Comparative Analysis of Various National Building Codes and Carbon Payback Periods of Insulation Materials at Different Climate Zones in Canada

by

Alastair Alphonse Mascarenhas
B.Eng., R.V. College of Engineering, India, 2018

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTERS OF ENGINEERING

in the Department of Mechanical Engineering

© Alastair Mascarenhas, 2024
University of Victoria

All rights reserved. This document may not be reproduced in whole or in part, by photocopy or other means without the permission of the author.

Comparative Analysis of Various National Building Codes and Carbon Payback Periods of Insulation Materials at Different Climate Zones in Canada

by

Alastair Alphonse Mascarenhas
B.Eng., R.V. College of Engineering, India, 2018

Supervisory Committee

Dr. Caterina Valeo, Supervisor
Department of Mechanical Engineering

Dr. Phalguni Mukhopadhyaya, Co- Supervisor
Department of Civil Engineering

Dr. Milad Mahmoodzadeh, Committee member
Department of Civil Engineering

Disclaimer

This document presents the observations from an academic pilot study and these observations should not be implemented in real-life applications. While every precaution has been taken to ensure that the content of this document is accurate and representative, errors can occur.

Abstract

Single-family dwellings make a significant contribution to carbon emissions in Canada. The National Energy Code for Buildings (NECB) emphasizes reducing the operational carbon consumption of buildings. Using thermal insulation material in constructing building envelopes plays a crucial role in decreasing a building's operational carbon. However, since insulation materials have embodied carbon, therefore, for optimal building performance and design, designers should take into account both the operational and embodied carbon of insulation materials. This paper compares the embodied carbon and operational energy savings resulting from the use of thermal insulation material. It also presents Carbon Payback Period (CPP) values of different thermal insulation materials in various Canadian cities representing different climate zones. A model is created using the Athena Impact Estimator (AIE) tool, based on a three-bedroom single-family home with a wood-frame structure. Three insulation materials, namely Batts Fiberglass, Blown Cellulose and Mineral Wool, are evaluated in three different cities, namely Vancouver, Toronto and Calgary, representing three climate zones (zones 4, 5 and 7a). The HOT2000 energy simulator calculates operational carbon consumption using the energy mix comprising electricity and natural gas. The CPPs for selected materials were calculated using operational and embodied carbon data. A comparison of the Whole Building Life Cycle Analysis (WBLCA) Global Warming Potential (GWP) between the National Building Code (NBC) 1995 and 2020 versions revealed an average 25% decrease in Operational Carbon and an average 6% increase in Embodied Carbon. This compromise showed a shift towards standardizing energy-efficient buildings and selecting sustainable thermal insulation materials for construction. Identifying and using less carbon footprint materials can help reduce embodied carbon. In Calgary, the CPP for Blown Cellulose, Batts Fiberglass and Mineral Wool insulation were calculated to be 0.92, 0.94 and 1.09 years, respectively. In Toronto, the CPP for Blown Cellulose, Batts Fiberglass and Mineral Wool is 1.15, 1.17 and 1.39 years, respectively. Vancouver has longer CPP for Batts Fiberglass, Blown Cellulose and Mineral Wool with 2.66, 2.64, and 2.69 years, respectively. This indicates that as the heating degree days (HDD) increases, the CPP shortens. Graphing the CPP vs HDD can help designers and contractors make more informed decisions regarding the available choices of thermal insulations.

Table of Contents

List of Figures

List of Tables

Abbreviations

LCA	Life Cycle Assessment
EPD	Environment Product Declaration
WBLCA	Whole-Building Life Cycle Assessment
NBC	National Building Code
CO_2	Carbon Dioxide
GHG	Green House Gases
GWP	Global Warming Potential
CZ	Climate Zone
CPP	Carbon Payback Period
HDD	Heating Degree Days
DHW	Domestic Hot Water
SHC	Space Heating and Cooling
AEI	Athena Impact Estimator
NECB	National Energy Code for Buildings

Acknowledgments

I want to express my sincerest gratitude to my supervisors, Dr. Caterina Valeo and Dr. Phalguni Mukhopadhyaya, for their constant support, constructive criticism, and advice. I am incredibly grateful to Dr. Phalguni for spending countless hours reviewing my thesis and engaging in conversations about life and future goals. I would also like to extend my heartfelt thanks to Dr. Milad Mahmoodzadeh and Ivan Lee at Morrison Hershfield for their consultation and valuable insights in teaching me about building and construction.

To my family for their prayers and emotional support during difficult times, and to my friends for their companionship, the joy of laughter, deep conversations about life and family, holding me accountable, teaching me more about my faith, and inspiring me to become a better man.

Finally, I would like to express my gratitude to The Holy Family - my Lord and Saviour, Jesus Christ, Mother Mary and St. Joseph, for being my constant source of strength, inspiration and comfort. I would have been lost without them.

1. Introduction

The government of British Columbia launched a CleanBC initiative program in 2018 known as the Net Zero Energy Ready challenge which is committed to reducing greenhouse gas emissions by 16% below 2010 levels by 2025, 40% by 2030, 60% by 2040, and 80% by 2050 [1]. It provides financial support developments targeting net zero energy levels of performances [2]. The province is elevating standards for new constructions, promoting and encouraging energy-saving technological improvements in existing homes, schools, and offices, supporting communities in reducing greenhouse gases, and preparing for the effects of climate change. Every new construction project, whether commercial or residential, requires a permit before project commencement [3]. Those permits depend on the National Building Code (NBC) published by The National Research Council of Canada (NRC), which specifies the minimum building design and established standards. The model building code is the foundation of a national system of regulations, practices, and enforcement [3]. According to a 2021 report by Environment and Climate Change Canada, the building sector accounted for approximately 13% of Canada's total greenhouse gas emissions, including operational and embodied emissions, out of which 9% was contributed by private dwellings alone [4-9]. Since a significant proportion of said emissions come from single-family homes, the Canada Greener Homes Grant offers up to $5,000 in grants to homeowners for energy-efficient upgrades, such as insulation and high-efficiency heating systems [8]. This incentive program helps accelerate the achievement of CleanBC's goal.

The National Building Code (NBC) outlines the minimum requirements for ensuring building safety regarding public health, fire protection, accessibility and structural sufficiency [10]. This code applies to construction, renovation, demolition projects, and change-of-use projects that could result in increased hazards or maintenance and operation in an existing building. One of the key objectives of the NBC is to promote sustainable buildings, while the National Energy Code for Buildings (NECB) promotes energy-efficient buildings, focusing on reducing energy consumption for HVAC systems [10]. To achieve this, the code sets specific thermal resistance (RSI) values for walls, roofs, floors, and thermal transmittance (U) values for doors, windows, and skylights, which are crucial in improving energy efficiency [10]. Initially, the NBC was implemented in its entirety across Canada. However, in 2010, it was realized that the codes needed to be adjusted to account for the varying climate conditions in different provinces called Climate Zones (CZ), as Canada's climate ranges from CZ 4 to CZ 8 [10]. This led to the evolution of the codes, resulting in significant improvements in the operational emissions of buildings.

Insulation materials are directly linked to reducing operational carbon emissions. Choosing these materials with lower embodied emission play a vital role in reducing the overall GWP of the buildings. Such materials can contribute to mitigating climate change by either reducing carbon emissions or storing carbon for extended periods. [11, 12]. The most common building insulation materials are fiberglass, cellulose, and mineral wool insulation [13, 14]. They vary with characteristics such as the materials used to produce, thermal properties, reliability, forms of availability, and costs. Since there is a lack of comparisons of the embodied carbon of these materials in WBLCA, this study attempts to analyze that.

Models with selected locations such as Vancouver, Calgary, and Toronto each representing CZ 4, 5 and 7a respectively, as well as other versions of the NBC guidelines i.e., 1995, 2005, 2010, 2015, 2017 and 2020, are prepared. By doing so, they provide a more comprehensive understanding of the impact of insulation materials on the energy efficiency of buildings and their embodied emissions across different

CZ. This also confirms that NBC versions have improved the energy efficiency of buildings and allowed for a more robust evaluation of the environmental impact of insulation materials and development of more sustainable building practices. This study will also attempt to examine the overall carbon savings of the building by considering those selected insulations and calculating their Carbon Payback Period (CPP).

1.1 Whole-Building Life Cycle Assessment (WBLCA)

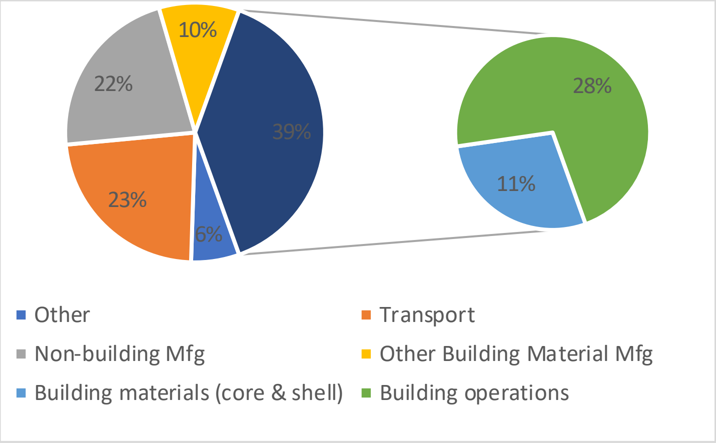


Figure 1: Global CO2 emission by sector in 2021 [15]

A recent article [15] states that despite investment in energy efficiency and lower energy intensity, the building and construction sector's energy consumption and carbon dioxide emissions have reached an all-time high after rebounding from the COVID-19 pandemic. The 2019 Global Status Report (GSR) for Buildings and Constructions finds that the sector accounted for more than 34% of energy demand and approximately 39% of energy and process-related CO_2 emissions in 2021 [15]. In the same year, Canada's construction sector emitted more than 95 million metric tonnes of carbon dioxide (MtCO2) into the atmosphere, dramatically increasing from around 70 MtCO2 in 1990 to nearly 98 MtCO2 in 2021 [16]. Figure 1 displays three major sectors: transportation, building operations, i.e., lighting, plug loads, HVAC, and non-building manufacturing, i.e., extraction, processes, and machinery, contributing to a significant release of emissions. It also shows that the building sector's overall environmental impact increases proportionately to its embodied emissions. To reduce overall emissions, the industry must improve building energy performance, decrease building materials' carbon footprint (in this case insulation materials), multiply policy commitments alongside the action, and increase investment in energy efficiency [17]. Engineers and architects developed a systematic evaluation method known as the LCA. It is a way of compiling and analyzing all the inputs, outputs, and potential environmental impacts of a system or product to help track carbon emissions from a cradle-to-grave perspective. LCA creates a way to help pinpoint which sector or module needs improvement and make projects more sustainable. Therefore, this method can potentially analyze an entire building system by compiling data from all the individual building sectors referred to as Whole Building Life Cycle Assessments (WBLCA) [17].

One of the main aims of LCA is to evaluate various environmental impacts, including global warming potential (GWP), acidification, eutrophication, ozone depletion, smog, and fossil fuel consumption. This is because variables such as raw material sources, supply chain processes, transportation distances, construction practices, building location and climate information are all combined to determine the lifetime carbon footprint of a building. Considering GWP, WBLCA in the project planning phase is crucial to making thoughtful, informative, evaluated decisions for the building. Presently, many designers are specifically focused on measuring and reducing the GWP of their projects, bearing in mind the growing urgency of the climate crises. A set of International European and North American standards governs LCA. Examples from the international standard organization and the European Committee for Standardization include the ISO 14040- Environmental Management: LCA

Principle and Framework [18], ISO 14044- Environmental Management: LCA Requirements and Guidelines [19], EN15643- Sustainability and Construction Works: Sustainability assessments of buildings and civil engineering work [20] and EN15978- Sustainability and Construction Works: Assessments of the environmental performance of buildings- Calculation method [21]. These standards form the backbone of the LCA methodology.

1.2 Embodied and Operational Carbon

Embodied carbon is the carbon dioxide (CO_2) emissions linked to construction processes and materials throughout a structure's whole lifecycle, from cradle to grave. It includes any CO_2 emissions from the extraction of raw materials, transportation to the manufacturer, delivery to the job site, and other construction methods, including using mechanical tools, excavators, etc. Embodied carbon, as it is further defined, is the amount of carbon released throughout the construction phase of a product, structure, or infrastructure project [22]. Operational carbon also includes the carbon dioxide created when a building is being used and maintained, such as for lighting, heating and air conditioning, and when it is eventually torn down, and the waste is transported, dumped, or recycled. As a result, operational carbon is different from embodied carbon.

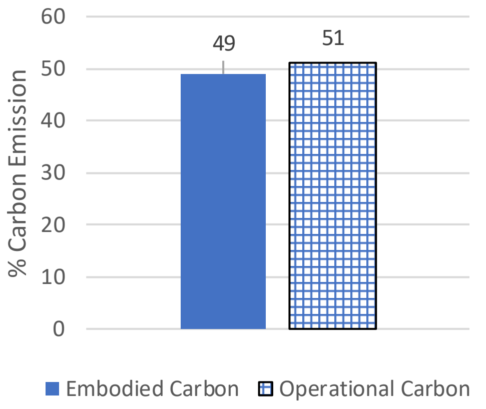


Figure 2: Total Carbon Emissions of Global New Construction from 2020-2050 [24]

As scientists and engineers progress toward reducing operation carbon, recent data from the World Green Building Council [23] show that embodied carbon is growing as a percentage of a building's overall carbon footprint. Figure 2 shows that embodied carbon is expected to account for nearly half of the overall carbon footprint of new constructions between now and 2050 [24]. As shown in Figure 3, compared between operation and embodied carbon, the left-hand side represents the building as-is; essentially a regular building with nothing altered to lower operation carbon, resulting in embodied carbon contributing a small fraction of carbon emissions. However, the high-performing building on the right side of Figure 3 is possible when improvisation and operational carbon reduction are considered.

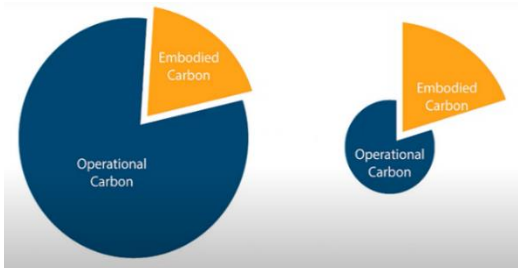


Figure 3: Building as usual (left) and high-performance building (right) [16][23]

1.3 Environmental product declarations (system boundaries)

A thorough report on a product's life cycle is provided through an Environmental Product Declaration (EPD). The EPD offers details about a product's potential to cause global warming, smog formation, water pollution, eutrophication, acidification, and ozone depletion, among other environmental effects. The availability of an EPD for a product means that environmental performance standards still need to be met. Rather, they serve as a disclosure tool that enables buyers and owners to choose products with better knowledge of their environmental impact and sustainable features. The EN15804 code models [25] the effects of construction items over four life-cycle stages:

- The product stage (A1-A3) demonstrates the effects of manufacture and the supply chain from the “cradle to gate”;
- The construction stage (A4-A5) illustrates the effects of transportation and on-site construction;
- The use stage (B1-B7) displaying the impacts of any emissions produced during use, maintenance, anticipated repair or replacement, and any water or energy consumed during its use;
- The end-of-life stage (C1-C4) depicts the effects of deconstruction or demolition, waste transportation for processing, and any processes for recovery or disposal.

Athena Impact Estimator (AIE) uses these stages, allowing users to populate information at every life cycle stage. It begins with producing the building's materials and components, followed by its construction, user operation, and demolition at the end of service life. Some studies also consider the positive effects of reusing and recycling building materials and energy recovery through carbon sequestration, which refers to the loads and benefits that extend beyond the life of the building. The time frame used to evaluate the structure is the reference study period. This time may coincide with the building's required service life or may be established by policy at a different service life [2]. The life of service needed for most structures in North America is typically between 50 and 100 years. This results in the need for a caution administrator to oversee the carbon emissions of a building with a lifespan of more than 30 years.

2. Literature Review

When starting most projects, operational carbon is released annually, and by the conclusion of the building's life cycle, it exceeds embodied carbon. In contrast to the embodied carbon, primarily released during construction, each year's impact is minimal [26]. This indicates that embodied carbon is the primary carbon source during the first few years of a building's existence. This brings up three reasons why embodied carbon in the built environment will be a significant issue during the next ten years. First, by 2030, 74% of total carbon emissions (embodied and operational) from newly constructed projects, as indicated in Figure 4 [26] below, will originate from their embodied carbon and just 26% from their operational carbon. Therefore, lowering embodied carbon must be a principal focus to meet Canada's short-term carbon emission goals (under the Paris Agreement [27], Canada is committed to decreasing emissions by 30% below 2005 levels by 2030).

Secondly, as time passes, the building will accumulate more operational carbon, which will reduce the significance of the embodied energy contribution. To ensure that the operational carbon for new constructions declines steadily, electric networks need to expand their proportion of renewable energies and decarbonize. Thirdly, building standards demand a minimum degree of energy efficiency, meaning new constructions emit less operational carbon than before, and with each code update, the efficiency requirements rise [27]. As a result, new constructions are subject to increasingly tight constraints on operational carbon.

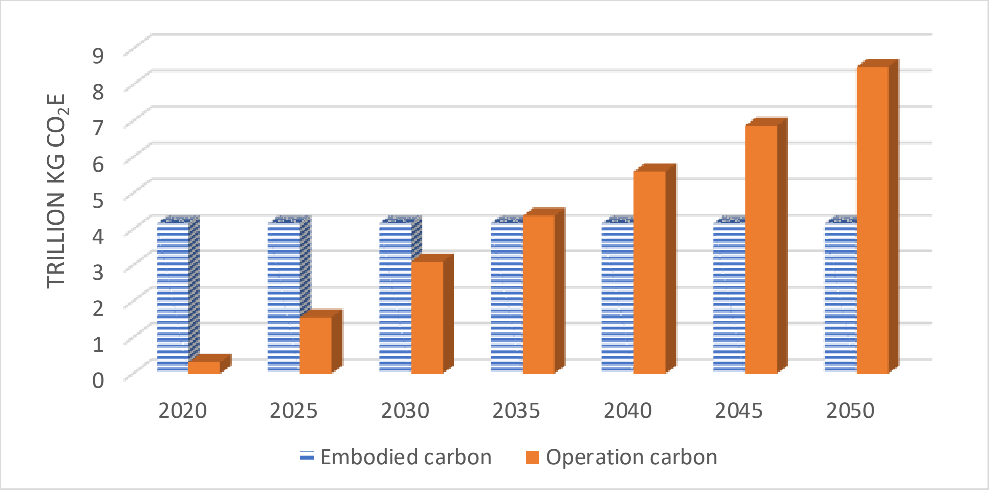


Figure 4: Total Carbon Emissions of Global New Construction from 2020-2050 [26]

In 1987, the Brundtland report [28] on the energy efficiency of a building referred to how well the energy consumption per square meter of floor area compares to established energy consumption benchmarked for that specific type of building under specified climatic conditions. The report revealed that insulation is the simplest and most cost-effective way to reduce carbon emissions by buildings. The report defined sustainability as a continuous economic and social advancement process in both emerging and industrialized countries that satisfies existing needs without jeopardizing the capacity of future generations to meet their own. This brought more attention to studying insulation materials; however, most researchers shifted their focus towards concrete as there were plenty of opportunities to improve. Another paper [33] shows that concrete, insulation and cladding are the three most emission-intensive categories of home-building materials, collectively representing 72% of the measured material carbon emission. Concrete and cement emit 33% more carbon than insulation, 26.1%, in buildings [33]. According to the authors, Rodriguez and Simonen [29] concluded that no standardized methodology is available for building designers after comparing methods regarding WBLCA that comply with the green building rating system (GBRS) [29]. The methods presented are diverse, with various standards serving as primary references. This results in disparities in goals and scope, especially in describing the functional or reference unit and system boundaries.

According to the KPMB study's embodied carbon results, XPS insulation is a clear outlier among popular insulation materials [30]. The emissions from XPS insulation were up to 15-20 times higher than those from other insulation materials. Only one manufacturer's lowest impact new XPS formulation came close to different insulation types, but it still had a longer carbon payback than other forms of insulation. Alternatives to XPS with relatively low embodied carbon, such as mineral wool, are commercially available for similar applications. Blown cellulose had the least embodied carbon among all the insulation materials studied [30].

In another study, Jang and Jeong [31] compared the LCA of marine insulation materials like glass wool, expanded polystyrene, and spray polyurethane foam to accommodate a nautical cargo ship. They evaluated the LCA comparison using GaBi software [32]. They discovered that better time and energy efficiency could be achieved in the distribution and construction stages due to substituting wool-based material with expanded polystyrene. As a result of the study's consideration of both environmental performance and weight, expanded polystyrene was deemed by the authors to be used in the marine industry. It comes with a shock knowing that polyurethane foam had the most significant environmental impact of the three materials; expanded polystyrene and wool-based insulation were regarded as eco-friendly materials with a low environmental impact [31]. Therefore, LCA can accurately pinpoint which system boundary stages can be improved. However, some limitations of the paper [32] are acknowledged, such as the need for more optimization of the thickness of insulation materials or division of the disposal phase in the research.

The Renovation Wave program was launched by the European Green Deal to improve the energy efficiency of buildings and promote sustainable resource usage. Presently, over 30% of buildings in the EU are over 50 years old, and roughly 70% of these buildings are energy-inefficient [34]. The European Commission has estimated that the annual rate of medium energy renovations (30-60% savings) for residential buildings is almost 1% in the EU. In comparison, deep renovations (>60% savings) account for only 0.2% per year [35]. For light renovations (3-30% savings) and below-threshold changes (<3% savings), the renovation levels were 3.9% and 7.1%, respectively. As for non-residential buildings, it is estimated that annual savings of about 4.1%, 3.0%, 2.1%, and 0.3% can be achieved through weighted below-threshold, light, medium, and deep energy renovations, respectively.

Sadowski [38] aimed to present the CPP of different types of thermal insulation for various types of existing external walls of 1 m^2 in area. The study concluded that in certain instances, the CPP can be either very long (especially when heating with partially renewable energy sources like biomass) or very short (for materials with a low carbon footprint or when heating spaces with high-emission electricity). The results for different EU countries can differ due to specific conditions like high non-renewable primary energy factor (PEFn) value and climatic differences. In this study [38], the average CPP for cellulose was less than a year for the selected European countries. The author also added that comparing them is inappropriate due to the transport of materials between countries. Additionally, the study revealed significant gaps in the availability of certain materials to Environmental Product Declarations (EPDs) at the level of selected EU countries, which limits the study and the accuracy of the results. Therefore, it is necessary to analyze available solutions and insulation materials on a case-by-case basis.

These researchers [39-44] performed LCA analyses for single-family houses and residential buildings [45,46]. Results from these studies are progressively being applied in the design phase. For example, Dahlstrøm et al. [41] carried out the LCA of a single-family residence built in conventional and passive house standards. The author concluded that a standard building envelope with a heat pump system reduced environmental impact to a level comparable with a passive house with only electric heating. A comparison of greenhouse gas emissions pointed out that the reduction in the passive design is almost 30% [41]. Another study [47] aimed to assess the environmental impacts of family houses designed as buildings with green technologies and materials. The presented results display that a house with built-in green materials and technologies causes significantly lower environmental impacts compared to a house where both green technologies and conventional materials are built. This is because of green materials and technologies, the operation phase (B6) of the system boundaries presented in WBLCA has more significant environmental impacts than the product and construction phases and the deconstruction phase. With percentage weights of 70% and 96%, the major contributors to GWP expressed as equivalent CO2 emissions are energy (operation) use (B6). Because of the use of natural building materials such as wood and straw, the product phase (A1-A3) reduces CO_2 eq emissions by 11% [48]. These studies did not focus much on insulation materials and their contribution to environmental impact.

Journals and documents dating 2014 onwards, scientists have studied various energy areas, such as energy efficiency, energy performance, energy management, energy saving, and renewable energy sources in sustainable and green buildings by utilizing multiple measures, such as [36], [37], [48], [49], [50], [51], [52] systems mentioned by numerous authors such as [53], [54], [55], [56] technologies, such as [57], [58], [59], [61]; even though research institutions, universities, and governments in developing and developed countries have conducted numerous studies on sustainable development, no systematic review may have aided in the achievement of energy efficiency in sustainable buildings. Recent 2023 published paper, the authors Hafez and Bahaaeddin [60] firmly concluded that the future work pathways would guide future scientists and researchers in adopting systems, strategies, logical methods, analysis techniques, improved software, parameters, and models to overcome the challenges associated with improving building energy efficiency. Most of these challenges are related to a need for knowledge, comprehension, evidence of findings, parameters, natural resources, policies, systems, techniques, methods, and other issues. By addressing these energy efficiency challenges, buildings can achieve sustainability and energy efficiency.

Separate extensive analyses and case studies have examined the carbon footprint of insulation materials [38, 40-42, 62-63] in the literature, including studies analyzing typical partitions and insulation for European countries. Although numerous studies have been carried out on various insulation materials, there needs to be more research regarding comparative analyses considering the Carbon Payback Period (CPP) of insulation materials concerning whole building and at varying location in Canada. Therefore, this study's main objective is to present a carbon footprint analysis of both embodied and operational carbon of the entire building by substituting selected insulation materials in different cities representing different climate zones in Canada. The study will also perform a comparative analysis of different versions of NBC to assess improvements in operational carbon. The CPP will be evaluated for the three most popular selected thermal insulation in three selected climate zones in Canada. This considers the savings of the operational carbon footprint in climate zones with their energy mix comprising electricity and natural gas; heat pump as primary heating source and gas-powered furnace/boilers as secondary. These sources are not individually evaluated to reduce complexities and iterations in computer simulations. This paper aims to assist investors, designers, and contractors in selecting the most favourable insulation materials at varying locations regarding environmental impact.

3. Materials and Methods

3.1 Life Cycle Assessment Framework for Whole Building

The majority of WBLCA studies found in the literature adhere to the traditional process-based LCA approach [64] which is based on four steps established by the International Organization for Standardization (ISO) in ISO 14040 and 14044 [71]. These four steps are as follows:

- Goal and Scope Definition, which defines the objectives and reasons for conducting the study. The scope includes functions, functional units, system boundaries, allocation procedures, data requirements, and limitations.

- The Life Cycle Inventory (LCI) stage collects emission and resource use data from life-cycle databases. This is because LCA results depend on the quality of LCI [72]; this is a comprehensive and critical phase.
- Life Cycle Impact Assessment (LCIA) translates LCI data into quantifiable environmental impacts. The LCIA has three substages: impact category definition, classification, and characterization.
- Interpretation, in which the LCI and LCIA results are interpreted and improved to present meaningful information to decision-makers [73].

The European EN 15978 LCA standard is quickly becoming the industry standard for describing the system boundary of whole-building LCA [67, 68]. The standard defines four life cycle stages: product, construction, use, and end of life, subdivided into 16 substages [20], as shown in Figure 5. The goal and scope definition define the functional unit, system boundaries, and inventory data quality criteria. The system boundary was defined in this study as the process beginning with resource extraction and construction product manufacturing, moving to site preparation and the building construction process (this is also known as the pre-occupancy phase), then to the operating energy and maintenance phase, also known as the occupancy phase, and finally to the building demolition process calling it the post-occupancy phase.

