Analyzing the Environmental Impacts of Imported Insulation Materials: A Comparative Study in a Canadian residential building

by

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Disclaimer

This document is part of an academic research project and is intended for informational purposes only. The analysis and observations presented herein are based on the specific methodology and assumptions employed in the study, including but not limited to the comparison of environmental impacts of insulation materials from different geographic origins (Europe and the United States) in the context of building lifecycle assessments (LCA) focusing on stages A1-A4. The findings reflect the data available at the time of the research and should not be generalized beyond the scope of this study.

While considerable effort has been made to ensure the accuracy, completeness, and reliability of the data and interpretations, unforeseen errors or omissions may exist. The results should not be construed as final or exhaustive, and their application to real-world construction projects or decision-making should be approached with caution. No responsibility or liability is accepted for any losses or damages arising from the use of the content of this document in any form.

The author recommends consulting qualified professionals or conducting further analyses before implementing any of the findings or methodologies outlined in this research. Additionally, as this is a pilot study, further investigation and validation may be necessary before drawing definitive conclusions or making practical applications.

Abstract

This study examines the life cycle environmental impacts of different insulation materials used in residential buildings in Vancouver, with a particular focus on the A1-A4 stages[1]—raw material extraction(A1), transportation to manufacturing (A2), manufacturing processes(A3), and transport to the construction site(A4). Under the CleanBC mandate to reduce greenhouse gas emissions by 40% by 2030, addressing both operational carbon (B1-B6) and embodied carbon (A1-A5) is crucial, particularly as embodied carbon is becoming a larger portion of total lifecycle emissions. This shift occurs because operational carbon can be reduced incrementally each year through improvements in building mechanical system efficiency. As a result, focusing on reducing embodied carbon during the design and construction phases is essential to achieving long-term sustainability goals in building lifecycle assessments.

Through a comparative analysis of insulation materials sourced from the United States and Europe, this study examines their Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Acidification Potential (AP) using Life Cycle Assessment (LCA), such as *Athena Impact Estimator, openLCA*. The findings indicate that U.S.-sourced insulation materials, such as rock wool and cellulose, generally exhibit lower environmental impacts across most metrics in the A1-A4 stages compared to European materials. U.S.-sourced cellulose consistently shows reduced GWP, ODP, and AP, making it a more sustainable choice for Canadian building applications. However, European materials demonstrate advantages in Ozone Depletion Potential (ODP) in certain cases, highlighting the significant influence of regional production and transportation processes on environmental performance.

The insights from this study offer a valuable basis for architects, engineers, and policymakers to make informed material sourcing decisions, thereby contributing to the broader goals of decarbonization and sustainable construction in Canada.

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[1] Life stages: A1: raw material extraction; A2: transport; A3: manufacture; A4: transport; A5: construction; B1: use; B2: Maintenance; B3: repair; B4: Replacement; B5: Disposal; B6: Operational energy; B7: Operational water; C1: Demolition; C2: Transport; C3: Waste processing; C4: Disposal;

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Abbreviations

LCA	Life Cycle Assessment
EPD	Environment Product Declaration
WBLCA	Whole-Building Life Cycle Assessment
NBC	National Building Code
CO2	Carbon Dioxide
GHG	Green House Gases
GWP	Global Warming Potential
CZ	Climate Zone
AIE	Athena Impact Estimator

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1. Introduction

The Government of British Columbia's CleanBC[2] initiative mandates a 40% reduction in greenhouse gas emissions by 2030, with CO2 being the primary driver of climate change. As of 2022, approximately 37% of CO2 emissions originate from the building sector [1]. Consequently, reducing emissions in this sector is critical for achieving broader climate targets. While operational carbon—the emissions generated during a building's use phase—has been extensively studied, embodied carbon, which accounts for the emissions from material production, transportation, and construction processes, has received comparatively less focus. However, addressing both operational and embodied carbon is essential for holistic decarbonization of the building sector. More recently, increased attention has been given to embodied carbon due to the realization that it is increasingly representing a large percentage of the total lifecycle GHG[3] emissions, in some cases representing more than 50% of the lifecycle emissions [2]. As buildings become more energy efficient, and energy sources, especially grid electricity become less carbon intensive, embodied emissions will represent an even higher percentage of life cycle emissions [1], as demonstrated in Figure 1.

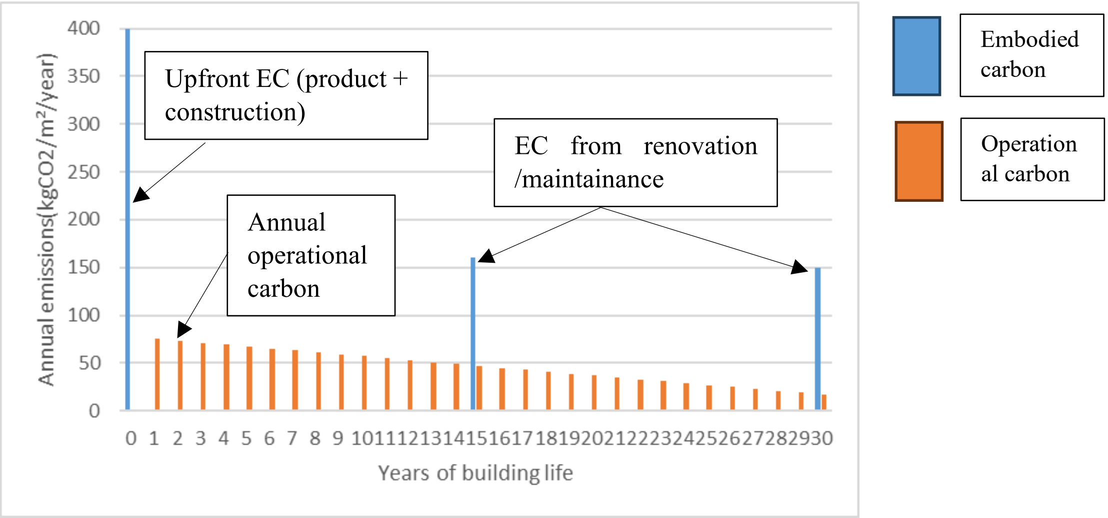

Fig. 1: Building materials, embodied and operational carbon [1]

According to the principles of Life Cycle Assessment (LCA), stages A1 to A4 (including raw material extraction, transportation to the manufacturing site, manufacturing, and subsequent transport of materials to the construction site) generally account for over 50% of the total embodied carbon emissions in a building . This substantial contribution highlights the critical need for careful material selection and efficient logistics management to mitigate carbon impacts during these early stages of the construction lifecycle [3].

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[2] CleanBC: A government's plan to lower climate-changing emissions by 40% by 2030.

[3] GHG: Greenhouse gas, e.g. CO2

Insulation materials are closely tied to reducing operational carbon emissions by enhancing energy efficiency. However, they also represent the second-largest source of embodied carbon emissions within the A1-A4 life cycle stages. Therefore, minimizing the upfront carbon emissions associated with insulation materials is essential for achieving substantial reductions in the overall carbon footprint of a building. Figure 2 illustrates the ranking of insulation materials in terms of their embodied carbon impact.

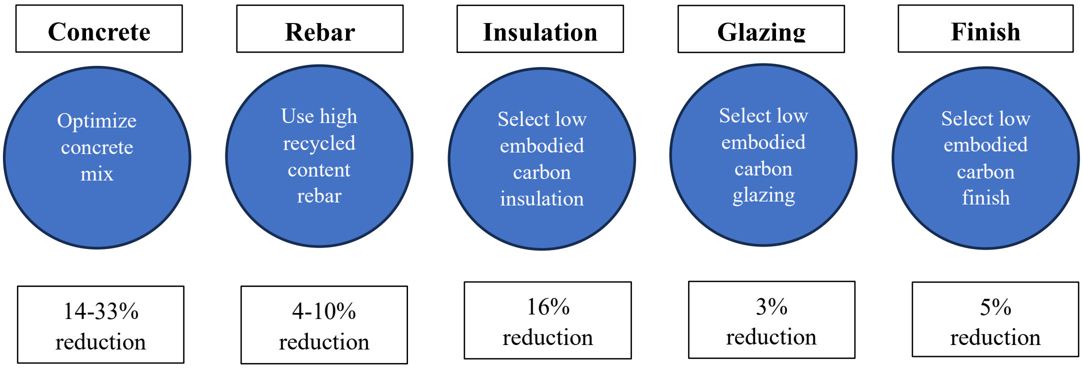


Fig. 2: Top categories for reducing embodied carbon [4]

1.1 LCA assessment – A1-A4

Life Cycle Assessment (LCA) is a widely adopted methodology for evaluating the environmental impact of buildings and construction materials throughout their life cycle, from raw material extraction (A1) to end-of-life stages (C4). The most commonly used LCA frameworks follow international standards such as ISO 14040 and EN 15978. Mainstream LCA tools, such as *openLCA, Athena Impact Estimator*, and *GaBi*, allow users to model the environmental impacts of construction materials and processes. These tools quantify emissions across multiple life cycle stages, including embodied carbon in stages A1-A3, which cover raw material extraction, processing, and transportation. The Athena Impact Estimator for Buildings is a software tool available at no cost for conducting a comprehensive life cycle assessment of buildings. It draws on an embedded database of regionally specific material life-cycle data. The tool allows for side-by-side comparisons allowing for a clear understanding of the impacts of various design choices [5]. *OpenLCA* is an open-source, modular framework designed to accommodate various plug-ins and modules. Some of the modules will also run as stand-alone applications [6]. However, many LCA tools face limitations when it comes to adjusting for variability in raw material sources or transportation distances, limiting their applicability for detailed regional analyses. To complement these tools, Environmental Product Declarations (EPDs) provide standardized data on material-specific environmental impacts, offering a reliable way to estimate embodied carbon in key life cycle stages.

Several mainstream open-source LCA software tools are available for conducting life cycle assessments. However, many of these tools are limited in their ability to modify specific parameters of the raw material extraction phase (A1), such as selecting different raw material sources or adjusting transportation distances and methods (A2).

This limitation can affect the accuracy of the assessment. To address this, Environmental Product Declarations (EPDs) offer provide a more accurate basis for estimating the embodied carbon in stages A1-A3, as they provide standardized and detailed information about material sourcing and processing. By utilizing EPDs, a more reliable estimation of the environmental impact during these early life cycle stages can be achieved.

For stage A4, *openLCA* is an appropriate tool for conducting calculations due to its availability of open-source and reliable transportation input data.

1.2 Embodied carbon and operational carbon

Embodied carbon refers to the carbon dioxide (CO2) emissions associated with the entire life cycle of a structure, from raw material extraction to its eventual disposal, commonly termed as "cradle to grave." It encompasses CO2 emissions generated during raw material extraction, manufacturing, transportation to the construction site, and the construction processes. These processes include the use of machinery, such as mechanical tools and excavators. Despite its critical importance, the strategies for addressing embodied carbon in buildings have remain underexplored in the US, resulting in a significant knowledge gap for engineers, architects, contractors, policymakers, and building owners.[5] In contrast, operational carbon refers to CO2 emissions associated with the building's operational phase, including energy consumption for heating, cooling, lighting, and maintenance. It also includes emissions at the building's end-of-life stage, such as those from demolition, transportation of waste, and disposal or recycling activities.

1.3 Environmental product declarations

An Environmental Product Declaration (EPD) provides a comprehensive report on the environmental impact of a product throughout its life cycle in accordance with ISO 14025. The EPD includes detailed information including the product's contributions to environmental issues such as global warming potential, smog formation, water pollution, eutrophication, acidification, and ozone depletion, among others. It is important to note that the existence of an EPD does not imply that the product meets specific environmental performance standards. Instead, EPDs function as disclosure tools, enabling stakeholders to make informed decisions about the environmental performance and sustainability of the products they are considering.

1.4 Research gap

The environmental impacts of insulation materials have been well-documented, particularly concerning embodied carbon and global warming potential (GWP). Existing literature primarily focuses on comparing different types of insulation materials, such as mineral wool, cellulose, and foam, with an emphasis on the energy efficiency and carbon payback periods of these materials. However, there is a significant research gap concerning the impact of geographical origin on the environmental performance of insulation materials during the A1-A4 stages, including raw material extraction, transportation, and manufacturing processes.

While some studies account for transportation as a contributing factor in the overall environmental impact, they seldom provide a comprehensive comparison of how sourcing materials from different regions, such as Europe and the United States, influences life cycle environmental indicators, such as GWP or ozone depletion potential (ODP), during these early stages. This gap is especially pronounced when analyzing materials for a specific building design and location, such as a residential building in Canada, where the origin of the insulation materials can significantly influence the overall environmental footprint owing to differences in production processes, energy sources, and transportation emissions.

Therefore, this research aims to address this research gap by conducting a country-specific comparative life cycle assessment (LCA) of insulation materials from Europe and the U.S. This approach will provide critical insights into how the geographical origin of materials influences the A1-A4 life cycle stages, facilitating more informed and sustainable material selection for construction projects.

