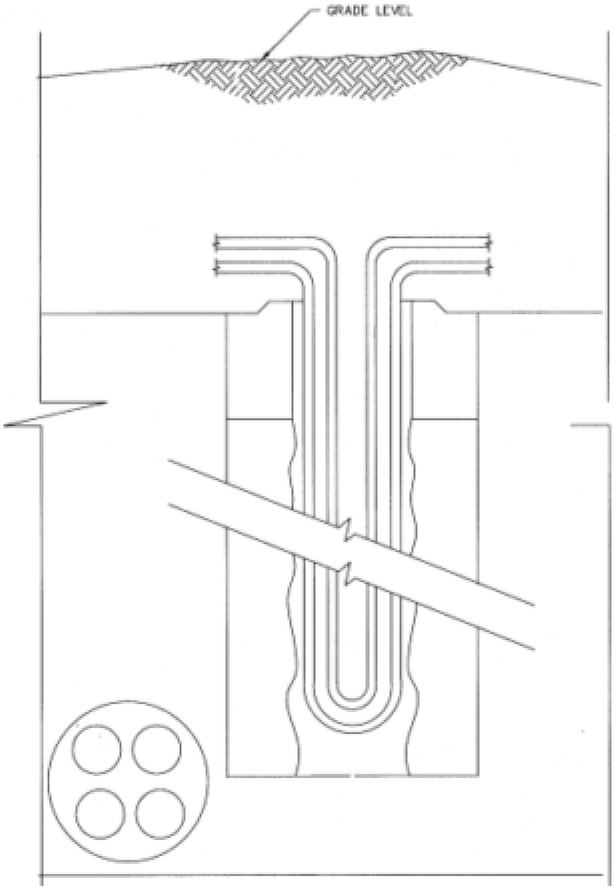

Figure 4.10 Typical bore hole cross-section

4.5 Photovoltaic System

The solar panels selected to offset the energy consumption of the near net zero energy building, allowing it to meet net zero energy standard, are SunPower Maxeon M-Series: SPR-M440-H-AC. SunPower uses Interdigitated Back Contact (IBC) cells. Unlike the common monocrystalline and polycrystalline solar cells, which use front-mounted busbars and fingers to collect current, IBC cells have a fine grid of conductors integrated into the rear side of the cell The IBC cell design uses a grid of N and P-type silicon on the rear side of the cell, which increases efficiency by eliminating the need for front exposed busbars that partially shade the cell. The SunPower Maxeon M-Series: SPR-M440-H-AC module has an efficiency rating of 22.8 % and a nominal power output of 440 W (DC). Each module has a total area of 20.75 ft^2 (SunPower, 2022). The solar panels are installed as a fixed array, with a support system anchored to the ground for arrays installed on the ground, and the roof of the building for arrays installed on the roof. Because the system uses a fixed array, the panel orientation is optimized for year-round production with a tilt of 45° and an azimuth of 180° (i.e. facing south). The system has an inverter efficiency of 96 % and a ground coverage ratio of 0.4. The specifications for the PV modules and the solar array used are included in Appendix B.

Chapter 5 Results and Analysis

5.1 Energy Consumption of Building in its Current State

The total site electricity consumption of the base case building is equal to 2,273,000 kWh, with a total site energy use intensity (EUI) equal to 8.51 kWh/ft^2 [1]. The four largest consumers of energy are heating, interior equipment, interior lighting, and water systems. The total annual energy end use of the building in its current state is shown in Figure 5.1.

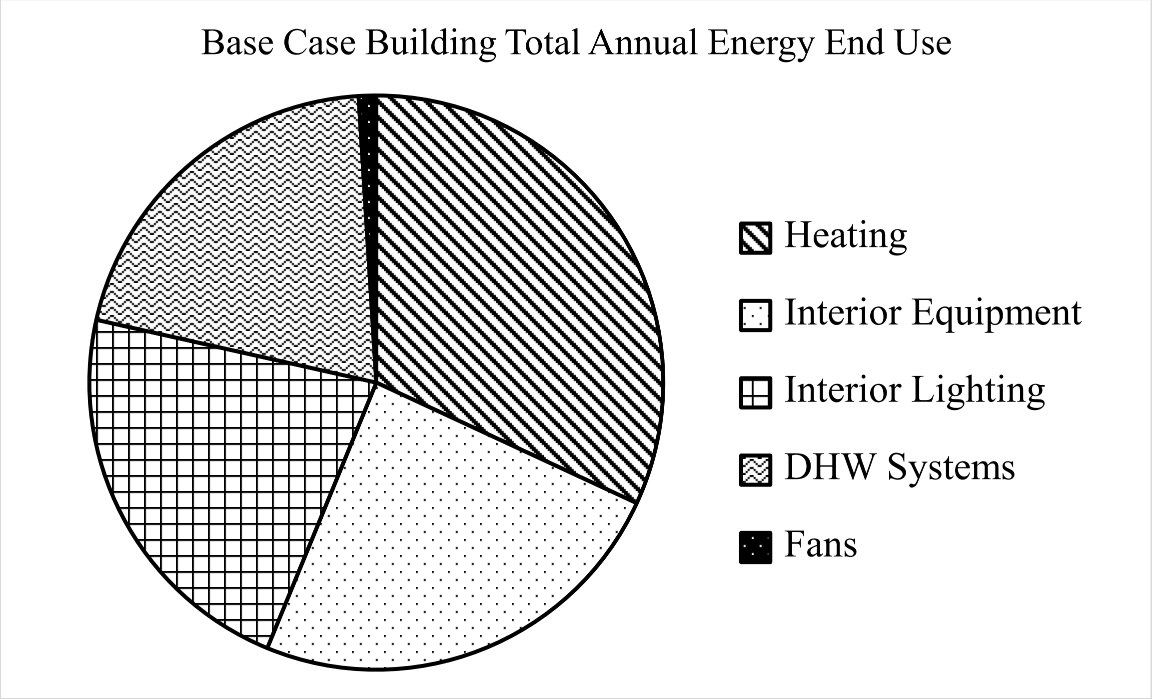

Figure 5.1 Base case building total annual energy end use

The electricity consumption values for each end-use category are provided in Table 5.1.

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[1] kWh/ft^2 is a mixed unit, however it is used here because it is a commonly used unit, when the building is fully electric

Table 5.1 Base case building total annual electricity end use

End Use	Electricity Use (kWh)
Heating	725,000
Interior Equipment	552,400
Interior Lighting	506,900
DHW Systems	465,900
Fans	22,500

The monthly electricity consumption is shown in Figure 5.2. The months with the highest consumption of electricity are December, January, and February, while the months with the lowest consumption of electricity are July and August. The high electricity consumption in the winter months is due to the increased heating load from the electric baseboard heaters and shorter days resulting in increased lighting loads. The electricity consumption of the interior equipment remains relatively constant throughout the entire year.

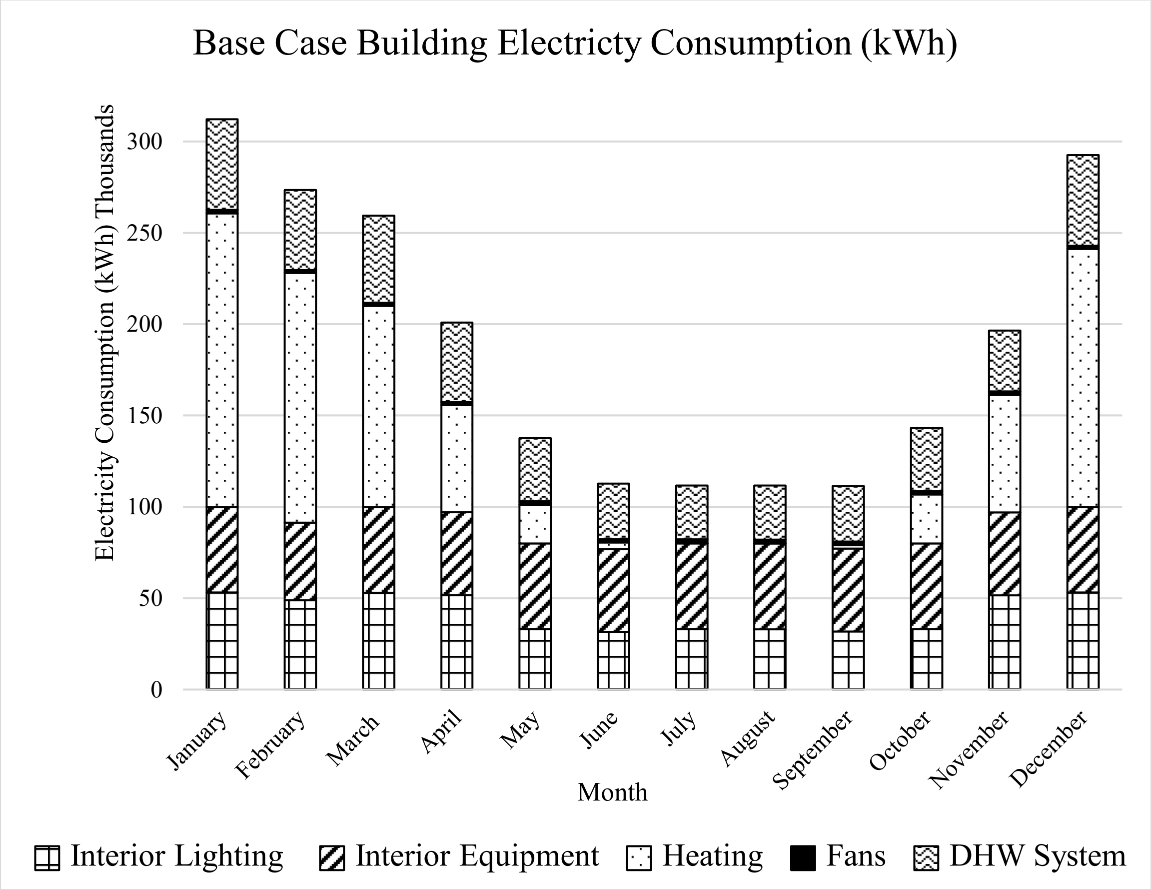


Figure 5.2 Base case building electricity consumption (kWh)

The electricity values for each end-use category per month are provided in Table 5.2.