The system boundary for this project is illustrated in Figure 5. When conducting an LCA for residential buildings, it is essential to determine the functional unit. Thermal insulation products use the thermal resistance R, measured in m^2K/W, as a practical and meaningful functional unit [38]. This unit enables the balancing of environmental impacts during production, installation, and disposal with the benefits that can be obtained during the insulation's use phase. This study defines the functional equivalent as the square meter size of residential neighbourhoods with an average lifespan of 60 years for a small family.

This study uses the life cycle inventory analysis (LCIA) to collect and synthesize information on the bill of materials and energy use. The results section contains informed discussions on those analyses. In the life cycle impact assessment, seven impact categories, including the unit used to express them (i.e., category indicators), were chosen: global warming potential (kg CO_2 equivalents [eq]), fossil fuel consumption (MJ), acidification potential (H+ mol eq), eutrophication potential (kg N eq), ozone depletion potential (kg CFC-11 eq), human health and respiratory effects potential (kg PM10 eq), and smog potential (kg NO_x eq). These environmental impact indicators were calculated using the AIE [73], software based on the North America Life Cycle Inventory database (Version 5.4). Finally, the interpretation of the results addresses identifying and evaluating significant results. This LCA was carried out following ISO 14044 guidelines.

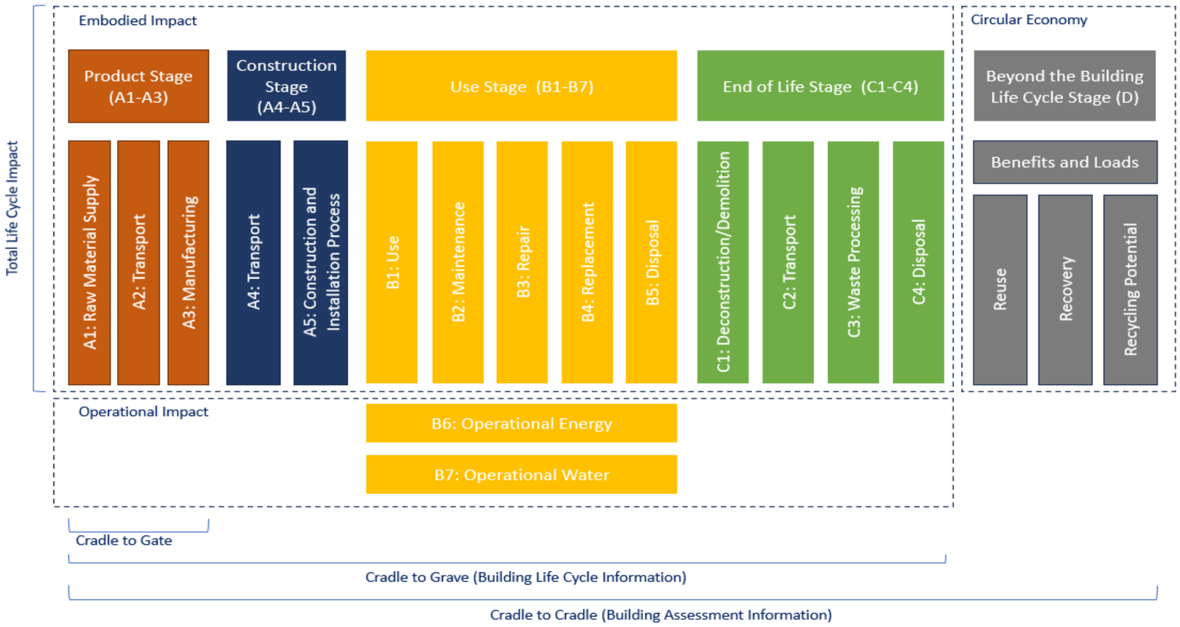


Figure 5: EN 15978 System boundary [20]

3.2 Carbon Payback Period

The Carbon Payback Period (CPP) is the time it takes for carbon storage to equal the amount of carbon released from the initial harvest, accounting for carbon debt and eliminating fossil fuel use [87]. Considering the calculation method from the author Sadowski [38], $CPP_{i,j,k,S}$, which is the payback period for the selected whole building (i), insulated with the material chosen (j), in the selected location (S) and for the heat source chosen (k), can be expressed as:

$$CPP_{i,j,k,S} = \frac{C_{E,j,S}}{C_{O,i,j,s,}}, [years] \qquad \dots\ Eq\ (1)\ \ [38]$$

Where, $C_{E,j,S}$ is the embodied carbon reported as GWP (for the selected insulation material (j) in the chosen location (S)), and $C_{o,i,j,S}$ is the annual operational CO_2 savings (for the whole building (i), insulated with the chosen material (j) in the chosen location (S)). The annual operational CO_2 savings is focused primarily on annual space heating and cooling of the home model. Since insulation does not directly affect lighting, internal loads, and DHW, they are exempted from evaluating for annual operational CO_2 savings. The CPP evaluation assesses and compares various insulation materials installed for the entire building. It clearly indicates how long a particular insulation material needs to be used to achieve significant CO_2 savings in terms of embodied carbon. It also ensures that this period is within the material's life-cycle time. The AIE reports embodied and operational carbon in GWP units and the annual operational CO_2 saving for the whole building can be calculated as follows:

$$C_{O,i,j,s,} = C_{NI.O.i.j.s} - C_{WI.O.i.j.s}\,, \qquad [KgCO_2\,eq] \qquad \dots Eq\ (2)\ [38]$$

Where, $C_{NI.O.i.j.s}$ is the annual operational CO_2 emission of non-insulated walls of a whole building (i), in the selected location (S), and $C_{WI.O.i.j.s}$ is the annual operational CO_2 emissions with insulated whole building (i) insulated with the selected insulation material (j) in the selected location (S).

3.3 Insulation materials

The construction market offers many insulation materials that differ in physical properties, price and availability, and the materials that provide the best performance per unit cost are the most popular. There are also so-called environmentally friendly materials (renewable materials). Taking into account the purpose and scope of the study, the North American Insulation Manufacturing Association (NAIMA) [87] considers Fiberglass, Cellulose and Mineral wool insulation materials to be the most popular on the construction market, and the availability of information on environmental impact in the form of EPD. Table 1 displays the selected materials used in this study along with their basic properties. Table 2 presents the R-value relative to 1-inch thickness for these materials. The study relies on the Environmental Product Declarations (EPDs) of the insulation materials, which are stored in the Athena Impact Estimator (AIE) material library for analysis.

Table 1: Properties of insulation materials [88]

Material	Density (kg/m^3)	Thermal conductivity (W/m K)
Batts Fiberglass	12	0.037
Blown Cellulose	30	0.042
Mineral wool	13	0.039

Table 2: R-value for the 1-inch thickness of insulation [88]

Material	Thickness (Inch)	RSI (m^2 K/W)
Blown Cellulose	1	0.60
Batts Fiberglass	1	0.54
Mineral wool batt	1	0.58

3.4 Small family residential model

The building studied here is a single-family residential building comprising three bedrooms, one living room, and a kitchen; a blueprint is shown below in Figure 6. The total floor area is 248.6 m^2, the total height of the building is 3.1 m, and the foundation of the house is made using concrete and steel rebar materials, which are considered the heaviest parts of the building. The home structure is built of wood materials using 2X6 in. (38x140 mm) wood studs. This home only includes a ground floor. See *Appendix A* for the 3D model of the house designed in Sketchup 2017.

The framework's structural system, including the floors and walls, was constructed mainly from many wood materials. The three cities selected are Vancouver, Calgary and Toronto which represent Climate Zone (CZ) 4, 5 and 7A respectively for different provinces of Canada. Heating Degree Days (HDD) for selected location (S) where the number of the heating degree days with the base temperature equal 18^{0}C in these main cities.: Vancouver- 2768, Toronto- 3559 and Calgary- 4876 [91]. Heating degree days are necessary to track energy use; without it, comparing the energy use over seasons would be challenging. HDD is considered since HOT2000 evaluates only for HDD. See Appendix E to view all the input variables in HOT2000. These cities associated with their climate data are available in the AEI software.

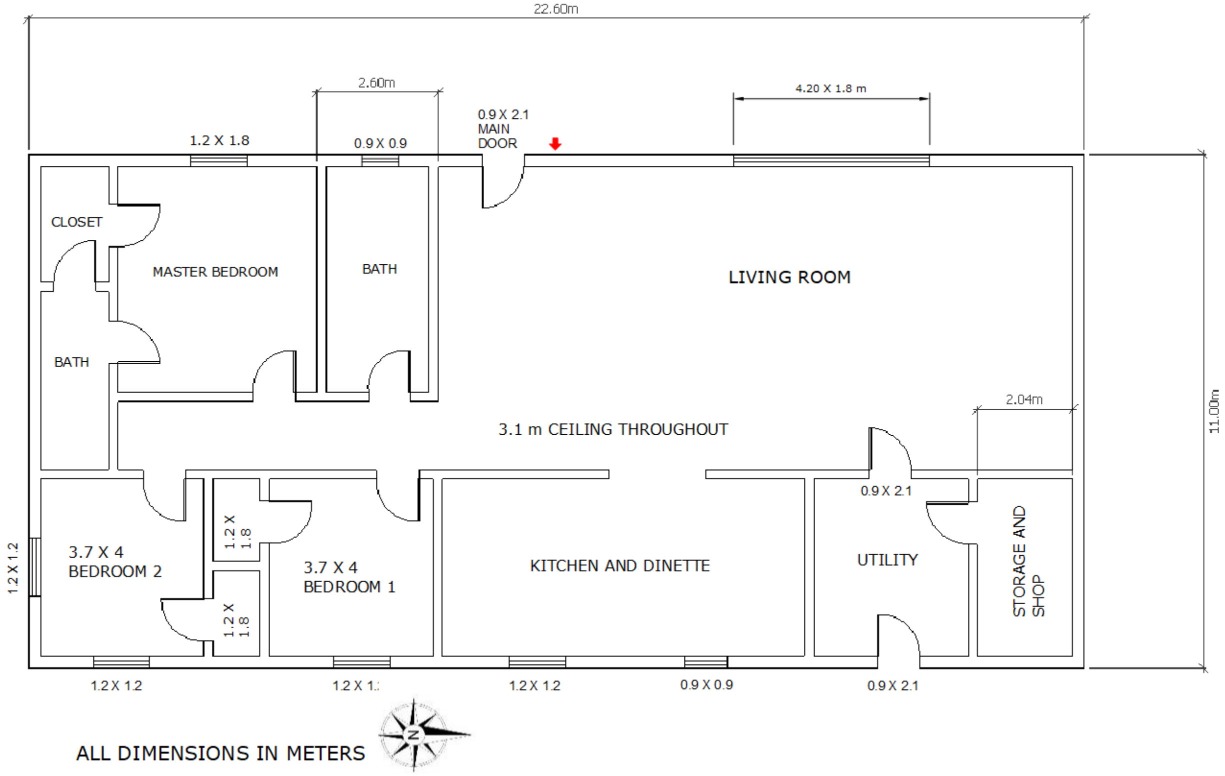


Figure 6: Blueprint of a single-family three-bedroom home (ground floor plan)

According to NBC, this house is considered a part 9 home since the total area of the house is less than 350 sq mt [73]. Part 9 homes are single-family homes constructed using conventional methods in Canada, and these homes are usually smaller in size and are built on individual lots. These homes are built using wood framing, a standard construction method in Canada. Part 9 homes are known for their affordability and ease of construction, making them a popular choice for many Canadian families. The National Building Code of Canada [73] and Canada's Mortgage and House Construction (CMHC) [74]. These resources provide detailed information on the construction and design of Part 9 homes and regulations and guidelines for their development.

The insulation details will involve adaptations of RSI values from the National Building Code 1995, 2005, 2010, 2015, 2017, and 2020. The Athena building estimator [68] application was used in this study to build a home model. HOT2000 [65] will evaluate the thermal transmittance/movement around the build model. The scope of the LCA includes cradle-to-grave analysis of a lifespan of 60 years assumed for the house. The LCA primarily draws on data from the AIE, augmented with the Institute's secondary databases and the materials' Environmental Product Declarations (EPDs) [70].

The system boundary was defined as "cradle to grave," which includes the product (A1-A3), construction (A4-A5), use (B2, B4), and end of life (C1-C4) stages [17]; see Figure 5. System expansion was used to account for the net benefits of material and product reuse and recycling and energy recovery from materials, such as wood incineration, beyond the system boundary (D). Several stages within Module B were excluded from the comparative LCA for this study due to the assumption of a lack of empirical data for repairing and refurbishing single resident buildings, the premise of lack of data available in the Athena Software for evaluation, and the lack of water consumption data. As a result, B1-Use, B3-Repair, B5-Refurbishment, and B7-Operational Water were left out of the analysis. The overall global warming impact of the building LCA is primarily due to operational energy such as electricity and natural gas used during the building's lifetime. The minimum overall RSI (m^2K/W) required for walls, roofs, and ceilings are declared concerning different climate zones in the NBC and deemed mandatory to follow [71]; see Table 3. These RSI values have been refined and tuned over the years, and NBC 2020 is the most updated code available and is followed by contractors, engineers, and architects in Canada.

Table 3: Effective Thermal Resistance of Above-ground Opaque Assemblies in Buildings without a Heat-Recovery Ventilator for different CZs with respective Heating Degree Days (HDD)

Above-ground Opaque building assembly	**Zone 4: <3000**	**Zone 5: 3000 to 3999**	**Zone 6: 4000 to 4999**	**Zone 7A: 5000 to 5999**
	Minimum effective thermal Resistance (RSI), m^2K/W			
Cathedral ceilings and flat roof	4.67	4.67	4.67	5.02
Walls	2.78	3.08	3.08	3.08
Floors over unheated space	4.67	4.67	4.67	5.02

Table 4 below displays collective information on updates and careful refinement of the RSI values in NBC from 1995 to 2020. The RSI values are recorded regarding the minimum ratio of thermal resistance outboard of the material's inner surface to total thermal resistance in the inner surface.

Table 4: Refinement of RSI-values in NBC from 1995 to 2020

	Above-ground opaque building assembly	**Zone 4: <3000**	**Zone 5: 3000 to 3900**	**Zone 6: 4000 to 4999**	**Zone 7A: 5000 to 5999**	**Zone 7B: 6000 to 6999**	**Zone8: >=7000**
		Minimum effective thermal resistance (RSI), m^2K/W					
1995 [75]	Walls	2.64	2.64	2.81	2.81	3.33	3.33
	Roofs	2.64	2.64	2.81	2.81	3.33	3.33
	Floors	2.64	2.64	2.81	2.81	3.33	3.33
2005 [76]	Walls	2.64	2.64	2.81	2.81	3.33	3.33
	Roofs	2.64	2.64	2.81	2.81	3.33	3.33
	Floors	2.64	2.64	2.81	2.81	3.33	3.33
2010 [77]	Walls	2.78	2.78	2.78	2.81	2.81	3.08
	Roofs	4.67	4.67	4.67	5.02	5.02	5.02
	Floors	4.67	4.67	4.67	5.02	5.02	5.02
	Walls	2.78	3.08	3.08	3.08	3.85	3.85

2015 [78]	Roofs	4.67	4.67	4.67	5.02	5.02	5.02
	Floors	4.67	4.67	4.67	5.02	5.02	5.02
2017 [79]	Walls	2.78	3.08	3.08	3.08	3.85	3.85
	Roofs	4.67	4.67	4.67	5.02	5.02	5.02
	Floors	4.67	4.67	4.67	5.02	5.02	5.02
2020 [73]	Walls	2.78	3.08	3.08	3.08	3.85	3.85
	Roofs	4.67	4.67	4.67	5.02	5.02	5.02
	Floors	4.67	4.67	4.67	5.02	5.02	5.02

U-value is the heat transmission rate through an assembly's elements when subjected to temperature variations. In metric units, it is the inverse of thermal resistance, and U equals one divided by the effective RSI value in simple math [82]. The higher the RSI value, the better the assembly's thermal performance. Therefore, RSI values over these 25 years have slightly increased, as seen in Table 4. In addition to changes in RSI values presented to walls, roofs and floors, the NBC also depicts visible and documented changes to U-values for windows, doors and skylights. Tables 5 and 6 exhibit those values between NBC 1995 to 2020.

Table 5: RSI-values for Doors and fenestrations between NBC 1995 to 2020

NBC	**Zone 4 < 3000**	**Zone 5 3000 to 3999**	**Zone 6 4000 to 4999**	**Zone 7A 5000 to 5999**	**Zone 7B 6000 to 6999**	**Zone 7B 6000 to 6999**
	Minimum effective thermal resistance (RSI), m^2K/W					
2020	0.54	0.54	0.62	0.62	0.69	0.69
2017	0.56	0.56	0.62	0.62	0.69	0.69
2015	0.56	0.56	0.62	0.62	0.69	0.69
2010	0.56	0.56	0.62	0.62	0.69	0.69
2005	0.5	0.5	0.5	0.5	0.5	0.5
1995	0.5	0.5	0.5	0.5	0.5	0.5

Table 6: RSI-values for Skylights between NBC 1995 to 2020

NBC	**Zone 4 < 3000**	**Zone 5 3000 to 3999**	**Zone 6 4000 to 4999**	**Zone 7A 5000 to 5999**	**Zone 7B 6000 to 6999**	**Zone 7B 6000 to 6999**
	Minimum effective thermal resistance (RSI), m^2K/W					
2020	0.34	0.34	0.36	0.36	0.41	0.41
2017	0.34	0.34	0.36	0.36	0.41	0.41
2015	0.34	0.34	0.36	0.36	0.41	0.41
2010	0.34	0.34	0.36	0.36	0.41	0.41
2005	0.32	0.32	0.32	0.32	0.32	0.32
1995	0.32	0.32	0.32	0.32	0.32	0.32

3.5 Inputs for walls

Each wall in Figure 5 is labelled, and details are entered into the estimator. The east wall (bottom of Figure 5) has four windows and one door. The southern wall contains a 1.2x1.2 m window, while the western wall contains three windows and one door (backdoor of the house). The northern wall has no doors or windows. With plywood sheathing, a 2x6 inches (38x140 mm) wood stud with stud spacing of 400 on-center (oc.) is used. In this case, the load-bearing type is chosen as the wall type. The estimator is fed the following inputs for Table 7. In Athena, the standard door size is 32"x84" (0.813x2.13 m) [69]. Table 8 displays all the layers of the walls fed into the estimator for climate zone 4. All the information in Table 4 was taken from NBC 2020 [71] because the study will focus on the latest version of the building code for calculating CPP. The minimum door jamb width required for walls constructed with 2x6” studs is 6.5 inches. This considers 2x6” width: 5.5" and wall surface thickness on each side: 0.5".

Table 7: Inputs applied for windows and doors for walls for Vancouver (CZ 4) and Toronto (CZ 5)

East wall	**Frame**	**Glazing type**	**No.**	**Total window area (m^2)**
Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	4	5.13
	Door type	**Standard size**		
Doors	Solid wood door	32” x 84” or 2.67 x7 ft	1	
South wall	**Frame**	**Glazing type**	**No.**	**Total window area m^2**
Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	1	1.44
	Door type	**Standard size**		
Doors	Solid wood door	32” x 84” or 2.67 x7 ft	0	
West wall	**Frame**	**Glazing type**	**No.**	**Total window area m^2**
Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	3	7.29
	Door type	**Standard size**		
Doors	Solid wood door	32” x 84” or 2.67 x7 ft	1	
North wall	**Frame**	**Glazing type**	**No.**	**Total window area m^2**

Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	0	0
	Door type	**Standard size**		
Doors	Solid wood door	32” x 84” or 2.67 x7 ft	0	

Note: Triple glazing pane, low-E 0.04 (soft) with argon, is used for location Calgary (CZ 7A) as per minimum NBC 2020 requirements for windows and skylights [73].

Table 8: Layers of the wall fed in the estimator for climate zone 4 [71]

Wall Envelope parts		**Thickness (mm)**	**R-value**
	Exterior air		0.17
Exterior Insulation*		-	-
Cladding	Vinyl Sliding	-	0.62
Gypsum Board	Gypsum regular 1/2"	12.7	0
Insulation /2*6 studs with 400oc (on-center)	Blown Cellulose/ Batts Fiberglass/ Mineral Wool	140	13.51
Paint	Latex water-based	-	0
Vapor and Air Barrier	Polyethylene 6 mil	6	0
Gypsum board	Gypsum regular 1/2"	12.7	0.45
	Interior air		0.68
Total		**171.45**	**16.04**
*Note: To follow the code for climate zones 5 and above, exterior insulation must be added beside the cladding.			

Batts Fiberglass is the most popular interior insulation for walls in Canada [82] as it is significantly cost-effective. The most popular exterior insulation is Expanded Polystyrene (EPS) foam board; however, it has a slightly higher embodied carbon [83]. After a succinct evaluation of available external insulations in the Athena materials library, the Polyisocyanurate foam board had the lowest embodied carbon (See *Appendix B*).

3.6 Inputs for Floors and Foundation

The description of the proposed building floor can be viewed in Table 8 with XPS insulation. The ground floor consists of about 4 inches (101.6mm) of gravel placed to facilitate drainage underneath the slab acting as a capillary break. Lengths of extruded polystyrene (XPS) are placed on the interior perimeter of the stem wall (to act as insulation material and provide thermal break) as well as on top of the gravel bed, followed by a six-mil polyethylene vapor barrier. Rebars are then aligned and placed above the prepared bed, and the concrete mixture, i.e., slab, is poured. Plywood decking and interior finish board are laid down, completing the house's ground floor. The RSI value for interior air (0.16 m^2K/W) is, by default, considered in the Athena Impact Estimator. It's important to note that XPS will remain constant for floor insulation throughout the computer simulations as the focus remains on wall insulation alone.

Table 9: Layers of the ground floor and foundation with XPS insulation for CZ 4, CZ 5 and CZ 7A [73]

Floor Envelope layers	Thickness mm	RSI (m^2K)/W	R-value
Gravel [71]	101.6	0.02	0.1
Insulations XPS R30 [71]	152	5.28	30.13
6 mil polyethylene Vapor barrier	6		0
Concrete foundation with rebar	101.6	0.04	0.23
Interior finish plank (hardwood) board [71]	12	0.07	0.37
Interior air		0.16	0.91
Total	**373.2**	**5.47**	**31.74**

3.7 Inputs for Roofs

A joist on the roof is required to preserve the structural integrity of the framework of the house, followed by attaching gypsum boards underneath the joist. The vapor barrier is installed on top, followed by adding Polyiso insulation. Insulation here is installed above the joist. A 4-Ply modified bitumen roofing system allows each ply to be embedded in a packed bed of hot bitumen. The roofing membrane completely adheres to the underlayment, typically including a vapor barrier and Polyiso insulation. These two felt layers and modified bitumen are laminated together as roof envelopes. Finally, the roofing asphalt protects the bitumen from the sun's ultraviolet light and erosion caused by harsher nature, such as wind, snow, hail, and rain. These have been depicted in Table 10 below. The AIE considers the RSI of interior and exterior air of value 0.11 and 0.03 m^2K/W, respectively. It is important to note that Polyiso will remain constant for roof insulation throughout the computer simulations.

Table 10: Layers of the roof with Polyiso insulation for CZ 4, CZ 5 and CZ 7A [73]

Roof envelope layers	Thickness (mm)	RSI (m^2K)/W	R-value
Exterior air		0.03	0.17
2 Ply Mod Bitumen standard –roof envelope	7	-	-
Asphalt (protective) board	12.7	0.08	0.44
Insulations Poyiso foam board R30	120	5.33	30.25
Gypsum sheathing	12.7	0.11	0.62
Joists/studs (241.3 mm * 0.0085 RSI/mm)	241.3	0.22	1.26
Polyethylene vapor barrier	6		0
Gypsum board	12.7	0.08	0.45
Interior air		0.11	0.63
Total	**412.4**	**5.96**	**33.8**

3.8 HOT2000 energy simulator tool

The building model evaluation tool, known as HOT2000, considers various inputs, such as climate and weather, temperatures, energy sources, ventilations, and baseloads, to determine the total operational energy of a building. The report highlights the significant cost savings achieved by adopting the 2020 National Building Code (NBC). The yearly cost structure is based on data borrowed from HOT2000 energy modelling software and evaluated using the “Ottawa08” fuel cost library. The software makes calculations based on the entered data and assumptions, considering factors such as construction practices, localized weather, equipment characteristics, and the occupants' lifestyle.

The modelled house includes a washer (197 kWh/yr), dryer (916 kWh/yr), range hood (565 kWh/yr), refrigerator (639 kWh/yr), dishwasher (260 kWh/yr) and three-bathroom exhaust fans (3.5 kWh/yr each). The whole house system has a forced air heating ductwork that circulates air for 8 hours daily with a fan power of approximately 100 W. The primary space-heating fuel is a 7kW capacity heat pump operating at 8.3^{0}C. In contrast, the secondary heating fuel is natural gas for the furnace/boiler and domestic hot water heating system, with a 7.5kW output capacity and a tank capacity of 188.4 L. Finally, the air conditioning system is integrated with the heating system and is a central split system.

3.9 Limitations of the Study

This paper limits on cost impacts and analysis of the overall building and operational savings. Heat pumps and gas-fired furnaces as mechanical systems are considered to simulate energy use annually to calculate operational carbon and savings, but a deeper study on how each mechanical system affects the operation use is out of scope. The study covers only the issues related to calculating the CPP for a given insulation material used in the chosen location. Considering insulation on the roofs and floors would increase the simulation matrix, making it complex and time-consuming; hence, the authors of this study agreed to include it in the list of future works. This also applies limiting to three climate zones represented by three cities.

When analyzing specific insulating materials, it is important to consider the possibility of insulating partitions from the inside. This is a technically complex issue that shall be added to future works. Factors limiting this study include the impact of internal and solar heat gains on energy losses, the orientation of the partition, exposure to external conditions, the method of installing insulation on walls, the presence of thermal bridges, and the use of specific finishing materials. These factors mean that actual heat losses may differ from the presented results. The author, however, omitted the impact of these factors, focusing on reducing additional parameters to make the results clearer and less complex to strip apart. It should be noted that the actual CPP, taking into account these additional factors, may differ slightly. Additionally, due to the abundance of information available on sustainability-rating methods for all types of homes, including small residential homes, investigating these rating systems is beyond the scope of this study.

4. Results

After closely observing Table 4, the RSI values of walls, roofs and floors for 1995 and 2005 are the same, even across zones 4 to 8. From 2010 onwards, these values have been incremented slightly. What stands out is that the RSI values for the walls from 2010 to 2015 in Climate Zones (CZ) 7A to 8 increased slightly and remained constant from 2015 onwards. Figure 7 depicts a detailed WBLCA GWP, i.e., the graph's y-axis, from cradle to grave of the house i.e., a life span of 60 years, with the earlier revealed designs. Notice that the GWP for the construction process, use, and end of life remains constant as they are a part of the embodied carbon of the building. However, the GWP of the product bars rose from 2010 and remained flat. This is due to the increase of insulation in the building walls, floors and roofs which will raise the RSI value instructed in NBC. Adding more insulation resulted in increase in embodied carbon. Furthermore, notice that the overall WBLCA operational carbon for CZ 7A (Calgary) is at a 16.49% decrease, while a rise of 7.38% in embodied carbon is noted with the updation of NBC. It's clear from Figure 7 that building codes neglect embodied carbon in the focus on improving operational carbon. The embodied and operational carbon ratio for Calgary as of the NBC 2020 result is 0.07.