2. Literature review

The literature on embodied carbon highlights its substantial contribution to overall building-related emissions. According to the 2021 report by RMI, embodied carbon encompasses the CO2 emissions resulting from the extraction of raw materials, their transportation, and the manufacturing processes involved in construction. These emissions represent approximately 11% of global carbon emissions. A considerable portion of these emissions arises during the A1-A3 stages of the life cycle, which include the raw material supply, manufacturing, and transportation phases. This underscores the importance of addressing embodied carbon early in the design and construction phases to effectively reduce the environmental impact of buildings.[5]

The embodied carbon full report highlights that traditional insulation materials, such as rigid foam boards and spray foam, contribute considerably to a building’s carbon footprint due to the high emissions from their production and the use of hydrofluorocarbons (HFCs) as blowing agents. However, emerging low-carbon alternatives, such as mineral wool and plant-based insulation products, have the potential to substantially reduce the carbon footprint during the A1-A4 phases.[4]

The Environmental Product Declaration (EPD) for ROCKWOOL™ Stone Wool Insulation provides a detailed analysis of the Global Warming Potential (GWP) and environmental impacts associated with the A1-A3 stages (raw material extraction, transportation, and manufacturing) of stone wool production in US. The stone wool insulation is produced in facilities located in Milton (Ontario, Canada), Grand Forks (British Columbia, Canada), and Byhalia (Mississippi, US), with environmental impacts based on aggregated data from these plants. The A1-A3 phase accounts for a significant portion of the product’s embodied carbon, with a GWP of 1.31 kg CO2-eq per m^2 of thermal insulation with an R-value of 1 m^2K/W. [7]

The Environmental Product Declaration (EPD) for ROCKWOOL Stone Wool Insulation produced in Germany provides a comprehensive analysis of the A1-A3 life cycle stages (raw material extraction, transportation, and manufacturing) and their contribution to embodied carbon. The insulation is produced at facilities in Gladbeck, Neuburg, Germany, and the data is representative of the production processes in these locations.

For a declared unit of 1 m^3 of uncoated stone wool insulation with a density of 99 kg/m^3, the Global Warming Potential (GWP) for the A1-A3 stages is 115 kg CO_2-eq. The majority of emissions are from raw material extraction and the energy-intensive manufacturing process. This underscores the significant environmental impact of the early stages in the life cycle of insulation materials and highlights the need for optimization to reduce embodied carbon.[8]

The AFT Carbon Smart™ Loose-Fill Cellulose Insulation, produced in Ohio, USA, utilizes recycled paper fibers, primarily recovered newsprint and cardboard, reducing its environmental impact. The A1-A3 life cycle stages (raw material extraction, transportation, and manufacturing) account for the majority of the product's Global Warming Potential (GWP), with a result of 0.389 kg CO2-eq per square meter of insulation. This low GWP is largely due to the use of locally sourced recycled materials and energy-efficient manufacturing.[9]

Ecocel Cellulose Fiber Insulation, produced in Cork, Ireland, is derived from recycled paper and used in pitched roofs, walls, and floor spaces. The A1-A3 life cycle stages—comprising raw material extraction, transportation, and manufacturing—contribute to a total Global Warming Potential (GWP) of 3.49 kg CO2-eq per square meter of installed insulation. This breakdown includes 1.60 kg CO2-eq for raw material sourcing (A1), 0.128 kg CO2-eq for transportation (A2), and 1.76 kg CO2-eq for the manufacturing phase (A3).[10]

"Comparative Analysis of Various National Building Codes and Carbon Payback Periods of Insulation Materials at Different Climate Zones in Canada" examines the environmental impact of thermal insulation materials in single-family homes across various Canadian climate zones. By evaluating Batts Fiberglass, Blown Cellulose, and Mineral Wool insulation materials in cities like Vancouver, Toronto, and Calgary, the study emphasizes the balance between embodied carbon and operational carbon savings, crucial for sustainable construction.

Using the Athena Impact Estimator (AIE) tool and HOT2000 energy simulator, the study calculates the Carbon Payback Period (CPP) for each insulation material, reflecting how quickly the operational carbon savings offset the embodied carbon. Results indicate that colder climates, with more heating degree days (HDD), experience shorter CPPs due to higher operational savings, as seen in Calgary. In contrast, warmer climates like Vancouver have longer CPPs. The findings underscore that material choice should consider both embodied and operational carbon impacts, tailored to the specific climate. [11]

In recent studies on reducing embodied carbon in buildings, the accuracy of the databases used to calculate carbon emissions has been shown to significantly influence the outcomes of Life Cycle Assessments (LCA). One study "The Role of Embodied Carbon Databases in the Accuracy of Life Cycle Assessment (LCA) Calculations for the Embodied Carbon of Buildings" that examined the embodied carbon of a standard Lidl supermarket highlighted the difference between using a general database versus a more detailed database. The results demonstrated that employing a more detailed database resulted in a 35.2% reduction in the calculated embodied carbon compared to using a general database. Furthermore, when Environmental Carbon Factors (ECFs) were selected to closely match material specifics, the embodied carbon was reduced by an additional 5.5%. This finding underscores the importance of accurate data in achieving reliable assessments.

The study emphasizes that the overestimation of embodied carbon, which can arise from the use of generalized approaches or databases, may lead to an inflated baseline, thereby complicating subsequent reduction efforts. Establishing an accurate baseline is critical to maximizing the effectiveness of any carbon reduction strategies. Moreover, the study identified limitations in available databases, particularly when conducting early design-stage LCAs, as these databases often lack the necessary variety of material-specific alternatives. The absence of an official national ECF database can introduce confusion into the LCA process, leading to increased labor and acting as a deterrent to carrying out detailed embodied carbon calculations. This highlights the need for the development of more consistent, nationalized ECF databases to support more accurate and accessible carbon assessments in the construction industry. [12]

In recent studies concerning the environmental impacts of insulation materials, both embodied energy (EE) and global warming potential (GWP) have emerged as critical factors for consideration. The findings of this study emphasize the wide variability in EE and GWP values across product sub-categories, reinforcing the necessity of utilizing specific Life Cycle Assessment (LCA) or Environmental Product Declaration (EPD) data where available. When such detailed product-specific data is absent, the study suggests using median values as the most representative estimates for insulation material categories.

A key observation from this research is the differentiation required between cellulose-based insulation materials, particularly those made from wood fibers through wet-forming methods, and those derived from recycled paper. These two sources exhibit distinct environmental profiles, highlighting the importance of product-specific data in material selection. Furthermore, the study underscores the importance of evaluating environmental impacts over the entire life cycle of materials, not just up to the factory gate, ensuring more comprehensive environmental assessments.

The research reviewed over 60 environmental product declarations (EPDs) of various insulation materials, including glass wool, mineral wool, expanded and extruded polystyrene, polyurethane, foam glass, and cellulose. The analysis revealed that hydrocarbon-based insulation materials tend to have higher GWP and EE values compared to inorganic or cellulose-based materials when measured by product volume. However, when evaluated on a functional unit basis (1 m^2 of insulation with R = 1 m^2 K/W), these distinctions often diminish, with some cellulose-based products showing surprisingly high EE values.

The relationship between EE and GWP was also examined, finding a correlation of 15.8 megajoules per kilogram of CO2 equivalents. This relationship offers a critical insight into the trade-offs between different insulation products, especially when comparing their environmental impacts. The study highlights the importance of using appropriate functional units and ensuring that insulation material selection in building projects is informed by specific environmental data to avoid reliance on generalized, less accurate information. [12]

Another research on thermal insulation materials highlights significant opportunities for improving energy efficiency and reducing embodied carbon emissions in residential buildings. A study focusing on Egypt shows that replacing traditional clay bricks with Autoclaved Aerated Concrete (AAC) and Expanded Polystyrene (EPS) sandwich panels can reduce energy use by 15%. Additionally, adding polyurethane insulation to clay brick and hollow block walls enhances their U-values, contributing to further energy savings of up to 15%. Achieving a U-value range between 0.38 and 0.5 W/m²K for exterior walls also improves thermal performance, with similar reductions possible for roofs and windows.

The environmental impact of traditional clay bricks is also noted, as their production releases significant carbon emissions. In contrast, AAC and EPS panels reduce embodied carbon by 32% and 35% during the A1-A3 stages of the life cycle. The study underscores the need for Egypt to adopt low-carbon materials and design strategies to meet decarbonization goals.

Methodologically, the study uses EDGE and One Click LCA tools to calculate energy savings and carbon reductions. It emphasizes the importance of creating a localized database for Egyptian building materials to improve accuracy in environmental assessments. [13]

Another study assesses the EC of a green office building in Sri Lanka and proposes strategies to reduce EC in the construction industry. Using Life Cycle Assessment (LCA), the study found that the building's EC amounted to 583.82 kgCO2e/m² of gross floor area, with reinforcement steel being the largest contributor (47.88%). Other materials such as concrete, cement blocks, and aluminum also had significant impacts.

The study highlights the need for low-carbon materials, efficient design, and the use of recycled or locally sourced materials to reduce EC. However, it acknowledges limitations due to the absence of country-specific carbon data for Sri Lanka and the exclusion of mechanical, electrical, and plumbing services from the assessment.

The findings are consistent with global research and underscore the importance of adopting sustainable practices, particularly in developing countries where construction growth is rapid. The results provide valuable insights for policymakers and designers aiming to reduce EC and support decarbonization in the building sector. [14]

Another recent study emphasizes the need for a holistic approach to reducing energy, carbon, and water footprints in building construction. Reducing embodied impacts requires not only choosing lower-impact materials but also improving energy generation processes. While operational energy is a significant factor, the embodied energy (EE), carbon (EC), and water (EW) from construction materials and processes are critical to understanding the full environmental impact. This study evaluates the embodied impacts of four university buildings, revealing EE values between 13.1 and 51.1 GJ/m², EC between 1.4 and 10.0 kgCO2/m², and EW between 2,820 and 12,900 gal./m². A strong correlation between EE and EW suggests that addressing energy consumption could also help reduce water use, though a majority of EW does not stem directly from energy use.

The findings highlight the significant role of materials like aluminum, structural steel, and drywall, which have high EE and EW due to electricity and coal use. Reducing the water footprint in energy generation, especially from fossil fuels, could significantly impact EW reduction. Recycling and reusing materials can further decrease direct EE and EW. The study underscores the importance of adopting an energy-carbon-water nexus approach to building design and optimizing material choices based on their performance and environmental impact. [15]

Green building certification systems (GBCSs) play a crucial role in sustainable city development, but they often overlook embodied energy (EE) and thermal insulation. Another study evaluates the life cycle energy of non-residential buildings in Malaysia, comparing green-rated and non-green buildings. The findings show that EE accounts for 16–19% of total energy consumption, emphasizing its importance in GBCS. The material phase contributes 68–74% of the total EE, suggesting that using recycled and low-embodied materials, like recycled steel, should be incentivized.

Additionally, implementing insulation materials in building walls can reduce cooling energy demand by 85%, with cellulose fiber being the most energy-efficient option. To align with global energy reduction targets, EE should be integrated into GBCS to address short-term energy consumption, complementing efforts to reduce operational energy (OE). The study also recommends incorporating other criteria, such as water efficiency and carbon analysis, for a more comprehensive assessment of green buildings. Expanding the research to include urban industrial symbiosis and economic analysis of embodied materials is suggested to further improve GBCS development. [16]

Another study about reducing embodied carbon, reducing EC can be achieved through material substitution, using low-carbon materials like mass timber, and demand reduction, promoting material reuse and renovation over new construction. Cities like Vancouver have implemented deconstruction policies to encourage reuse, aligning with circular economy principles.

Embodied energy (EE) and embodied water (EW) are also critical, particularly with energy-intensive materials like steel and aluminum. Reducing EE through the use of recycled materials offers potential to lower both EC and EW.

Despite progress in material science and policy, widespread adoption of EC reduction strategies remains limited. Integrating EC considerations into existing urban policies focused on waste, equity, and preservation can enhance sustainable building practices. [17]

Another new study is integrating green building materials like phase change materials

(PCM) and fly ash into construction practices, particularly in colder climates. Recent research has highlighted the potential of these materials to reduce both energy consumption and carbon emissions, underscoring the importance of life cycle assessments (LCA) in evaluating the environmental performance of green versus conventional buildings.

Embodied carbon (EC) plays a key role in assessing the overall environmental footprint of buildings. Studies utilizing the ReCiPe2016 Midpoint (E) method have demonstrated that green buildings with PCM and higher percentages of fly ash cement significantly reduce carbon emissions. For example, incorporating 35% fly ash cement and PCM has been shown to lower carbon emissions to 9.68×10^4 kg CO2 equivalent, a notable reduction compared to conventional buildings emitting 1.04×10^5 kg CO2 equivalent. This demonstrates the efficacy of using advanced materials like PCM in reducing the carbon footprint of buildings, particularly in cold climates like Norway.

In terms of energy efficiency, PCM plays a critical role in reducing heating and cooling demands in buildings. Research indicates that the combination of 35% fly ash cement and PCM can result in a 15% reduction in cooling energy and a 6.9% reduction in heating energy, with an overall annual energy consumption of 97,453.09 kWh. These findings emphasize the potential for green building materials to improve energy performance while reducing operational energy consumption (OE).