Table 5.2 Base case building electricity consumption (kWh)

	Heating	Interior Lighting	Interior Equipment	Fans	DHW
January	160,700	53,100	46,900	1,800	49,500
February	136,800	48,900	42,400	1,700	43,700
March	110,050	53,000	46,900	1,800	47,600
April	58,600	51,700	45,400	1,800	43,300
May	21,200	33,100	46,900	1,900	34,600
June	3,500	31,600	45,400	1,900	30,300
July	65	33,100	46,900	2,100	29,600
August	60	33,000	46,900	2,100	29,600
September	1,900	31,700	45,400	1,900	30,300
October	26,800	33,100	46,900	1,900	34,600
November	64,300	51,600	45,400	1,800	33,300
December	141,200	53,100	46,900	1,800	49,600

The base case building heating load profile and outside air dry bulb temperature are shown in Figure 5.3. The highest heating loads are observed in the winter months when the temperature is the lowest. There is little to no heating in the summer months when the outdoor temperature reaches its peak.

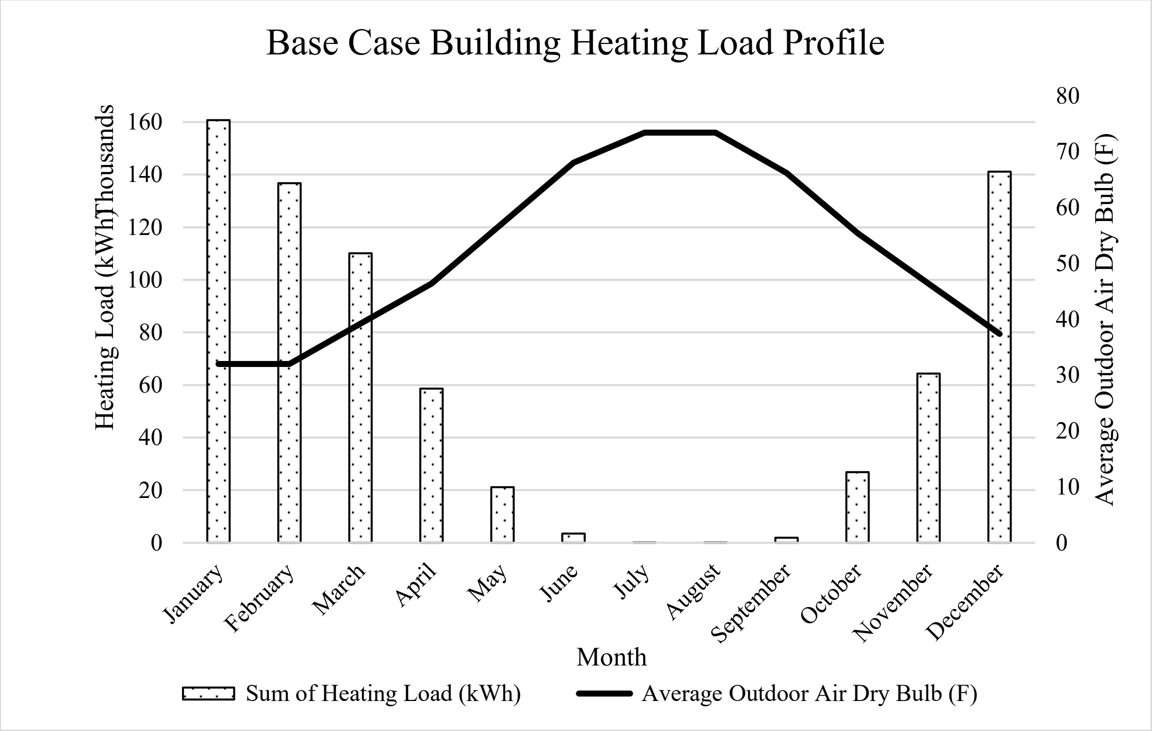


Figure 5.3 Base case building heating load and average outdoor temperature

The electricity values for monthly heating loads as well as the average monthly outside temperature are provided in Table 5.3.

Table 5.3 Base case building monthly heating load vs average outdoor temperature

Month	Average Outdoor Air, Dry Bulb (F)	Heating Load (kWh)
January	32	160,700
February	32	136,800
March	39	110,100
April	46	58,600
May	57	21,200
June	68	3,500
July	73	64
August	73	62
September	66	1,900
October	55	26,800
November	46	64,300
December	37	141,200

5.2 Energy Consumption of Building After First Iteration of Energy Efficiency Modifications

The total site energy of the building after the first iteration of energy efficiency modifications is equal to 1,667,600 kWh, with a total site energy use intensity (EUI) equal to 6.24 kWh/ft^2. The four largest consumers of energy are heating, interior equipment, interior lighting, and water systems. The total annual energy end use of the energy efficient model is shown in Figure 5.4.

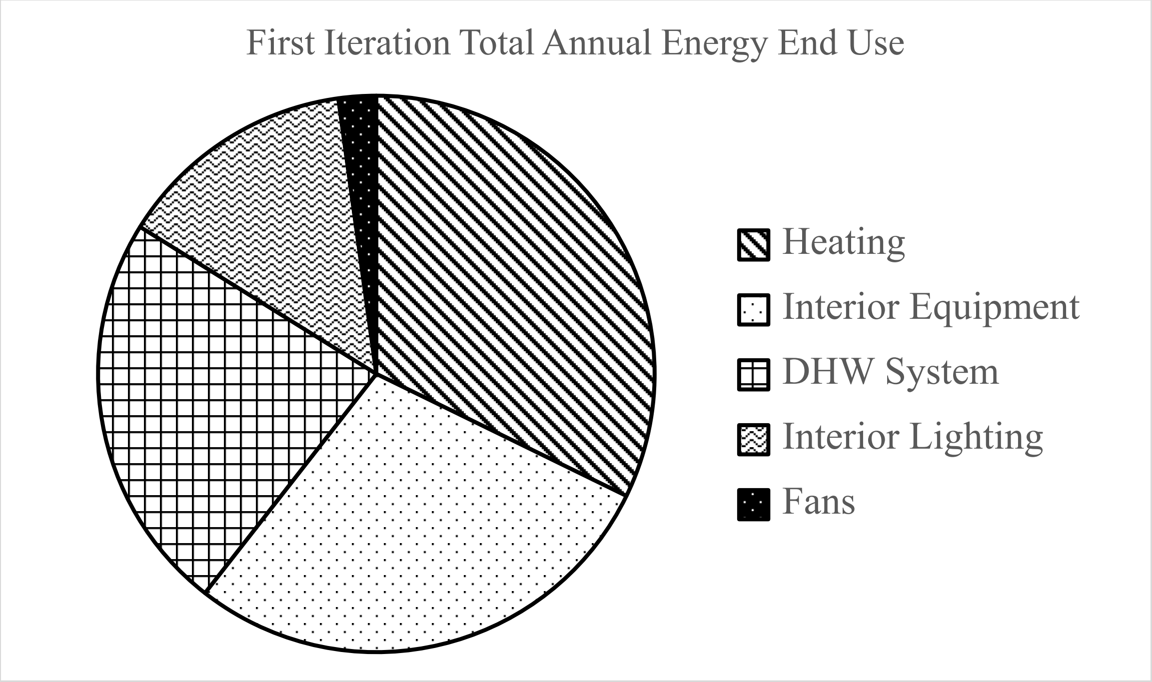


Figure 5.4 First iteration of energy efficiency modifications total annual energy end use

The electricity consumption values for each end-use category of the base case building as well as the building after the first iteration of energy efficiency measures are provided in Table 5.4.

Table 5.4 Electricity consumption values for each end-use category

End Use	Electricity Use Base Case Building (kWh)	Electricity Use First Iteration (kWh)	Electricity Use Reduction (%)
Heating	725,000	438,300	40
Interior Equipment	552,400	385,300	30
Interior Lighting	506,900	189,800	63
DHW System	465,900	316,900	32
Fans	22,500	29,700	32

The monthly electricity consumption is shown in Figure 5.5. The months with the highest consumption of electricity are December, January, and February, however the overall electricity consumption is less than that of the baseline model. The months with the lowest consumption of electricity are June to September.

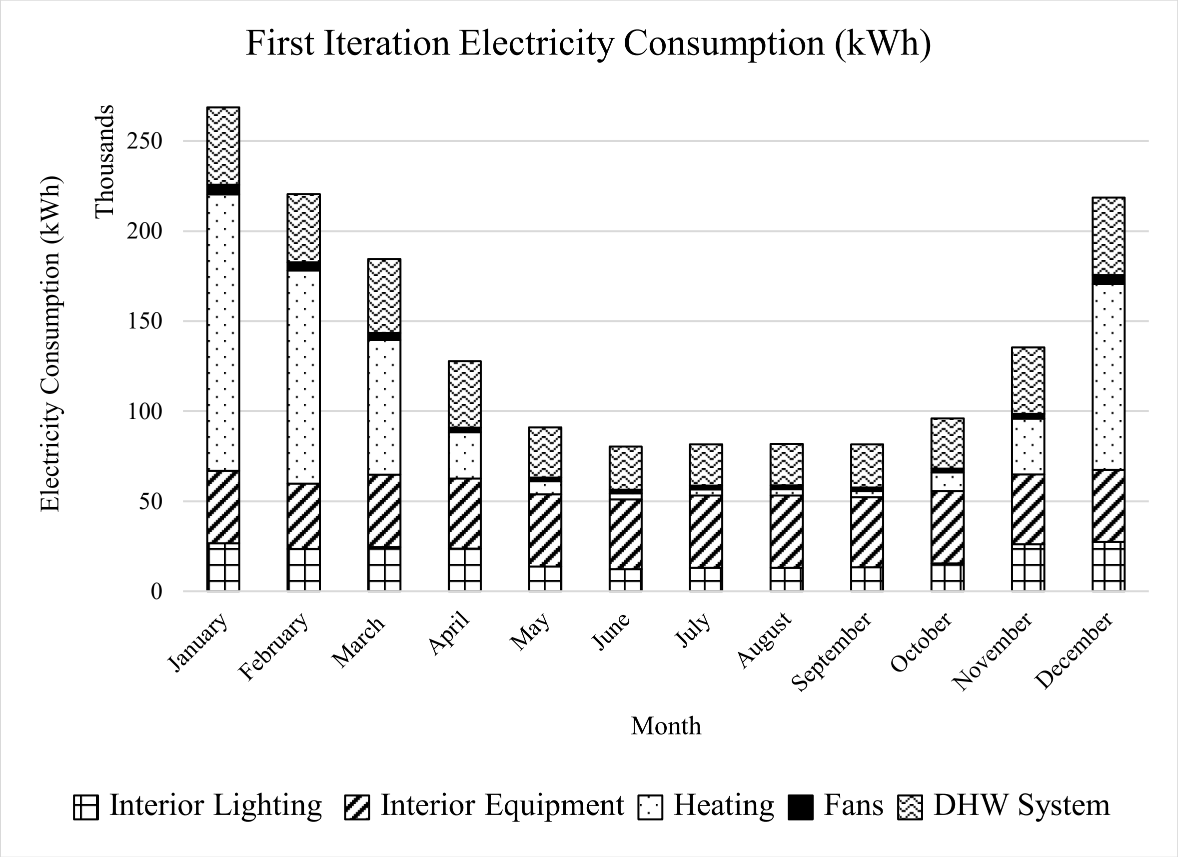


Figure 5.5 First iteration of energy efficiency modifications electricity consumption (kWh)

The electricity consumption for DHW and interior equipment remains relatively constant throughout the entire year. Electricity consumption is less than the base case building due to the higher efficiency appliances, daylighting sensors, plug load sensors and water use reduction equipment that was installed. The electricity values for each end-use category per month are provided in Table 5.5.