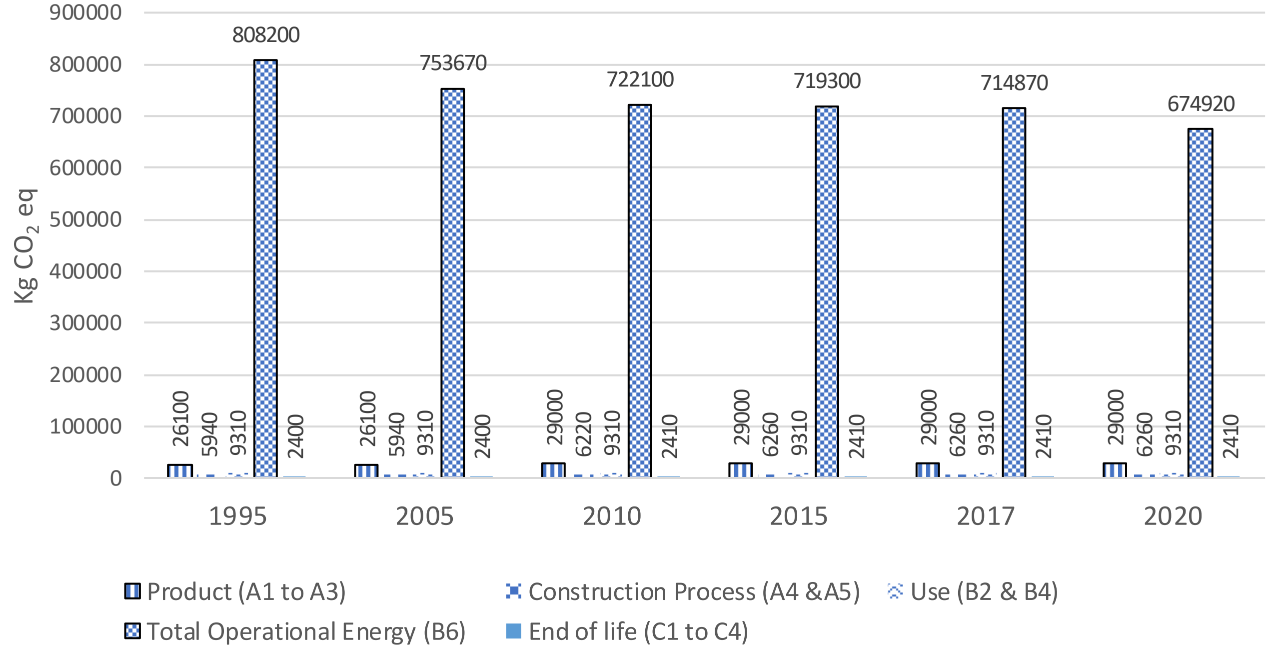


Figure 7: Comparison of Global Warming Potential by Life Cycle Stages regard with different NBC editions for Calgary location

Overall WBLCA operational carbon for CZ 4 (Vancouver) and CZ 5 (Toronto), shown in Figures 8 and 9, decreased by 21.87% and 19.53%, respectively, when compared between NBC 1995 and 2020. The operational carbon in Figures 8 and 9 abruptly reduced in 2010 and continued to decline smoothly.

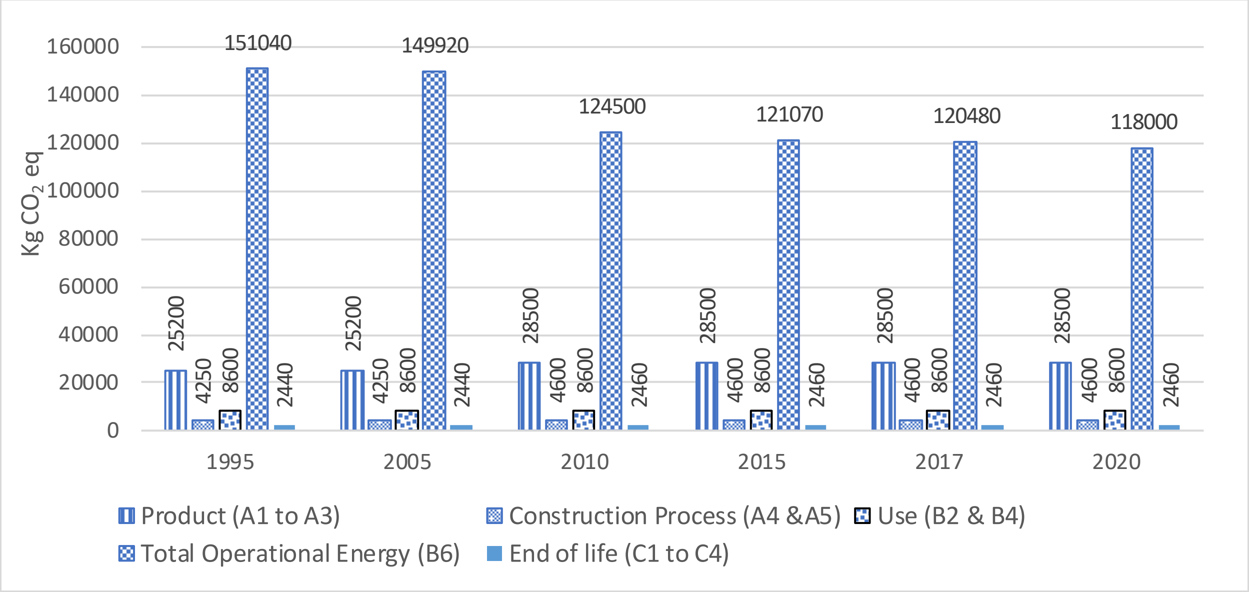


Figure 8: Comparison of Global Warming Potential by Life Cycle Stages regard with different NBC editions for Vancouver location

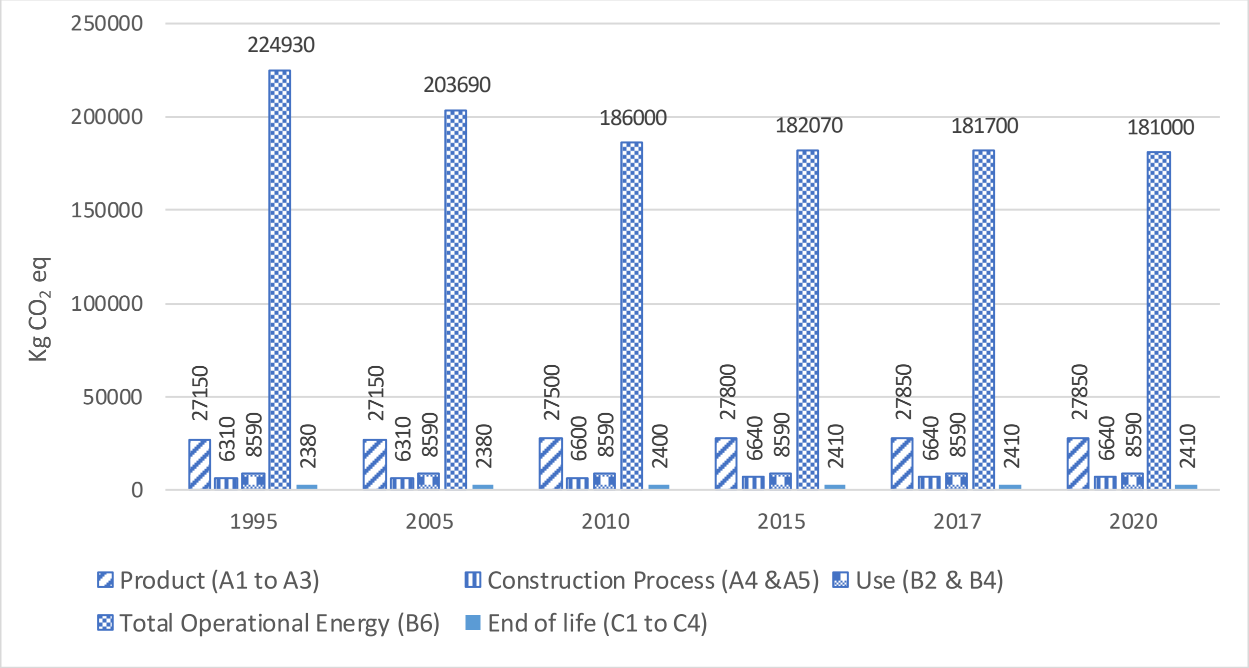


Figure 9: Comparison of Global Warming Potential by Life Cycle Stages regard with different NBC editions for the Toronto location

Similarly, assessing the oldest and latest codes, the embodied carbon increased by 9.06% and 2.5%, respectively, observed for Vancouver and Toronto. Comparing the two cities would be inappropriate due to Toronto's vast geographic area. Factors such as extraction, transportation, production, construction process, and more dramatically affect embodied carbon evaluation. The information based on those factors is inherently coded into the AEI library to ease the simulation process. The ratio of embodied carbon to operational carbon NBC2020 results for Vancouver and Toronto are 0.37 and 0.25 respectively. The results also show that Blown Cellulose had the lowest GWP embodied carbon 3130 $kgCO_2$ eq followed by Batts Fiberglass with 3200 $kgCO_2$ eq and lastly Mineral wool, 3820 $kgCO_2$ eq, for Calgary. Similarly, Blown Cellulose had the lowest GWP embodied carbon 3070 $kgCO_2$ eq followed by Batts Fiberglass with 3130 $kgCO_2$ eq and lastly Mineral wool, 3730 $kgCO_2$ eq, for Toronto. For Vancouver, the insulation with lower embodied carbon was found to be Blown Cellulose once again at 3090 $KgCO_2$ eq followed by Batts Fiberglass with 3100 $kgCO_2$ eq and Mineral wool with 3190 $kgCO_2$ eq.

According to NBC 2020, based on the studs selected to model the house, Vancouver does not require external insulation as it satisfies the NBC requirement by adding wall insulation alone. However, external insulation must be added to the model for the Toronto and Calgary locations. To choose the best external insulation for Calgary and Toronto, a comparison of embodied carbon was performed, which can be found in *Appendix B*. Polyiso foam board external insulation was concluded to be better than XPS and EPS foam board.

Figures 10-12 depict Vancouver, Toronto, and Calgary's estimated annual fuel consumption, including electricity and natural gas. These figures show a gradual decrease in energy consumption for space heating and cooling. This is because the RSI value of insulation for walls, roofs, floors, doors, skylights, and windows has increased over the years due to evolving codes. Additionally, they compare the total fuel consumed by the building when modeled according to NBC codes from 1995 to 2020.

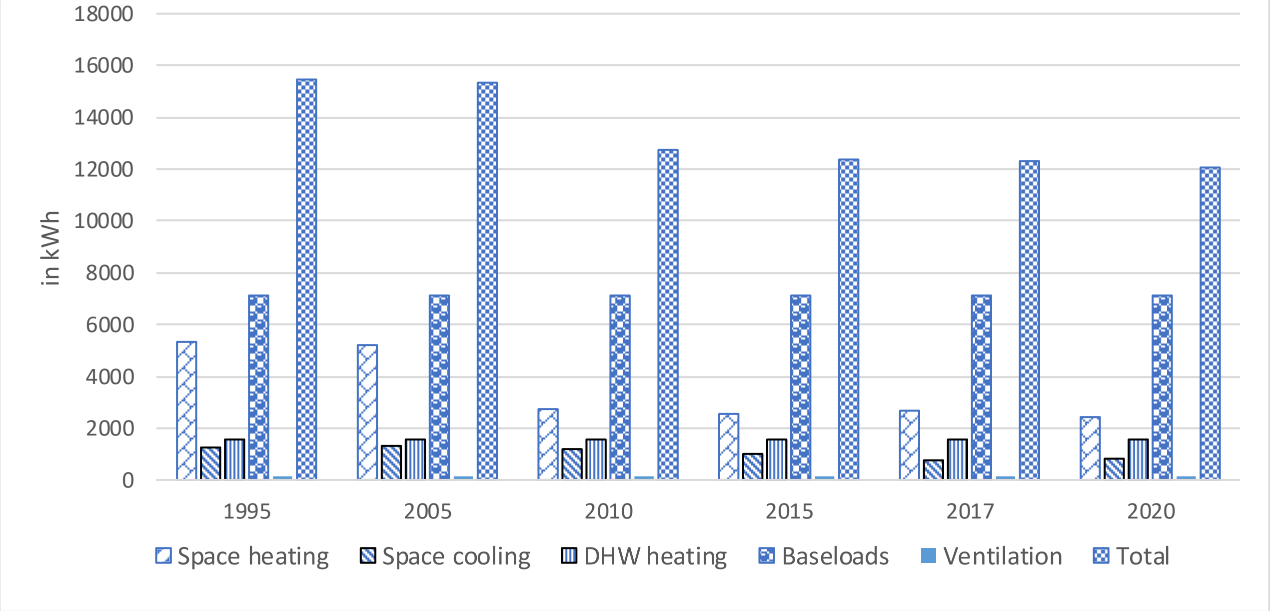


Figure 10: Estimated Annual Fuel Consumption Summary (Electricity as fuel in kWh) for location Vancouver

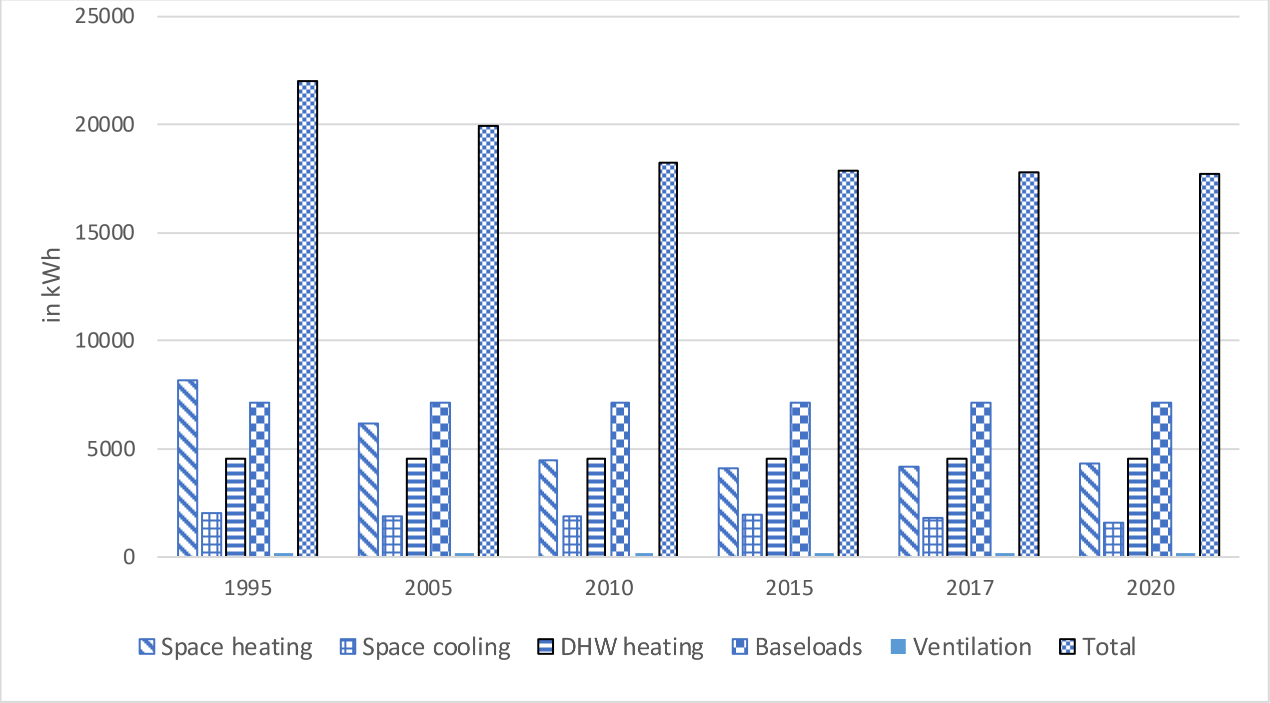


Figure 11: Estimated Annual Fuel Consumption Summary (Electricity as fuel only in kWh) for location Toronto

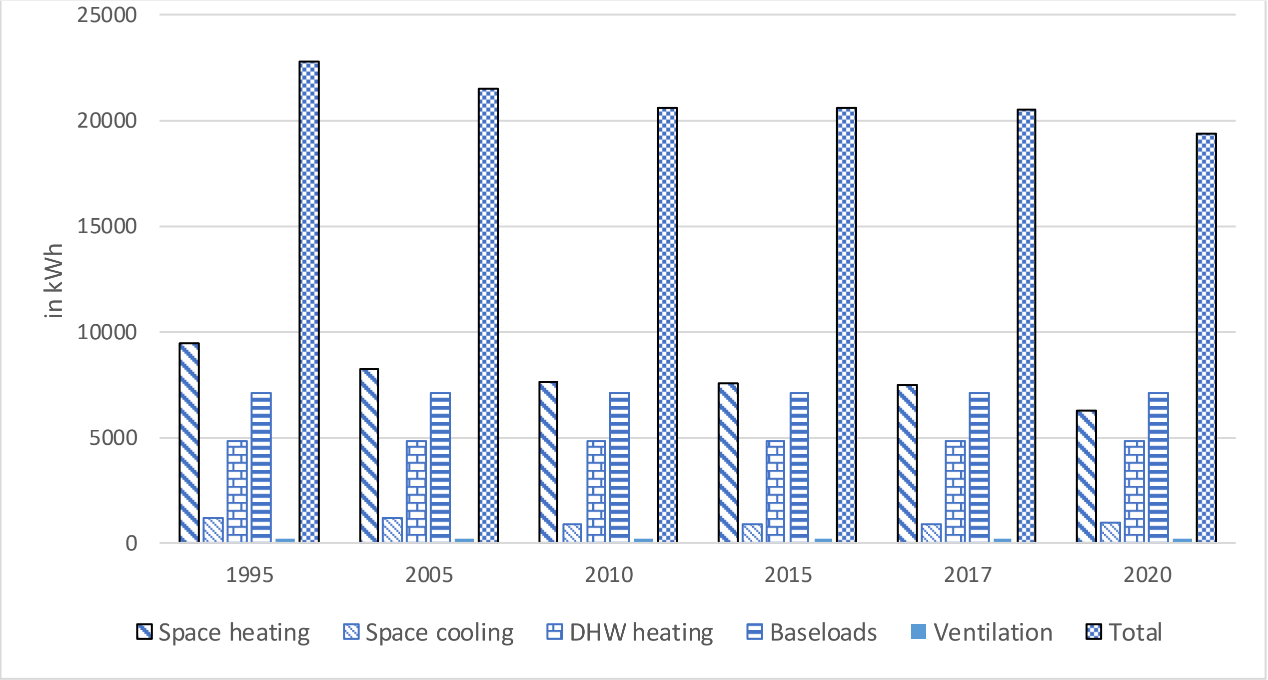


Figure 12: Estimated Annual Fuel Consumption Summary (Electricity as fuel only in kWh) for location Calgary

Table 11: Estimated annual fuel consumption Summary with Electricity and natural gas as fuel

Insulation	**Location** (Wall R-Value) (Roof R-Value) (Floor R-Value)	**Fuel**	**Space heating**	**Space cooling**	**DHW heating**	**Baseloads**	**Ventilation**	**Total**	**Annual costs $$$**
Fiberglass	**Vancouver** (R- 16.93) (R- 30.22) (R- 28.77)	Electricity kWh	2402.9	1135.1	0	7117.4	168.9	10514.3	1437.51
		Natural gas m^3	1.2	0	628.8	0	0	630.1	
	Toronto (R- 19.62) (R- 33.81) (R- 31.74)	Electricity kWh	3290	1666.1	0	7117.4	168.9	12242.3	1653.11
		Natural gas m^3	131.9	0	653.9	0	0	785.8	
	Calgary (R- 19.62) (R- 33.81) (R- 31.74)	Electricity kWh	3184.5	1026.5	0	7117.4	168.9	11497.3	1749.97
		Natural gas m^3	379.6	0	690.7	0	0	1070.4	
Blown Cellulose	**Vancouver** (R- 16.74) (R- 30.22) (R- 28.77)	Electricity kWh	1556.2	1143.5	0	7117.4	168.9	9986	1419.48
		Natural gas m^3	1.1	0	628.8	0	0	629.9	
	Toronto (R- 18.94) (R- 33.81) (R- 31.74)	Electricity kWh	3170.4	2007.6	0	7117.4	168.9	12164.3	1596.18
		Natural gas m^3	129.1	0	653.9	0	0	745	
	Calgary (R- 18.94) (R- 33.81) (R- 31.74)	Electricity kWh	3164.7	935	0	7117.4	168.9	11386	1695.32
		Natural gas m^3	289.9	0	690.7	0	0	980.7	
Mineral Wool	**Vancouver** (R- 16.87) (R- 30.22) (R- 28.77)	Electricity kWh	1353.6	1475.5	0	7117.4	168.9	10115.4	1422.81
		Natural gas m^3	1.2	0	628.8	0	0	629.8	
	Toronto (R- 19.58) (R- 33.81) (R- 31.74)	Electricity kWh	3070.6	1990.4	0	7117.4	168.9	12347.3	1646.62
		Natural gas m^3	105.5	0	653.9	0	0	759.4	
	Calgary (R- 19.58) (R- 33.81) (R- 31.74)	Electricity kWh	3228.5	914.9	0	7117.4	168.9	11429.7	1715.88
		Natural gas m^3	323.4	0	690.7	0	0	1014.1	
No Insulation	**Vancouver**	Electricity kWh	2992.9	1216.2	0	7117.4	168.9	11495.4	2898.69
		Natural gas m^3	2110.4	0	629.7	0	0	2740.1	

	Toronto	Electricity kWh	4483.6	2496.3	0	7117.4	168.9	14266.2	4403.99
		Natural gas m^3	5149.1	0	654.1	0	0	5803.2	
	Calgary	Electricity kWh	5558.2	1229.6	0	7117.4	168.9	14074.1	5566.88
		Natural gas m^3	7375.1	0	690.9	0	0	8066	

Note: "No insulation" means a home with no insulation. The reason is to evaluate the annual operational carbon savings for whole buildings with and without insulation and then proceed to calculate the savings contributed by wall insulation alone.

Table 12: Comprehensive calculation for selected thermal insulation materials for selected cities for the whole building including roof and floor insulations

Calgary (CZ 7A)

	Wall insulation with roof (Polyiso) and Floor (XPS) insulation	**A. Embodied carbon without insulation (KgCO$_2$ eq)**	**B. Embodied carbon (EC) with insulation (KgCO$_2$ eq)**	**C. Embodied carbon (EC) of insulation invested (KgCO$_2$ eq)**	**D. Total operational carbon without insulation for 60 years (kgCO$_2$ eq)**	**E. Total operational carbon with insulation for 60 years (kgCO$_2$ eq)**	**F. Annual space heating and cooling (SHC) without insulation (KgCO$_2$ eq)**	**G. Annual space heating and cooling (SHC) with insulation (KgCO$_2$ eq)**	**H. Annual space heating and cooling (SHC) savings (kgCO$_2$ eq)**	***I. CPP = C. / H (years)**	**J. SHC savings for remaining years (KgCO$_2$ eq)**	**K. Total Annual SHC savings 60 years (with insulation) (KgCO$_2$ eq)**	**L. Total Annual SHC savings 60 years (without) insulation) (KgCO$_2$ eq)**	**M. Percentage SHC saved %**	**N. Percentage operational carbon saved %**
	Blown Cellulose	33820	48910	15090	998000	809000	18698.2	1558.67	17139.53	0.88	1013281.8	1028371.8	1121892.0	91.66	18.94
	Fiberglass	33820	48900	15080	998000	819000	18698.2	1562.91	17135.29	0.88	1013037.4	1028117.4	1121892.0	91.64	17.94
	Mineral Wool	33820	50030	16210	998000	817000	18698.2	1617.47	17080.73	0.95	1008633.8	1024843.8	1121892.0	91.35	18.14

Note: Values in columns A, B and D - G were taken from HOT2000 v11.10b and Athena v5.4.0103

$C = B - A$

$H = F - G$

*I (carbon payback period) = Embodied Carbon invested / Annual SHC (KgCO$_2$ eq), SHC is calculated by adding the values in kWh. Converting m^3 to kWh

$J = H * (60 - I)$

$K = J + C$

L = Annual space heating and cooling (SHC) without insulation in KgCO$_2$ eq * 60 years [Annual SHC (kgCO$_2$eq) for Calgary = 18698.20, Toronto = 14736.54 and Vancouver = 6497.62]

$M = 100 - (L - K)/L * 100$, $N = (D - E)/D * 100$

Toronto (CZ 5)															
	Wall insulation	**A. Embodied carbon without insulation (KgCO_2 eq)**	**B. Embodied carbon (EC) with insulation (KgCO_2 eq)**	**C. Embodied carbon (EC) of insulation invested (KgCO_2 eq)**	**D. Total operational carbon without insulation for 60 years (KgCO_2 eq)**	**E. Total operational carbon with insulation for 60 years (kgCO_2 eq)**	**F. Annual space heating and cooling (SHC) without insulation (KgCO_2 eq)**	**G. Annual space heating and cooling (SHC) with insulation (KgCO_2 eq)**	**H. Annual space heating and cooling (SHC) savings (KgCO_2 eq)**	***I. CPP = C. / H (years)**	**J. SHC savings for remaining years (KgCO_2 eq)**	**K. Total Annual SHC savings 60 years (with insulation) (KgCO_2 eq)**	**L. Total Annual SHC savings 60 years (without) insulation) (KgCO_2 eq)**	**M. Percentage SHC saved %**	**N. Percentage operational carbon saved %**
	Blown Cellulose	33100	45970	12870	245000	181000	14736.54	1352.01	13384.53	0.96	790201.8	803071.8	884192.4	90.83	26.12
	Fiberglass	33100	45940	12840	245000	182000	14736.54	1365.44	13371.10	0.96	789426.0	802266.0	884192.4	90.73	25.71
	Mineral Wool	33100	47340	14240	245000	184000	14736.54	1325.64	13410.90	1.06	790414.0	804654.0	884192.4	91.00	24.90

Vancouver (CZ 4)															
	Wall insulation	**A. Embodied carbon without insulation (KgCO_2 eq)**	**B. Embodied carbon (EC) with insulation (KgCO_2 eq)**	**C. Embodied carbon (EC) of insulation invested (KgCO_2 eq)**	**D. Total operational carbon without insulation for 60 years (kgCO_2 eq)**	**E. Total operational carbon with insulation for 60 years (kgCO_2 eq)**	**F. Annual space heating and cooling (SHC) without insulation (KgCO_2 eq)**	**G. Annual space heating and cooling (SHC) with insulation (KgCO_2 eq)**	**H. Annual space heating and cooling (SHC) savings (kgCO_2 eq)**	***I. CPP = C. / H (years)**	**J. SHC savings for remaining years (KgCO_2 eq)**	**K. Total Annual SHC savings 60 years (with insulation) (KgCO_2 eq)**	**L. Total Annual SHC savings 60 years (without) insulation) (KgCO_2 eq)**	**M. Percentage SHC saved %**	**N. Percentage operational carbon saved %**
	Blown Cellulose	31240	44600	13360	230000	152000	6497.62	645.58	5852.04	2.28	337762.4	351122.4	389857.2	90.06	33.91
	Fiberglass	31240	44560	13320	230000	155000	6497.62	688.25	5809.37	2.29	335242.2	348562.2	389857.2	89.41	32.61
	Mineral Wool	31240	45890	14650	230000	157000	6497.62	602.84	5894.78	2.49	339036.8	353686.8	389857.2	90.72	31.74

The comparison reveals that implementing the 2020 building code results in an average energy saving of 25% for the entire building, primarily consuming less energy for space heating and cooling (SHC). Therefore, for evaluating the CPP of selected thermal insulation in selected climate zones, NBC 2020 will be considered. Table 11 comprehensively summarizes fuel sources, i.e., electricity and natural gas, and insulation materials for different locations. Insulation use directly affects the SHC with heat pumps as the primary and furnace/boilers as secondary sources. In analyzing annual fuel consumption costs, Batts Fiberglass insulation employed at home in Vancouver had low yearly energy costs, while Blown Cellulose employed at home in Toronto and Calgary resulted in low annual energy costs.