At the midpoint level, the most significant environmental impacts of building materials are associated with freshwater and marine ecotoxicity. At the endpoint level, the primary impacts are on human health and ecosystems, making it essential to adopt sustainable materials and designs to mitigate these effects.

However, despite the progress made in incorporating PCM and fly ash into construction, research limitations persist. These include data quality issues, generalizability to different geographic regions, and the need for more comprehensive assessments of indirect impacts, such as social and economic factors. Additionally, evolving technological advancements may further refine the accuracy of LCA models in the future. [18]

As the EU directives mandate all new buildings to be nearly Zero Energy Buildings (nZEB) by 2021 and all buildings by 2050, the focus has shifted to reducing operational energy. However, research highlights that increasing energy efficiency often raises embodied energy and carbon impacts, particularly due to material production (Din and Brotas, 2016).

Life Cycle Assessment (LCA) has become a valuable tool to assess these impacts, though precise calculations remain complex. The integration of LCA into Sustainable Building Rating Systems (SBRS) is essential for balancing energy efficiency and environmental performance. While SBRS provides a structured approach, inconsistencies in methodologies and interpretations across different systems reveal a need for standardized protocols.

Low-energy buildings, such as passive houses, benefit from LCA by considering both material environmental impacts and energy efficiency, yet discrepancies in SBRS applications highlight the challenges in achieving uniformity. Future research should address these variations to enhance the use of LCA in building assessments and support the EU's climate goals. [19]

Another research on GHG emissions from the Canadian construction sector shows that while direct emissions from construction activities account for only 2-3% of industrial emissions, the sector drives 13% of consumption-based emissions. This underscores the value of consumption-based models, such as Environmentally Extended Input-Output (EEIO) models, for contextualizing emissions in the Canadian construction industry, which is often overlooked in production-based climate policies.

The analysis also reveals significant regional variation in construction emissions, driven by factors such as population growth, the oil and gas industry, and differences in construction efficiency (measured in kgCO2eq per dollar spent). These differences are influenced by the cleanliness of local electricity generation and the origin of imported construction materials. Such regional discrepancies highlight the need for tailored policy interventions that account for local conditions and industry practices when addressing emissions in the construction sector. [20]

The transfer of embodied CO2 emissions through international trade has become a crucial factor in global climate change strategies, with studies highlighting the need to address emissions transferred through exports. Research using the World Input–Output Database (WIOD) and the Asian Development Bank's Multiregional Input–Output Database (ADB-MRIO) has provided valuable insights into Canada's embodied emissions in exports (EEE) from 2000 to 2018. The study reveals that intermediate exports are the primary contributor to Canada's EEE, with an increasing complexity in emission paths involving multiple countries. This trend, driven by the expansion of global supply chains, complicates the traceability of Canada's emissions.

Canada's energy and resource sectors—including electricity, petroleum, wood, and metals—are critical drivers of these emissions, as they transfer a substantial portion of embodied emissions downstream along supply chains. The study underscores the importance of adopting life cycle approaches for emission reduction, addressing the entire product/service supply chain rather than focusing solely on domestic industries.

Key findings indicate that while export expansion tends to increase emissions, sectoral decarbonization—especially in energy and transportation—helps mitigate this impact. Addressing international leakage through collaborative governance is essential for effective global climate policies. The research framework also holds potential for application in other countries to assess embodied emissions and inform policy interventions targeted at key industrial sectors. [21]

The increasing demand for housing and the need to reduce embodied greenhouse gas (GHG) emissions in construction are critical challenges in mitigating climate change. Material production accounts for over 25% of global GHG emissions, necessitating more efficient housing strategies. Recent studies highlight the potential of missing middle housing—low-rise, multi-unit residential buildings—as a solution to provide housing while reducing embodied GHG emissions. By comparing missing middle housing to single-family and mid/high-rise buildings, researchers found that missing middle forms generally exhibit lower embodied GHG emissions per bedroom, ranging from 5,540 to 39,600 kgCO2eq. Notably, multi-unit missing middle buildings have significantly lower embodied GHG emissions compared to single-family homes (12,700 vs. 17,000 kgCO2eq/bedroom).

Despite the overall trend, variability within housing forms exceeds that between forms, underscoring the importance of building design in reducing emissions. Key strategies to minimize embodied GHG include reducing substructure sizes, limiting parking spaces, and selecting low-GHG materials like eco-friendly insulation. For mid/high-rise buildings, reducing slab thickness is critical, as 69.5% of their superstructure emissions are related to concrete volume. These findings suggest that adopting best-in-class design strategies and promoting missing middle housing can substantially cut future residential embodied emissions, particularly in Ontario, Canada, where emissions could be reduced by up to 46.7% without requiring changes in material technology. Future work should focus on expanding Building Information Modeling (BIM) for GHG accounting and further implementing material efficiency strategies in residential construction. [22]

Another study highlights the limitations of existing tools and proposes a partial LCA framework to optimize carbon emission calculations during construction. By comparing five commonly used LCA tools, the study identifies their strengths and weaknesses and introduces a newly developed carbon calculation system designed to address these gaps.

The system integrates three databases—for building materials, transportation, and construction equipment—offering a comprehensive and customizable approach for users to assess embodied carbon in construction plans. Unlike traditional LCA tools, this system allows users to modify data and compare substructure options, providing detailed output forms to simplify analysis. The system's flexibility and user-friendly interface support sustainable decision-making during the design and construction phases, offering practical solutions for reducing embodied carbon.

A case study comparing masonry walls and timber frame structures demonstrates that timber frames reduce embodied carbon emissions by 16%, primarily due to the reduction in the use of concrete, steel, and blocks, key contributors to carbon emissions. The study emphasizes that material choice and recycling can significantly reduce embodied carbon, particularly through the reuse of steel and other recyclable materials. This research provides valuable insights into improving sustainability in the construction phase and offers a framework for integrating sustainable materials and design choices to optimize carbon emissions in future projects. [23]

The pursuit of net zero energy-ready buildings (NZErB) in Canada has led to significant research on both new constructions (NBs) and retrofitted buildings (RBs). Studies show that 83.3% of NBs achieve level 5 in thermal energy demand intensity (TEDI) due to advanced insulation materials like blow-in cellulose, while only 50% of RBs reach this level, highlighting retrofitting challenges. Mechanical energy use intensity (MEUI) is similarly high in NBs, with 91.6% achieving level 5, aided by efficient systems such as air source heat pumps (ASHP) and heat recovery ventilators (HRV). In contrast, 70% of RBs meet level 5 MEUI through diverse heating systems, including ground source heat pumps (GSHP).

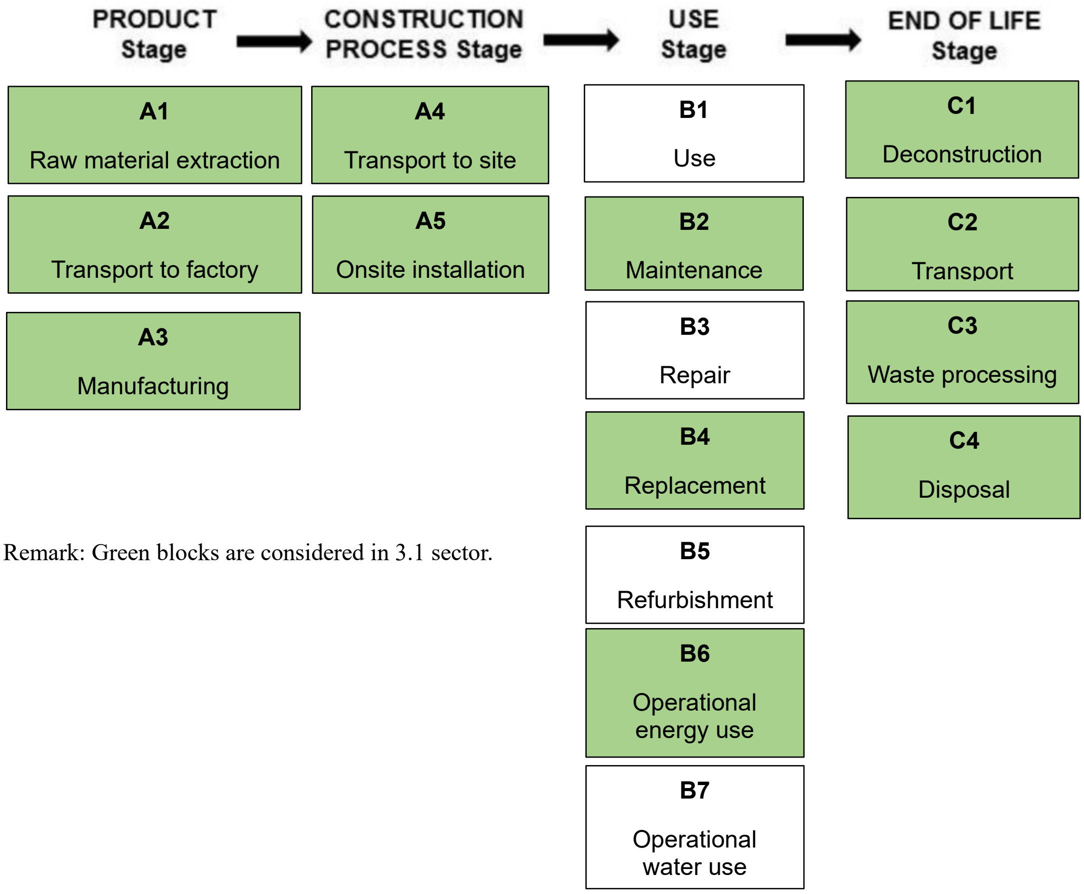
Life cycle assessments reveal that cellulose insulation has the lowest global warming potential (GWP) at 12.07 kg CO_2-e·m−3, while polyurethane (PUR) insulation exhibits the highest at 203.73 kg CO_2-e·m−3, underscoring the importance of selecting sustainable insulation materials. Although retrofitting remains cost-intensive, it provides a viable path to NZErB status through strategic improvements in airtightness, insulation, and heating systems. [24]

3. Materials and Methods

3.1 AIE application of a Vancouver located residential building model

Although some studies suggest that embodied carbon accounts for approximately 45% of a building's total carbon emissions, the data for buildings located in Vancouver is not detailed enough to be relied upon for a rigorous academic analysis. Therefore, it is crucial to run a simulation using AIE software to determine the exact contribution of embodied carbon, particularly focusing on the A1-A4 stages, within the full life cycle of a building. This approach will provide more precise data, essential for accurately assessing the environmental impact of construction in a specific context. [30]

AIE software follows the guidelines set by ISO 14040:2006 and ISO 14044:2006. These standards outline four main life cycle stages: product, construction, use, and end of life, which are further divided into 16 substages [25], as illustrated in Figure 3. This framework provides a comprehensive approach to assessing environmental impacts across the entire life cycle of a building, ensuring consistency and accuracy in life cycle assessments.



Remark: Green blocks are considered in 3.1 sector.

Fig. 3: System boundary used by AIE software [26].

Take the building insulation material for example, see table 1:

Table 1: A life stages explanation example

Life stages	Explanation
A1	Get raw material from stone (nature)
A2	Transport raw material to factory
A3	Process the raw material to insulation product
A4	Transport the product to construction site
A5	Installation on construction site
B2	Maintenance for the insulation product in building envelope
B4	Replace the insulation product
B6	The energy to run the building (not specifically for insulation), e.g. electricity of HVAC
C1	Demolish the product
C2	Transport the garbage to waste process center
C3	Waste recycles (if applicable)
C4	Waste disposal

The goal and scope definition outlines the functional unit, system boundaries, and criteria for inventory data quality. In this study, the system boundary begins with resource extraction and construction product manufacturing, extends to site preparation and the building construction process (pre-occupancy phase), continues through the operating energy and maintenance phase (occupancy phase), and concludes with the building demolition process (post-occupancy phase), as illustrated in Figure 3.

For residential buildings, determining the functional unit is essential when conducting an LCA. For thermal insulation products, the functional unit is defined as thermal resistance (R) in m^2K/W, which balances environmental impacts during production, installation, and disposal with the benefits realized during use. This study uses a functional equivalent based on the square meter size of residential neighborhoods with an average lifespan of 60 years.

The life cycle inventory analysis (LCIA) collects and synthesizes data on materials and energy use. Seven impact categories were assessed using AIE software and the US Life Cycle Inventory database (Version 5.5), including global warming potential, fossil fuel consumption, acidification potential, and others. The LCA follows ISO 14044 guidelines, with significant results discussed in the interpretation section.

3.2 The model for AIE's simulation

3.2.1 single family residential model

The building analyzed in this study is a single-family residential home consisting of three bedrooms, a living room, and a kitchen. A bird view is provided in Figure 4. The total floor area is 248.6 m^2, with a building height of 3.1 meters. The foundation is constructed from concrete and steel rebar, which are the heaviest components of the structure. The main frame of the house is built using 2x6 inch (38x140 mm) wood studs. This is a single-story building with no additional floors. A detailed 3D model of the house, created in SketchUp, can be found in Appendix A.