Table 5.5 First iteration electricity consumption (kWh)

Month	Heating	Interior Lighting	Interior Equipment	Fans	DHW
January	153,500	26,700	40,100	5,300	43,00
February	118,300	23,600	36,200	4,700	37,800
March	74,700	24,600	40,100	4,100	41,000
April	25,700	23,700	38,800	2,600	36,900
May	7,300	13,700	40,100	2,000	28,000
June	3,400	12,200	38,800	1,900	23,900
July	3,400	12,900	40,100	2,100	23,000
August	3,500	13,100	40,100	2,100	23,000
September	3,300	13,400	38,800	2,000	23,900
October	10,400	15,400	40,100	2,000	28,000
November	30,800	26,100	38,800	2,800	36,900
December	103,200	27,300	40,100	5,000	43,000

The heating load profile of the first iteration and the outside air dry bulb temperature are shown in Figure 5.6. Overall, the total heating load is reduced, however the greatest reduction is seen in the late spring and early fall. A high heating load is still needed in the colder months. The reduced heating load is due to the installation of PTHPs, and the air-to-air heat recovery in the ventilation systems.

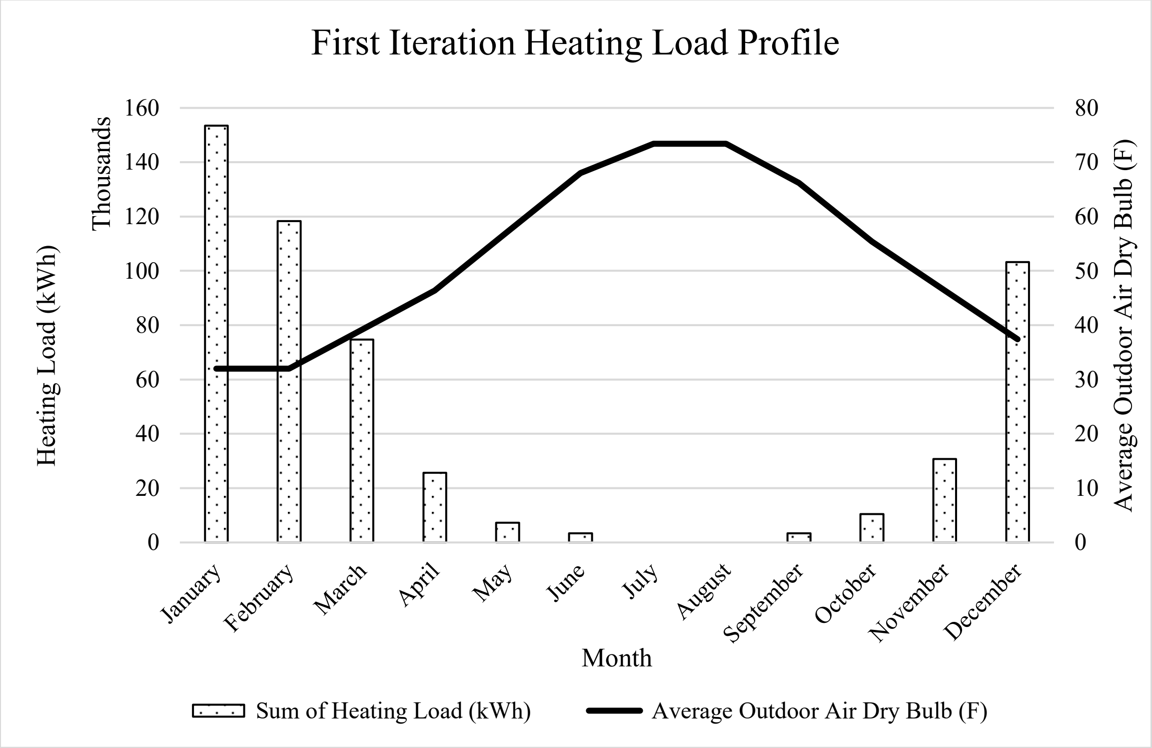


Figure 5.6 First iteration of energy efficiency modifications heating load and average outdoor temperature

The electricity consumption values for monthly heating loads of the base case building as well as after the first iteration of energy efficiency measures, and the average monthly outside temperature are provided in Table 5.6.

Table 5.6 Base case building and after first iteration monthly heating load vs average outdoor temperature

Month	**Average Outdoor Air, Dry Bulb (F)**	**Heating Load Base Case Building (kWh)**	**Heating Load First Iteration (kWh)**	**Electricity Use Reduction (%)**
January	32	160,700	153,500	4
February	32	136,800	118,300	14
March	39	110,100	74,700	32
April	46	58,600	25,700	56
May	57	21,200	7,300	66
June	68	3,500	3,400	4
July	73	64	0	100
August	73	62	0	100
September	66	1,900	3,300	75
October	55	26,800	10,400	61
November	46	64,300	30,800	52
December	37	141,200	103,200	27

5.3 Energy Consumption of Building After Second Iteration of Energy Efficiency Modifications

The total site energy of the building after the second iteration of energy efficiency modifications is equal to 1,115,000 kWh, with a total site energy use intensity (EUI) equal to 4.16 kWh/ft^2. The upgrades made in the second iteration of energy efficiency modifications reduces the total annual energy consumption low enough for the building to reach net zero energy status, with the addition of a PV system, as shown in the next section. The four largest consumers of energy are heating, interior equipment, interior lighting, and water systems. The energy use of the end use category “pumps” is added due to the installation of the ground source heat exchanger. The total annual energy end use of the building after the second iteration of energy efficiency modifications is shown in Figure 5.7.

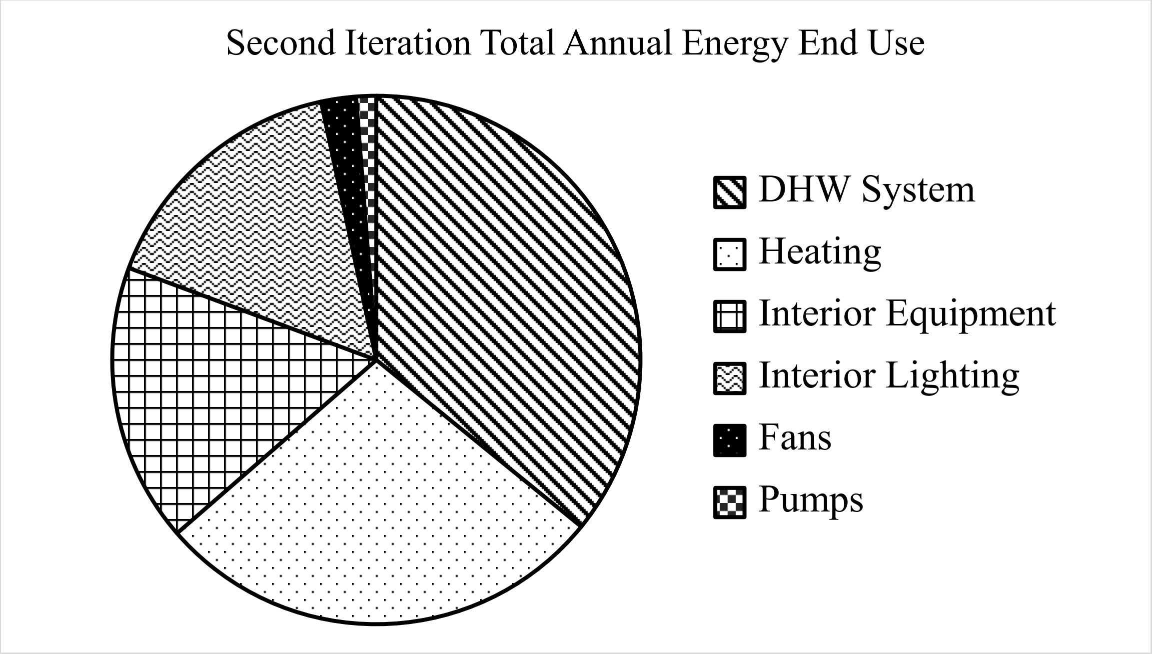


Figure 5.7 Second Iteration of energy efficiency modifications total annual energy end use

The electricity consumption values for each end-use category of the base case building as well as the building after the first and second iteration of energy efficiency measures are provided in Table 5.7.

Table 5.7 Electricity consumption for each end-use category

End Use	Electricity Use Base Case Building (kWh)	Electricity Use First Iteration (kWh)	Electricity Use Reduction of First Iteration (%)	Electricity Use Second Iteration (kWh)	Electricity Use Reduction of Second Iteration, from Base Case (%)
Heating	725,000	438,300	40	245,000	66
Interior Equipment	552,400	385,300	30	150,600	73
Interior Lighting	506,900	189,800	63	141,100	72
DHW System	465,900	316,900	32	316,700	32
Fans	22,500	29,700	32	18,900	16
Pumps	0	0	0	10,800	0

The monthly electricity consumption is shown in Figure 5.8. The months with the highest consumption of electricity are December and January, however the overall electricity consumption is less than that of the building after the first iteration of energy efficiency modifications. The remaining months have a relatively consistent energy consumption. There is still some electricity consumption from heating due to the water-to air heat pumps having a backup electric heating coil. The ground source heat-exchanger is sized to 80 % of the maximum load. The times when the heating load exceeds that of what the heat pumps can produce, the electric backup coils are turned on.