Table 12 thoroughly evaluates three wall insulation options, complete with data on embodied carbon invested and operational carbon savings (in $kgCO_2$ eq units) for SHC. The results from Table 11 show that insulation mainly affects SHC over domestic hot water, baseloads, and ventilation. Hence, the authors focused on calculating CPP based only on SHC. The findings indicate that all three selected wall insulations with roof and floor insulation options offer significant annual savings for space heating and cooling (SHC). With overall (including roof and floor) insulation of the building, one having blown Cellulose offers a rating of 91.66%, 90.83% and 90.06% for Calgary, Toronto and Vancouver respectively, with Batts Fiberglass of 91.64%, 90.73% and 89.49% for Calgary, Toronto and Vancouver respectively and Mineral Wool, 91.35%, 91% and 90.72% for the same respectively. The natural gas usage mainly for space heating and domestic hot water (DHW) heating is presented in Figure 13. Electricity is consumed primarily in SHC, as depicted in Figure 14. Both these figures compare using different insulations at given locations. For calculating the CPP, the m^3 units of natural gas are converted to kWh. The CPP of all insulations in the model that involves Blown Cellulose was found to be 0.88, 0.96 and 2.28 years for Calgary, Toronto and Vancouver respectively. Similarly, the CPP of all insulations in the model that involves Batts Fiberglass was 0.88, 0.96 and 2.29 years for Calgary, Toronto and Vancouver respectively. The CPP of all insulations in the model that involves Mineral Wool insulation was 0.95, 1.06 and 2.49 years for Calgary, Toronto, and Vancouver respectively.

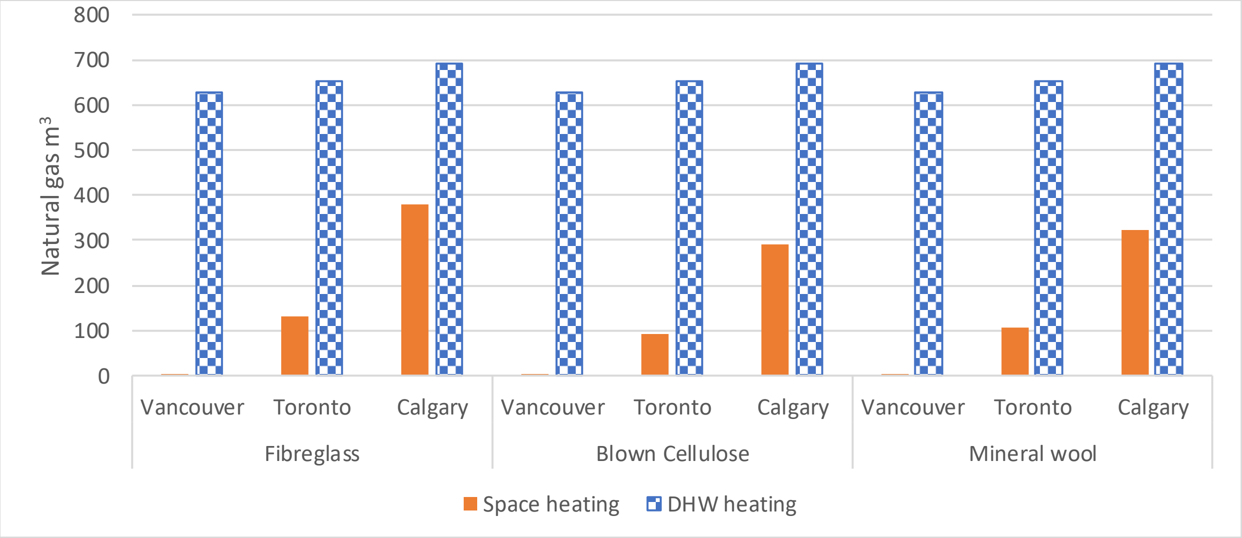


Figure 13: Natural gas usage for different insulation at different locations

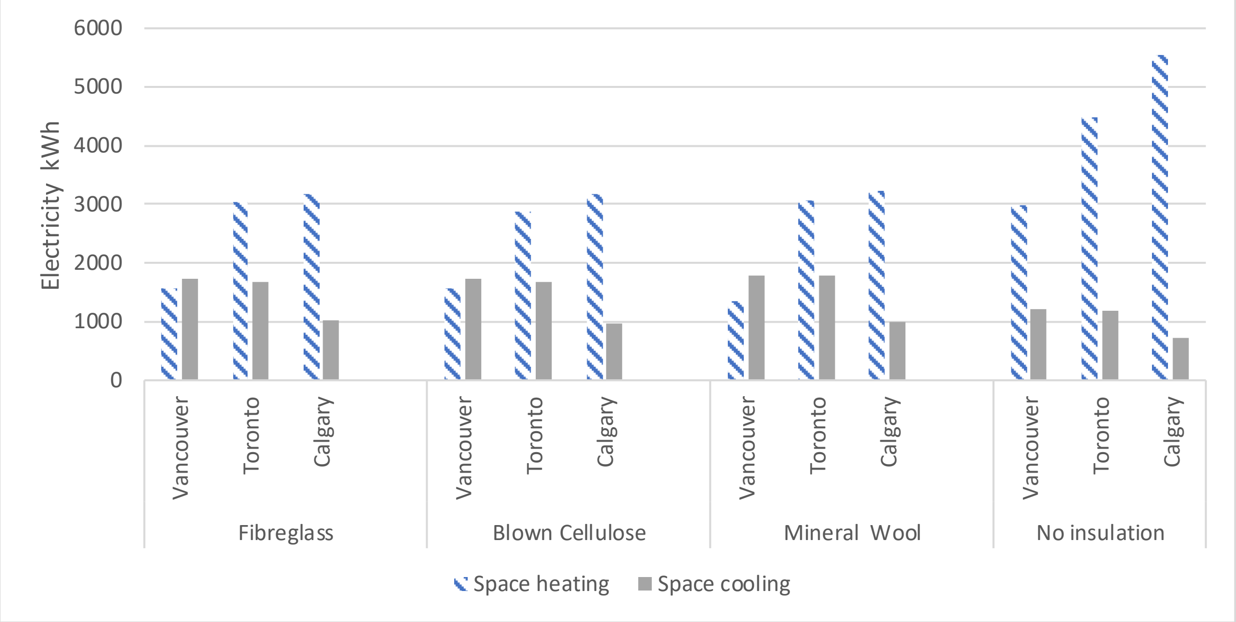


Figure 14: Electricity usage for different insulation materials at different locations

Figure 13 displays the amount of natural gas required for domestic water heating concerning space heating. Calgary consumes more natural gas fuel, followed by Toronto. British Columbia is one of Canada's largest clean energy producers, generating electricity through abundant hydropower [90], resulting in minimal natural gas usage, which can be reflected in Figures 13 and 14. Even after factoring in electricity usage, Vancouver still uses less energy overall than other locations. Figure 15 presents the variation of fuel bills in different locations when considering the same insulation material. Calgary has higher annual costs, followed by Toronto and then Vancouver. According to the fuel cost library in the HOT2000, the electricity rate is \$10/kWh while \$14/m^3 for natural gas.

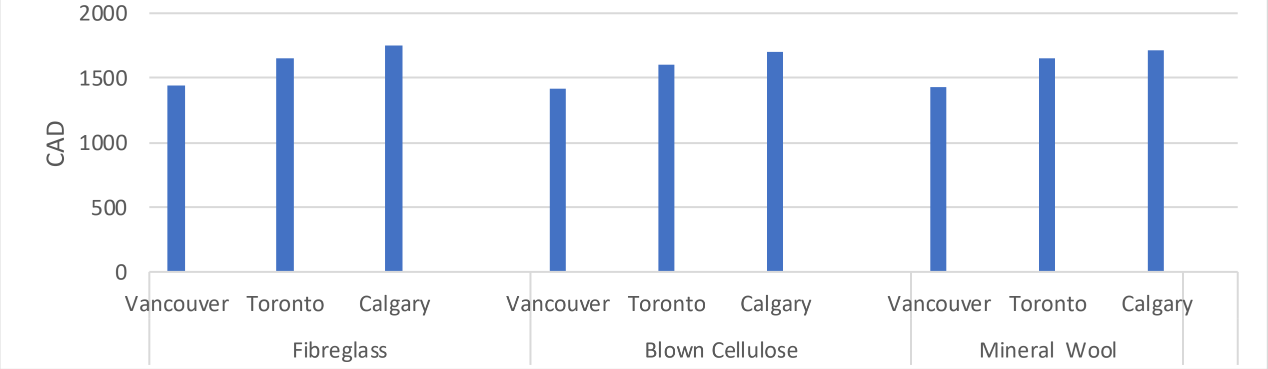


Figure 15: Annual estimated cost of fuel comprising electricity and natural gas

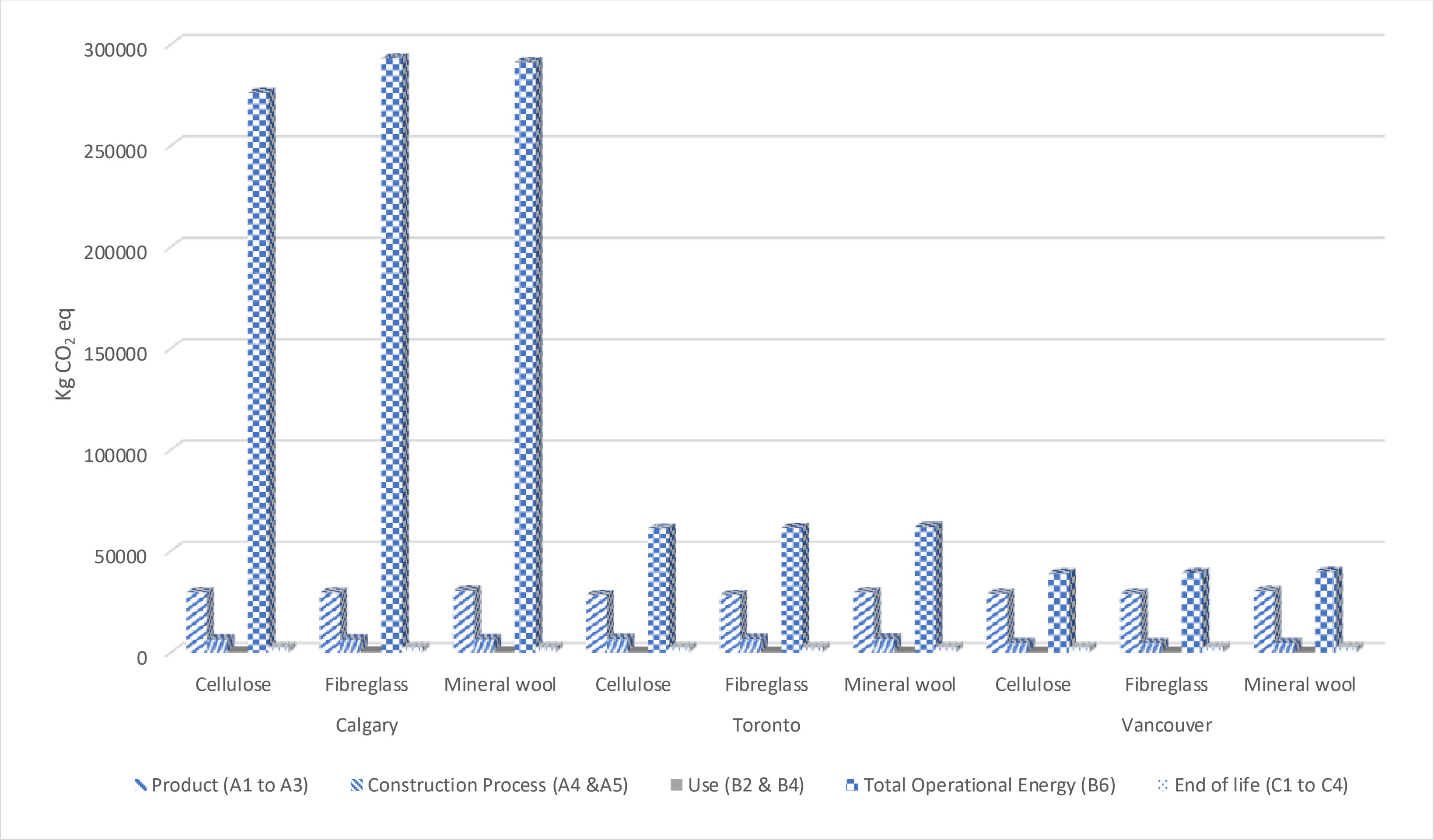


Figure 16: Comparison of GWP by Life Cycle Stage (20 years)

After the completion of energy simulations for selected materials and locations, all the reports with their data regarding energy consumption report, monthly energy profile (see *Appendix D*), and heating and cooling performances were collected and compiled in Table 11. The estimated annual fuel consumption for each case was then computed into the operating energy consumption in the AIE. Four separate simulations were conducted based on the age of the building, that is, one year, five years, 20 years and 60 years (see *Appendix C*); Figure 16 displays the 20 years evaluation and comparison of GWP by life cycle stage. The reason for considering these years is to compare the Use stage, i.e., B2 and B4 of LCA boundaries, and the gradual growth (cumulative) of operational carbon over time. This paves the way for evaluating operational savings, which are used to calculate the carbon payback period (CPP) of each insulation material for an entire building. When comparing Figure 16 with Figure 4, Calgary is the only location resulting in exponential cumulative operational carbon. The colder climate and higher HDD result in significant energy use to keep the house warm yearly.

Table 13 displays the calculated CPP for only the wall insulation of the entire model. The CPP for Blown Cellulose is 0.92, 1.15, and 2.64 years for Calgary, Toronto, and Vancouver, respectively. The CPP for Batts Fiberglass insulation is 0.94, 1.17, and 2.66 years for Calgary, Toronto, and Vancouver, respectively. The CPP for mineral wool insulation is 1.09, 1.39, and 2.69 years for Calgary, Toronto, and Vancouver respectively. When considering the overall insulation of the building, blown Cellulose offers a rating of 20.11%, 20.02%, and 21.71% for Calgary, Toronto, and Vancouver, respectively. Batts Fiberglass has ratings of 19.95%, 19.98%, and 21.73% for Calgary, Toronto, and Vancouver, respectively, while Mineral Wool has ratings of 20.42%, 20.07%, and 21.85% for the exact locations. This data clearly demonstrates that wall insulation contributes an average of 20% of SHC savings compared to the overall insulation, including walls, roofs, and floors, calculated at an average of 90%. It’s worth noting that the CPP of all the home's insulation, i.e., walls, floor and roof, collectively presents slightly lower results than the individual CPP of the wall insulation. This underscores the importance of considering the individual CPP values of the roof and floor thermal insulation, which can vary due to their higher embodied carbon.

Table 13: CPP evaluation for selected insulation materials (only wall insulation) in different locations

Location	Material	Total R-Value (Walls)	Embodied Carbon of insulation invested (KgCO2eq)	Annual Space heating and cooling savings (KgCO2eq)	CPP (years)
Calgary	Blown Cellulose	18.74	3130	3427.91	0.92
	Batts Fiberglass	19.62	3200	3419.06	0.94
	Mineral wool	19.58	3820	3488.15	1.09
Toronto	Blown Cellulose	18.74	3070	2676.90	1.15
	Batts Fiberglass	19.62	3130	2671.22	1.17
	Mineral wool	19.58	3730	2692.18	1.39
Vancouver	Blown Cellulose	16.04	3090	1170.41	2.64
	Batts Fiberglass	16.93	3100	1161.87	2.66
	Mineral wool	16.87	3190	1187.95	2.69

A graph is then plotted using the calculated CPP of the walls in relation to heating degree days (HDD) for different locations. Figure 17 clearly shows that the CPP reduces with an increase in HDD. The red dot on the graph represents Mineral Wool. Blown Cellulose’s CPP is slightly lower than Batts Fiberglass.

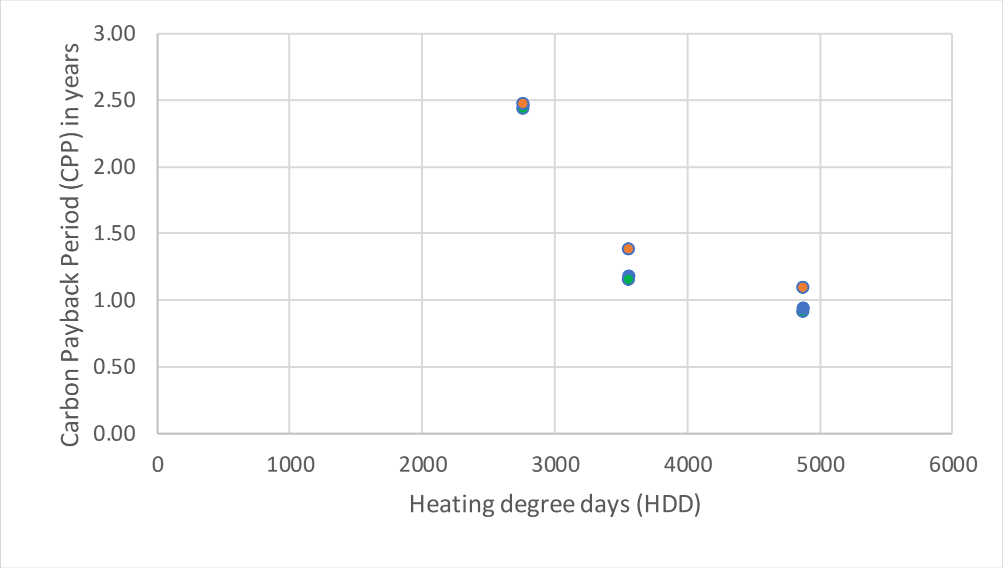


Figure 17: Relationship between Carbon Payback Period (CPP) and Heating Degree days (HDD)

Sadowski [38] provided average CPP values for various types of thermal insulation, including Stone wool, Glass wool, Expanded polystyrene (EPS), Extruded polystyrene (XPS), Polyurethane (PUR), and Cellulose. These values were specific to different types of existing external walls (1 m^2 area) used in European residential buildings. Notably, Sadowski's study considered different locations, such as Europe, Austria, Germany, Poland, the Czech Republic, and Finland. Also, he considered various energy sources, including electricity, natural gas, wood, and oil. This comprehensive approach provided a robust foundation for his findings.

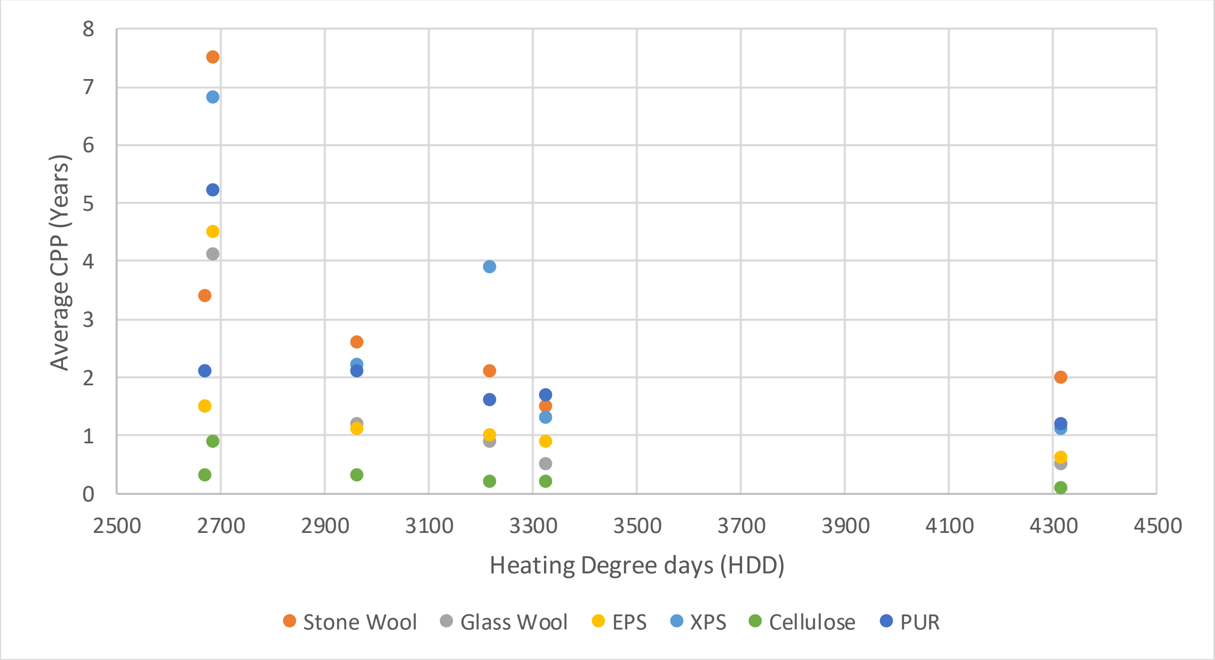


Figure 18: Average CPP values for European countries [38]

The significant findings obtained by Sadowski showed that Cellulose insulation had lower embodied carbon compared to the rest of his selected thermal insulation choices. Cellulose also resulted in a lower CPP of less than a year compared to other insulations. With energy sources such as electricity, CPP can be lowered to less than a year while CPP for natural gas takes less than three years for those countries. The heating degree days listed by the author were as follows: Germany- 2962, Austria- 2685, Europe- 2671, Poland- 3220, Czech Republic- 3328, and Finland- 4318. These results were then compiled into a graph was plotted, as shown in Figure 18. A noteworthy observation from Sadowski's results is that the CPP for thermal insulation shortens as HDD increases.

5. Conclusions

Interpreting the results of LCA often raises concerns about the inherent uncertainty and variability in the data. This uncertainty arises from the challenge of converting real-life situations into LCA data and parameters. This is especially true for buildings, which are typically made up of over 1000 products, analyzing each component with available data is challenging, making it tough to maintain a high level of accuracy. Authors [66 – 68] have performed studies focusing on different insulation materials, including the insulations mentioned in this study; however, none have performed WBLCA with these materials, nor have they evaluated for CPP regarding the whole building. Various versions of National Building Codes (NBCs) from 1995 to 2020 are assessed in this study, including different cities representing different climate zones (CZ). After accumulating these results, we discovered that the embodied carbon from NBC 1995 to 2020 increased and the operational carbon decreased. WBLCA GWP for Vancouver (CZ 4), Toronto (CZ 5) and Calgary (CZ 7a) had a decrease of 21.87%, 19.53% and 16.49% in operational carbon, respectively. On the other hand, the embodied carbon increased by 9.06%, 2.5% and 7.38% for Vancouver, Toronto and Calgary. It is important to note that this is purely theoretical as it does not consider the maintenance of the house for 60 years. This brings to light that NBC focuses on reducing operational carbon but overlooks the growth of embodied carbon in the whole building. The comparison of results between different codes reveals that implementing the 2020 building code results in an average operational energy saving of 25% for the entire building. Blown Cellulose was also found to have lower embodied carbon followed by Batts Fiberglass and Mineral Wool having the highest.

In analyzing annual fuel consumption costs, it's clear that installing Fiberglass insulation at homes in Vancouver is cost-efficient, bringing down energy use and yearly energy costs. At the same time, Blown Cellulose is cost-efficient when installed at homes in Toronto and Calgary. Unlike Fiberglass, Cellulose is preferred in colder climates as it holds up to its performance, is denser and can retain its R-value better than Fiberglass [91-92]. The evaluation revealed that for Calgary, the Carbon Payback Period (CPP) for Blown Cellulose and Batts Fiberglass insulation is 0.92 and 0.94 years respectively. In comparison, Mineral Wool takes 1.09 years to offset the carbon footprint embodied in the insulation material through savings on the operational carbon footprint. In Toronto, the CPP for Blown Cellulose and Batts Fiberglass is 1.15 and 1.17 years respectively, while Mineral Wool takes 1.39 years to offset. Vancouver has longer breakeven points, with Fiberglass, Blown Cellulose, and Mineral Wool having CPPs of 2.66, 2.64, and 2.69 years respectively. The CPP shortens with an increase in heating degree days (HDD). It's essential to consider other factors contributing to the overall carbon footprint, such as transportation, installation, maintenance, and replacement. This study demonstrates the possibility of assessing the environmental impact of different insulation materials in various Canadian climate zones, which can aid in making more environmentally friendly choices.

6. Future Scope

Many unknowns in this field of study require further exploration. The study found that the carbon footprint payback period varies greatly depending on location and the energy sources. It would be helpful to examine each energy source separately. A deeper dive into researching energy sources would be interesting as we can determine the amount of renewable and non-renewable fuel a house consumes for its operation. Location-specific conditions, such as differences in climate, also make it challenging to compare results between different provinces in Canada. An example would be the differences in the transportation of materials from the production area to the field location. This hints at a necessity to have a deeper understanding of the boundary layers of LCA. To gain a better understanding, the study can be expanded to include multiple insulation variations to closely document their embodied carbon and have a comprehensive relation between their CPP value and the HDD of those locations evaluated.

Environmental Product Declarations (EPDs) for other available insulation materials were not available in Athena and HOT2000 software, limiting the accuracy of the results; hence, collecting EPDs and its revisioning would be a future scope. Additionally, the study briefly explored carbon-friendly external insulation materials, but a more thorough understanding is possible (refer to Appendix B). The insulation used for the roofs and floors is different from the selected materials and, therefore, needs to be evaluated in the future to pick a material with low embodied carbon and high-performing thermal resistance. While the research addressed energy gain profile and annual heating curves for specific locations (refer to Appendix D), the cooling curve requires further investigation, including estimating the energy costs of individual sources. The author also anticipates that the RSI value for floors, roofs, walls, doors, windows, fenestration, and skylights may decrease even further in future updates to NBC.