The structural system of the building, including both floors and walls, is predominantly constructed from wood materials. The building is located in Vancouver, where the Heating Degree Days (HDD), with a base temperature of 18°C, total 2,768. HDD is a crucial metric for tracking energy consumption, as it allows for consistent comparisons of energy use across different seasons. The inclusion of HDD is essential because the energy modeling software HOT2000 evaluates building performance based on HDD. Vancouver climate data are available in the AEI software.[11]

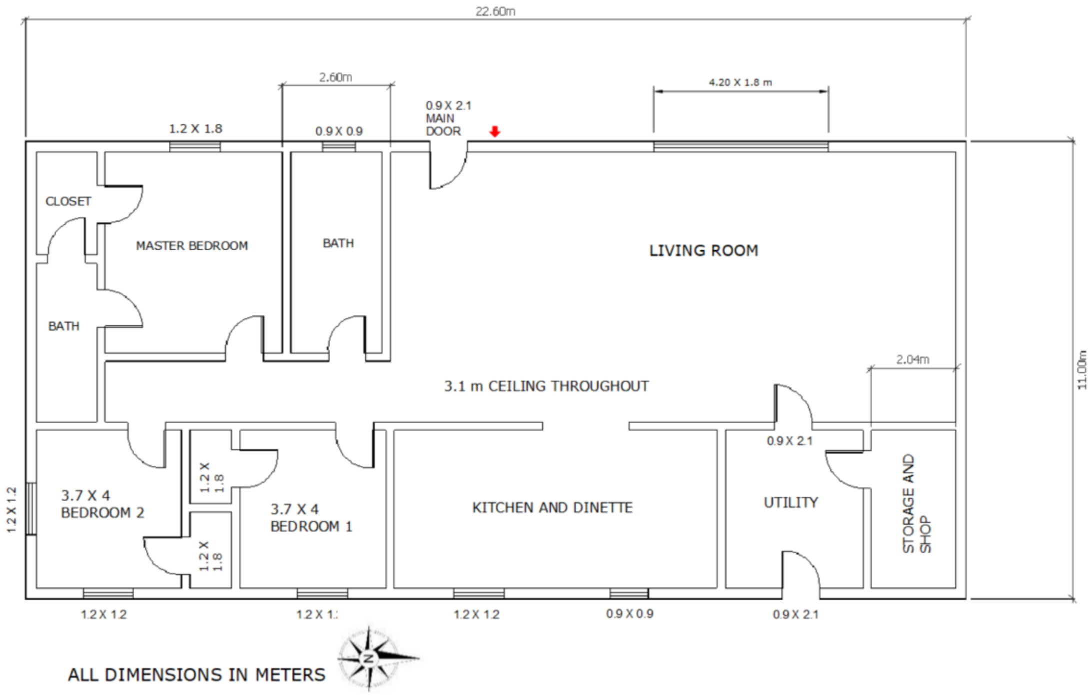


Fig. 4: Bird view of a Single-family three-bedroom home [11]

According to the National Building Code (NBC), this house qualifies as a Part 9 home, as its total area is less than 350 m² [27]. Part 9 homes are single-family residences built using conventional construction methods in Canada. These homes are typically smaller and constructed on individual lots. The most common construction method for Part 9 homes is wood framing, which is widely used across the country. Part 9 homes are known for their affordability and ease of construction, making them a popular choice among Canadian families.

The Athena Building Estimator application was used in this study to develop a model of the home, while HOT2000 was employed to assess the thermal transmittance and movement within the model. The scope of the life cycle assessment (LCA) includes a cradle-to-grave analysis, assuming a 60-year lifespan for the house. The LCA primarily relies on data from the AIE, supplemented by secondary databases from the Institute and Environmental Product Declarations (EPDs) of the materials used. Due to the AIE software limitation, B1-Use, B3-Repair, B5-Refurbishment, and B7-Operational Water were left out of the analysis. The overall global warming impact of a building's life cycle assessment (LCA) is predominantly attributed to operational energy consumption, such as electricity and natural gas, throughout the building's lifetime. The minimum required overall RSI (m^2K/W) values for walls, roofs, and ceilings are specified for various climate zones in the National Building Code (NBC) and are considered mandatory for compliance. Refer to Table 2. The RSI values have been systematically refined and calibrated over the years, with the National Building Code of Canada (NBC) 2020 serving as the most up-to-date standard. This code is widely adopted by contractors, engineers, and architects across Canada.[28]

Table 2: Effective Thermal Resistance of Above-ground Opaque Assemblies in Buildings without a Heat-Recovery Ventilator for Vancouver (Zone 4) with HDD

	Min effective thermal Resistance (RSI), m²K/W
Above-ground Opaque building assembly	Zone 4 <3000, Vancouver HDD = 2768
flat roof	4.67
Walls	2.78
Floors over unheated space	4.67
Doors and fenestrations	0.54
Skylight	0.34

3.2.2 Inputs for walls

Each wall depicted in Figure 4 is labeled, and the corresponding details are input into the estimator. The east wall (the bottom of Figure 4) contains four windows and one door. The southern wall features a 1.2 × 1.2 m window, while the western wall includes three windows and one door (the back door of the house). The northern wall has neither doors nor windows.

The walls are constructed with plywood sheathing and 2×6-inch (38 × 140 mm) wood studs, spaced 400 mm on-center (oc). In this case, the wall type selected is load-bearing. The estimator is provided with the inputs detailed in Table 3. According to AIE software setting, the standard door size is 32″ × 84″ (0.813 × 2.13 m). Table 4 presents all the layers of the walls input into the estimator for climate zone 4. All information in Table 1 is sourced from NBC 2020 [28] . The minimum door jamb width required for walls constructed with 2×6″ studs is 6.5 inches. This dimension accounts for the 5.5-inch width of the 2×6″ studs and an additional 0.5-inch wall surface thickness on each side.

Table 3 Inputs applied for windows and doors for walls for Vancouver (Zone 4)

East wall	**Frame**	**Glazing type**	**Number**	**Total window area (m²)**
Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	4	5.13
	Door type	**Size**		
Doors	Solid wood type	W*H: 0.813 × 2.134 m	1	-
South wall	**Frame**	**Glazing type**	**Number**	**Total window area (m²)**
Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	1	1.44
	Door type	**Size**		
Doors	-	-	0	-
West wall	**Frame**	**Glazing type**	**Number**	**Total window area (m²)**
Windows	Unclad wood window frame double pane	Double glazed hard coated Argon	3	7.29
	Door type	**Size**		
Doors	Solid wood type	W*H: 0.813 × 2.134 m	1	
North wall	**Frame**	**Glazing type**	**Number**	**Total window area (m²)**
Windows	-	-	0	-
	Door type	**Size**		
Doors	-	-	0	-

Table 4: Layers of the wall fed in the estimator for Vancouver (Zone 4)

Wall envelope parts		**Thickness(mm)**	**RSI**
Envelope category	Envelope material		
Exterior air	NA	NA	0.17
Cladding	Vinyl Sliding	-	0.62
Gypsum Board	Gypsum regular 1/2"	12.7	-
Insulation	Blown Cellulose	140	7
Paint	Latex water-based	NA	-
Vapor and Air Barrier	Polyethylene 6 mil	6	-
Gypsum board	Gypsum regular 1/2"	12.7	0.45
Interior air	NA	NA	0.68

Cellulose insulation material is used in this LCA calculation because it is one of the most popular insulation materials in US. Moreover, valid and updated Environmental Product Declarations (EPDs) for insulation materials are only available for cellulose and rock wool insulation. To maintain consistency in the study, cellulose material was chosen.

3.2.3 Inputs for Floors and Foundation

The proposed building's ground floor design is described in Table 5, which includes cellulose insulation. Blown cellulose is applied along the interior perimeter of the stem wall, serving as both an insulation material and a thermal break. Following this, a six-mil polyethylene vapor barrier is installed. The floor is then finished with a layer of lightweight gypsum and interior finish paint, completing the construction of the ground floor.

Table 5: Layers of the floor and foundation fed in the estimator for Vancouver (Zone 4)

Floor & Foundation envelope layer	**Thickness/mm**	**RSI(㎡ K/W)**
Blown cellulose insulation	140	7
Polyethylene Vapor barrier	6	0
Gypsum lightweight	12.7	0.08
Latex Water based	0.1	0

3.2.4 Inputs for roofs

A joist on the roof is necessary to maintain the structural integrity of the house's framework. Gypsum boards are then attached beneath the joist, followed by the installation of a vapor barrier on top, with loose fill cellulose insulation placed above the joist. The insulation is installed above the joist to enhance thermal performance. A 4-ply modified bitumen roofing system is applied, where each ply is embedded in a hot bitumen layer. These two felt layers and modified bitumen are laminated together to form the roof envelope. Finally, roofing asphalt is applied to protect the bitumen from ultraviolet light and environmental wear caused by wind, snow, hail, and rain. These details are summarized in Table 6 below. The AIE considers the RSI values of the interior and exterior air to be 0.11 m^{2}K/W and 0.03 m^{2}K/W, respectively. It is important to note that loose fill cellulose insulation will remain constant throughout the computer simulations for roof insulation.

Table 6: Layers of the roof with loose fill cellulose insulation for CZ 4

Roof envelope layers	**Thickness (mm)**	**RSI (m2K)/W**
Exterior air	-	0.03
2 Ply Mod Bitumen standard	7	-
Asphalt board	25.4	0.08
Loose fill cellulose insulation	220	5.5
Polyethylene vapor barrier	6	-
Gypsum board	12.7	0.08
Interior air	-	0.11

3.3 HOT2000 energy simulator tool

The building performance evaluation tool, HOT2000, incorporates various inputs such as climate, weather conditions, temperature, energy sources, ventilation systems, and baseloads to calculate the total operational energy of a building. The report emphasizes the substantial cost savings achieved by implementing the 2020 National Building Code (NBC). The annual cost structure is derived from data provided by the HOT2000 energy modeling software, utilizing the "Ottawa08" fuel cost library. The software performs calculations based on the entered data and assumptions, accounting for factors such as construction methods, local weather patterns, equipment specifications, and occupant behavior.

The modeled house includes several energy-consuming appliances: a washer (197 kWh/year), dryer (916 kWh/year), range hood (565 kWh/year), refrigerator (639 kWh/year), dishwasher (260 kWh/year), and three-bathroom exhaust fans (each consuming 3.5 kWh/year). The heating system operates with forced air ductwork circulating air for 8 hours daily, powered by a fan with an approximate consumption of 100 W. The primary space heating is provided by a 7-kW capacity heat pump, operating at 8.3°C. The secondary heating source is natural gas, used for both the furnace/boiler and the domestic hot water system, with a capacity of 7.5 kW and a tank volume of 188.4 L. Finally, the air conditioning system, integrated with the heating system, is a central split unit. Since this study's focusing on the A1-A4's LCA results, HOT 2000 output refers to the study of "Comparative Analysis of Various National Building Codes and Carbon Payback Periods of Insulation Materials at Different Climate Zones in Canada". [12]

One notable study "A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate" focused on three commonly used thermal insulation materials in the Spanish market: mineral wool (MW), polyurethane (PU), and polystyrene (XPS). The study applied Life Cycle Assessment (LCA) methodologies, ReCiPe (End-Point) and IPCC 2013 (GWP), to evaluate the environmental impacts of these materials during the manufacturing and operational phases. By using the Ecoinvent v3.5 database, the research provided a comprehensive analysis of the environmental footprint of these materials.

A key outcome of the study was the comparison between two functional units: the entire cubicle and floor m². This dual approach allowed for both internal comparison within the study and broader comparison with existing literature. The findings revealed that PU had the highest environmental impact during the manufacturing phase, followed closely by XPS. However, XPS exhibited the worst overall environmental performance when both methodologies were considered. In contrast, MW showed better environmental performance, making it a more sustainable option among the materials tested.

In terms of energy savings, the study found that the insulated cubicles with PU, XPS, and MW achieved reductions in electricity consumption of 27%, 25%, and 23%, respectively, compared to a non-insulated cubicle. Furthermore, the environmental payback periods were 7 years for MW, 10 years for PU, and 12 years for XPS using the ReCiPe indicator. When the GWP100a indicator was applied, the payback periods extended to 12 years, 15 years, and 19 years, respectively.

The study also acknowledged the limitations of generalizing these results to all climates, highlighting the need for further experimental research to better understand the thermal behavior and environmental impacts of insulation materials under varying conditions. This research is part of a larger effort to evaluate the environmental impacts of building components from a cradle-to-grave perspective, aiming to guide designers in making more informed decisions regarding the environmental implications of material selection. This study contributes valuable insights into the environmental performance of insulation materials and reinforces the importance of considering both energy savings and environmental impacts in sustainable building design. [29]

3.4 A Comprehensive LCA Calculation (A1-A3) for insulation material with Various Countries of Origin

Due to the lack of a specific database for the A1-A3 phases of insulation materials, conducting LCA calculations using software is not currently feasible. However, Environmental Product Declarations (EPDs) have been recommended by industry professionals as a reliable source for obtaining LCA results. By accessing available EPDs online, the LCA results for rock wool and cellulose insulation can be standardized by converting them to a uniform volume unit, ensuring they are comparable based on the same thermal conductivity performance. Since each EPD employs a different functional unit, it is essential to convert these units into a common format. The allocation method used in the report is volume-based.