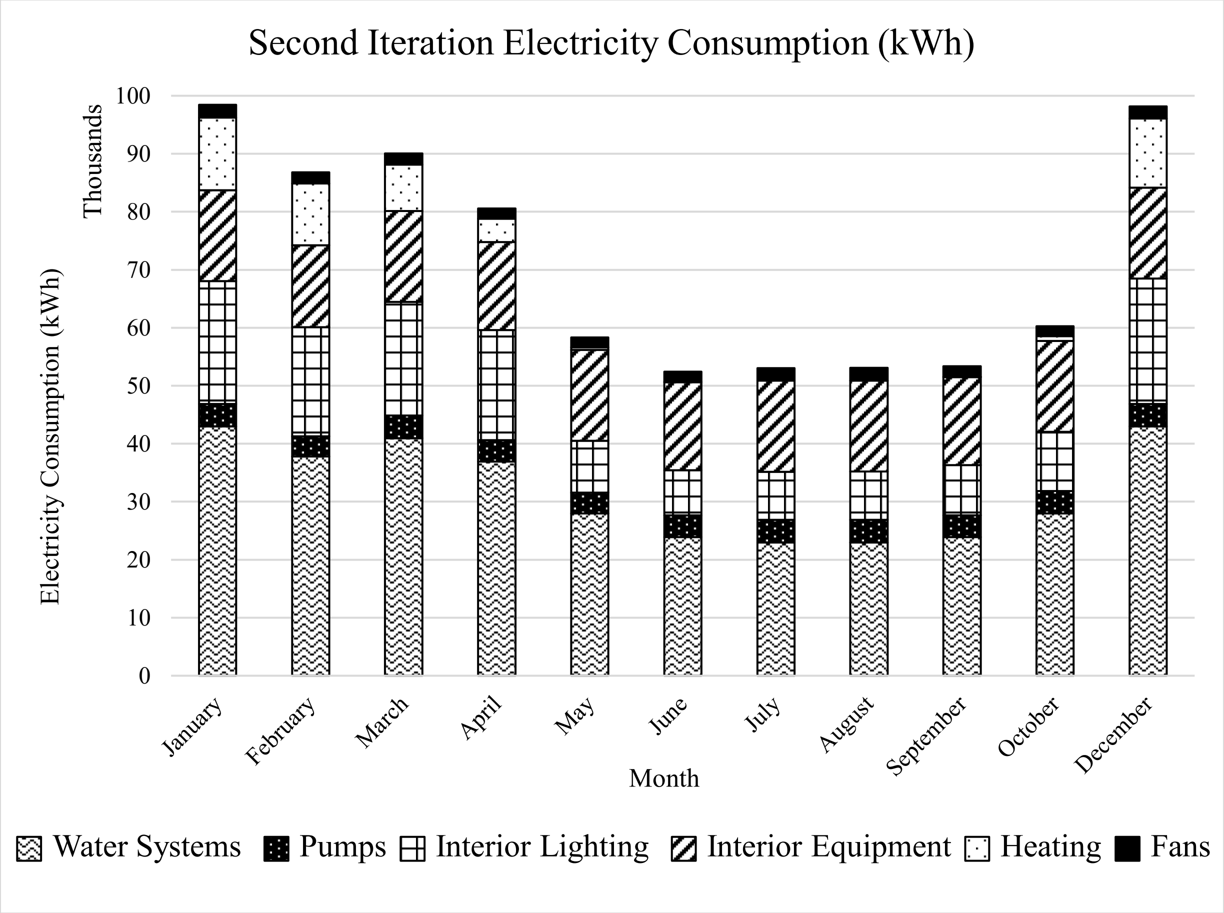


Figure 5.8 Second iteration energy efficiency modifications electricity consumption (kWh)

Lighting and interior equipment loads are further reduced by installing more daylighting and nighttime plug load sensors in residential common spaces. The largest energy savings is seen in the heating load. The electricity values for each end-use category per month are provided in Table 5.8.

Table 5.8 Second iteration electricity consumption (kWh)

Month	Heating	Interior lighting	Interior Equipment	Fans	Pumps	DHW
January	12,500	21,200	15,700	2,200	3,900	43,000
February	10,700	18,800	14,200	1,900	3,500	37,800
March	8,000	19,600	15,700	2,000	3,900	41,000
April	4,000	19,000	15,200	1,700	3,700	37,000
May	460	8,900	15,700	1,700	3,600	28,000
June	12	7,800	15,200	1,800	3,800	24,000
July	0	8,300	15,700	2,200	3,900	23,000
August	0	8,300	15,700	2,200	3,900	23,000
September	0	8,700	15,200	1,900	3,800	24,000
October	840	10,200	15,700	1,700	3,900	28,000
November	4,700	20,700	15,200	1,800	3,800	37,000
December	11,900	21,600	15,700	2,200	3,900	43,000

The heating load profile of the building's second iteration, and the outside air dry bulb temperature are shown in Figure 5.9. The total heating load is less than that of the first iteration. No heating load is required in the months June, July, August, and September. The reduced heating load is because of the installation of more efficient space conditioning systems, but also due to the improved building envelope. By increasing the exterior wall and roof insulation, adding insulation to balconies to reduce the effect of thermal bridges, and increasing the airtightness of the building, allowed for more conditioned air to stay inside and not escape. Some electricity for the heating load is still needed in the colder months. In the summer months the building residents can open windows and exterior doors to allow for natural cooling and to maintain a comfortable interior living condition. The unit heat pumps can also be run in cooling mode, however, the energy consumption for cooling is not considered here because the base case building did not have cooling. The more efficient space conditioning systems includes a water-to-air heat pump, water-to-air heat exchanger in the ventilation systems, and the vertical ground source heat exchanger.

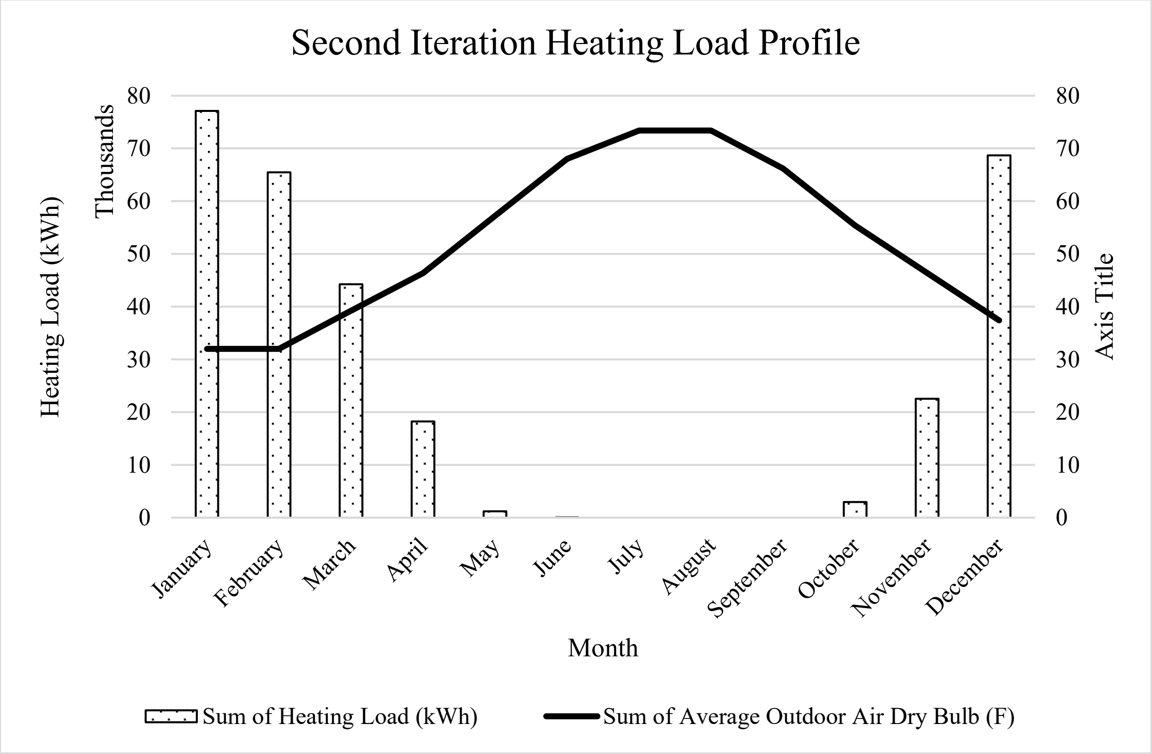


Figure 5.9 Second iteration of energy efficiency modifications heating load vs average outdoor temperature

The electricity consumption values for monthly heating loads of the base case building as well as after the first and second iteration of energy efficiency measures, vs the average monthly outside temperature is provided in Table 5.9.

Table 5.9 Base case building and after first and iteration monthly heating load vs average outdoor temperature

Month	Average Outdoor Air, Dry Bulb (F)	Heating Load Base Case Building (kWh)	Heating Load First Iteration (kWh)	Electricity Use Reduction of First Iteration (%)	Heating Load Second Iteration (kWh)	Electricity Use Reduction of Second Iteration, from Base Case (%)
January	32	160,681	153,463	4	77,089	52
February	32	136,778	118,281	14	65,448	52
March	39	110,054	74,724	32	44,255	60
April	46	58,619	25,700	56	18,250	69
May	57	21,169	7,263	66	1,234	94
June	68	3,511	3,373	4	12	100
July	73	64	0	100	0	100
August	73	62	0	100	0	100
September	66	1,905	3,341	75	0	100
October	55	26,840	10,431	61	2,940	89
November	46	64,334	30,791	52	22,547	65
December	37	141,156	103,211	27	68,669	51

5.4 Photovoltaic System and NZE Building

The second iteration of energy efficiency modifications reduces the total annual energy consumption and allows the building to reach net zero energy status with the addition of a PV system. In order to meet net zero energy operation, the building needs to offset the annual energy consumption with a net total energy production through renewable resources either on-site or nearby. In order to meet the 1,115,000 kWh electricity generation, a solar array consisting of 2,280 SunPower Maxeon M-Series: SPR-M440-H-AC modules, or 47,400 ft^2 of solar cells. The system is slightly oversized, to ensure that if the energy consumption of the building varies from year to year, the net PV energy production would still be greater than the total annual energy consumption of the building.

The total area of the roof is 17,390 ft^2, therefore, using a ground coverage ratio of 0.4, it was determined that 500 PV units can be installed on the roof. The remaining 1,780 units that are unable to fit onto the roof would have to be installed on-site but, on the ground, next to the building. The remaining units are over three times that of the units that are able to be installed on the roof. The number of PV units required to allow the building to reach net zero energy operation make this installation unrealistic. The monthly PV array energy production is shown in Figure 5.10.