References

[1] Developed by UBC and ZEBx, Webinar-"Life Cycle Assessment Process to estimate Embodied Carbon in buildings", 2021. Life Cycle Assessment Process to Estimate Embodied Carbon in Buildings - YouTube [Accessed on September, 2022]

[2] J. Grace; "The Evolution of Building Codes", *Robertson Building Systems*, published September 2020, [Online] available: https://www.robertsonbuildings.com/blogpost/the-evolution-of-building-codes/

[3] Z. Chen, A. Hammad, I. Kamardeen, and A. Akbarnezhad, "Optimising Embodied Energy and Thermal Performance of Thermal Insulation in Building Envelopes via an Automated Building Information Modelling (BIM) Tool," *Buildings*, vol. 10, no. 12, p. 218, Nov. 2020, doi: 10.3390/buildings10120218.

[4] B. Plumptre, "Canada's National Inventory Report shows a plateau in carbon pollution. That's not good enough", *Pembina institute*, a blog published on April 2021, available:

https://www.pembina.org/blog/canadas-carbon-pollution-plateaus-thats-not-good-enough [Accessed on February 2023]

[5] “Distribution of residential real estate units in Canada in 2021, by building type”, published by *Statista Research Department*, February 2023

[6] “Energy Efficiency 2018: Analysis and outlooks to 2040”, *International Energy Agency*, published in 2018, available: https://www.iea.org/reports/energy-efficiency-2018

[7] M. Reynolds; B. Pierson, “Canada Greener Homes Grant 2022 - The "How To Apply" Guide - Step By Step”, *Ecohome,* published in July 2022, available: https://www.ecohome.net/guides/1168/canada-greener-homes-grant-2022-step-by-step-guide-how-to-apply/

[8] Climate change- *Province of British Columbia* [online], Available:
https://www2.gov.bc.ca/gov/content/environment/climate-change [accessed on November 17, 2022]

[9] UN environmental programme, “Climate change emissions from buildings and construction hit a new high: Report”, [Online], https://phys.org/news/2022-11-climate-emissions-high.html, published on November 2022.

[10] “National Building Code of Canada 2020”, *Government of Canada*, modified last on March 2022, [Online}; https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-canada-publications/national-building-code-canada-2020 [Accessed on 12th December, 2022]

[11] Maximilian Schulte; Lewandowski I., “Comparative life cycle assessment of bio-based insulation materials: Environmental and economic performances”, *GCB- Bioenergy: Bioproducts for a sustainable bioeconomy*, published March 2021, DOI: https://doi.org/10.1111/gcbb.12825

[12] Svensson, E.; Panojevic, D. “A Life Cycle Assessment of the Environmental Impacts of Cross-Laminated Timber”, MA. Eng. Thesis, Lund University, Lund, Sweden, January 2019.

[13] Energy Saver, “Insulation Materials”, energy.gov [blog],
https://www.energy.gov/energysaver/insulation-materials, [accessed on November 17, 2022]

[14] Pro-line Blog, “5 of the Most Common Building Insulation Materials”, *Pro-line construction materials Ltd.*, published May 7, 2020; https://proline-construction.com/5-of-the-most-common-building-insulation-materials/

[15] Global Status Report 2019, " 2019 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector", *UN Environment programme*, November 2022, https://wedocs.unep.org/handle/20.500.11822/30950

[16] “Carbon dioxide emissions of the building sector in Canada from 1970 to 2021 (in million metric ton)”, *Statista*, [online] Available: https://www.statista.com/statistics/1290641/building-sector-emissions-in-canada/

[17] V.E.Garcia, “Embodied Carbon and Whole Building Life Cycle Assessment”, *Ambient Energy- A Mead & Hunt Company*, Webinar IBPSA- Denver, October 2021 Embodied Carbon and Whole Building Life Cycle Assessment (WBLCA) - YouTube

[18] ISO-14040:2006- Environmental management, last viewed and confirmed in 2022, ISO - ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework

[19] ISO-14044:2006- Environmental management, last viewed and confirmed in 2022, ISO - ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines

[20] ITEH Standards: EN15643:2021, reviewed in 31st June 2021, EN 15643:2021 - Sustainability of construction works - Framework for assessment of buildings and (iteh.ai)

[21] European Committee for Standardization (CEN), EN15978: calculation method, published Nov 2011 and reviewed in 2018, CEN - EN 15978 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method | Engineering360 (globalspec.com)

[22] Carbon Cure, "What is Embodied Carbon?", published in Sept 2020, [Online]; https://www.carboncure.com/concrete-corner/what-is-embodied-carbon/#:~:text=Put%20simply%2C%20embodied%20carbon%20is,the%20waste%2C%20and%20recycling%20it [Accessed on 12th December, 2022]

[23] World Green Building Council, "Bringing embodied carbon upfront", Report 2019, website visited 12th December 2022, Embodied Carbon - World Green Building Council (worldgbc.org)

[24] Architecture inc. 2030. UN Environment Global Status Report 2017; *EIA international energy outlook* 2017, https://worldgbc.org/wp-content/uploads/2022/03/UNEP-188_GABC_en-web.pdf [Report]

[25] EPD Ireland, "What is an EPD?", *website IGBC* visited on 9th December 2022, What is an EPD? - Irish Green Building Council (igbc.ie)

[26] Mantle Developments, "Mass Timber's Carbon Impact", published on 25th November, 2020; [Online]; https://mantledev.com/insights/embodied-carbon/mass-timber-carbon-impact/ [Accessed on 11th December 2022]

[27] Canada.ca, "United Nations Framework Convention on Climate Change and the Paris Agreement", *Government of Canada*, revised on February 2022, [Online], https://www.canada.ca/en/environment-climate-change/corporate/international-affairs/partnerships-organizations/united-nations-framework-climate-change.html [Accessed on 11th December 2022]

[28] Jarvie M.; "Brundtland Report- World Commission on Environment and Development", *Britannica*, an article published 1987; available: https://www.britannica.com/topic/Brundtland-Report

[29] B.X. Rodriguez and K. Simonen; "Comparison of methodologies for Whole Building Life Cycle Assessment: A Review", *University of Washington- Department of Architecture*, published April 2017, p 7. Available: https://www.carbonleadershipforum.org/wp-content/uploads/2018/01/LCA-Method-Comparison_04.06.2017.pdf

[30] Turnbull G., Graham J., "Embodied Carbon Values in Common Insulation Materials", KPMB architects + KPMB lab, published May 2021, https://www.kpmb.com/wp-content/uploads/2021/04/KPMB-LAB_Embodied-Carbon-in-Insulation.pdf

[31] H. Jang, Y. Jang, B. Jeong, and N.-K. Cho, “Comparative Life Cycle Assessment of Marine Insulation Materials,” Journal of Marine Science and Engineering, vol. 9, no. 10, p. 1099, Oct. 2021, doi: 10.3390/jmse9101099.

[32] PE-International. GaBi Paper Clip Tutorial: Handbook for Life Cycle Assessment, Using the GaBi Software; PE International GmbH and Universität Stuttgart: Stuttgart, Germany, 2011. [Online]

[33] Researchers Toronto, “Emissions of Materials Benchmark Assessment for Residential Construction”, *Builders for Climate Action and Passive Buildings Canada*, Report, pg 24 https://www.greenbuildingadvisor.com/app/uploads/2022/04/EMBARC-1.pdf

[34] European Parliament and the Council Directive (EU) 2010/31 of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast). Available online: http://data.europa.eu/eli/dir/2010/31/oj, accessed on 29 November, 2022

[35] COM 662 Final, “A Renovation Wave for Europe—Greening Our Buildings, Creating Jobs, Improving Lives”, *Communication from the Commission to the European Parliament, the Council, the European Social and Economic Committee and the Committee of the Regions*, published 2020; available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662, accessed on 30 October 2022.

[36] Aditya, L.; Mahlia, T.M.I.; Rismanchi, B.; Ng, H.M.; Hasan, M.H.; Metselaar, H.S.C.; Muraza, O.; Aditiya, H.B; “A review on insulation materials for energy conservation in buildings”, *Renewable and Sustainable Energy Reviews*, published June 2017, 73, 1352–1365, https://doi.org/10.1016/j.rser.2017.02.034

[37] Mohsen, M.S.; Akash, B.A. “Some prospects of energy savings in buildings”, *Energy Conversion and Management,* published July 2001, 42, 1307–1315, https://doi.org/10.1016/S0196-8904(00)00140-0

[38] Sadowski, K; “Comparison of the Carbon Payback Period (CPP) of Different Variants of Insulation Materials and Existing External Walls in Selected European Countries”, *Energies*, published 22nd December, 2022, 16, 113. https://doi.org/10.3390/en16010113

[39] Moncaster, A. M., Pomponi, F., Symons, K. E., & Guthrie, P. M., “Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system”, *Energy and Buildings*, 173, 389–398. Published in 2018, DOI: https://doi.org/10.1016/j.enbuild.2018.05.039

[40] Ashby, M., “Material property data for engineering materials”, *4th edition, Cambridge*: University of Cambridge Engineering Department and Grants Design, published in 2016

[41] Dahlstrøm, O.; Sørnes, K.; Eriksen, S.T.; Hertwich, E.G; “Life cycle assessment of a single-family residence built to either conventional-or passive house standard”, Energy Build, published in 2012, 54, 470–479.

[42] CEN; EN 15804:2012+A2:2019. “Sustainability of construction works”, *Environmental product declarations—core* rules for the product category of construction products. Brussels: Comité Européen de Normalisation (CEN).

[43] Monteiro, H.; Freire, F., “Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods”, *Energy Build,* published in 2012, *47*, 572–583.

[44] Shirazi, A.; Ashuri, B., "Embodied life cycle assessment comparison of single-family residential houses considering the 1970s transition in the construction industry: Atlanta case study", *Building Environment,* published in 2018, *140*, 55–67.

[45] Peuportier, B.L.P., "Life cycle assessment applied to the comparative evaluation of single-family houses in the French context", *Energy Building,* Published in 2001, *33*, 443–450.

[46] Cuéllar-Franca, R.M.; Azapagic, A., "Environmental impacts of the UK residential sector: Life cycle assessment of houses", *Building Environment,* published in 2012, *54*, 86–99.

[47] Lavagna, M.; Baldassarri, C., "Benchmarks for the environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock", *Building Environment,* published in 2018, *145*, 260–275.

[48] Adalberth, K.; Petersen, E.H., "Life cycle assessment of four multi-family buildings", *International Journal Low Energy Sustainable Energy Building,* published in 2001, *2*, 1–21.

[49] Monokova, A.; Vilcekova, "Environmental Impacts of Detached Family Houses Used Natural Building Materials", *Multidisciplinary Digital Publishing Institute Proceedings,* published in 2018, *2*, 1301.

[50] P. Jiang, Y. Chen, W. Dong, B. Huang; "Promoting low carbon sustainability through benchmarking the energy performance in public buildings in China", *Urban Climate*, published in 2014, pp. 92-104, 10.1016/j.uclim.2014.10.004

[51] G. Di Foggia; "Energy efficiency measures in buildings for achieving sustainable development goals", *Heliyon*, published in 2018, 10.1016/j.heliyon.2018.e00953, p1–21.

[52] K. Rakhshan, W.A. Friess; "Effectiveness and viability of residential building energy retrofits in Dubai", *Journal of Building Engineering*, published in 2017, pp. 116-126, 10.1016/j.jobe.2017.07.010

[53] U. Amin, M.J. Hossain, J. Lu, E. Fernandez; "Performance analysis of an experimental smart building: expectations and outcomes", *Energy*, 135, published in 2017, pp. 740-753, 10.1016/j.energy.2017.06.149

[54] Y. Jeong, M. Lee, J. Kim; "Scenario-Based Design and Assessment of renewable energy supply systems for green building applications", *Energy Procedia*, published in 2017, pp. 27-33, 10.1016/j.egypro.2017.10.259

[55] A. Chel, G. Kaushik; "Renewable energy technologies for sustainable development of energy-efficient building", *Alexandria Engineering Journal*, published in 2018, pp. 655-669, 10.1016/j.aej.2017.02.027

[56] M. Alvand, Z. Gholami, M. Ferrara, E. Fabrizio; "Assessment of cost-optimal solutions for high-performance multi-family buildings in Iran", *Energy Procedia*, published in 2017, pp. 318-327, 10.1016/j.egypro.2017.03.102

[57] A.P. McCoy, D. Zhao, T. Ladipo, P. Agee, Y. Mo; "Comparison of green home energy performance between simulation and observation: a case of Virginia, United States", *Journal of Green Building*, published in 2018, pp. 70-88, 10.3992/1943-4618.13.3.70

[58] A.K. Shukla, K. Sudhakar, P. Baredar, R. Mamat; "BIPV based sustainable building in South Asian countries", *Solar Energy*, published in 2018, pp. 1162-1170, 10.1016/j.solener.2018.06.026

[59] W. Wei, H.M. Skye; "Residential net-zero energy buildings: review and perspective", *Renewable and Sustainable Energy Reviews*, published in 2021, Article 110859, 10.1016/j.rser.2021.110859

[60] F. Hafez, & B. Sa'di, & S. Gamal, & S. Mekhilef; “Energy Efficiency in Sustainable Buildings: A Systematic Review with Taxonomy, Challenges, Motivations, Methodological Aspects, Recommendations, and Pathways for Future Research”, *Energy Strategy Reviews*. 45. (2022) 101013. 10.1016/j.esr.2022.101013.

[61] F. Karimi, N. Valibeig, G. Memarian, and A. Kamari, “Sustainability Rating Systems for Historic Buildings: A Systematic Review,” *Sustainability*, vol. 14, no. 19, p. 12448, Sep. 2022, doi: 10.3390/su141912448.

[62] Grazieschi, G.; Asdrubali, F.; Thomas, G.; “Embodied energy and carbon of building insulating materials: A critical review”, *Cleaner Environmental Systems*, published June 2021, 2, 100032, https://doi.org/10.1016/j.cesys.2021.100032

[63] Yard, S.; “Developments of the payback method”, *International Journal of Production Economics*, published in September 2000, 67, 155–167, https://doi.org/10.1016/S0925-5273(00)00003-7

[64] S. Füchsl; F. Rheude; H. Röder, “Life cycle assessment (LCA) of thermal insulation materials: A critical review”, *Cleaner Materials*, Volume 5, 2022, 100119, ISSN 2772-3976, https://doi.org/10.1016/j.clema.2022.100119.

[65] National Resource Canada, “Energuide Rating System Technical Procedures Version 15.1”, November 2015, [online pdf]: https://www2.nrcan-rncan.gc.ca/oee/nh-mn/documents/eg/tech/EnerGuide%20Rating%20System%20Technical%20Procedures%20Version%2015.1.pdf

[66] S. Shrestha; M. Bhandari; K. Biswas; A. Desjarlais, “Lifetime Energy and Environmental Impacts of Insulation Materials in Commercial Building Applications –Assessment Methodology and Sample Calculations”, *US Department of Energy, Oak Ridge National Laboratory report*, published December 2014; https://info.ornl.gov/sites/publications/files/Pub53860.pdf

[67] R. Tolia; S. Foroushani, “Assessing the Embodied Emissions of Building to the Energy Step Code- report”, *UBC Sustainability Scholars*, published August 2020; https://sustain.ubc.ca/sites/default/files/2020-26_Assessing_Embodied_Emissions_of_buildings_Tolia.pdf

[68] Ortiz, O, F Castells, and G Sonnerman . "Sustainability in the construction industry: A review of recent developments based on LCA." *Construction of Building Materials*, published in 2009: 23, 1, 28-39.

[69] Collinge, WO, et al. "Integrating Life Cycle Assessment with Green Building and Product Rating Systems: North American Perspective", *Elsevier*, published in 2015. 662-669.

[70] ISO. 14044, Environmental management—life cycle assessment. Standard, Geneva, Switzerland: ISO, published in 2006

[71] Athena Sustainable Materials Institute, "Athena Impact Estimator for Buildings," www.athenasmi.org, 2023. [Online]. Available: http://www.athenasmi.org/our software data/impact estimator/

[72] Athena Sustainable Materials Institute, "Athena Impact Estimator for Buildings- V 4.5 user Manual, Software and Database Overview", published Nov 2013, Available: https://calculatelca.com/wp-content/uploads/2013/11/IE4B_User_Guide_Nov2013.pdf

[73] “National Building Code of Canada 2020”, *Government of Canada*, modified last on March 2022, website visited on 12th December, 2022; https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-canada-publications/national-building-code-canada-2020

[74] Canada Mortgage and Housing Corporation (CMHC), “Canadian Wood Frame House Construction”, [online pdf] available: https://chbanl.ca/wp-content/uploads/CMHC-Canadian-Wood-Frame-House-Construction.pdf

[75] “National Building Code of Canada 1995”, *National Science Library - National Research Council Canada / Bibliothèque scientifique nationale - Conseil national de recherches Canada*, published December 1995, ISBN: 0-660-17714-5, 571p, available: https://doi.org/10.4224/40001252

[76] “National Building Code of Canada 2005”, National Science Library - National Research Council Canada / Bibliothèque scientifique nationale - Conseil national de recherches Canada, published 2008, ISBN: 0-660-19425-2, doi: https://doi.org/10.4224/40001245

[77] “National Building Code of Canada 2010”, National Science Library - National Research Council Canada / Bibliothèque scientifique nationale - Conseil national de recherches Canada, published April 2010, DO: 10.4224/40001268, doi: https://doi.org/10.4224/40001268

[78] “National Building Code of Canada 2015”, National Science Library - National Research Council Canada / Bibliothèque scientifique nationale - Conseil national de recherches Canada, published January 2015, ISBN: 0-660-03633-5, doi: https://doi.org/10.4224/40002005

[79] “National Building Code of Canada 2017”, National Science Library - National Research Council Canada / Bibliothèque scientifique nationale - Conseil national de recherches Canada, published 2017, ISBN: 0-660-24321-4, doi: https://doi.org/10.4224/40002011

[80] Soprema, “Thermal Performance U-Value VS Effective R-Value”, *SOPREMA- Canada*, published in 2018, [online article] available: https://www.soprema.ca/thermal-performance-of-assemblies-effective-r-value-vs-u-value/

[81] Canadian Home Inspection Service; https://www.canadianhomeinspection.com/home-reference-library/attic-roof-space/insulation/#:~:text=Glass%20Fiber%20Insulation%20is%20one,as%20well%20as%20loose%20fill [accessed on 22nd April 2023]

[82] Government of Canada- Natural Resources Canada, “Keeping The Heat In - Section 7: Insulating Walls: insulating, and building additions”, website accessed on 22nd April 2023: https://natural-resources.canada.ca/energy-efficiency/homes/make-your-home-more-energy-efficient/keeping-the-heat/chapter-7-insulating-walls/15641

[83] Kohta Ueno, “Residential Exterior Wall Superinsulation Retrofit Details and Analysis”, *ASHRAE, Applied Building Technology Group,* Report*,* December 2010, https://www.researchgate.net/publication/318700218_Residential_Exterior_Wall_Superinsulation_Retrofit_Details_and_Analysis

[84] Berardi U., “The impact of temperature dependency of the building insulation thermal conductivity in the Canadian climate”, *Science Direct- Energy Procedia,* 11th Nordic Symposium on Building Physics, NSB2017, published on June 2017, Trondheim, Norway, p 237-242: https://www.sciencedirect.com/science/article/pii/S1876610217348312?via%3Dihub

[85] Atlas website, “Polyisocyanurate insulation: what is the R-value and ten other common questions about polyiso insulation answered”, ATLAS- Polyiso Roof and Wall Insulation, website accessed on 23rd April 2023: https://www.atlasrwi.com/polyiso-insulation/#:~:text=For%20the%20R%2Dvalue%20of,of%20around%206.0%20per%20inch

[86] J. G. Jonker, M. Junginger, A. Faaij; “Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States”, *GCB Bioenergy*, published April 2013, https://doi.org/10.1111/gcbb.12056

[87] NAIMA Canada; “Comparing Insulation Options for Homeowners”, website visited on 24th July 2023, doi: https://www.naimacanada.ca/for-homeowners/comparing-insulation-options/

[88] Athena Sustainable Materials Institute, "User Manual and Transparency Document- impact estimator for buildings v.5", published May 2019, p18; Available: www.athenasmi.org

[89] Canada Energy Regulator, “Canada’s Renewable power – British Columbia”, [online report] available: https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/electricity/report/canadas-renewable-power/provinces/renewable-power-canada-british-columbia.html [Accessed on 24th July, 2023]

[90] HOT2000 Climate Map, [Online] website:https://fgp-pgf.maps.arcgis.com/apps/webappviewer/index.html?id=1f4a2a144bc1406f9deca7713986ced2 [Accessed on March, 2023]

[91] A. A. Bailes, “Does fiberglass insulation really lose R-value?”, *Green Building Advisor-Building Science*, report, published in January 2019, https://www.greenbuildingadvisor.com/article/fiberglass-attic-insulation-really-lose-r-value

[92] K. E. Wilkes; P. W. Childs, “Thermal performance of Fiberglass and Cellulose Attic Insulations”, *The Oak Ridge National Laboratory*, research paper, published 1990, https://www.dropbox.com/sh/1ulqvybz7h8pzkh/AAAev2D6o9DjVCTKiJpg1DYna?dl=0&preview=JM-IST09-005_ENG_Convection_in_Fibrous_Attic_Insulation.pdf

Appendix A: Sketchup model of the house with X-rays

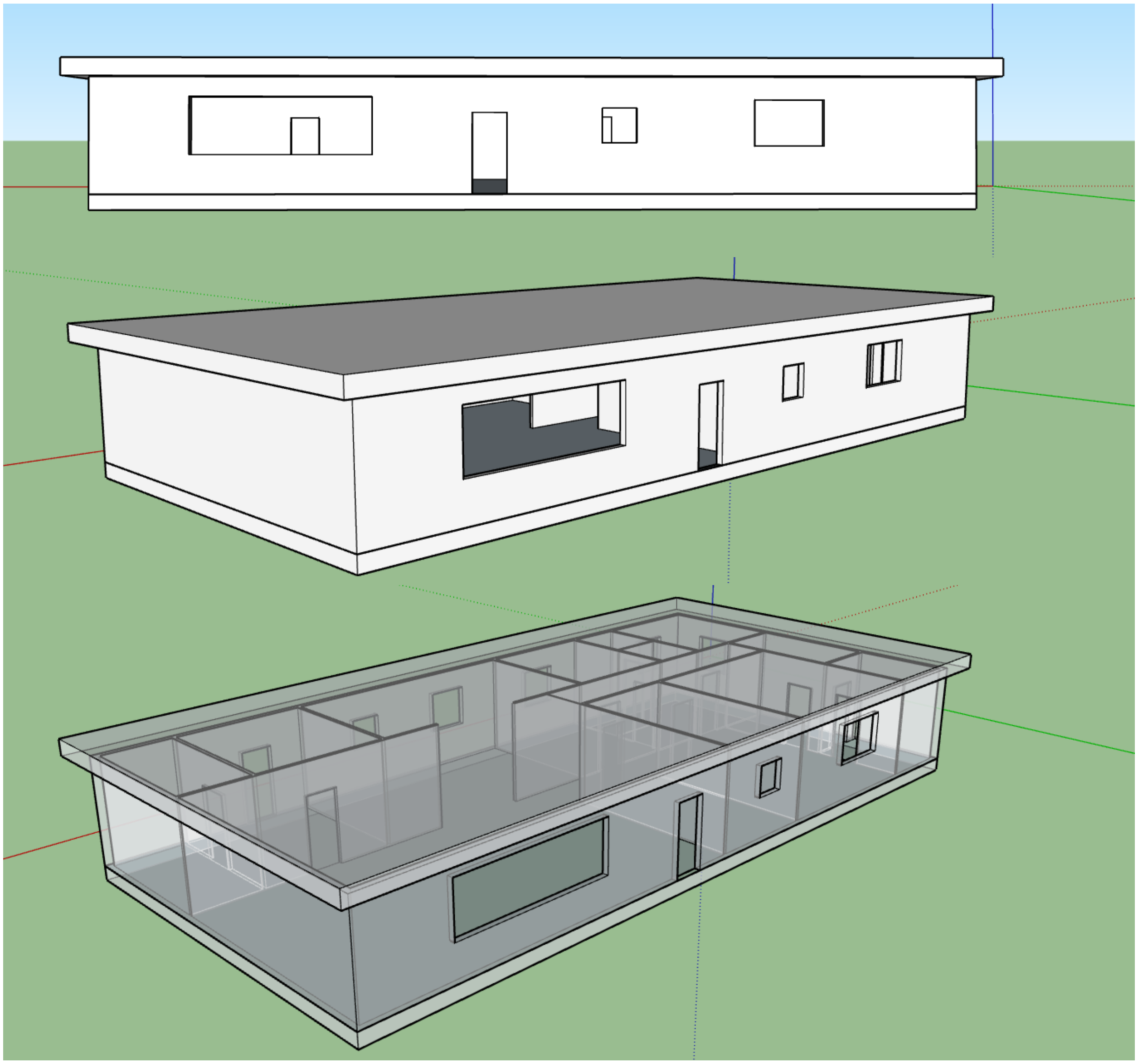


Figure 19: Front, isometric and X-ray isometric view of the house model on Sketchup 17.1

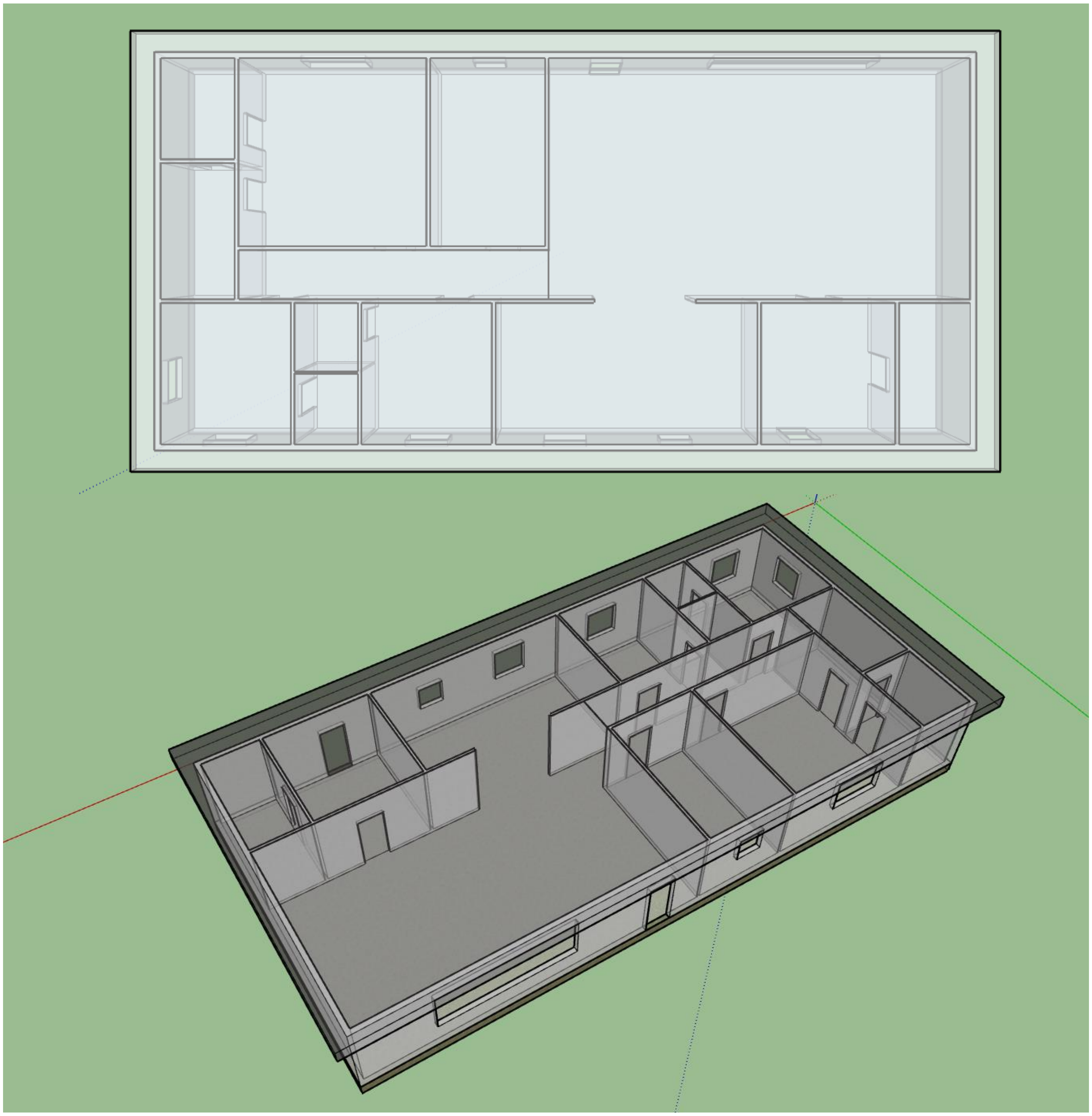


Figure 20: Top view and a view without the ceiling of the house

Appendix B: for external insulation

For Vancouver, exterior insulation for walls may not be necessary since the 2x6-inch stud designs can hold the R-value that falls under the minimum wall insulation requirements. However, external insulation must follow the minimum standards for Toronto (CZ 5) and Calgary (CZ 7A). Figure 21 shows the GWP WBLCA comparison by life cycle stages of different exterior insulations for Calgary based on NBC 2020 edition. This needed to be done to be assertive of a better balance between a low carbon footprint and the performance of insulations available in the Athena tool. The foil facer polyiso foam board has the lowest GWP compared to other insulation materials, followed by the polyiso foam board without the foil facer, as shown in Table 14. From the report prepared by ASHRAE [84], heating and cooling energy cost savings followed the expected pattern of more significant savings with increasing R-value; i.e., when applied over an existing insulated frame wall, the one-inch (25 mm) foil-faced polyisocyanurate showed typical savings in the 10-15% range for whole-house energy simulation than polyiso foam board without foil facer and XPS [84]. Polyiso foam typically has a higher thermal conductivity in colder climates. However, upon close examination by Berardi and Naldi [85], polyiso with foil facer showed reduced thermal conductivity in colder weather. It is important to note that Operational Energy (B6) is zero since simulating External insulation in HOT2000 energy software was not performed as it is out of scope.