3.5 A4 calculation by open LCA with various countries of origin

3.5.1 Declaration of methodological framework

The LCA calculation is declared under “transportation between manufacture site and construction site” system boundary. As such, it includes life cycle stage A4.

To keep the consistency throughout the report, the assessment was conducted using a building service life of 60 years. Allocation of transportation was based on volume while taking into account the utilization rate.

3.5.2 Properties of declared products as delivered

For Rock wool insulation, US produced has an average density of 40kg/m³, the functional unit is 1 ㎡ rock wool batt for wood or steel frame construction with a thermal resistance of R=1 ㎡*K/W. Thermal conductivity is 0.037W/(m*K). European produced has an average density of 99kg/m³, the functional unit is 1 ㎡ rock wool batt for wood or steel frame construction with a thermal resistance of R=1 ㎡ *K/W. Thermal conductivity is 0.04W/(m*K).

For cellulose insulation, US produced has an average density of 25.21kg/m³, the functional unit is 1 ㎡ cellulose batt for wood or steel frame construction with a thermal resistance of R=1 ㎡*K/W. Thermal conductivity is 0.038W/(m*K). European produced has an average density of 37kg/m³, the functional unit is 1 ㎡ cellulose batt for wood or steel frame construction with a thermal resistance of R=1 ㎡*K/W. Thermal conductivity is 0.033W/(m*K).

3.5.3 Transportation

For rock wool and cellulose insulation products produced in US, in the A4 phase, transportation is modeled by volume, with a truck as the default vehicle, following the most conservative approach. The transportation distance is around 4000km. [8]

For rock wool and cellulose insulation products produced in Europe, in the A4 phase, transportation is modeled by volume, with a container ship as the main transportation tool and a truck as the last on-land transportation, following the most conservative approach. The transportation distance of a container ship is 18000 km, that of a truck is 100km.

3.5.4 Data source

The LCA data is derived from several Environmental Product Declarations (EPDs) for rock wool and cellulose, using the *ELCD_3_2_greendelta v2-18* database, processed with *openLCA* software. For truck transportation, the dataset "*Lorry transportation, Euro1-4, 22t total weight, 17.3t max payload*" is utilized, while for container ship transportation, "*Container ship ocean, technology mix, 27.5 dwt payload capacity*" is employed.

3.6 Flow chart

The figure illustrates the project's objectives, approach, and underlying motivations.

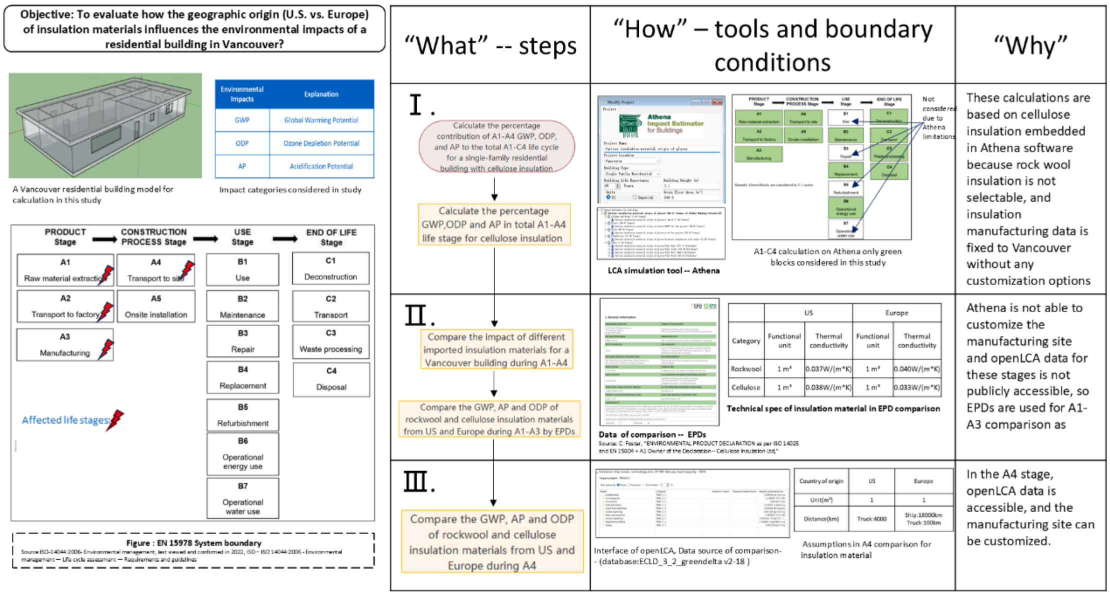


Fig. 5: Flow chart of this study

3.7 Limitations of the study

This paper specifically focuses on two insulation materials—cellulose and rock wool—without considering other prevalent insulation options such as fiberglass, which inherently limits the breadth of the analysis. While the environmental impacts beyond the A4 stage are recognized, they are not directly assessed, potentially limiting the comprehensive understanding of the full life cycle impacts of these materials. Furthermore, the LCA calculations for A1-A3 are based on the conversion of existing Environmental Product Declaration (EPD) reports rather than software simulations, which may introduce inaccuracies due to the inherent variability and standardization issues present in EPDs. Additionally, the study's reliance on open LCA databases was constrained by accessibility challenges, which restricted the ability to conduct a more in-depth analysis using richer datasets.

Regarding the life cycle assessment (LCA) of the residential building, the life cycle stages B1 (use phase), B3 (repair), and B5 (refurbishment) are excluded from the analysis due to inherent limitations of the Athena Impact Estimator (AIE) software, which lacks data for these specific stages. Consequently, the assessment focuses primarily on stages such as A1-A4 (material extraction, production, and transportation) as well as operational energy use. While the exclusion of stages B1, B3, and B5 may lead to a slight underestimation of the building's full life cycle impacts, the analysis remains sufficiently robust for evaluating the environmental performance of the included stages.

Moreover, the study focuses primarily on insulation materials, without addressing other building materials that contribute approximately 90% of the total environmental impacts during the A1-A4 stages. This limitation results in an incomplete understanding of the overall environmental impacts of residential buildings.

Additionally, the Environmental Product Declarations (EPDs) utilized in this study do not encompass all environmental impact categories, restricting the analysis to Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Acidification Potential (AP). Crucial impact categories such as eutrophication, photochemical smog, and water consumption, which may also significantly influence the environmental assessment, are excluded due to limitations in data availability.

Lastly, for the LCA results in the A4 transportation stage, a volume-based allocation method was employed. Although thermal resistance and material density were normalized to enhance comparability, this approach still assumes a linear relationship between environmental impacts and product characteristics, which may oversimplify the complexities associated with co-products and material performance. Consequently, the allocation method adopted may not fully capture the intricate environmental impacts linked to transportation and product attributes. Future research could benefit from employing more sophisticated allocation methods that better reflect the interactions between materials and their corresponding environmental impacts.

4. Results

4.1 LCA calculation (Gradle to grave) of a residential building

After the input put into the Athena software, the LCA of a residential building in Vancouver was shown in table 7.

Table 7: GDP, AP and ODP results and the percentage of A1-A4 from A1-C4

	A1-A4	**A5**	**B2, B4 & B6**	**C1 to C4**	**Percent**
GWP	4.65E+04	5.59E+03	4.35E+05	1.18E+04	9%
AP	2.06E+02	4.65E+01	3.30E+03	6.92E+01	6%
ODP	2.18E-03	1.39E-04	5.57E-03	2.58E-04	27%

As shown in figure 5, different stages GWP contribution of the single-family residential building is listed.

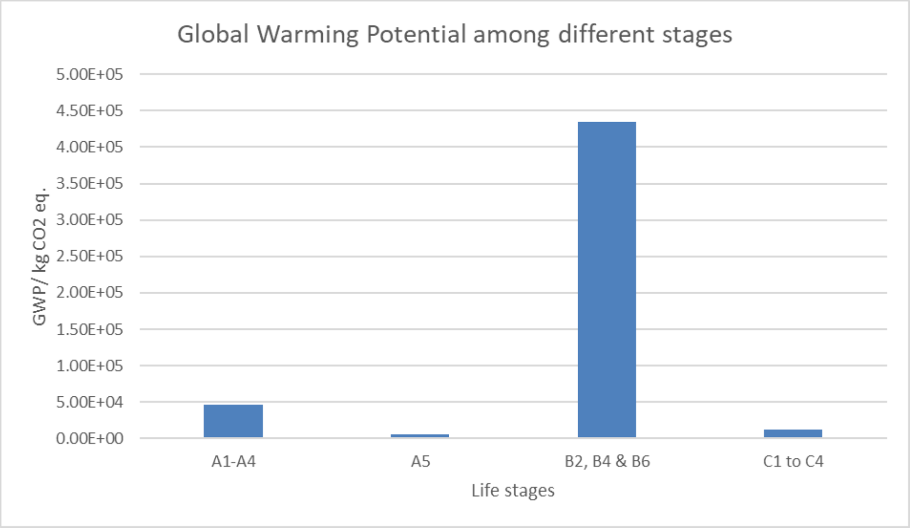


Fig. 6: GWP value by life cycle stages for the single-family residential building

As shown in figure 6, different stages AP contribution of the single-family residential building is listed

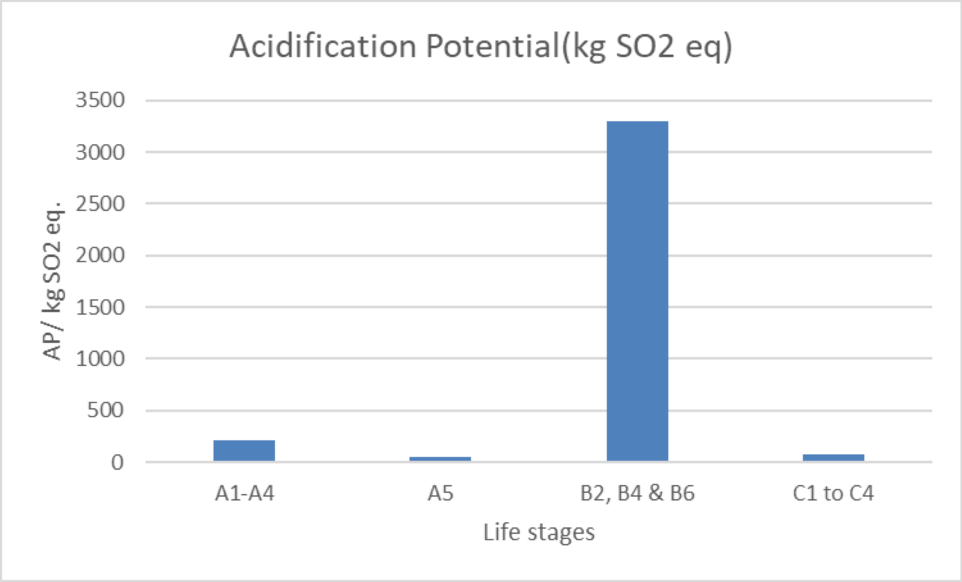


Fig. 7: AP value by life cycle stages for the single-family residential building

As shown in figure 7, different stages ODP contribution of the single-family residential building is listed

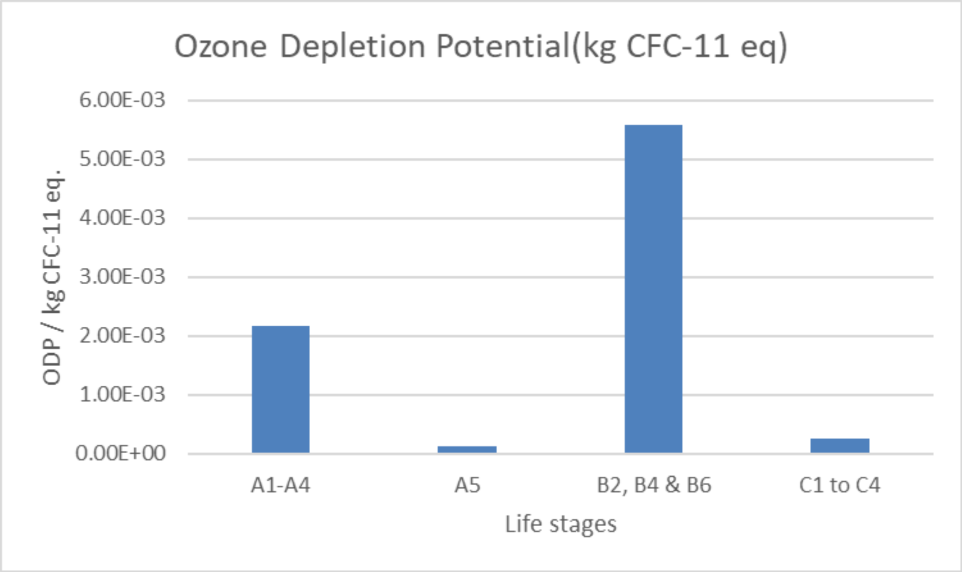


Fig. 8: ODP value by life cycle stages for the single-family residential building

To sum up, figure 8 shows the percentage of A1-A4 among the whole life stages of GWP, AP and ODP.