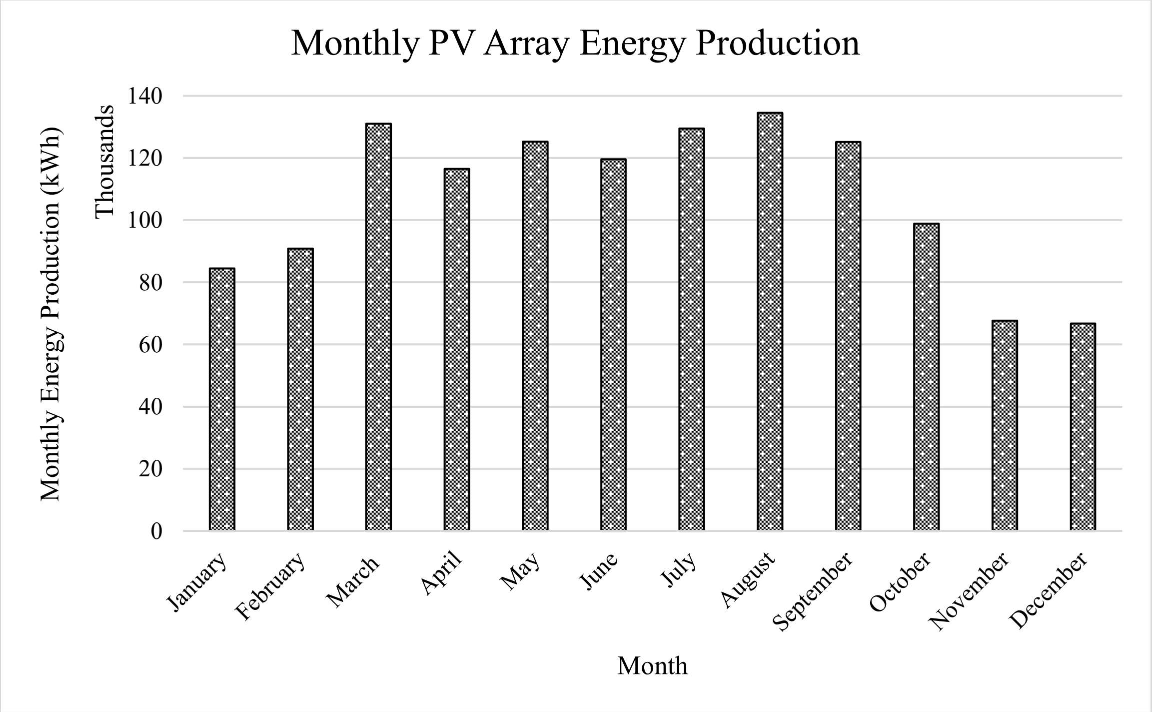


Figure 5.10 Monthly PV array energy production

The second iteration of energy efficiency modifications allowed for the building to reach net zero energy status with the addition of a solar PV array. The total annual energy consumption for the building in its current state, after the first and second iteration of energy efficiency modifications, and then when the building reaches net zero energy operation is shown in Figure 5.11.

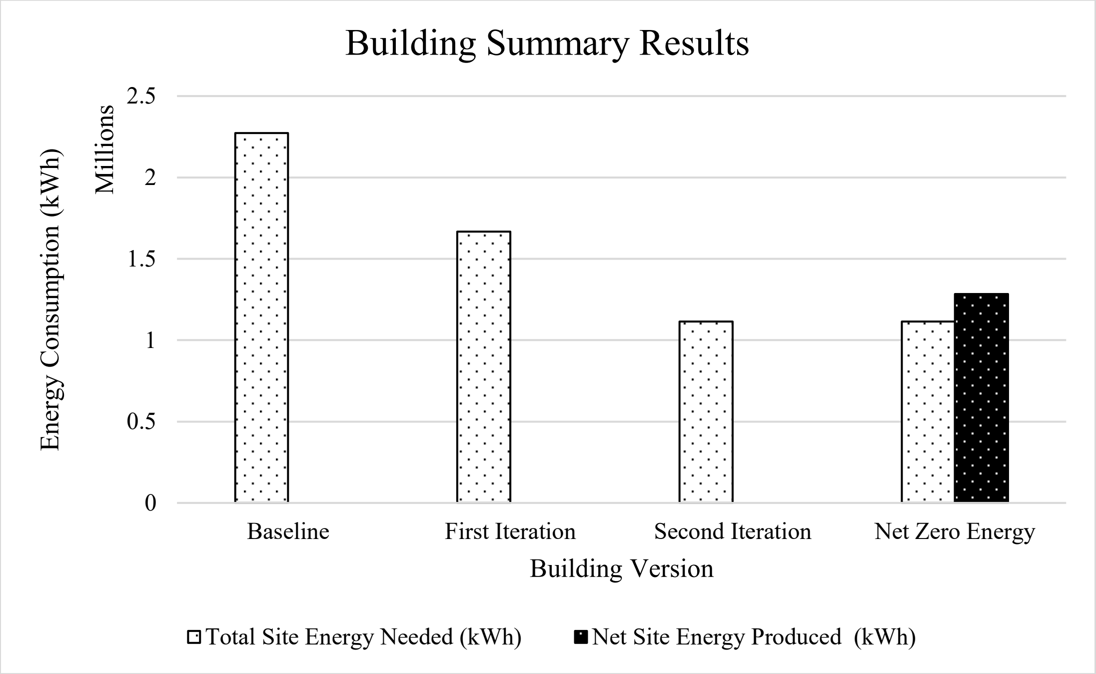


Figure 5.11 Building summary results

5.5 Economic Analysis

The base case building was first modeled in its current state to provide the base case energy requirement. Then energy efficiency modifications as well as a PV system were added to the model and simulated to assess the energy requirement after the building had reached net zero energy operation. The difference between the base case energy requirements and the energy requirement after energy efficiency modifications and PV system have been implemented, represents the energy savings due to the net zero energy retrofit. The building is net zero energy, therefore it is assumed that excess energy produced by the PV system is sold back to the grid, and offsets any cost of electricity that the building draws from the grid throughout the year, when the PV system is not able to meet the buildings energy demand.

The amount of electricity savings (kWh/ year), the unit price of electricity ($/kWh) and the value of savings ($/year) as a result of a net zero energy retrofit of the base case building are presented in Table 5.10. The unit electricity price used in calculating the value of savings was obtained from Nova Scotia Power (NS Power, 2021).

Table 5.10 Electricity and cost savings associated with the net zero energy retrofit

Parameter	Value
Electricity Savings (kWh/year)	2,273,400
Price of Electricity ($/kWh)	0.15
Cost Savings ($/year)	341,000

Since there is uncertainty in predicting future interest and electricity price escalation rates, instead of using a single value for these parameters, a range of values were used to demonstrate the impact of these values on TCC. The ranges of values used for interest and electricity price escalation rates are given in Table 5.11. The electricity price escalation rates used are based on the 2012 electricity price outlook published by the National Energy Board of Canada (NEB, 2012). The range of values used for interest rate reflects the bank of Canada prime rate (BOC, 2021).

Table 5.11 Range of interest and electricity price escalation rates and acceptable payback periods

Parameter	Low	Medium	High
Electricity price escalation rate (%)	2	5	10
Interest Rate (%)	3	6	9
Acceptable payback period (year)	10	20	30

The values of TCC for the net zero energy retrofit are shown in Figure 5.12 for the range of interest and electricity price escalation rates given in Table 5.11, payback periods, and demonstrating the impact of these parameters on the TCC.

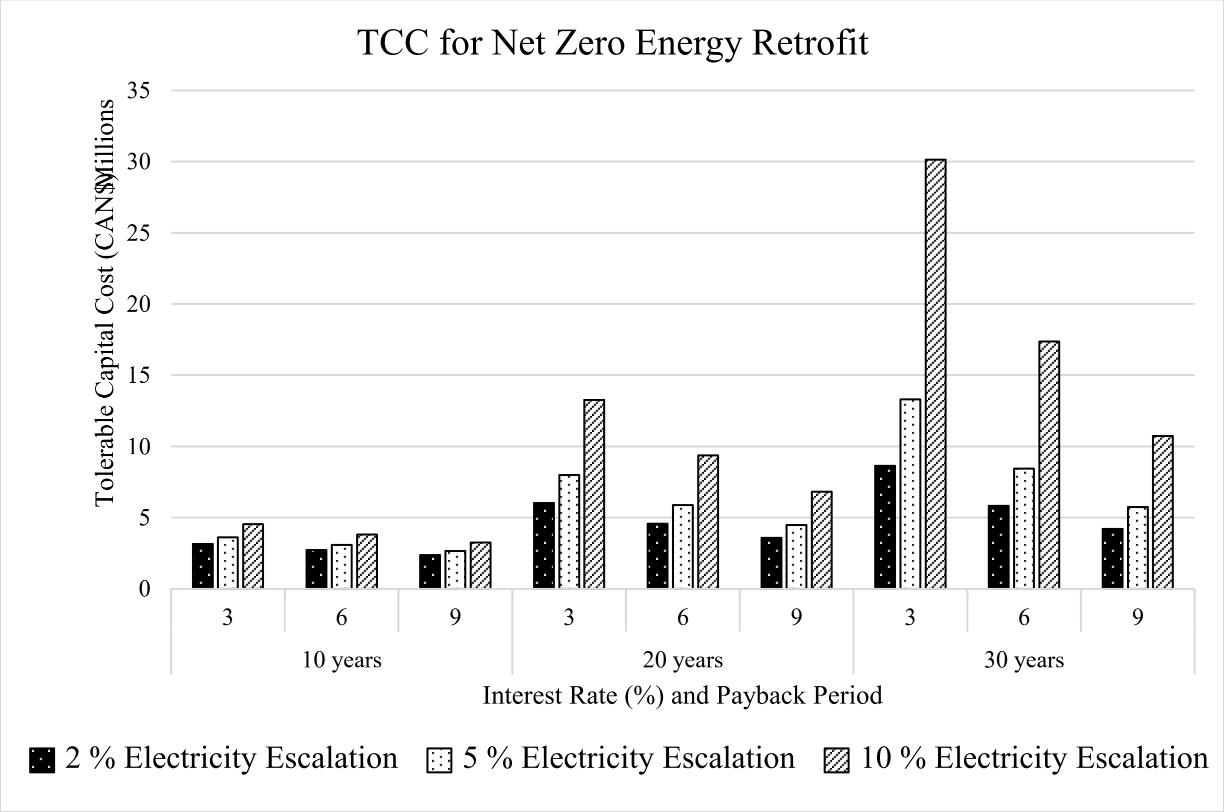


Figure 5.12 TCC of net zero energy retrofit under a range of interest rates (3, 6, 9 %), electricity price escalation rates (2, 5, 10 %) and acceptable payback periods (10, 20, 30 years)

These results indicate that depending on the acceptable payback period, the available interest rate, and the expected electricity price escalation rate, the TCC varies significantly. The lowest TCC, $ 2,363,000, is at an interest rate of 9 %, an electricity price escalation rate of 2 %, and a payback period of 10 years. The highest TCC, $ 30,150,000, is at an interest rate of 3 %, an electricity price escalation rate of 10 %, and a payback period of 30 years. These results allow an owner or decision maker to determine at what capital cost this energy efficiency retrofit and PV system will be economically feasible. The TCC values of a net zero energy retrofit, under a range of interest rates (3, 6, 9 %), electricity escalation rates (2, 5, 10 %) and acceptable payback periods (10, 20, 30 years) are shown in Table 5.12.