Table 14: Comparison of WBLCA GWP by life cycle stage with different external insulation for Calgary

Exterior insulation	**Unit**	**Product (A1 to A3)**	**Construction Process (A4 &A5)**	**Use (B2 & B4)**	**Total Operational Energy (B6)**	**End of life (C1 to C4)**	**Total Embodied Carbon (kgCO$_2$ eq)**
XPS foam board	kg CO$_2$ eq	29100	6240	9310	0	2410	**47060**
Polyiso foam board	kg CO$_2$ eq	28700	6230	9310	0	2410	**46650**
EPS foam	kg CO$_2$ eq	28800	6210	9310	0	2410	**46730**
Wall polyiso foam board foil facer	kg CO$_2$ eq	28600	6240	9310	0	2410	**46560**
Mineral wool batt	kg CO$_2$ eq	28700	6220	9310	0	2410	**46640**
Totals	kg CO$_2$ eq	**143900**	**31140**	**46550**	**0**	**12050**	**233640**

For a more assertive conclusion, a similar approach to the examination was carried out for Toronto; their results are shown in Table 15 and Figure 22. Wall polyiso foam board with foil facer has slightly lower overall embodied carbon than the rest of the insulation and hence makes a good candidate for exterior insulation. Polyiso foam board with foil facer has an RSI-Value 1.01/inch (R-6/inch) than polyiso foamboard, which has an RSI-Value 0.96/inch (R-5.5/inch) [86].

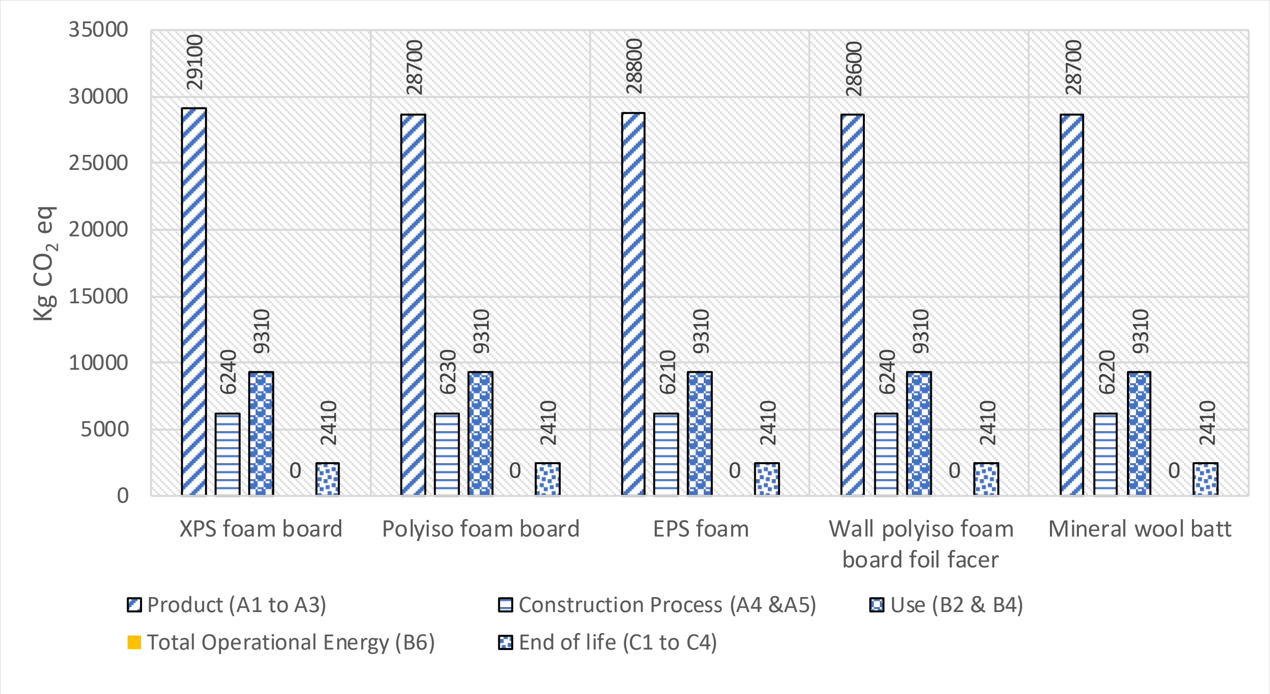


Figure 21: Comparison of Global warming potential by life cycle stage with exterior insulation for Calgary (Climate Zone 7a) based on NBC 2020 edition

Table 15: Comparison of WBLCA GWP by life cycle stage with different external insulation for Toronto

Exterior insulation	**Unit**	**Product (A1 to A3)**	**Construction Process (A4 &A5)**	**Use (B2 & B4)**	**Total Operational Energy (B6)**	**End of life (C1 to C4)**	**Total**
XPS foam board	kg CO_2 eq	28800	6670	8590	0	2410	**46470**
Polyiso foam board	kg CO_2 eq	28400	6640	8590	0	2410	**46040**
EPS foam	kg CO_2 eq	28500	6650	8590	0	2410	**46150**
Wall polyiso foam board foil facer	kg CO_2 eq	28400	6650	8590	0	2410	**46050**
Mineral wool batt	kg CO_2 eq	28300	6640	8590	0	2410	**45940**
Totals	kg CO_2 eq	**142400**	**33250**	**42950**	**0**	**12050**	**230650**

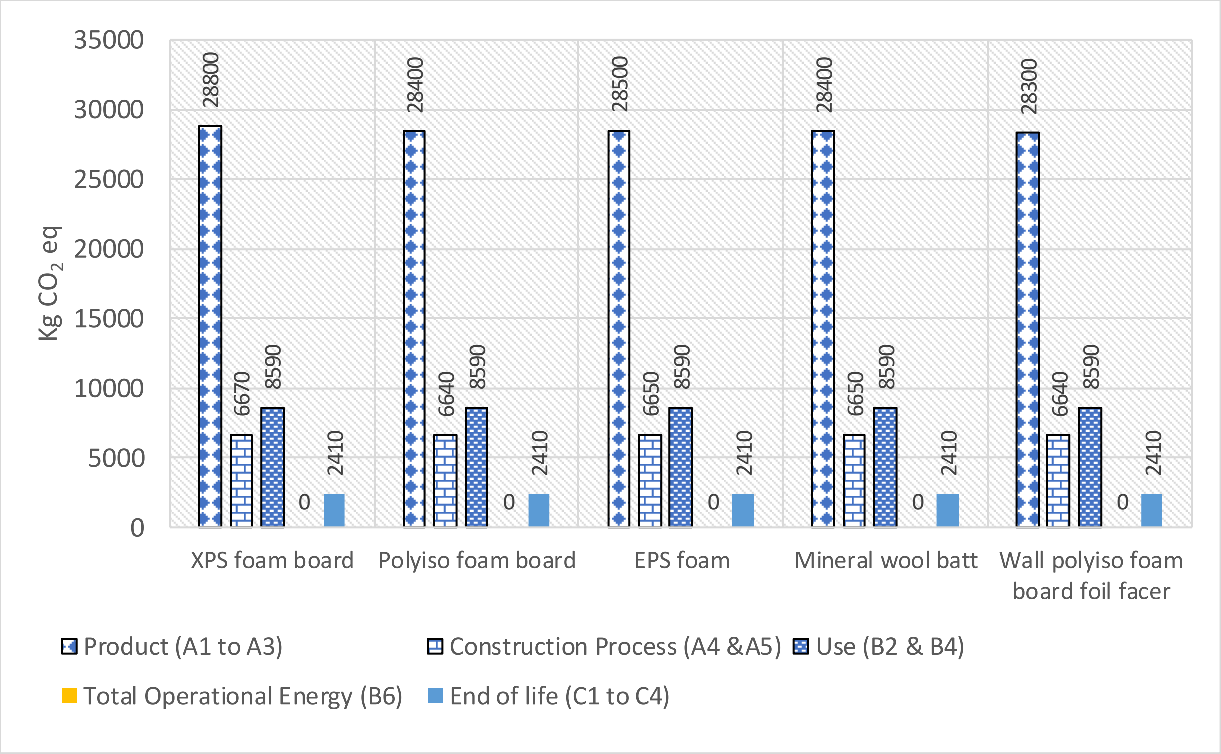


Figure 22: Comparison of Global warming potential by life cycle stage for exterior insulations (Toronto CZ 5) based on NBC 2020 edition

The WBLCA GWP evaluation of a house model for Vancouver, Calgary, and Toronto, together with interior insulation Batts Fiberglass, Cellulose fiber and Mineral wool, and exterior insulation foil facer polyiso for Toronto and Calgary, is displayed in Figure 23. There are variations seen while comparing the GWP at each life cycle stage. However, exterior insulation foil facer has lower embodied carbon than the rest of the exterior insulation compared. The Athena tool has pre-recorded variables on different sections for each life cycle stage, such as raw material supply, transportation to the factory or site or waste disposal, manufacturing, construction installation, and more, as seen in Figure 5.

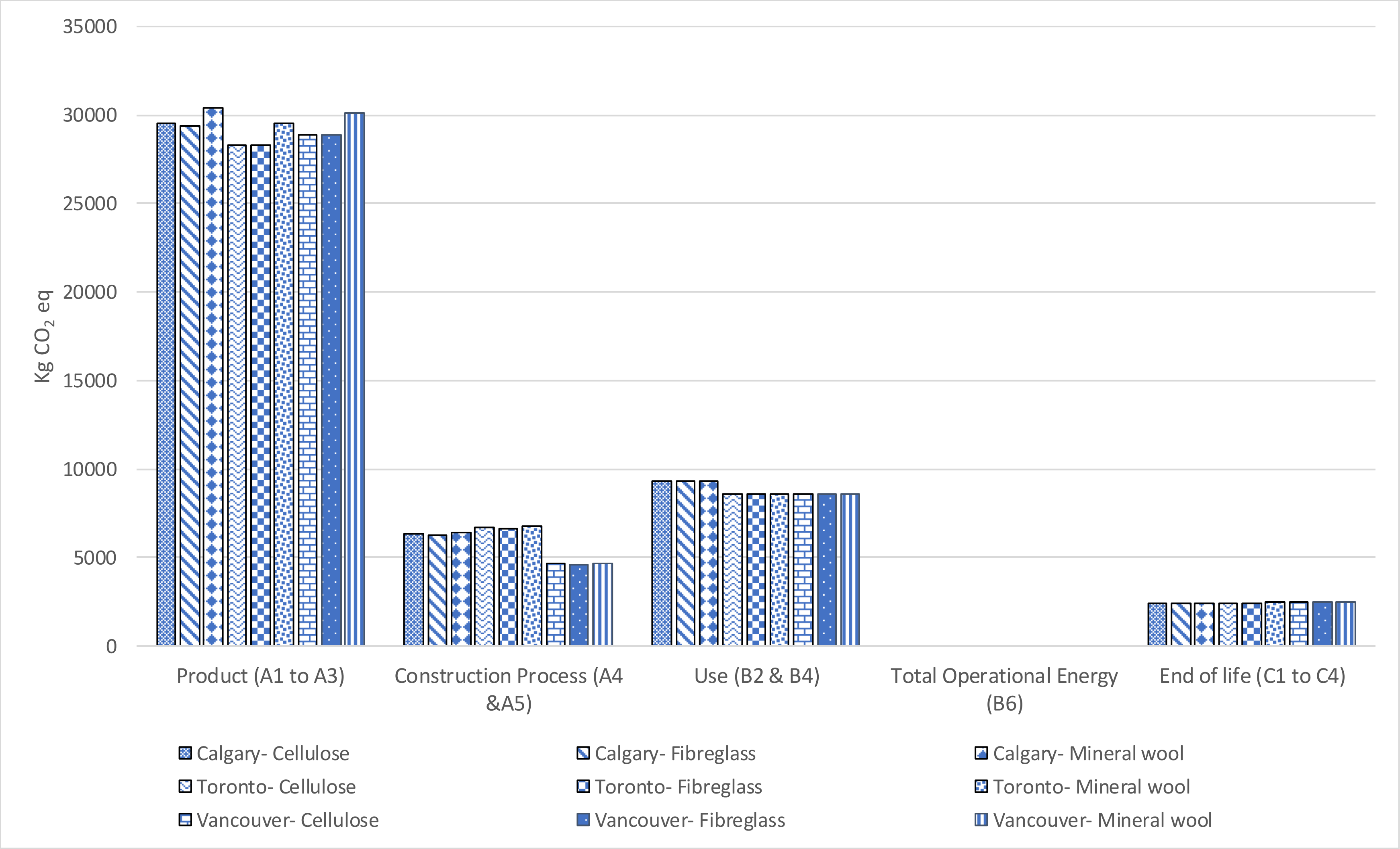


Figure 23: Comparison of GWP by life cycle stage for Vancouver, Calgary and Toronto with three interior insulation materials and polyiso foil facer as exterior insulation following NBC 2020 edition

Appendix C: 1 year, 5 and 60 years GWP operational carbon cumulative

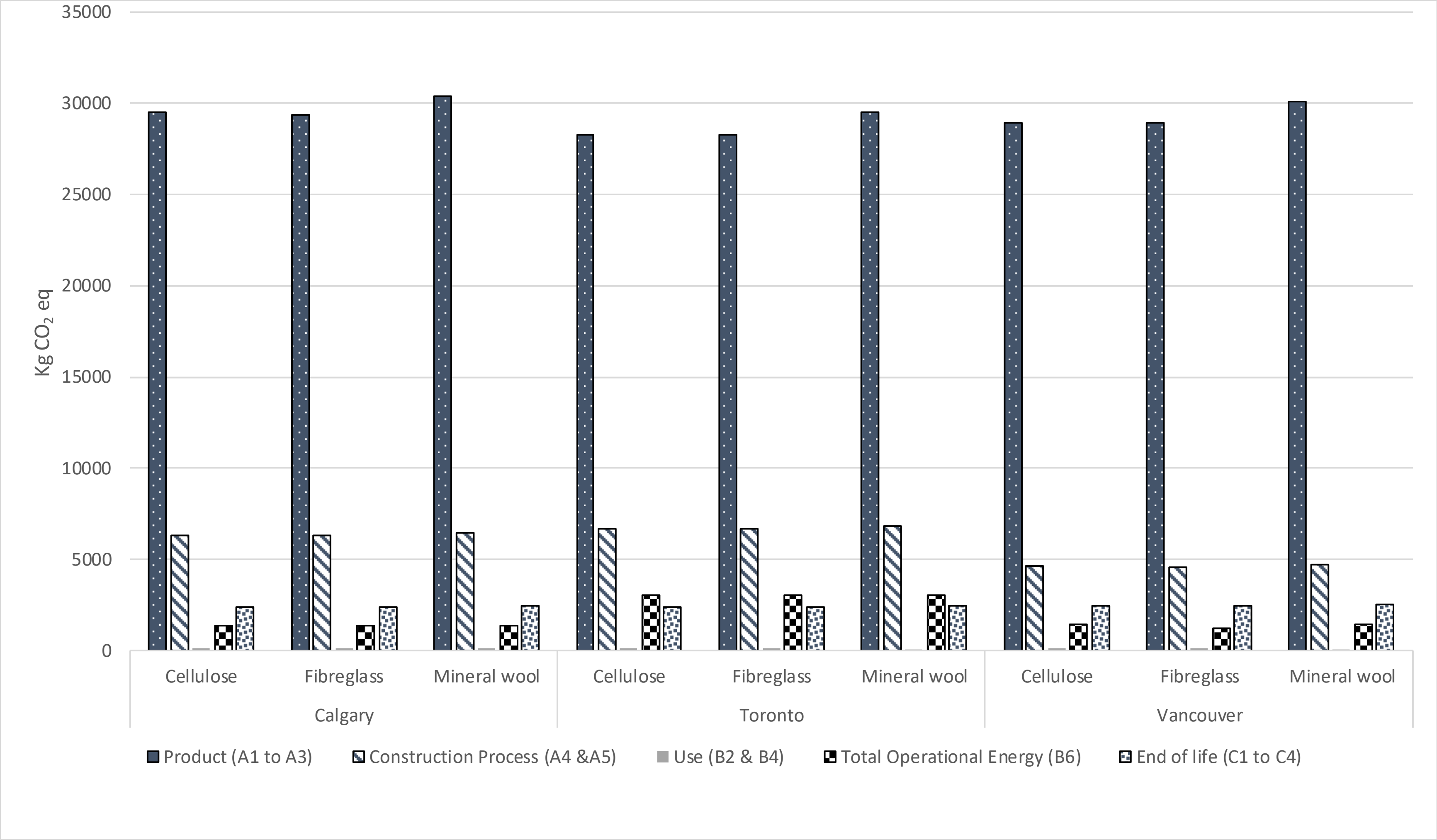


Figure 24: Comparison of GWP by Life Cycle Stage (1 year)

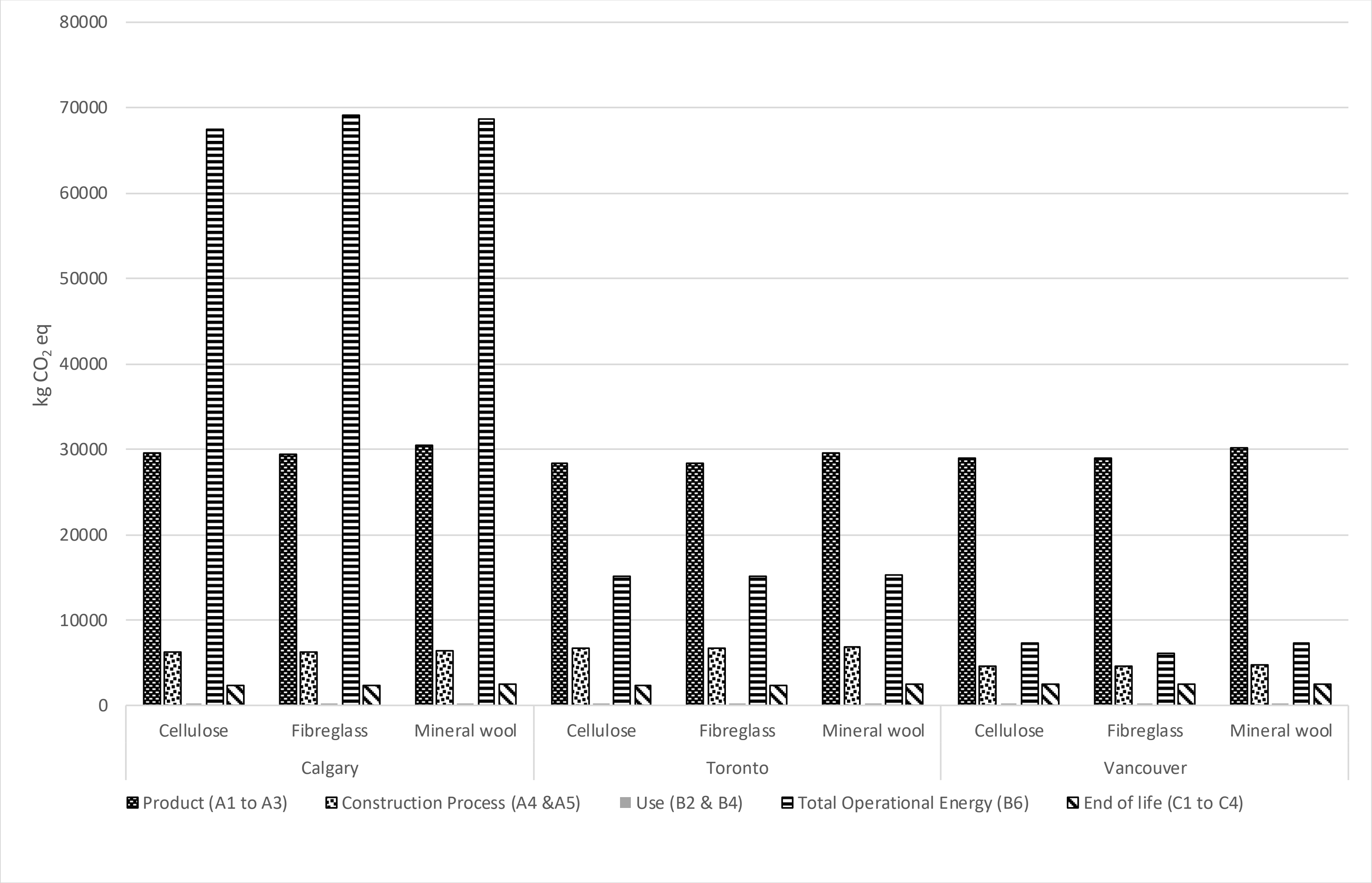


Figure 25: Comparison of GWP by Life Cycle Stage (5 years)

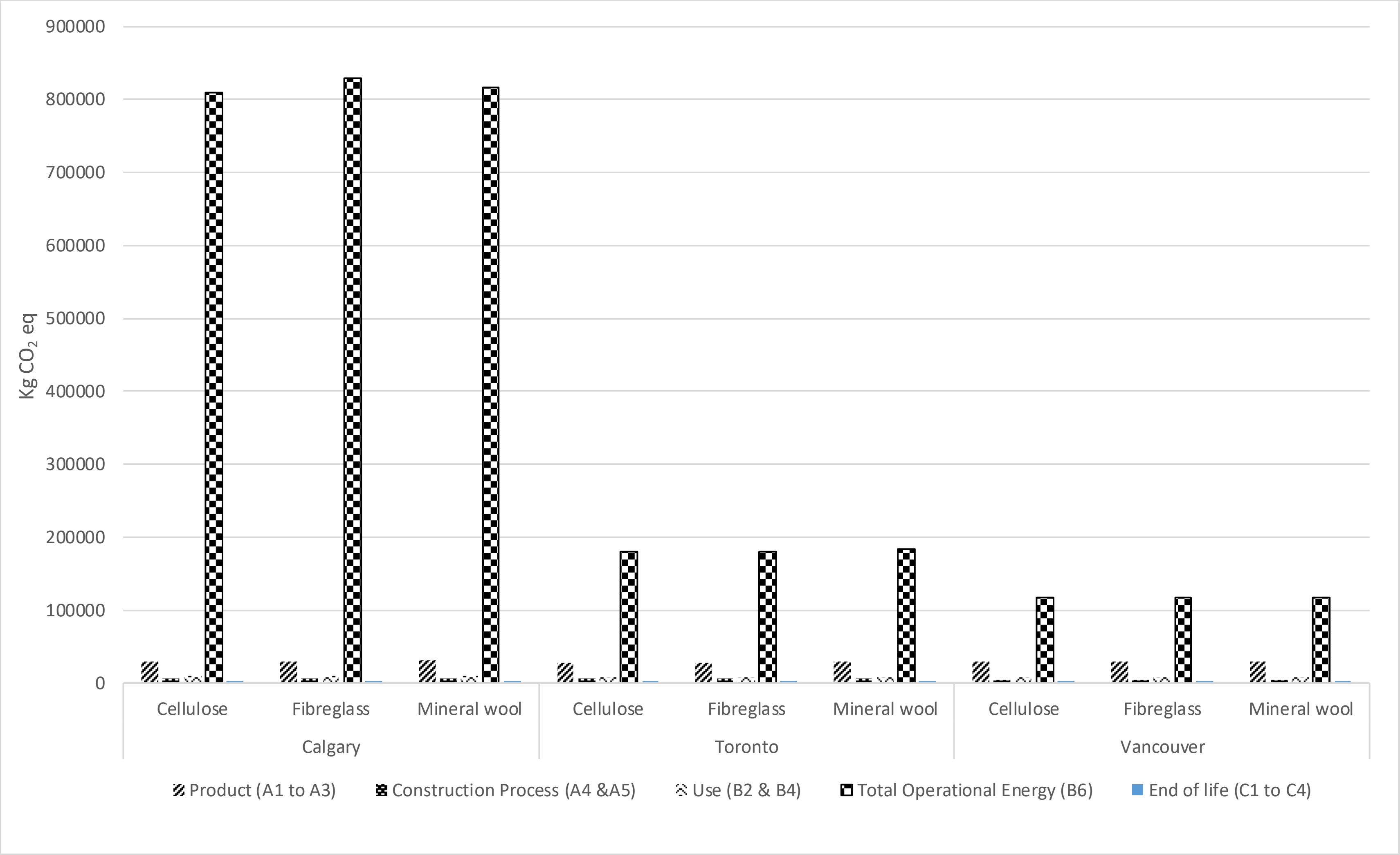


Figure 26: Comparison of GWP by Life Cycle Stage (60 years)