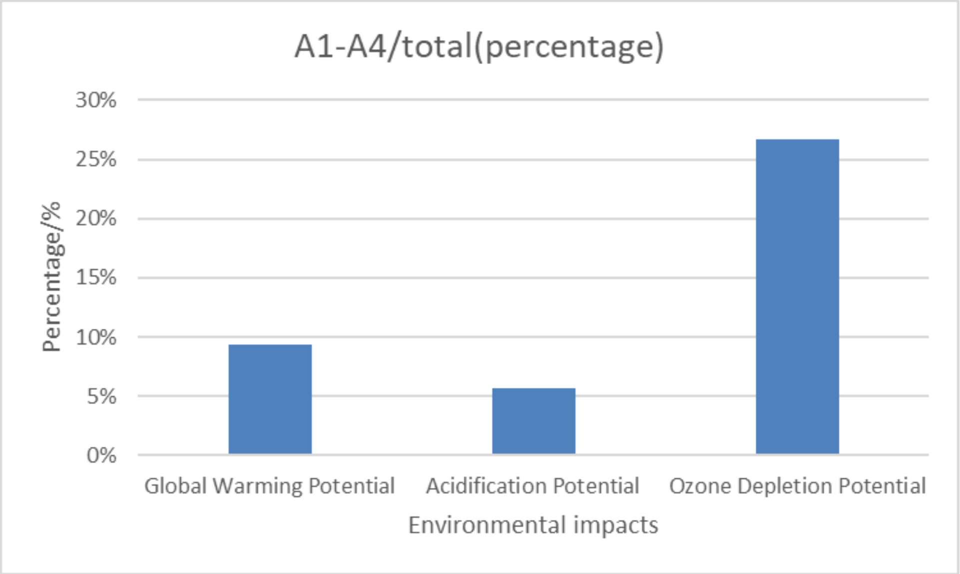


Fig 9: The percentage of A1-A4 among total life cycle stages

Figure 8 highlights that, while the use stage (B2, B4, and B6) accounts for a significant portion of the environmental impact, the A1-A4 stages also play a critical role, particularly in terms of Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). Specifically, A1-A4 contribute roughly 10% to GWP and nearly 30% to ODP, underscoring the need to pay close attention to these life cycle stages.

Rather than seeking innovation within the A1-A4 stages to reduce these impacts, this insight emphasizes the importance of focusing on this phase when assessing the environmental performance of residential buildings in Vancouver. The contribution of A1-A4 should serve as a basis for comparing the environmental impacts of materials sourced from different regions, enabling architects, engineers, and policymakers to make informed decisions that can mitigate the overall environmental footprint of the building.

For example, raw materials extracted and manufactured in one region may have significantly lower GWP and ODP due to local energy sources or production processes, while materials sourced from another region may contribute more to environmental degradation due to factors such as longer transportation routes or reliance on non-renewable energy during manufacturing. By conducting a detailed comparison of A1-A4 processes for materials from various regions, it is possible to identify which sources offer the most sustainable options.

This approach is particularly relevant in the context of Vancouver's construction industry, where regional factors such as proximity to raw material sources and energy grids with lower carbon intensity can make a considerable difference. For instance, comparing the environmental impacts of materials produced locally in British Columbia to those imported from overseas may reveal that local sourcing offers a significant advantage in terms of both GWP and ODP. Such analysis not only supports better decision-making for specific building projects but also contributes to the broader goal of minimizing the environmental impacts of urban development.

Given that various components contribute to the overall Global Warming Potential (GWP), Acidification Potential (AP), and other environmental impacts, it is more practical for the study to focus on one specific component within the A1-A4 life cycle stages. As previously mentioned, insulation materials have been identified as the second largest area for potential optimization. To validate this, the A1-A4 LCA results for insulation materials are presented in the figures below.

Table 8: GWP, AP and ODP results in A1-A4 and insulation results percentage

	A1-A4(Only Insulation)	**A1-A4(Total)**	**Percent**
GWP	2989.97	46518.65191	6%
AP	20.66	205.7747781	10%
ODP	2.97E-04	2.18E-03	14%

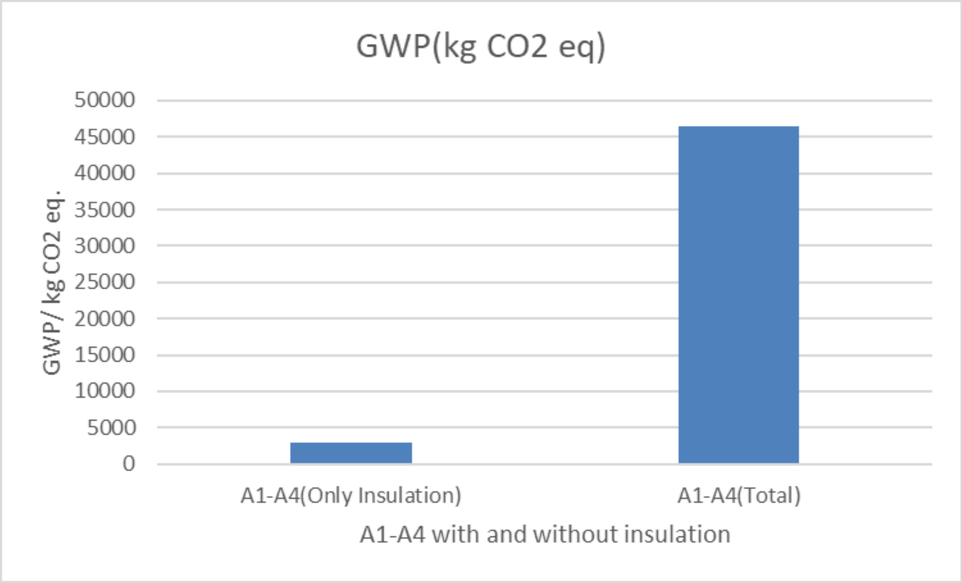


Fig. 10: GWP during A1-A4 comparison between insulation material and total building

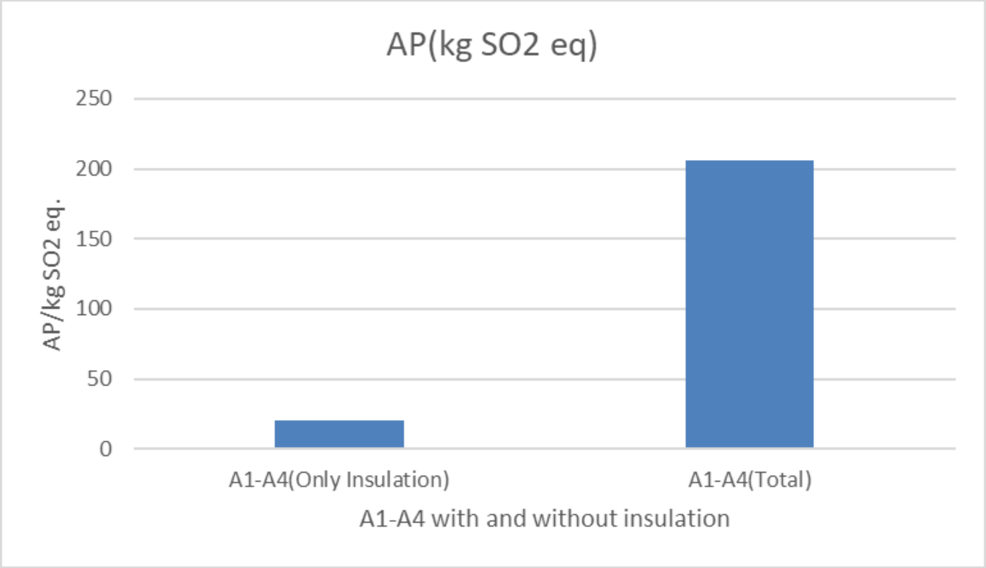


Fig. 11: AP during A1-A4 comparison between insulation material and total building

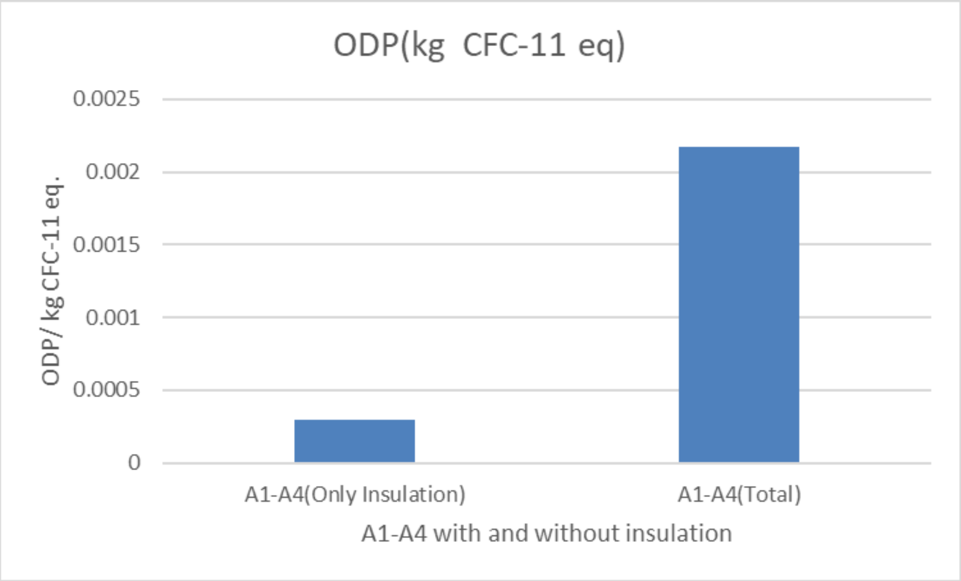


Fig. 12: ODP during A1-A4 comparison between insulation material and total building

Figure 9,10 and 11 presented above indicate that insulation materials alone contribute over 6% of the total Global Warming Potential (GWP), more than 10% of the Acidification Potential (AP), and approximately 15% of the Ozone Depletion Potential (ODP). These significant contributions underscore the importance of identifying opportunities for improvement in the A1-A4 life cycle stages specifically related to insulation materials. Given the current environmental landscape and the pressing need for sustainable construction practices, it becomes increasingly relevant to explore how these impacts can be mitigated through a detailed analysis of insulation materials sourced from different countries of origin.

This approach allows for a more nuanced understanding of how variations in raw material extraction, manufacturing processes, and transportation methods across different regions contribute to the overall environmental performance of insulation materials. By investigating the regional differences, we can pinpoint areas within the A1-A4 stages where improvements could lead to substantial reductions in GWP, AP, and ODP. Such an analysis not only highlights the potential for optimization within this specific component but also aligns with broader sustainability goals, providing a pathway to reduce the environmental footprint of residential buildings in Vancouver and beyond. Therefore, identifying these regional variations in the life cycle of insulation materials is essential for making informed decisions that will result in more environmentally responsible construction practices.

4.2 Comparative LCA (A1-A4) of insulation materials across different countries of origin.

Due to limited Environmental Product Declarations (EPDs) and time constraints, the analysis focuses on insulation materials sourced from two regions: the United States and Europe. Given the variance in functional units across the available EPDs, all results have been standardized to a common functional unit—1 m^2 of insulation material with a thermal conductivity of approximately 0.037 W/m·K, and a thickness of 1 meter. Table 9 presents the environmental impact results for both cellulose and rock wool insulation materials after conversion to this functional unit.

Table 9: Rock wool insulation GWP, AP and ODP results (A1-A3) comparison between Europe and US

	Europe		
Rock wool insulation	Impact category	$1m^3$ ($1m^2$*1m thickness)	Unit
	GWP	115	kg CO2 eq.
	ODP	1.27E-10	kg CFC11 eq.
	AP	1.05	kg SO^2-Eq.
	US		
	Impact category	$1m^3$ ($1m^2$*1m thickness)	Unit
	GWP	87.63	kg CO2 eq.
	ODP	1.59E-07	kg CFC11 eq.
	AP	0.68	kg SO^2-Eq.

Table 10: Cellulose insulation GWP, AP and ODP results (A1-A3) comparison between Europe and US

	Europe		
Cellulose insulation	Impact category	$1m^3$ ($1m^2$*1m thickness)	Unit
	GWP	11.63	kg CO2 eq.
	ODP	1.26E-06	kg CFC11 eq.
	AP	0.08	kg SO^2-Eq.
	US		
	Impact category	$1m^3$ ($1m^2$*1m thickness)	Unit
	GWP	10.21	kg CO2 eq.
	ODP	1.29E-06	kg CFC11 eq.
	AP	0.08	kg SO^2-Eq.

Based on the table 10, we can compare the differences in Global Warming Potential (GWP), Ozone Depletion Potential (ODP), and Acidification Potential (AP) between the two countries of origin. These indicators provide insights into the environmental impact of materials or processes from each country, allowing for a clearer understanding of how regional factors influence sustainability metrics. Analyzing these differences can help inform more environmentally conscious decisions in material sourcing and life cycle assessments.