Table 5.12 TCC values of net zero energy retrofit under a range of interest rates (3, 6, 9 %), electricity price escalation rates (2, 5, 10 %) and acceptable payback periods (10, 20, 30 years)

Payback Period	Interest Rate (%)	TCC with a 2 % Electricity Escalation Rate	TCC with a 5% Electricity Escalation Rate	TCC with a 10% Electricity Escalation Rate
10 Years	3	3,169,900	3,615,600	4,530,600
	6	2,722,300	3,083,900	3,822,200
	9	2,363,200	2,659,400	3,260,900
20 Years	3	6,045,100	7,997,900	13,274,500
	6	4,575,300	5,888,900	9,358,000
	9	3,580,000	4,489,200	6,833,700
30 Years	3	8,653,000	13,309,500	30,150,200
	6	5,836,700	8,440,300	17,375,700
	9	4,206,500	5,748,200	10,748,200

Chapter 6 Conclusions

The energy consumption and GHG emissions of buildings vary due to their design, location, orientation, and use. Implementing energy efficiency measures in the building sector will assist in reducing energy consumption and has the potential for substantial CO_2 reductions. There is an increased interest for Net-Zero Energy Buildings (NZEB) to reduce the high energy demands associated with buildings.

This research provides insight into the modifications necessary for an existing MURB to reach net zero energy status. A baseline model is developed, to which upgrades are applied in two iterations. The first iteration includes low cost, low disruption modifications using easily accessible technology. The second iteration includes more aggressive modifications to the envelope and space conditioning systems, with the goal of reducing the energy consumption as much as possible before offsetting the energy consumption with a net solar production of energy. These results indicate what is required of a MURB retrofit to reach net zero energy status.

The first iteration of energy efficiency modifications show that simple and readily available technological upgrades can result in significant energy savings. More aggressive energy efficiency modifications such as improving the building envelope and installing a ground source heat pump, as described in the second iteration demonstrate that reducing the energy consumption even further is possible. Net zero energy status is achieved by using the second iteration of energy efficiency modifications and then installing 2,280 Solar panels, or 47,400 ft^2 of solar cells, with 500 being installed on the roof and the remaining 1,780 units being installed on-site or nearby. The required number of PV units to allow for the building to reach net zero energy operation, make this PV installation unrealistic. This demonstrates the difficulty of achieving net zero energy operation of a MURB with on-site generation.

Economic analysis of the net zero energy retrofit was conducted by calculating the Tolerable Capital Cost under a range of interest rates (3, 6, 9 %), electricity price escalation rates (2, 5, 10 %) and acceptable payback periods (10, 20, 30 years). The results of the TCC method allow for decision makers to determine at what price the net zero energy retrofit will be economically feasible.

We can conclude from this research that:

1. Simple and readily available technological upgrades can result in significant energy savings,
2. Net zero energy status is achieved through aggressive energy efficiency measures,
3. Net zero operation is achieved through the installation of renewable energy, such as photovoltaics, and,
4. The TCC method allows for decision makers to determine at what price the net zero energy retrofit will be economically feasible.

By achieving a net zero energy retrofit design for a multi-unit residential building, using technology available to consumers, this work will provide guidance for developers and condominium corporations in Nova Scotia to improve existing MURB’s into net zero energy ready and net zero energy status, through retrofit.

References

Alirezaei, M., Noori, M., & Tatari, O. (2016). Getting to net zero energy building: Investigating the role of vehicle to home technology. *Energy and Buildings, 130*, 465-476.

American Society of Heating, R (ASHRAE). (2019). *2019 ASHRAE handbook : Heating, ventilating, and air-conditioning applications.* (SI ed.). Atlanta, GA: ASHRAE.

Attia, S. (2018). Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmaps for Project Analysis.

Bank of Canada (BOC). (2021). Rates and statistics. Retrieved from http://www bankofcanada.ca/rates/

BEST Directory. (2018). *Building energy software tools – whole building energy simulation.* Retrieved from https://www.buildingenergysoftwaretools.com/

Canada Energy Regulatory. (2020, October 9). *Market Snapshot: Growing heat pump adoption – how does the technology work?* https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2019/market-snapshot-growing-heat-pump-adoption-how-does-technology-work.html?=undefined&wbdisable=true

Canadian Centre for Policy Alternatives [CCPA]. (2007, June 7). *Nova Scotia vulnerable to rising energy costs and supply shortfalls.* https://www.policyalternatives.ca/newsroom/news-releases/nova-scotia-vulnerable-rising-energy-costs-and-supply-shortfalls-report

Canadian Home Builders' Association [CHBA]. (2017). *CHBA Net Zero Home Labelling Program.* https://www.chba.ca/CHBA/HousingCanada/Net_Zero_Energy_Program/CHBA/Housing_in_Canada/Net_Zero_Energy_Program/NZE_Program_Landing_Page.aspx?hkey=4af3da17-b4da-42ef-bf20-261a9cfbe39f

Canadian Home Builders' Association [CHBA]. (2020a). *CHBA Net Zero MURBs Initiative Leading the Way to Voluntary Adoption of Advanced Building Science.* https://www.chba.ca/CHBA/News/CHBA_Net_Zero_MURBs_Initiative_Leading_the_Way_to_Voluntary_Adoption_of_Advanced_Building_Science.aspx

Canadian Home Builders' Association [CHBA]. (2020b). *Net Zero MURBS.* https://www.chba.ca/CHBA/HousingCanada/Net_Zero_Energy_Program/NEW__Net_Zero_MURBs/CHBA/Housing_in_Canada/Net_Zero_Energy_Program/Net_Zero_MURBs.aspx?hkey=2fe3c949-db79-41d9-8813-c9a6a5859a70

Canadian Mortgage and Housing Cooperation [CMHC]. (2011). Near-net zero-energy retrofits for homes. Ottawa Ontario: Canada Mortgage and housing corporation, 2011

Coleman, S. (2020). *NET ZERO ENERGY MURBS – The future of Multi-Unit Residential Housing in Canada.* Retrieved from https://www.linkedin.com/pulse/net-zero-energy-murbs-future-multi-unit-residential-housing-coleman/

Delaney, D.T., O'Hare, G.M.P., & Ruzzelli, A.G. (2009). Evaluation of energy-efficiecny in lighting systems using sensor networks. Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy-Efficency in Buildings. Retrieved from: https://researchrepository.ucd.ie/bitstream/10197/1898/1/buildLight.pdf

Design Builder. (2014). *ANSI/ASHRAE Standard 140-2011 Building Thermal Envelope and Fabric Load Tests.* Retrieved from http://files.designbuilder.cl/200000036-348f735887/DesignBuilder_v4.2_ASHRAE140_2.pdf

Efficiency Nova Scotia. (2020). Net Zero Ready. Retrieved from https://www.efficiencyns.ca/net-zero-ready/

Energy Hub. (2020). *Complete Guide for Solar Power in Nova Scotia*. https://www.energyhub.org/nova-scotia/

Energy Nova Scotia. (2020). *Consumer Natural Gas*. https://energy.novascotia.ca/oil-and-gas/consumer-natural-gas

EnergyPlus. (2004). *EnergyPlus Testing with HVAC BESTTEST*. Retrieved from https://simulationresearch.lbl.gov/dirpubs/epl_bestest_hvac.pdf

EnergyPlus. (2022a). *Introduction to EnergyPlus*. Retrieved from https://energyplus.net/

EnergyPlus. (2022b). *Engineering Reference*. Retrieved from https://energyplus.net/assets/nrel_custom/pdfs/pdfs_v9.6.0/EngineeringReference.pdf

EnergyPlus. (2022c). *Testing and Validation*. Retrieved from https://energyplus.net/testing

Finch, G., Higgins, J., & Hanam, B. (2014). *The importance of balcony and slab edge thermal bridges in concrete construction.* 14th Canadian Conference on Building Science and Technology.

Good, C., Andresen, I., & Hestnes, A. (2015). Solar energy for net zero energy buildings – A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems. Solar Energy, 122(C), 986-996.

Halifax Water. (2021). *2020-21 Annual report*. Retrieved from https://halifaxwater.ca/sites/default/files/2021-09/2020-21%20Annual%20Report.pdf

Heritage Gas. (2018, January). *Reducing emissions in HRM with Natural Gas*. https://www.halifax.ca/sites/default/files/documents/city-hall/standing-committees/180201essc1031.pdf

Hernandez, P., & Kenny, P. (2010). From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings, 42*(6), 815-821.

IKEA. (2021). *IKEA Dartmouth – Solar Panels.* Retrieved from https://www.ikea.com/ca/en/newsroom/corporate-news/ikea-canada-announces-installation-of-solar-panels-on-alberta-stores-pub537e9c67

Intergovernmental Panel on Climate Change. (2014). Climate Change 2014 Synthesis Report

International Ground Source Heat Pump Association (IGSHPA). (2021). Software – GLHEPro. Retrieved from https://igshpa.org/software/

Ionescu, C., Baracu, T., Vlad, G., Necula, H., & Badea, A. (2015). The historical evolution of the energy efficient buildings. Renewable and Sustainable Energy Reviews, 49, 243-253.

Jinsung Byun, Insung Hong, Byoungjoo Lee, & Sehyun Park. (2013). Intelligent household LED lighting system considering energy efficiency and user satisfaction. IEEE Transactions on Consumer Electronics, 59(1), 70-76.

Kapsalaki, M., & Leal, V. (2011). Recent progress on net zero energy buildings. Advances in Building Energy Research, 5(1), 129-162.

Logue, Jennifer M, Turner, William J.N, Walker, Iain S, & Singer, Brett C. (2016). A simplified model for estimating population-scale energy impacts of building envelope air tightening and mechanical ventilation retrofits. *Journal of Building Performance Simulation, 9*(1), 1-16.