Appendix D: Energy Profile for each location

Monthly energy gain profile and heating system performance (kWh) for Vancouver

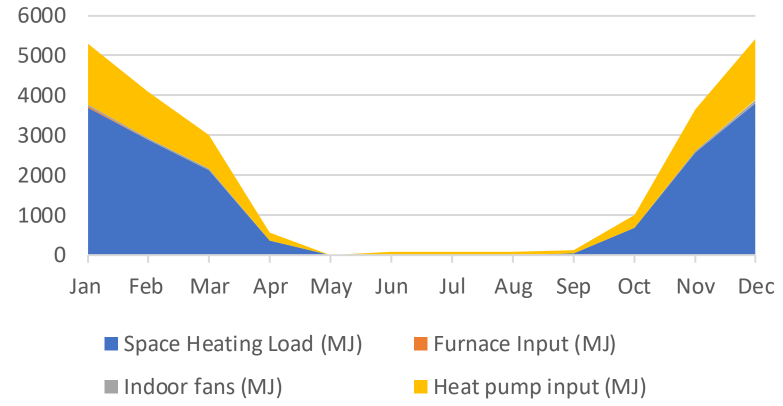


Figure 27: Space heating system performance for Vancouver (fibreglass)

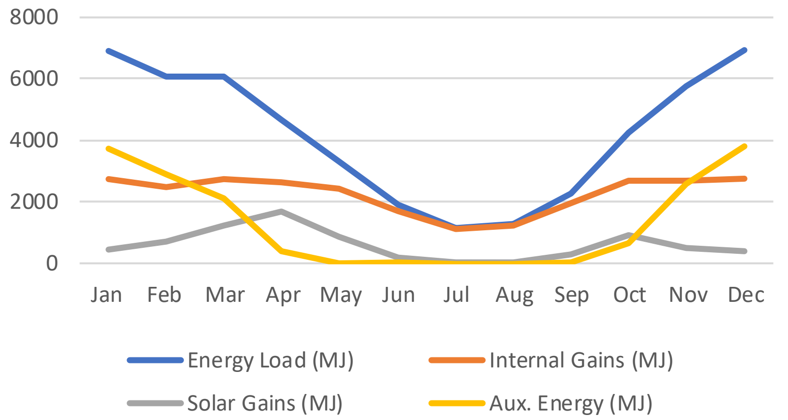


Figure 28: Monthly Energy Profile Vancouver (Fiberglass)

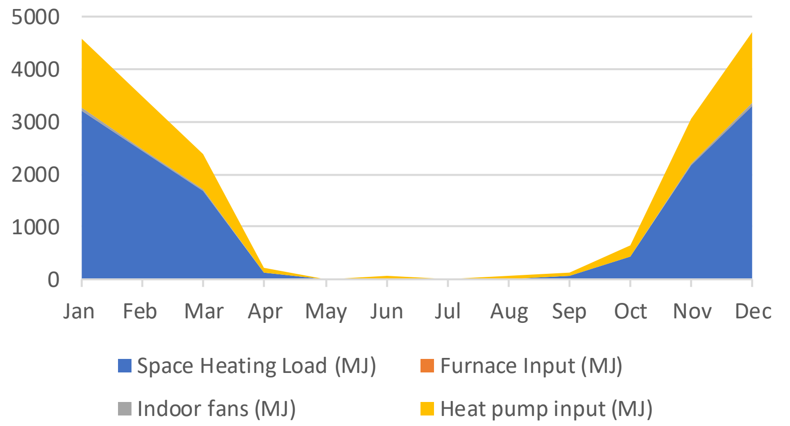


Figure 29: Space heating system performance for Vancouver (Blown Cellulose)

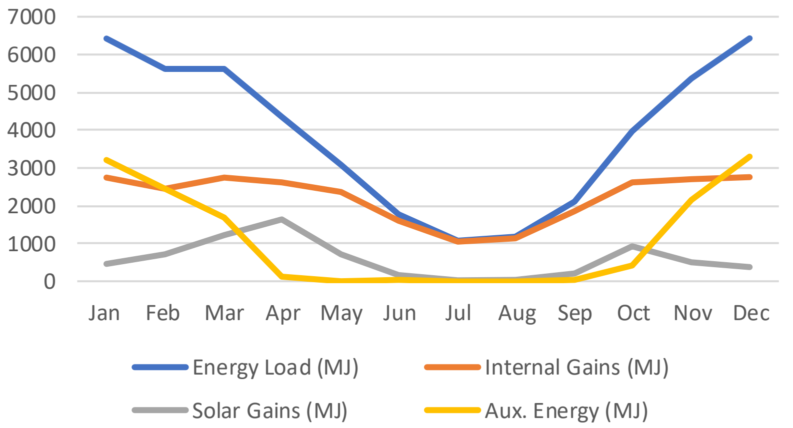


Figure 30: Monthly Energy Profile Vancouver (Blown Cellulose)

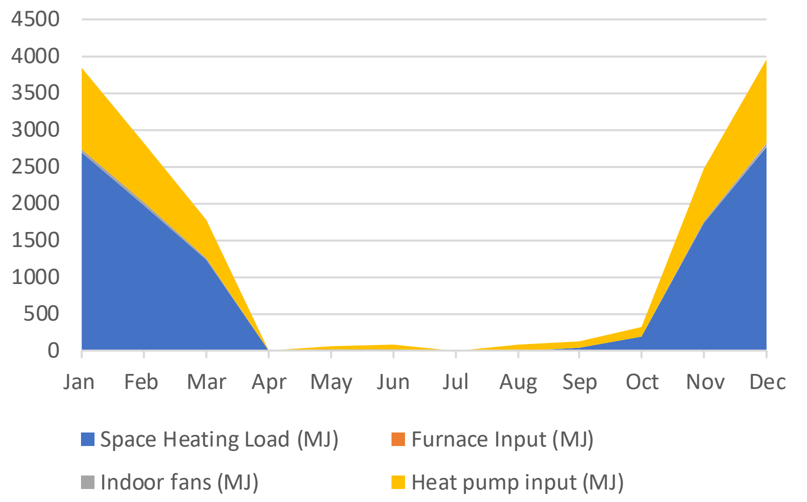


Figure 31: Space heating system performance for Vancouver (mineral wool)

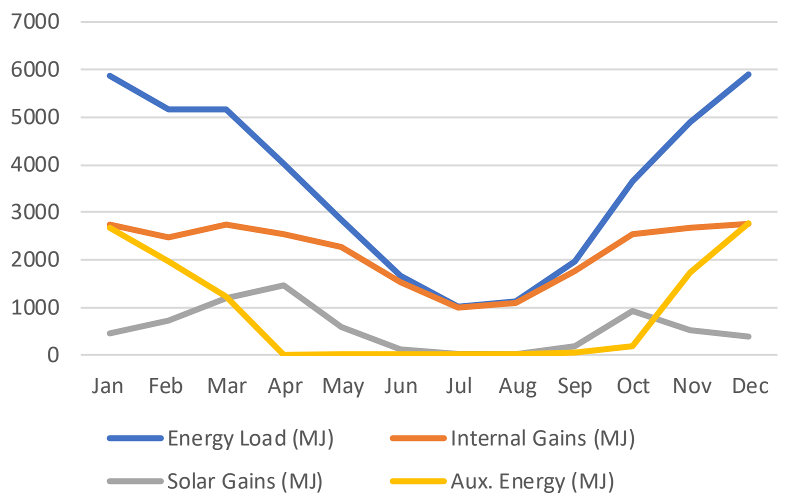


Figure 32: Monthly Energy Profile Vancouver (mineral wool)

To create a monthly energy profile for a house, the HOT2000 energy simulator evaluated energy gains from various sources, including solar radiation, internal heat from occupants and appliances, and auxiliary energy. Solar gain occurs via windows and skylights and increases the temperature in a space. Internal gains consider two adults and a child as occupants and include heat from lighting, electrical appliances, and more. The Auxiliary Energy result depends on factors like HVAC system type, specific Fan Power, variable speed pump selection, ductwork leakage classification, and room type during particular hours of operation. Figures 27-32 show that the house model with mineral wool insulation for its walls had the lowest space heating and energy load (kWh), followed by Blown Cellulose. The highest energy and space heating loads were consumed when Batts Fiberglass insulation was used. The simulation included both electricity and natural gas energy sources for Vancouver. Still, in British Columbia, the annual use of a furnace for heating water was minimalistic due to renewable energy availability such as hydropower.

Monthly energy gain profile and heating system performance (kWh) for Toronto

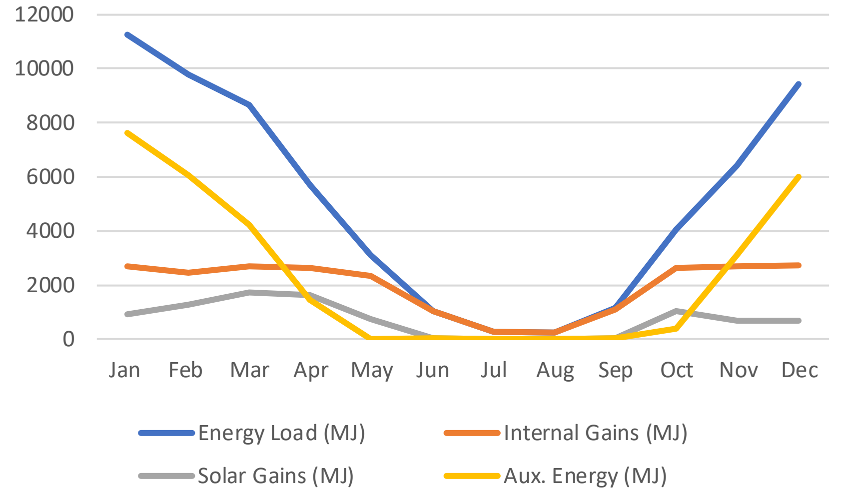


Figure 33: Monthly Energy Profile Toronto (Fibreglass)

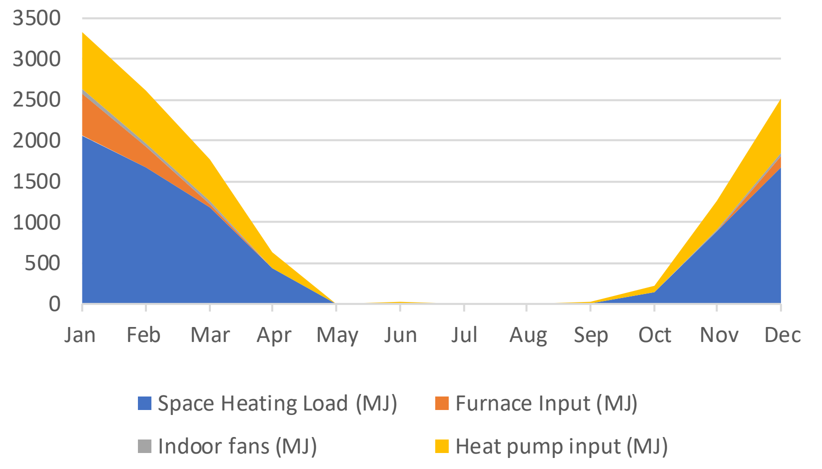


Figure 34: Space heating system performance for Toronto (Fibreglass)

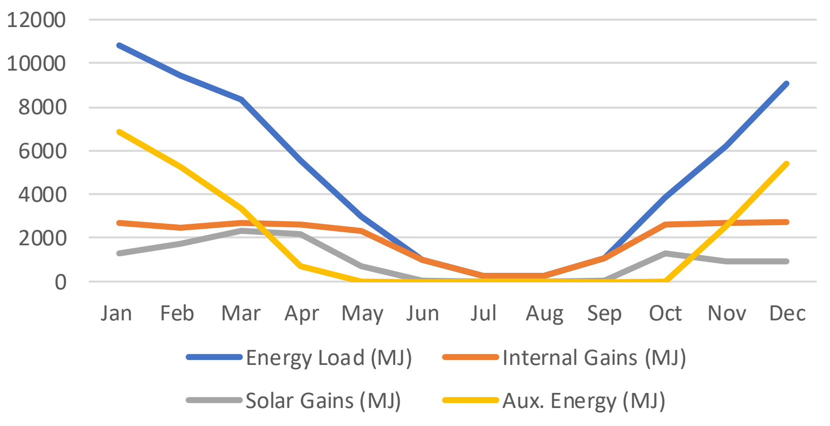


Figure 35: Monthly Energy Profile Toronto (Blown cellulose)

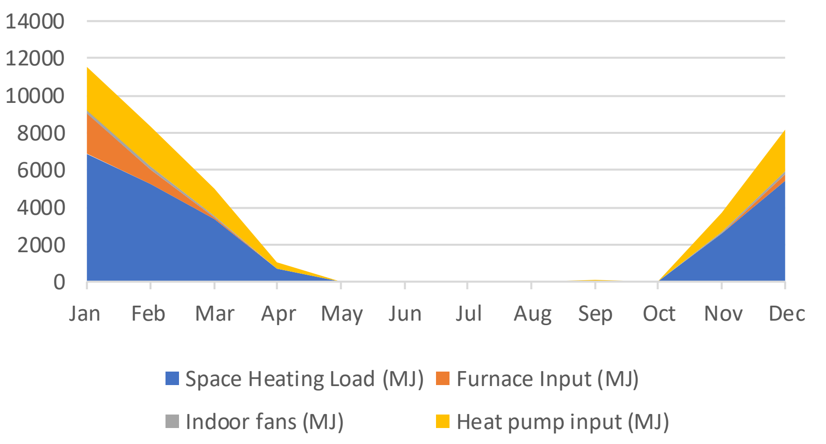


Figure 36: Space heating system performance for Toronto (blown cellulose)

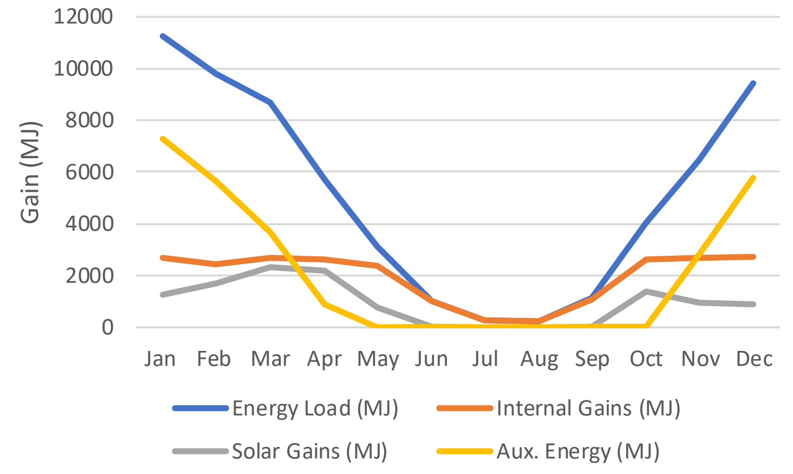


Figure 37: Monthly Energy Profile Toronto (mineral wool)

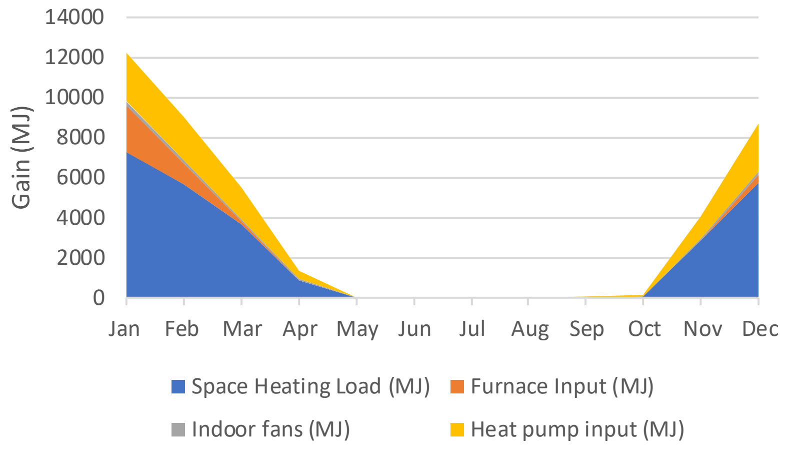


Figure 38: Space heating system performance for Toronto (mineral wool)

Upon reviewing Figures 33-38, the house model with Batts Fiberglass insulation for its walls had the lowest space heating and energy load, followed by Blown Cellulose. The highest energy and space heating loads were consumed when mineral wool insulation was used. The readings included both electricity and natural gas energy sources for Toronto. Additionally, the furnace played a role in heating water, especially at peak in January and gradual decrease to mid-March or early April.

Monthly energy gain profile and heating system performance (kWh) for Calgary

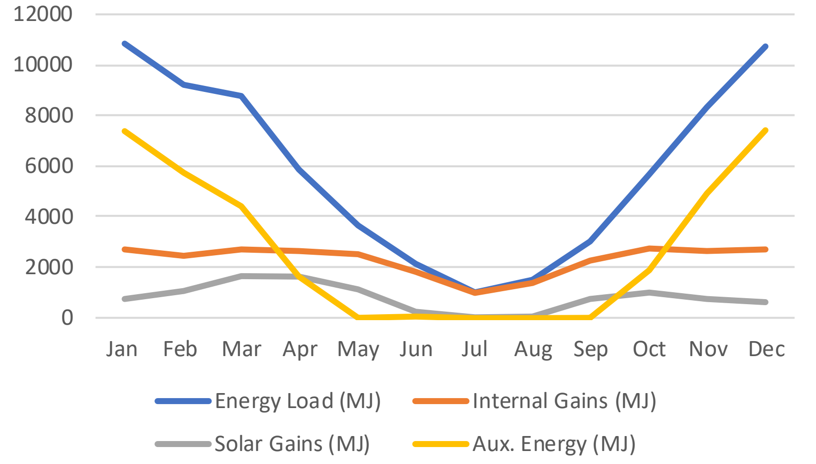


Figure 39: Monthly Energy Profile Calgary (fibreglass)

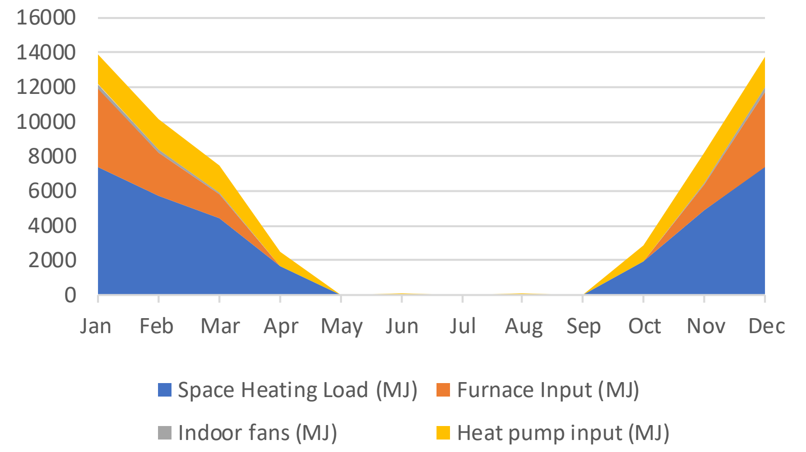


Figure 40: Space heating system performance for Calgary (Fibreglass)

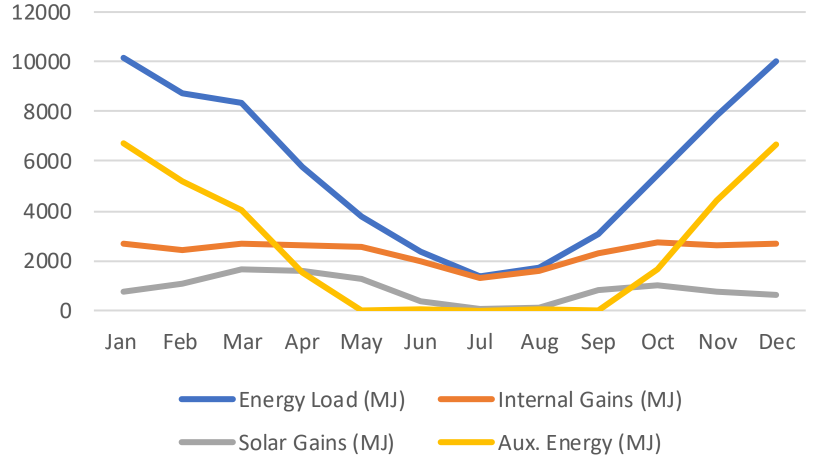


Figure 41: Monthly Energy Profile Calgary (Blown cellulose)

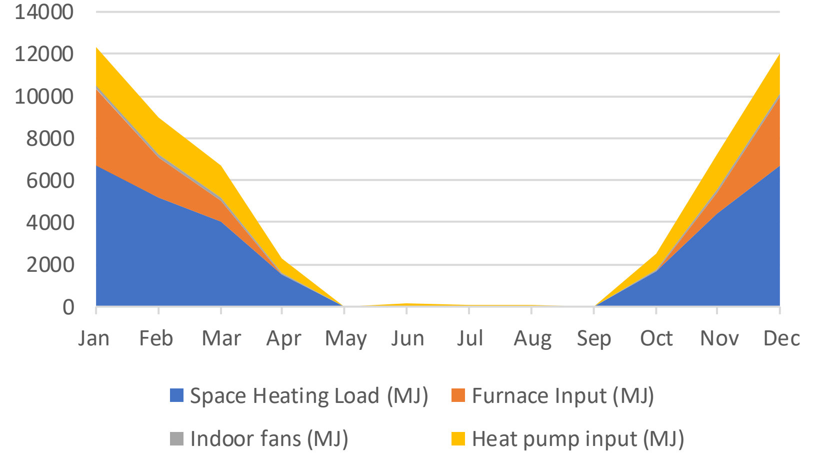


Figure 42: Space heating system performance for Calgary (Blown cellulose)

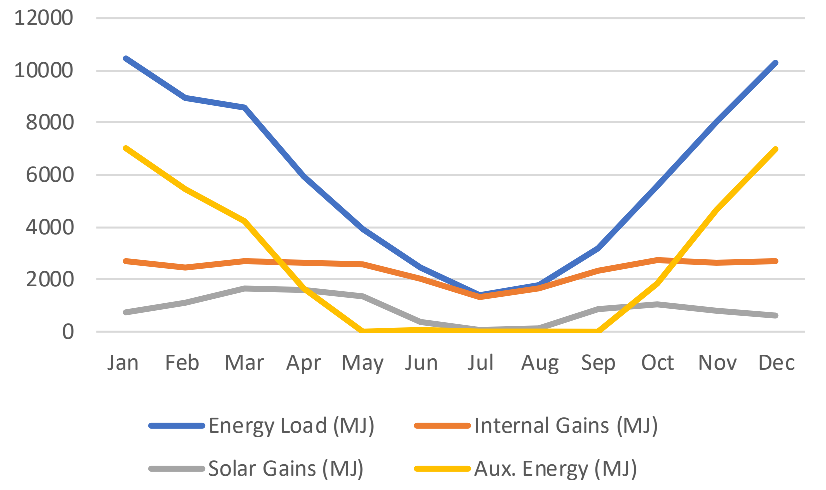


Figure 43: Monthly Energy Profile Calgary (Mineral wool)

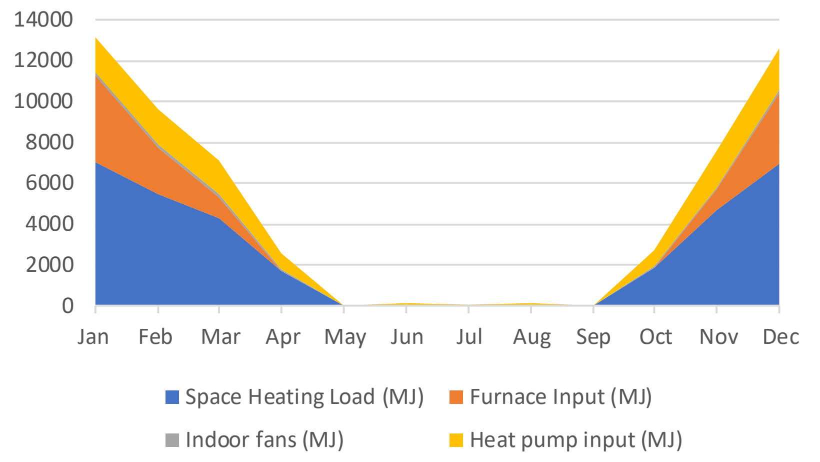
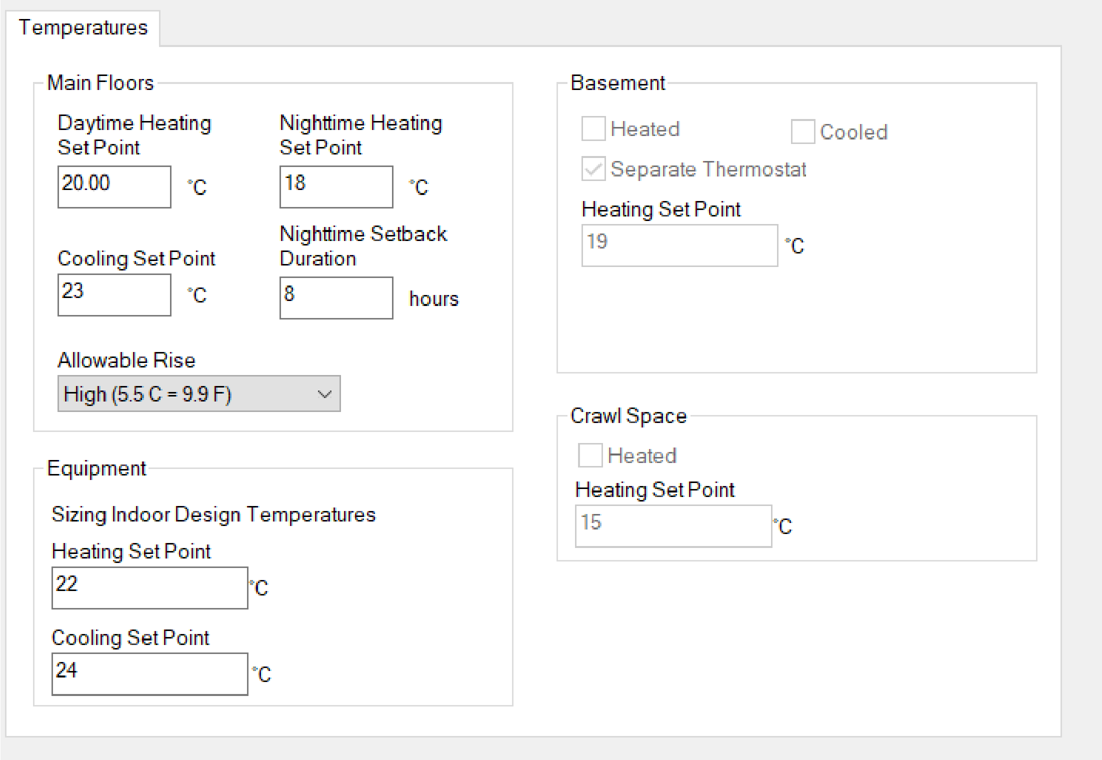


Figure 44: Space heating system performance for Calgary (Mineral wool)

The house model with Blown cellulose insulation for its walls had the lowest space heating and energy load, followed by mineral wool, as seen in Figures 39-44. The highest energy and space heating loads were consumed when Batts Fiberglass insulation was used. Two energy sources, electricity and natural gas, were considered for plotting the profile. Additionally, the furnace played a significant role in heating water, especially at peak between December and January and a gradual decrease to April.