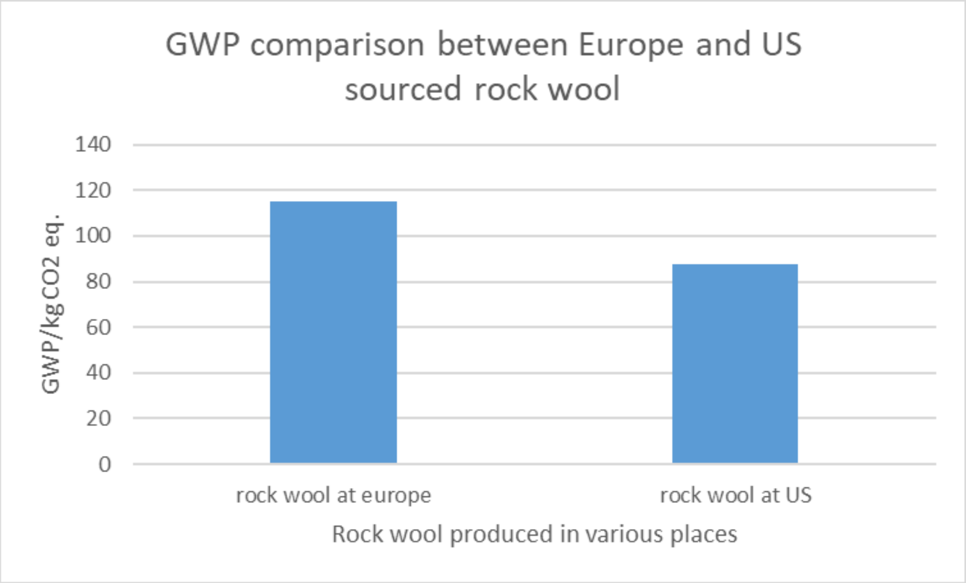


Fig. 13: GWP comparison between Europe and US in terms of rock wool insulation

As shown in Figure 12, when using the same functional unit and thermal resistance (with a volume-based allocation method), rock wool produced in the U.S. has 24% lower Global Warming Potential (GWP) during the A1-A3 phases compared to alternatives.

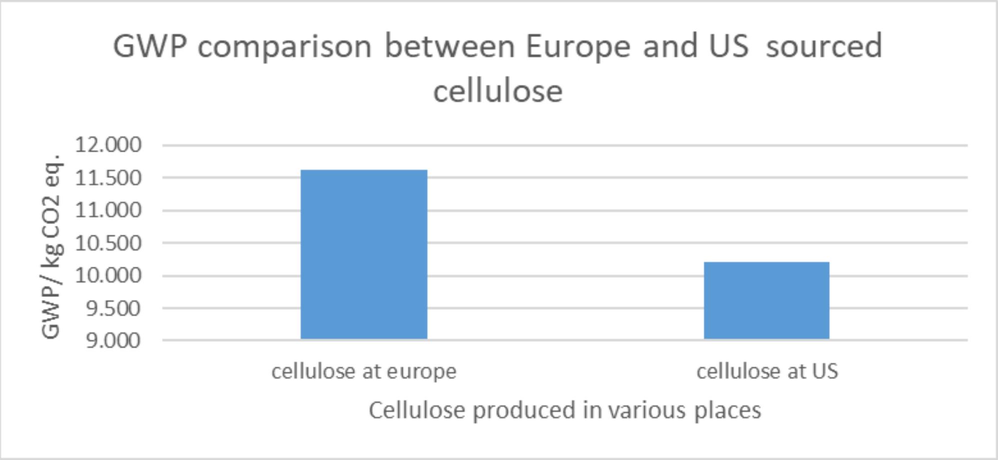


Fig. 14: GWP comparison between Europe and US in terms of cellulose insulation

As shown in Figure 13, when using the same functional unit and thermal resistance (with a volume-based allocation method), cellulose produced in the U.S. has 12% lower Global Warming Potential (GWP) during the A1-A3 phases compared to alternatives.

Based on the data comparison, results can be concluded that rock wool produced in the U.S. is 1250 times higher ODP than that produced in Europe during the A1-A3 life stages. In terms of AP, U.S. produced rock wool has 20% lower value during the A1-A3 stages. For cellulose, U.S. produced material has 3% higher ODP during the A1-A3 stages compared to that of Europe, U.S. produced material has 2% lower AP during the A1-A3 stages compared to alternatives.

In conclusion, with the exception of Ozone Depletion Potential (ODP), materials produced in the U.S. generally exhibit lower environmental impacts across various metrics. In terms of Acidification Potential (AP), materials produced in Europe show a slight advantage over U.S.-produced cellulose materials, and a more significant advantage over U.S.-produced rock wool during the A1-A3 life cycle stages. This highlights the regional differences in the environmental performance of building materials.

4.3 Comparative LCA (A4) of insulation materials across different countries of origin for Vancouver located building

For the same Vancouver located residential building, the difference in A4 is mainly contributed by the way of transportation and the detailed distance between the country of origin and the building in Vancouver.

Table 11 and 12 are the LCA results of A4 for various countries of origin of two insulation material (rock wool and cellulose).

Table 11: Rock wool insulation GWP, AP and ODP results (A4) comparison between Europe and US

Rock wool			
	Country of origin	Europe	US
A4 stage	Unit(kg)	100	100
	Distance(km)	Ship:18000 Truck:100	Truck:4000km
	GWP (kg CO2 eq)	61.94	39.78
	ODP (kg CFC11 eq)	7.41E-12	6.95E-06
	AP (kg SO2 eq)	0.80	0.10

Table 12: Cellulose insulation GWP, AP and ODP results (A4) comparison between Europe and US

Cellulose			
	Country of origin	Europe	US
A4 stage	Unit(kg)	100.00	100.00
	Distance(km)	Ship:18000 Truck:100	Truck:4000
	GWP (kg CO2 eq)	41.77	18.96
	ODP (kg CFC11 eq)	6.71E-06	4.58E-06
	AP (kg SO2 eq)	0.51	0.07

For both rock wool and cellulose, the materials originating from Europe have higher environmental impacts compared to those produced in the US. This is largely due to the transportation method, where European materials are shipped over long distances, followed by trucking, which increases the Global Warming Potential (GWP). The extensive use of shipping for European products leads to a more substantial environmental footprint, particularly in terms of global warming and acidification potential. Although the Ozone Depletion Potential (ODP) remains low for European materials, it is still higher than for their US counterparts.

4.4 Comparative LCA (A1-A4) of insulation materials across different countries of origin for Vancouver located building

Summing up the results from both the A1-A3 and A4 stages, the total LCA outcomes are presented in table 13.

Table 13: Rock wool insulation GWP, AP and ODP results (A1-A4) comparison between Europe and US

	Rock wool			**Cellulose**	
	Country of origin	Europe	US	Europe	US
A1-A4	Unit(m³)	1.00	1.00	1.00	1.00
	GWP (kg CO2 eq)	176.94	127.41	53.40	29.17
	ODP (kg CFC11 eq)	1.34E-10	7.11E-06	7.97E-06	5.87E-06
	AP (kg SO2 eq)	1.85	0.77	0.59	0.15

Since this is a comparative LCA, all results have been normalized to percentages, as shown in the figure below.

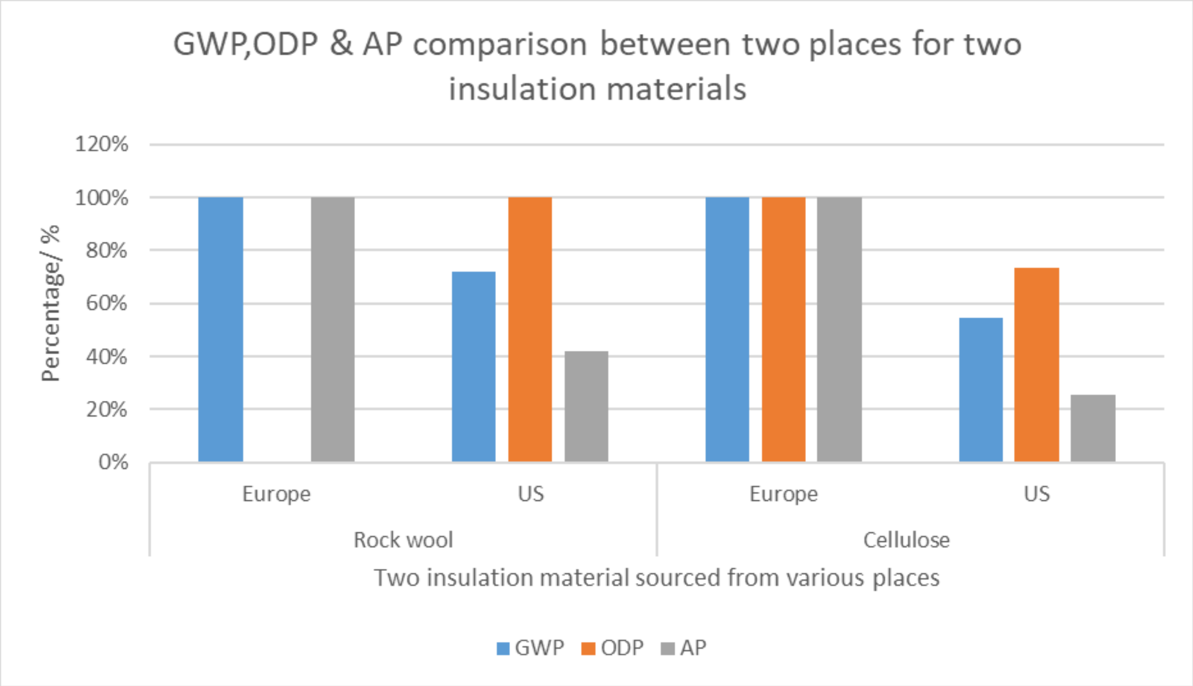


Fig. 15: Environmental impacts comparison (percentage based) of rock wool and cellulose insulation between Europe and US

For rock wool, the GWP of US-sourced material is significantly lower compared to European-sourced rock wool, indicating that the environmental impact of production and transportation is much greater in Europe. In terms of ODP, US rock wool shows a considerably higher percentage, whereas European-sourced rock wool has a much smaller impact in this category. For AP, European rock wool again demonstrates a much higher environmental burden compared to US rock wool, suggesting that transportation and production in Europe have a greater negative effect on acidification.

For cellulose, US-sourced material exhibits lower impacts across all categories—GWP, ODP, and AP—when compared to European-sourced cellulose. This indicates that the environmental footprint of cellulose insulation is consistently smaller when produced in US and transported to Canada.

5. Conclusions

This report presents LCA calculation of Global Warming Potential (GWP), Acidification Potential (AP), and Ozone Depletion Potential (ODP) for two insulation material – cellulose and rock wool from two countries of origin – US and Europe. The LCA analysis of a Canadian single-family residential building located in Vancouver reveals that the embodied carbon stages related to sourcing (A1: raw material extraction, A2: transportation from extraction to manufacturing site, A3: manufacturing, A4: transportation from manufacturing to construction site) contribute considerable part to the overall GWP, AP, and ODP impacts, across the entire life cycle (A1-C4). These findings highlight the significant role of A1-A4 stages in the environmental impacts of the building life cycle and underscore the need for attention to these stages.

The primary objective of this research is to conduct a comparative analysis of two insulation materials—cellulose and rock wool—sourced from the U.S. and Europe, focusing on their performance during the A1-A4 life cycle stages. The comparison is based on a functional unit of 1 m^3 of rock wool or cellulose batt with a thermal resistance of R=1 m^2*K/W, using volume as the allocation method. The findings indicate that insulation materials sourced from the U.S. generally exhibit lower environmental impacts due to reduced transportation distances. However, European-sourced rock wool demonstrates a lower Ozone Depletion Potential (ODP) during the A1-A4 life cycle stages.

Assumptions for the insulation materials are based on existing Environmental Product Declaration (EPD) reports. For U.S.-sourced materials, the average transportation distance is approximately 4,000 km by truck, using the "*ELCD_3_2_greendelta v2-18*" database, and the truck dataset used is "*Lorry transportation, Euro1-4, 22t total weight, 17.3t max payload.*" For European-sourced materials, the transportation distance is an average of 18,000 km via container ship and 100 km by truck, using the same truck dataset and the container ship dataset "*Container ship ocean, technology mix, 27.5 dwt payload capacity.*"

Key findings of this report include the following:

- The A1-A4 life stages contribute 9%, 6%, and 27% to the overall GWP, AP, and ODP impacts, respectively.
- Insulation materials account for 6%, 10%, and 14% of the overall GWP, AP, and ODP impacts during the A1-A4 stages.
- GWP: Europe-sourced rock wool has 139% of the impact of U.S.-sourced, while Europe-sourced cellulose has 187% of the impact of U.S.-sourced.
- AP: Europe-sourced rock wool shows 240% of the impact of U.S.-sourced, and Europe-sourced cellulose has 393% of the impact of U.S.-sourced.
- ODP: Europe-sourced rock wool exhibits 1.87 * 10^-7% of the impact of U.S.-sourced, while Europe-sourced cellulose has 136% of the U.S.-sourced impact.