NACM. (2016). 2016 Building Energy Efficiency Standards – Appendix 5.4B. Retrieved from https://energycodeace.com/site/custom/public/reference-ace-2016/index.html#!Documents/54spaceuses.htm

Nagouchi et al. (2009). Net Zero energy Homes of the future: A Case Study of the EcoTerra House in Canada. Presented at the Renewable Energy Congress, Glasgow, Scotland. Retrieved from: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/2008-112_OP-J_411-PVTZEH_EcoTerra.pdf

National Energy Board of Canada (NEB). (2012). *Energy pricing information for Canadian consumers.* Retrieved from http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/prcng/prcng-eng.html

Natural Resources Canada [NRCan]. (2012). *2012 R-2000 Standard*. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/2012%20R2000%20Standard%20EN.pdf

Natural Resources Canada [NRCan]. (2017). *Comprehensive Energy Use Database: Residential Sector – Nova Scotia.* https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_res_ns.cfm

Natural Resources Canada [NRCan]. (2020). *NetZero: Future Building Standards*. https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-homes/buying-energy-efficient-new-home/netzero-future-building-standards/20581

Natural resources Canada. (2004). *Heating and Cooling with a Heat Pump.* Retrieved from Natural Resources Canada Online database.

Natural Resources Canada. (2010). Home Lighting Design Guide Pocket Book: Energy Efficiency Reference Guide. Retrieved from: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/energystar/home-design-booklet-eng(1).pdf

Natural Resources Canada. (2016). Energy Use Data Handbook Table's: Canada's Secondary Energy Use (Final Demand) by Sector, End Use and Subsector

Natural Resources Canada. (2018a). Laying the foundation for net-zero energy ready building codes by 2030.

Natural Resources Canada. (2018b). Cooling and ventilation equipment for residential use. Retrieved from https://www.nrcan.gc.ca/energy/products/categories/cooling-ventilating/13756

Natural Resources Canada. (2019a). Energy Efficiency: Learning about LEDs. Retrieved from: https://www.nrcan.gc.ca/energy/products/reference/15476

Natural Resources Canada. (2019b). Energy Consumption of Major Household Appliances Shipped in Canada, Trends for 1990-2016. Retrieved from: http://oee.nrcan.gc.ca/publications/statistics/aham/2016/

Natural Resources Canada. (2019c). Energy Efficiency: Electronics. Retrieved from: https://www.nrcan.gc.ca/energy/products/categories/electronics/13710

Natural Resources Canada. (2019d). Energy Efficiency: standby Power and "smart" devices. Retrieved from: https://www.nrcan.gc.ca/energy/products/categories/electronics/14195

Natural Resources Canada. (2019e). Energy Efficiency: Water Heaters. Retrieved from: https://www.nrcan.gc.ca/energy/products/categories/water-heaters/13735

Natural Resources Canada. (2019f). Energy Efficiency: make small changes that add up. Retrieved from: https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-homes/make-small-changes-add/21850

Natural Resources Canada. (2019g). Energy Efficiency: Building-applied Photovoltaics. Retrieved from: https://www.nrcan.gc.ca/energy/efficiency/data-research-and-insightsenergy-efficiency/buildings-innovation/solar-photovoltaic-energy-buildings/building-applied-photovoltaics/3909

Natural Resources Canada. (2020). *Retrofitting*. https://www.nrcan.gc.ca/retrofitting/20707

Natural Resources Canada. (2022). Photovoltaic potential and solar resource maps of Canada. Retrieved from https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/renewable-energy/solar-photovoltaic-energy/tools-solar-photovoltaic-energy/photovoltaic-potential-and-solar-resource-maps-canada/18366

Nikoofard, S., Ugursal, V., & Beausoleil-Morrison, I. (2014). Technoeconomic Assessment of the Impact of Window Improvements on the Heating and Cooling Energy Requirement and Greenhouse Gas Emissions of the Canadian Housing Stock. *Journal of Energy Engineering, 140*(2), 4013018.

Nikoofard, S., Ugursal, V., & Beausoleil-Morrison, I. (2015). Economic Analysis of Energy Upgrades Based on Tolerable Capital Cost. *Journal of Energy Engineering, 141*(3), 6014002.

North Star. (2019). Commercial sizing guide – north star water conditioning. Retrieved from https://www.northstarwater.com/commercial-products/sizing-guide/

Nova Scotia Department of Energy. (2015). *Our Electricity Future: Nova Scotia's Electricity Plan, 2015-2040*. Energy Nova Scotia Online Database.

Nova Scotia Power (NS Power). (2021). How are rates changing this year? Retrieved from https://www.nspower.ca/docs/default-source/pdf-to-upload/rate-stability/2021/nsprates_7-3342x8-5_residential_dec1_2020_web.pdf?sfvrsn=fdf4135f_2&sfvrsn=fdf4135f_2

Nova Scotia Power. (2021). *Powering a green Nova Scotia, together*. Retrieved from https://www.nspower.ca/cleanandgreen/renewable-energy-sources#:~:text=Today%20about%2030%25%20of%20our,reach%20about%2040%25%20renewable%20energy.

NREL. (2014). 2014 Building America House Simulation Protocols. Retrieved from https://www.nrel.gov/docs/fy14osti/60988.pdf

NREL. (2016). *Airside HVAC BESTTEST: Adaptation of ASHRAE RP 865 Airside HVAC Equipment Modeling Test Cases for ASHRAE Standard 140*. Retrieved from https://www.nrel.gov/docs/fy16osti/66000.pdf

NREL. (2022). PVWatts Calculator. Retrieved from https://pvwatts.nrel.gov/pvwatts.php

OpenStudio. (2021). *Downloads*. Retrieved from https://openstudio.net/downloads

OpenStudio. (2022). *Introduction to OpenStudio*. Retrieved from https://openstudio.net

Passipedia: The Passive House Resource. (2015, April 14). *Saskatchewan Conservation House. https://passipedia.org/basics/the_passive_house_-_historical_review/poineer_award/saskatchewan_conservation_house*

Pegues, J. (2002). *The benefits of 8760 hour-by-hour building energy analysis*. Retrieved from http://www.knndassociates.com/wp-content/themes/knnd-associates/images/knowledge-center/8760_Energy_Analysis.pdf

PickHVAC. (2021). *Coefficient of performance – what is a good COP for a heat pump*. Retrieved from https://www.pickhvac.com/faq/heat-pump-cop/

Pratus. (2018). Modeling Appliance Loads in Multi-Unit Residential Buildings. Retrieved from https://sbcanada.org/wp-content/uploads/2018/06/Appliance_Energy_Modelling_SBC_Oleksandra_Onisko.pdf

Radiance. (2022). *About Radiance*. Retrieved from https://www.radiance-online.org/about

RDH Building Engineering Ltd. (2012, February). *Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia: Final Report.* BC Housing Research Centre Database.

Reisel, J., & McIver, K. (2016). *Principles of engineering thermodynamics* (SI ed.). Boston, MA: Cengage Learning.

Rosen, M.A. (2015) Net-Zero Energy Buildings and Communities: Potential and the Role of Energy Storage. Journal of Power and Energy Engineering, 3, 470-474. http://dx.doi.org/10.4236/jpee.2015.34065

Sartori, I., Napolitano, A., & Voss, K. (2011). Net zero energy buildings: A consistent definition framework. Energy & Buildings, 48(C), 220-232.

Saskatchewan Research Council [SRC]. (2018, April 17). *A closer look at the Saskatchewan Conservation House and four others. https://www.src.sk.ca/blog/closer-look-saskatchewan-conservation-house-and-four-others*

Schneider Electric. (2018). *Context MPPT 80 600 Solar PV Charge Controller*. Retrieved from https://solar.schneider-electric.com/product/conext-mppt-charge-controller-2/

Scognamiglio, A., Adinolfi, Graditi, & Saretta. (2014). Photovoltaics in Net Zero Energy Buildings and Clusters: Enabling the Smart City Operation. Energy Procedia, 61, 1171-1174.

SketchUp. (2019). *Downloading older versions*. Retrieved from https://help.sketchup.com/en/downloading-older-versions

Solar Data NS. (2019). *Solar Power Data for Nova Scotia* [Data Set]. https://www.solardatans.ca/data/

Statistics Canada. (2009). *Summertime control of temperature in Canadian homes: How Canadians keep their cool [Data Set].* https://www150.statcan.gc.ca/n1/pub/16-002-x/2011002/part-partie3-eng.htm

Strickland, C., & Nyboer, J. (2002). Cogeneration potential in Canada: Natural Resources Canada. Retrieved from: https://aceee.org/files/proceedings/2003/data/papers/SS03_Panel5_Paper_11.pdf

SunPower. (2022). *420-440W Residential AC Module.* Retrieved from https://us.sunpower.com/solar-resources/m-series-residential-m440-m435-m430-m425-m420

ThysseenKrupp. (2021). *ThysseenKrupp Elevators – Energy Calculator*. Retrieved from https://design.na.tkelevator.com/tools/energy-calculator

Tian, Y., & Zhao, C. (2013). A review of solar collectors and thermal energy storage in solar thermal applications. Applied Energy, 104(C), 538-553.

Tierra Concepts. (2012, November 29). Retrofit your home with passive solar design. https://tierraconceptssantafe.com/retrofit-your-home-with-passive-solar-design/

Ugursal, I.V. (2014). Energy consumption, associated questions and some answers. *Applied Energy, 130*, 783-792.

United Nations. (2019). Growing at a slower pace, world population is excpected to reach 9.7 billion in 2050 and could peak at nearly 11 billion around 2100. Retrieved from https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html

US Department of Energy. (2014). *A Common Definition for Zero Energy Buildings*. Retrieved from https://www.energy.gov/sites/default/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf

US Department of Energy. (2020a). *Ventilation.* https://www.energy.gov/energysaver/weatherize/ventilation

US Department of Energy. (2020b). *Wole House Ventilation*. https://www.energy.gov/energysaver/weatherize/ventilation/whole-house-ventilation

Voss, K., et al. (2010). *Load Matching and Grid Interaction of Net Zero Energy Buildings.* Proceedings of the EuroSun Conference. Retrieved from: http://repositorio.lneg.pt/bitstream/10400.9/963/1/EUROSUN2010_HGoncalves2.pdf

Wikipedia. (2022). *Finite Difference.* Retrieved from https://en.wikipedia.org/wiki/Finite_difference

Witte, M., Henninger, R., & Crawley, D. (2004). *Experience Testing EnergyPLus with the ASHRAE 1052-RP Building Fabric Analytical Tests*. Retrieved from https://simulationresearch.lbl.gov/dirpubs/SB04/sb10.pdf

Younger, M., Morrow-Almeida., Vindigui, S., & Dannenburg, A. (2008). The Built Environment, Climate Change, and Health. *American Journal of Preventative Medicine, 35*(5), 517-526.

Zero Energy Project. (2020). *Select Energy Efficient Lighting*. https://zeroenergyproject.org/build/twelve-steps-affordable-zero-energy-home-construction-design/select-energy-efficient-lighting-zero-energy-home-design/

Appendix A.