Appendix E: HOT2000 input variables



Main Floors

Daytime Heating Set Point: 20.00 °C

Nighttime Heating Set Point: 18 °C

Cooling Set Point: 23 °C

Nighttime Setback Duration: 8 hours

Allowable Rise: High (5.5 C = 9.9 F)

Equipment

Sizing Indoor Design Temperatures

Heating Set Point: 22 °C

Cooling Set Point: 24 °C

Basement

☐ Heated ☐ Cooled

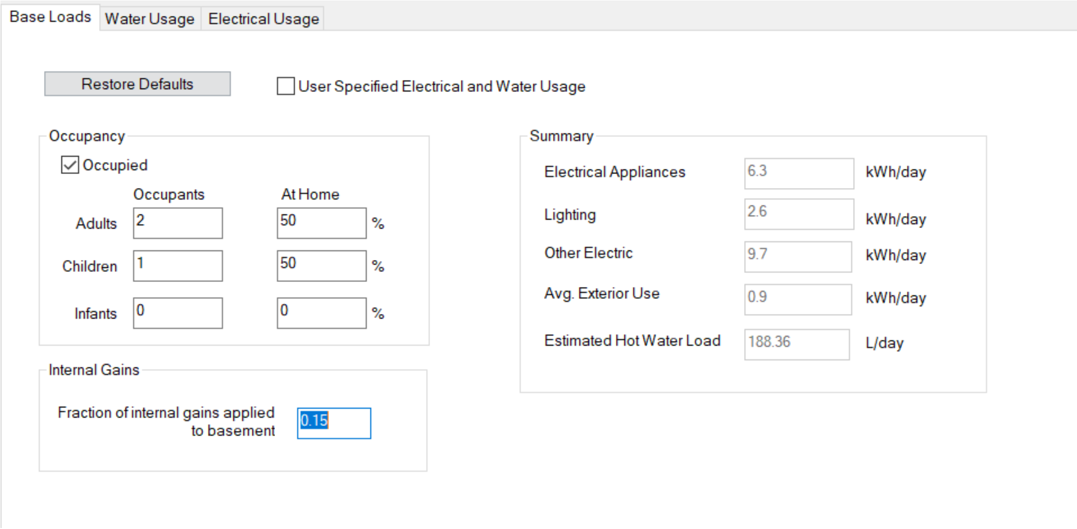
☑ Separate Thermostat

Heating Set Point: 19 °C

Crawl Space

☐ Heated

Heating Set Point: 15 °C



☐ User Specified Electrical and Water Usage

Occupancy

☑ Occupied

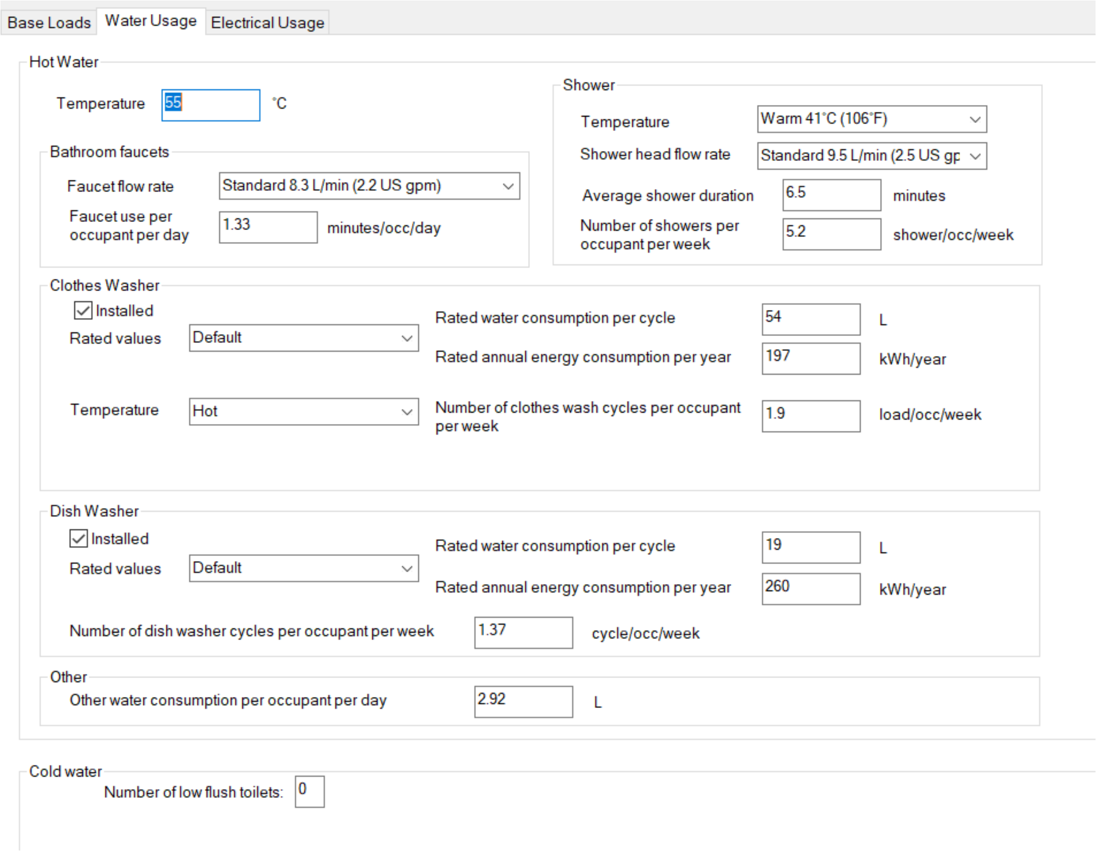
	Occupants	At Home
Adults	2	50 %
Children	1	50 %
Infants	0	0 %

Internal Gains

Fraction of internal gains applied to basement: 0.15

Summary

Electrical Appliances	6.3	kWh/day
Lighting	2.6	kWh/day
Other Electric	9.7	kWh/day
Avg. Exterior Use	0.9	kWh/day
Estimated Hot Water Load	188.36	L/day



Hot Water

Temperature 55 °C

Bathroom faucets

Faucet flow rate Standard 8.3 L/min (2.2 US gpm)

Faucet use per occupant per day 1.33 minutes/occ/day

Shower

Temperature Warm 41°C (106°F)

Shower head flow rate Standard 9.5 L/min (2.5 US gp

Average shower duration 6.5 minutes

Number of showers per occupant per week 5.2 shower/occ/week

Clothes Washer

☑ Installed

Rated values Default

Temperature Hot

Rated water consumption per cycle 54 L

Rated annual energy consumption per year 197 kWh/year

Number of clothes wash cycles per occupant per week 1.9 load/occ/week

Dish Washer

☑ Installed

Rated values Default

Rated water consumption per cycle 19 L

Rated annual energy consumption per year 260 kWh/year

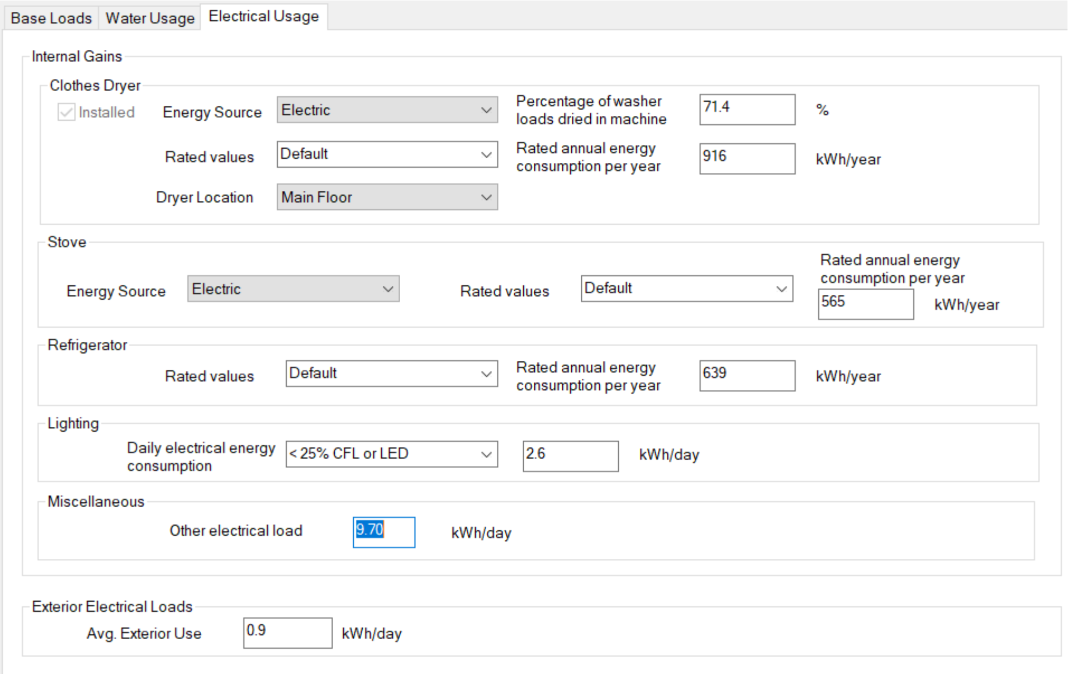
Number of dish washer cycles per occupant per week 1.37 cycle/occ/week

Other

Other water consumption per occupant per day 2.92 L

Cold water

Number of low flush toilets: 0



Internal Gains

Clothes Dryer

☑ Installed

Energy Source Electric

Rated values Default

Dryer Location Main Floor

Percentage of washer loads dried in machine 71.4 %

Rated annual energy consumption per year 916 kWh/year

Stove

Energy Source Electric

Rated values Default

Rated annual energy consumption per year 565 kWh/year

Refrigerator

Rated values Default

Rated annual energy consumption per year 639 kWh/year

Lighting

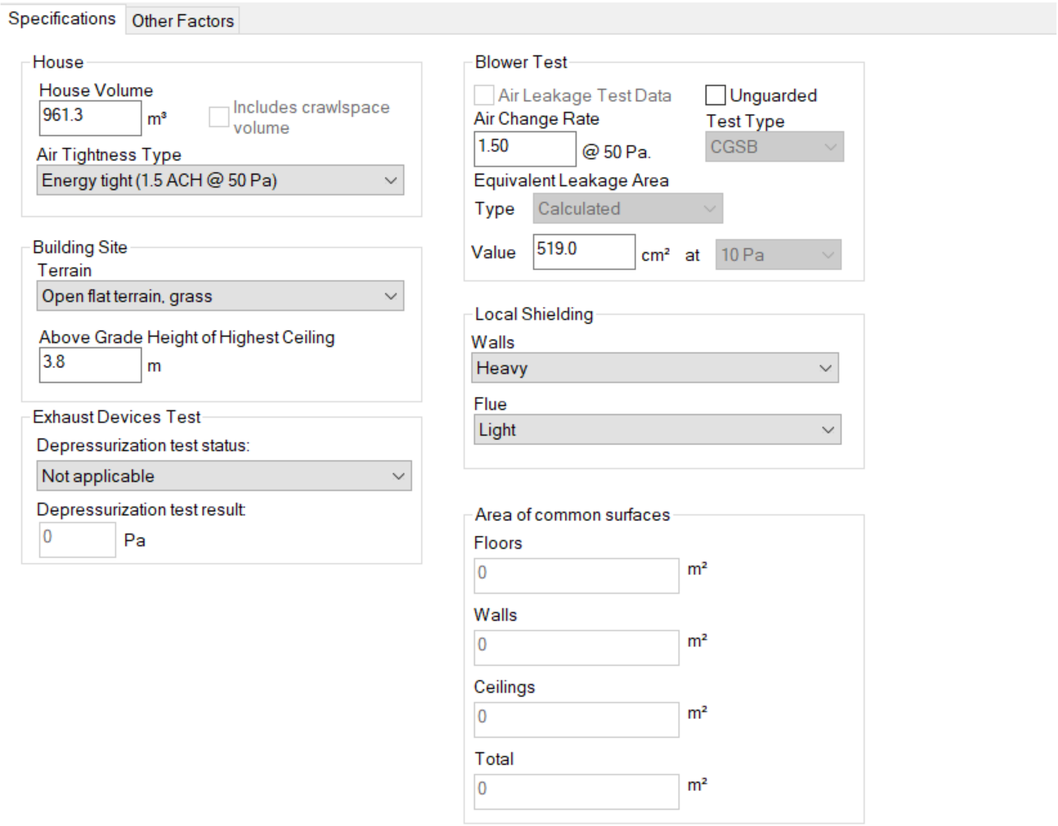
Daily electrical energy consumption < 25% CFL or LED 2.6 kWh/day

Miscellaneous

Other electrical load 9.70 kWh/day

Exterior Electrical Loads

Avg. Exterior Use 0.9 kWh/day



House

House Volume: 961.3 m³

☐ Includes crawlspace volume

Air Tightness Type: Energy tight (1.5 ACH @ 50 Pa)

Building Site

Terrain: Open flat terrain, grass

Above Grade Height of Highest Ceiling: 3.8 m

Exhaust Devices Test

Depressurization test status: Not applicable

Depressurization test result: 0 Pa

Blower Test

☐ Air Leakage Test Data

☐ Unguarded

Air Change Rate: 1.50 @ 50 Pa.

Test Type: CGSB

Equivalent Leakage Area

Type: Calculated

Value: 519.0 cm² at 10 Pa

Local Shielding

Walls: Heavy

Flue: Light

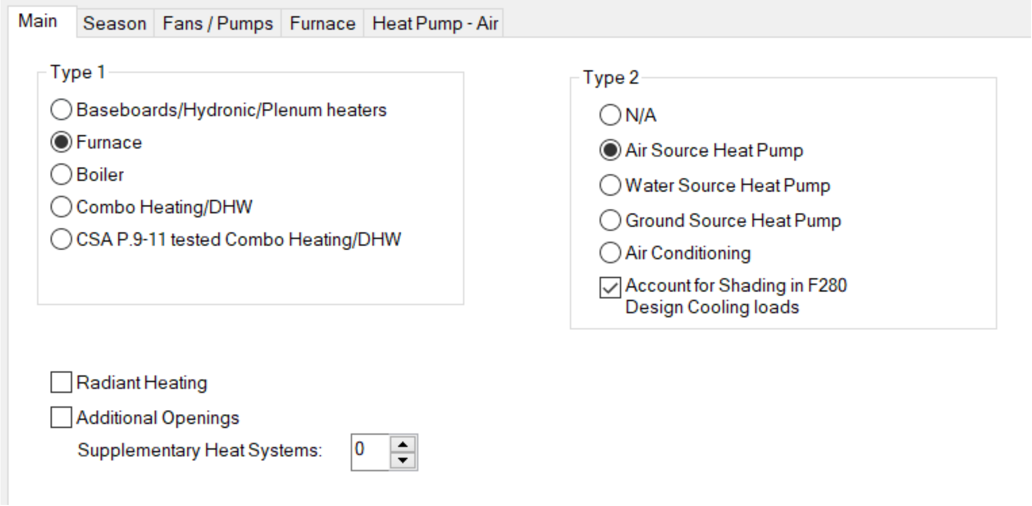
Area of common surfaces

Floors: 0 m²

Walls: 0 m²

Ceilings: 0 m²

Total: 0 m²



Type 1

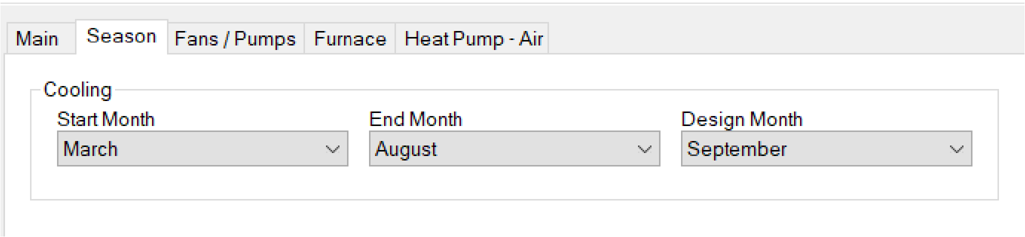
○ Baseboards/Hydronic/Plenum heaters
● Furnace
○ Boiler
○ Combo Heating/DHW
○ CSA P.9-11 tested Combo Heating/DHW

Type 2

○ N/A
● Air Source Heat Pump
○ Water Source Heat Pump
○ Ground Source Heat Pump
○ Air Conditioning
☑ Account for Shading in F280 Design Cooling loads

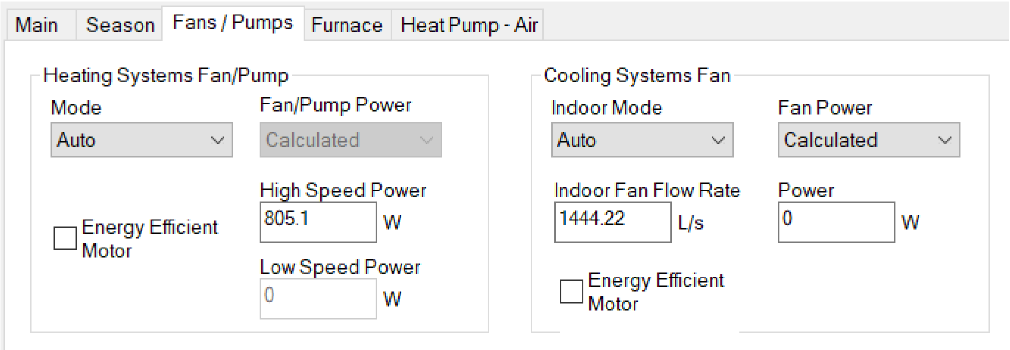
☐ Radiant Heating
☐ Additional Openings

Supplementary Heat Systems: 0



Cooling

Start Month: March
End Month: August
Design Month: September

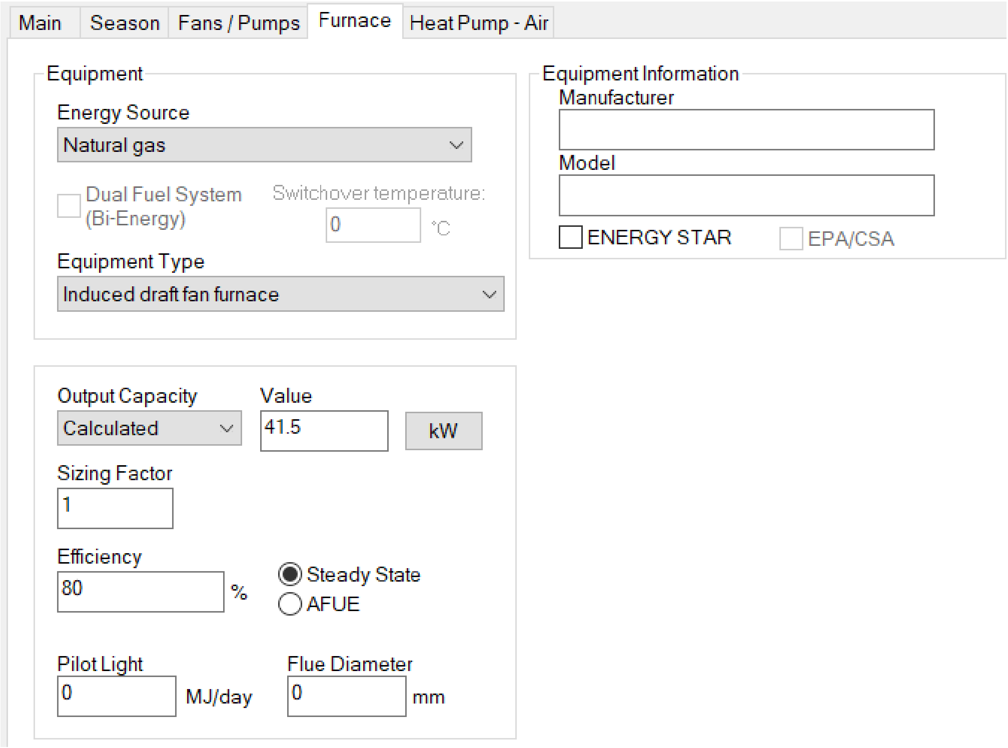


Heating Systems Fan/Pump

Mode: Auto
Fan/Pump Power: Calculated
High Speed Power: 805.1 W
☐ Energy Efficient Motor
Low Speed Power: 0 W

Cooling Systems Fan

Indoor Mode: Auto
Fan Power: Calculated
Indoor Fan Flow Rate: 1444.22 L/s
Power: 0 W
☐ Energy Efficient Motor



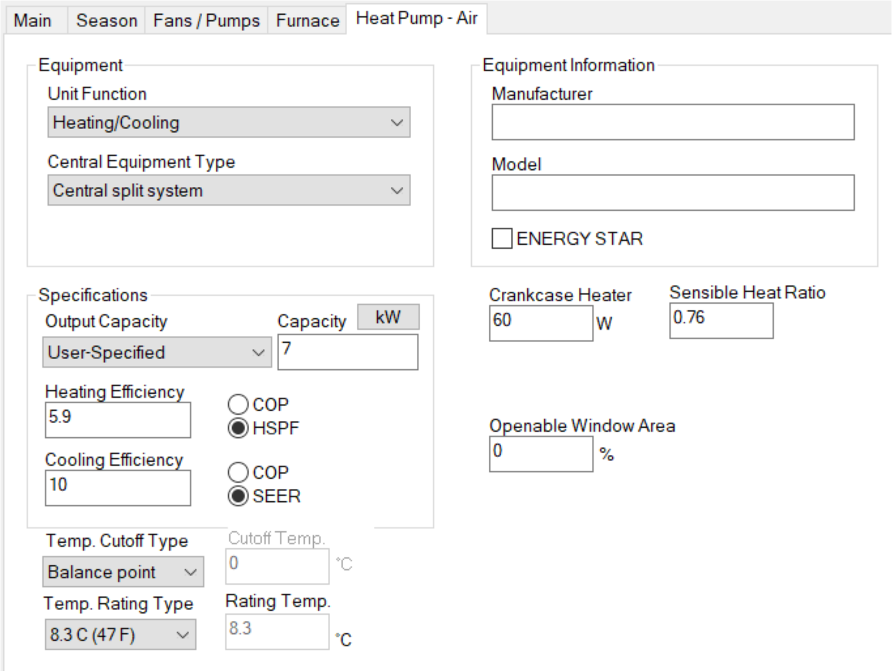
Equipment

Energy Source: Natural gas
☐ Dual Fuel System (Bi-Energy)
Switchover temperature: 0 °C
Equipment Type: Induced draft fan furnace

Equipment Information

Manufacturer:
Model:
☐ ENERGY STAR
☐ EPA/CSA

Output Capacity: Calculated
Value: 41.5 kW
Sizing Factor: 1
Efficiency: 80 %
● Steady State
○ AFUE
Pilot Light: 0 MJ/day
Flue Diameter: 0 mm



Equipment

Unit Function: Heating/Cooling

Central Equipment Type: Central split system

Equipment Information

Manufacturer:

Model:

☐ ENERGY STAR

Specifications

Output Capacity: User-Specified

Capacity: 7 kW

Heating Efficiency: 5.9 ○ COP ● HSPF

Cooling Efficiency: 10 ○ COP ● SEER

Crankcase Heater: 60 W

Sensible Heat Ratio: 0.76

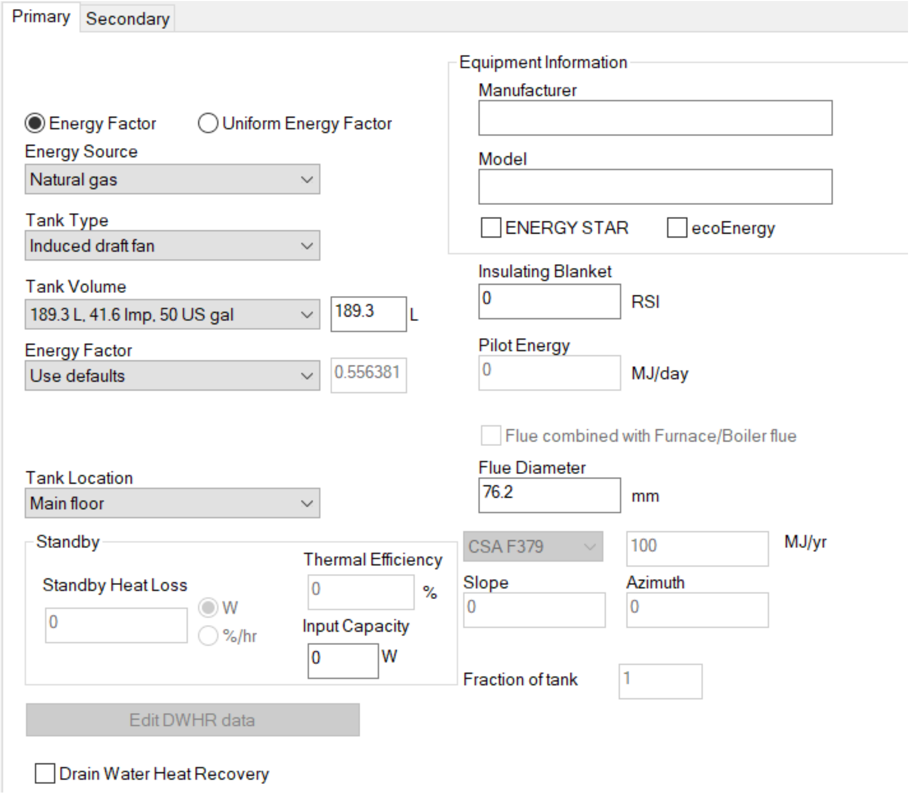
Openable Window Area: 0 %

Temp. Cutoff Type: Balance point

Cutoff Temp.: 0 °C

Temp. Rating Type: 8.3 C (47 F)

Rating Temp.: 8.3 °C



● Energy Factor ○ Uniform Energy Factor

Energy Source: Natural gas

Tank Type: Induced draft fan

Tank Volume: 189.3 L, 41.6 Imp, 50 US gal — 189.3 L

Energy Factor: Use defaults — 0.556381

Tank Location: Main floor

Equipment Information

Manufacturer:

Model:

☐ ENERGY STAR ☐ ecoEnergy

Insulating Blanket: 0 RSI

Pilot Energy: 0 MJ/day

☐ Flue combined with Furnace/Boiler flue

Flue Diameter: 76.2 mm

CSA F379 — 100 MJ/yr

Slope: 0

Azimuth: 0

Fraction of tank: 1

Standby

Standby Heat Loss: 0 ● W ○ %/hr

Thermal Efficiency: 0 %

Input Capacity: 0 W

☐ Drain Water Heat Recovery