This report presents a robust methodology for building professionals to make well-informed decisions regarding the selection of insulation materials from different regions, utilizing current Life Cycle Assessment (LCA) datasets. Through this methodology, professionals can quantify the A1-A4 environmental impacts—including Global Warming Potential, Acidification Potential, and Ozone Depletion Potential—of insulation materials with comparable thermal performance sourced from different regions. This enables them to select materials that contribute to reducing carbon emissions.

Applying these LCA-based calculations to material sourcing decisions allows for even minor adjustments that can lead to significant improvements in the environmental performance of construction projects.

6. Future scope

Owing to limitations in available resources and time, this study has certain constraints that provide opportunities for future research. Firstly, the current analysis is limited to a residential building of a specific type. Future research could extend the scope to include commercial buildings, which may exhibit varying environmental impacts due to differences in design and usage. Additionally, expanding the analysis to include multi-story residential designs, such as two- or three-story houses common in Vancouver, BC, would offer a more comprehensive understanding of the associated environmental impacts.

Furthermore, while this study focused on rock wool and cellulose insulation, future research should incorporate fiberglass, which is one of the most commonly used insulation materials for building envelopes, due to its extensive application. As more Environmental Product Declarations (EPDs) become available, they can provide a comprehensive dataset for further comparative analyses of insulation materials.

An additional direction for future research involves enhancing the utilization of open LCA databases. Although Environmental Product Declarations (EPDs) are valuable resources, they have inherent limitations—such as discrepancies in material density and functional units, necessitating manual standardization efforts in this study. The development of a more standardized and integrated LCA database could facilitate these comparisons and yield more precise insights into environmental impacts.

Apart from that, although insulation materials were the primary focus of this study, it is crucial to recognize that approximately 90% of the Global Warming Potential (GWP) and other environmental impact categories during the A1-A4 stages are attributable to other raw building materials. Therefore, future research should broaden its scope to include a comparative analysis of these materials from various countries of origin, as this could provide valuable insights for reducing the overall environmental impact throughout the building life cycle.

By broadening the scope to encompass a wider variety of building types, construction materials, and more efficient data tools, future research can offer a more in-depth analysis of the influence of material origin on the overall environmental impacts during the A1-A4 life cycle stages.

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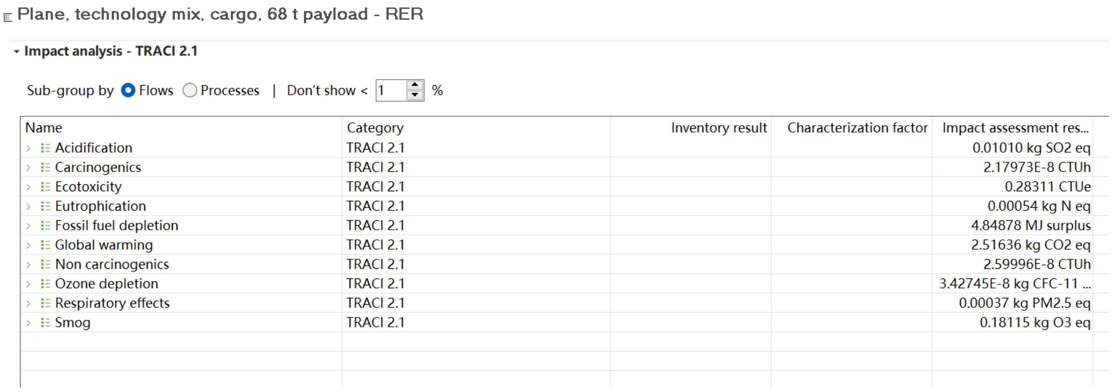
Appendix

1.openLCA dataset of various transportation methods (ELCD database embedded).

The figures show airflight environmental impacts, functional unit is 1t*km.



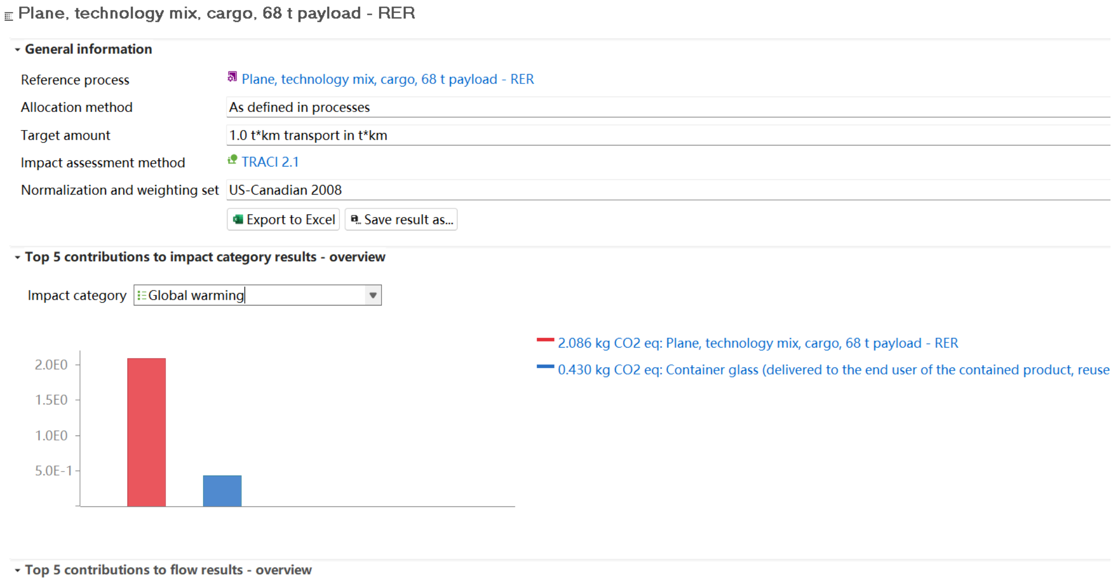
Plane, technology mix, cargo, 68 t payload - RER

Impact analysis - TRACI 2.1

Sub-group by ● Flows ○ Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment res...
Acidification	TRACI 2.1			0.01010 kg SO2 eq
Carcinogenics	TRACI 2.1			2.17973E-8 CTUh
Ecotoxicity	TRACI 2.1			0.28311 CTUe
Eutrophication	TRACI 2.1			0.00054 kg N eq
Fossil fuel depletion	TRACI 2.1			4.84878 MJ surplus
Global warming	TRACI 2.1			2.51636 kg CO2 eq
Non carcinogenics	TRACI 2.1			2.59996E-8 CTUh
Ozone depletion	TRACI 2.1			3.42745E-8 kg CFC-11 ...
Respiratory effects	TRACI 2.1			0.00037 kg PM2.5 eq
Smog	TRACI 2.1			0.18115 kg O3 eq

Fig. 16: Impact analysis results of 1 t*1km for airflight (*Plane, technology mix. Cargo, 68t payload*)


Plane, technology mix, cargo, 68 t payload - RER

General information

Reference process: Plane, technology mix, cargo, 68 t payload - RER
Allocation method: As defined in processes
Target amount: 1.0 t*km transport in t*km
Impact assessment method: TRACI 2.1
Normalization and weighting set: US-Canadian 2008

Top 5 contributions to impact category results - overview

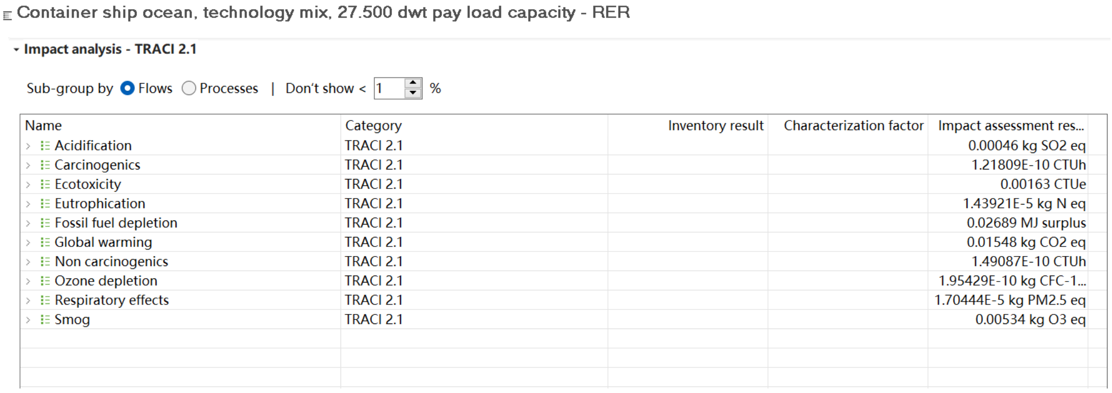
Impact category: Global warming

🟥 2.086 kg CO2 eq: Plane, technology mix, cargo, 68 t payload - RER
🟦 0.430 kg CO2 eq: Container glass (delivered to the end user of the contained product, reuse

Top 5 contributions to flow results - overview

Fig. 17: GWP result of 1 t*1km for airflight (*Plane, technology mix. Cargo, 68t payload*)

The figures below show containership environmental impacts (functional unit: 1t*km).

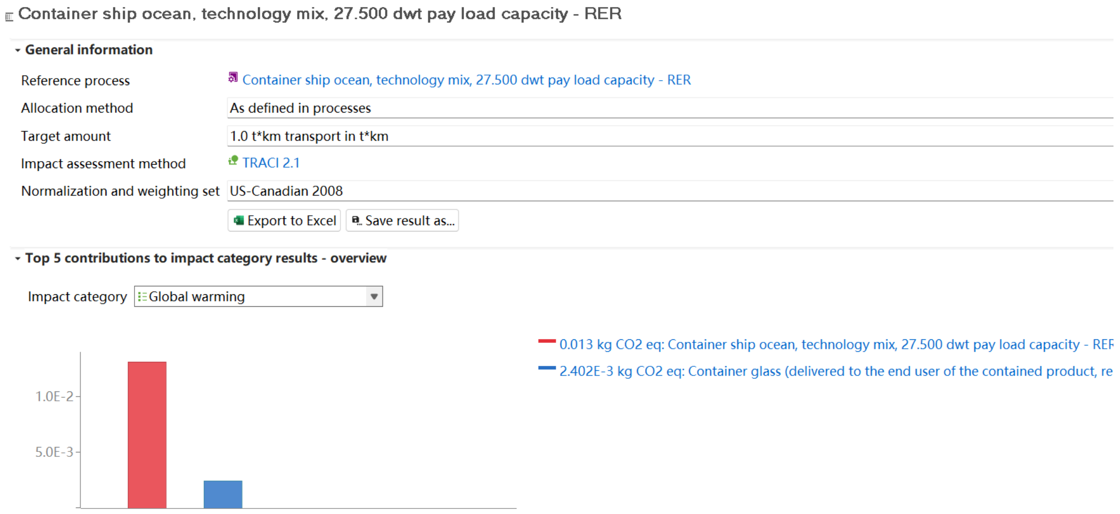

Container ship ocean, technology mix, 27.500 dwt pay load capacity - RER

Impact analysis - TRACI 2.1

Sub-group by ● Flows ○ Processes | Don't show < 1 %

Name	Category	Inventory result	Characterization factor	Impact assessment res...
Acidification	TRACI 2.1			0.00046 kg SO2 eq
Carcinogenics	TRACI 2.1			1.21809E-10 CTUh
Ecotoxicity	TRACI 2.1			0.00163 CTUe
Eutrophication	TRACI 2.1			1.43921E-5 kg N eq
Fossil fuel depletion	TRACI 2.1			0.02689 MJ surplus
Global warming	TRACI 2.1			0.01548 kg CO2 eq
Non carcinogenics	TRACI 2.1			1.49087E-10 CTUh
Ozone depletion	TRACI 2.1			1.95429E-10 kg CFC-1...
Respiratory effects	TRACI 2.1			1.70444E-5 kg PM2.5 eq
Smog	TRACI 2.1			0.00534 kg O3 eq

Fig. 18: Impact analysis results of 1 t*1km for container ship (*container ship ocean, technology mix. 27500 dwt, payload capacity*)



Container ship ocean, technology mix, 27.500 dwt pay load capacity - RER

General information

Reference process	Container ship ocean, technology mix, 27.500 dwt pay load capacity - RER
Allocation method	As defined in processes
Target amount	1.0 t*km transport in t*km
Impact assessment method	TRACI 2.1
Normalization and weighting set	US-Canadian 2008

Top 5 contributions to impact category results - overview

Impact category: Global warming

🟥 0.013 kg CO2 eq: Container ship ocean, technology mix, 27.500 dwt pay load capacity - REF

🟦 2.402E-3 kg CO2 eq: Container glass (delivered to the end user of the contained product, re

Fig. 19: GWP result of 1 t*1km for container ship (*container ship ocean, technology mix. 27500 dwt, payload capacity*)

2. Environmental product declaration sources.

Rockwool insulation EPD in Europe

rock wool at germany.pdf

Rockwool insulation EPD in U.S.

rockwool-stone-wool-environmen

Cellulose insulation EPD in Europe

EPD-Ecocel-Cellulose-Fibre-Insulat

Cellulose insulation EPD in U.S.

US location_Carbon_