Table A.1 Example of Solar PV data, solar array specifications (Solar Data NS, 2019)

Parameter	**Value**
Forward sortation area where the solar electric system is located	B3T
Overall DC system capacity (Watts)	8550
Number of modules	30
Module manufacturer	Silfab
Module model number	SLA285M
Peak operating power per module under standard test conditions (Watts)	285
Module efficiency	0.174
Number of inverters	30
Inverter manufacturer	Enphase Energy
Inverter model number	M250-60-2LL
Peak output AC power per inverter (Watts)	250
Overall AC system capacity (Watts)	7500
California energy commission (CEC) weighted inverter efficiency (%) at 240 VAC	0.965
Module tilt (0˚= horizontal/ 90˚= vertical)	18
Module orientation from south (180˚ is due south)	135

Appendix B.

Photovoltaic system

The NREL PV Watt's Calculator was used to determine the size of the solar array required to offset the net annual electricity consumption of the building. Inputs used for the calculation are listed in Table B.1.

Table B.1 PV System Specifications (NREL, 2022)

Parameter	**Value**
Requested Location:	Halifax, Nova Scotia
Location:	Lat, Lon: 44.65, -63.62
Lat (deg N):	44.65
Long (deg W):	63.62
Elev (m):	36.56
DC System Size (kW):	1000
Module Type:	SPR-M440-H-AC
Array Type:	Fixed (Roof Mount)
Array Tilt (deg):	45
Array Azimuth (deg):	180
System Losses:	14.08
Invert Efficiency (%):	96
DC to AC Size Ratio:	1.2
Average Cost of Electricity Purchased from Utility ($/kWh):	0.156
Capacity Factor (%)	14.7

The size of the solar array was first estimated using NREL's PVWatts Calculator, which takes the annual electricity usage (kWh) of the building, the sunshine hours per day based on the buildings location, and the percent of the electricity bill that the PV system is intended to offset. Using, the PWWatts Calculator, it was estimated that a 1,000 kW array would be required to offset the annual electricity consumption of the building. The inputs for the PVWatts Calculator are listed below.

Electricity consumption of the building: 1,115,047 kWh/year

Solar hours per day in Halifax = 3.6 (NRCan, 2022)

This number is not right. It is the average for winter months. The more realistic number is 1,970 hours per year, which translates to 5.4 hours per day.

% Electricity offset = 100

Solar array size estimate = 1,000 kW

Using the PV module efficiency and the module nameplate size, the size of the entire building array was estimated. The calculation steps followed are listed below.

SunPower Maxeon M-Series Efficiency (%) = 22.8

SunPower Maxeon M-Series Size (m^2) = 1.93

$$1{,}000\ kW\ \div \frac{1kW}{m^2} \div 22.8\ \% = 4{,}400\ m^2 = 47{,}400\ ft^2$$

$$4{,}400\ m^2 \div 1.93\ m^2 = 2280\ solar\ panels$$

In order to estimate the number of panels that could be installed on the roof, the area available for the roof mounted array was calculated and is shown in Figure B.1. Based on the area available on the roof for the array, and a ground coverage ratio of 0.4, it was determined that the space available on the roof could support a 230 kW array. The calculation steps followed to determine the number of solar panels that can be installed on the roof are listed below.

$$230\ kW \div \frac{1kW}{m^2} \div 22.8\ \% = 1{,}000\ m^2 = 10{,}800\ ft^2$$

$$1{,}000\ m^2 \div 1.93\ m^2 = 500\ solar\ panels$$

Figure B.1 PV System Customized to Roof (NREL, 2022)

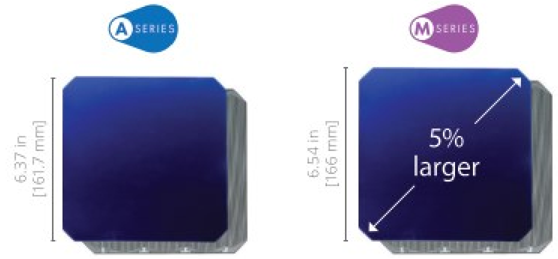
420-440W Residential AC Module

SunPower® Maxeon® Technology

Built specifically for use with the SunPower Equinox® system, the only fully integrated solar solution designed, engineered, and warranted by one company.

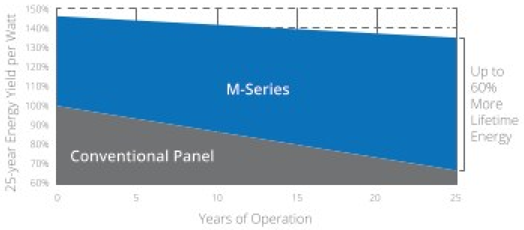
Highest Power AC Density Available.

The patented, solid-copper foundation Maxeon Gen 6 cell is over 5% larger than prior generations, delivering the highest efficiency AC solar panel available.[1]



Highest Lifetime Energy and Savings

Designed to deliver 60% more energy over 25 years in real-world conditions like partial shade and high temperatures.[2]



Best Reliability, Best Warranty

With more than 42.6 million and 15 GW modules deployed around the world, SunPower technology is proven to last. That's why we stand behind our module and microinverter with the industry's best 25-year Combined Power and Product Warranty.

Part of the SunPower Equinox® Solar System

- Compatible with mySunPower™ monitoring
- Seamless aesthetics

Factory-integrated Microinverter

- Highest-power integrated AC module in solar
- Engineered and calibrated by SunPower for SunPower AC modules

M-Series: M440 | M435 | M430 | M425 | M420 SunPower® Residential AC Module

AC Electrical Data		
Inverter Model: Type H (Enphase IQ7HS)	@240 VAC	@208 VAC
Max. Continuous Output Power (VA)	384	369
Nom. (L-L) Voltage/Range[3] (V)	240 / 211–264	208 / 183–229
Max. Continuous Output Current (Arms)	1.60	1.77
Max. Units per 20 A (L-L) Branch Circuit[4]	10	9
CEC Weighted Efficiency	97.0%	96.5%
Nom. Frequency	60 Hz	
Extended Frequency Range	47–68 Hz	
AC Short Circuit Fault Current Over 3 Cycles	4.82 A rms	
Overvoltage Class AC Port	III	
AC Port Backfeed Current	18 mA	
Power Factor Setting	1.0	
Power Factor (adjustable)	0.85 (inductive) / 0.85 (capacitive)	

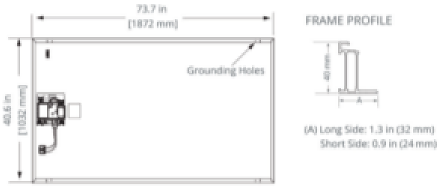
DC Power Data					
	SPR-M440-H-AC	SPR-M435-H-AC	SPR-M430-H-AC	SPR-M425-H-AC	SPR-M420-H-AC
Nom. Power[6] (Pnom) W	440	435	430	425	420
Power Tolerance	+5/−0%				
Module Efficiency	22.8%	22.5%	22.3%	22.0%	21.7%
Temp. Coef. (Power)	−0.29% / °C				
Shade Tolerance	Integrated module-level max. power point tracking				

Warranties, Certifications, and Compliance	
Warranties	• 25-year limited power warranty • 25-year limited product warranty
Certifications and Compliance	• UL 1741 / IEEE-1547 • UL 1741 AC Module (Type 2 fire rated) • UL 61730 • UL 62109-1 / IEC 62109-2 • FCC Part 15 Class B • ICES-0003 Class B • CAN/CSA-C22.2 NO. 107.1-01 • CA Rule 21 (UL 1741 SA)[5] (includes Volt/Var and Reactive Power Priority) • UL Listed PV Rapid Shutdown Equipment[7] Enables installation in accordance with: • NEC 690.6 (AC module) • NEC 690.12 Rapid Shutdown (inside and outside the array) • NEC 690.15 AC Connectors, 690.33(A)–(E)(1) When used with AC module Q Cables and accessories (UL 6703 and UL 2238)[7]: • Rated for load break disconnect
PID Test	1000 V: IEC 62804

Tested Operating Conditions	
Operating Temp.	-40° F to +185°F (-40°C to +85°C)
Max. Ambient Temp.	122°F (50°C)
Max. Test Load[8]	Wind: 125 psf, 6000 Pa, 611 kg/m² back Snow: 187 psf, 9000 Pa, 917 kg/m² front
Max. Design Load	Wind: 75 psf, 3600 Pa, 367 kg/m² back Snow: 125 psf, 6000 Pa, 611 kg/m² front
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)

Mechanical Data	
Solar Cells	66 Maxeon Gen 6
Front Glass	High-transmission tempered glass with anti-reflective coating
Environmental Rating	Outdoor rated
Frame	Class 1 black anodized (highest AAMA rating)
Weight	48 lb (21.8 kg)
Recommended Max. Module Spacing	1.3 in. (33 mm)

Packaging Configuration	
Modules per pallet	25
Packaging box dimensions	75.4 × 42.2 × 48.0 in. (1915 × 1072 × 1220 mm)
Pallet gross weight	1300.7 lb (590 kg)
Pallets per container	32
Net weight per container	41,623 lb (18,880 kg)



Please read the safety and installation instructions for details.

AC MODULE
GRID SUPPORT UTILITY INTERACTIVE
PV RAPID SHUTDOWN EQUIPMENT
LISTED
Module Fire Performance: Type 2

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1 Based on datasheet review of websites of top 20 manufacturers per Wood Mackenzie US PV Leaderboard Q3 2021.
2 Maxeon 435 W, 22.5% efficient, compared to a Conventional Panel on same-sized arrays (260 W, 16% efficient, approx. 1.6 m²), 7.9% more energy per watt (based on PVSyst pan files for avg. US climate), 0.5%/yr slower degradation rate (Jordan, et. al. "Robust PV Degradation Methodology and Application."PVSC 2018).
3 Voltage range can be extended beyond nominal if required by the utility.
4 Limits may vary. Refer to local requirements to define the number of microinverters per branch in your area.
5 Factory set to IEEE 1547a-2014 default settings. CA Rule 21 default settings profile set during commissioning.
6 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25°C). All DC voltage is fully contained within the module.
7 UL Listed as PVRSE and conforms with NEC 2014 and NEC 2017 690.12; and C22.1-2015 Rule 64-218 Rapid Shutdown of PV Systems, for AC and DC conductors; when installed according to manufacturer's instructions.
8 Please read the safety and installation instructions for more information regarding load ratings and mounting configurations.

See www.sunpower.com/company for more reference information.
Specifications included in this datasheet are subject to change without notice.

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