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The Extent to Which Hemp Insulation Materials Can Be Used in Canadian Residential Buildings

Chun Hua Julia Liu [1,2,*], Francesco Pomponi [3] and Bernardino D'Amico [1,2]

1 REBEL (Resource Efficient Built Environment Lab), Edinburgh EH11 4BN, UK; b.d'amico@napier.ac.uk
2 School of Engineering and Built Environment, Edinburgh Napier University, Edinburgh EH11 4BN, UK
3 Institute for Sustainability Leadership (CISL), University of Cambridge, Cambridge CB2 1GG, UK; francesco.pomponi@cisl.cam.ac.uk
* Correspondence: c.liu@napier.ac.uk

Abstract: The embodied carbon of building materials is a significant contributor to greenhouse gas (GHG) emissions. Hemp is widely acknowledged as the most used vegetal insulation in building and construction due to its comparable thermal properties and better environmental performance than that of mainstream insulation materials (MIMs). However, the application of hemp insulation materials (HIMs) in Canada is still in its infancy. Canada is currently the largest hemp oil and seed producer in the world. Most recent research on hemp in Canada has focused on the impact of legalising marijuana and the popularisation of hemp health products and cannabidiol (CBD). There is a lack of studies addressing the holistic impact of hemp in reducing emissions in Canadian residential buildings. This paper exams the feasibility of large-scale hemp cultivation in Canada and the suitability of HIMs for Canadian private dwellings. Material flow analysis (MFA) and life cycle assessment (LCA) were applied to evaluate different levels of carbon mitigation over time produced by HIM substitution. The results show that Canada has sufficient farmland and perfect geographic location and weather to implement large-scale hemp cultivation. HIM substitution can be accomplished for 81% of Canadian residential buildings. Full HIM substitution fulfilled through 5% hemp fibre insulation (HF) and 95% hempcrete (HC) will mitigate 101% of the GHG emissions caused by existing MIMs and contribute up to a 7.38% reduction in emissions to achieve the net zero emissions target by 2050.

Keywords: Canadian residential building stock; hemp building and construction; thermal insulation; material substitution; life cycle assessment

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1. Introduction

The climate is critical to the world. For millennia, climate change was low-impact and occurred gradually. The human impact on climate change was small because early humans thrived sustainably with abundant plants and animals. Wood was the major source of energy for cooking food and warming homes. Wood sequestrates carbon during its growth through photosynthesis, and the same amount of carbon was released into the atmosphere when burning wood [1]. In the 19th century, the human population increased explosively due to advancements in medicine and technology. Fossil fuels, made from decomposing plants and animals underneath Earth's crust and containing carbon, became the prime source of energy. The burning of fossil fuels emits carbon dioxide (CO_2) into the atmosphere [2]. Driven by industrialisation, population growth, and a higher standard of living, fossil fuel utilisation has been constantly growing. Nowadays, fossil fuels account for 86% of the primary global energy demand [3].

Greenhouse gases (GHGs) consist of mainly of water vapor (H_2O) with negligible anthropogenetic emission, which has trapped heat and provided a favorable average temperature for planet Earth for thousands of years. However, GHGs also contain CO_2, methane, nitrous oxide, ozone, CFCs, and HCFCs, which come from anthropogenic emissions and have caused the climate change in the past 250–300 years. CO_2 is the primary driver of global warming [4]. In 2007, the Intergovernmental Panel Climate Change (IPCC) warned that climate change due to human activities was happening and could lead to serious consequences [2]. Nowadays, most scientists agree that global warming is real and is causing disastrous impacts on the Earth [4]. Increasing temperatures, widespread melting of snow and ice, and rising sea levels are observed around the world. Extreme natural disasters are happening more frequently and severely. Growing health risks, food shortages, poverty, and displacement are spreading across the world [5].

In 2018, direct and indirect emissions from the building sector contributed 17.1% of the global GHG emissions; of this percentage, residential buildings emitted almost double the amount of GHGs into the atmosphere as non-residential buildings [6]. Canada is the top per capita emitter among the top emitting countries and regions, although its total emissions were ranked 10th. If business continues as usual, Canada will emit 798 $MtCO_2eq$ GHGs by 2050 [7]. Canada has committed to reducing its emissions by 40–45% of its 2005 levels by 2030 and reach net zero emissions by 2050. In 2020, Canada emitted 672 $MtCO_2eq$ GHGs. The building sector contributed 13% of the total emissions, ranked the third largest source of emissions [8].

Lancet has predicted that the Canadian population will grow steadily in the long term, from 35.98 million in 2017 to a peak 45.17 million in 2078 [9]. Statistics Canada has forecasted a similar trend in the Canadian population growth, based on the medium-growth scenario, from 38.2 million in 2021 to 56.5 million in 2068 [10]. Along with population growth, the Canadian residential floor space has increased from 1499 million square meters in 2000 to 2158 million square meters in 2018, which is a 2% compound annual growth rate (CAGR) [11]. Furthermore, in 2019, the Canadian residential floor area was about three times the size of the commercial and institutional floor space, and the energy consumed by Canadian households was about 1.4 times that consumed by commercial and institutional buildings [12,13]. Therefore, carbon reduction in the residential building sector is critical to achieve net zero emission by 2050.

The whole-life carbon (WLC) of buildings refers to the carbon emissions across a building's lifetime. It commonly includes operational carbon and embodied carbon. Operational carbon is attributed to operational energy consumption during a building's lifetime, such as energy used for lighting, power, heating, cooling, ventilation, and water services. Embodied carbon is related to building material production, building construction, material replacement, and end-of-life disposal [14]. Operational and embodied carbon are different but inter-related [15]. Embodied carbon is a significant part of the whole-life carbon emissions of buildings. While the efficiency of building operation keeps improving, embodied carbon will become the only source of carbon emissions in zero-energy buildings [16].

A building envelope is a system of materials, components, and assemblies that physically separate the exterior and interior environment. It is crucial to determine and maintain the indoor conditions regardless of the changes in the outdoor environment. Components of building envelopes include the walls, fenestration, roof, foundation, thermal insulation, thermal mass, and external shading devices [17]. In Canada, more efficient building envelopes and heating equipment have resulted in a 12% decrease in GHG emission between 2005 and 2013 in the building environment, despite a 17% increase in the floor space [18]. Thermal insulation plays an important role in improving the energy efficiency of buildings [19]. It not only provides resistance to heat flow and lowers the energy required for heating and cooling through the building envelope, but it also improves comfort. It is one of the most valuable tools in achieving energy conservation in buildings [20]. Thermal insulation based on its composition can be divided into four categories: inorganic mineral, organic fossil fuel, combined materials deriving from animal and plants, and new-technology materials. The mainstream insulations under each categories are shown in Figure 1 [21].

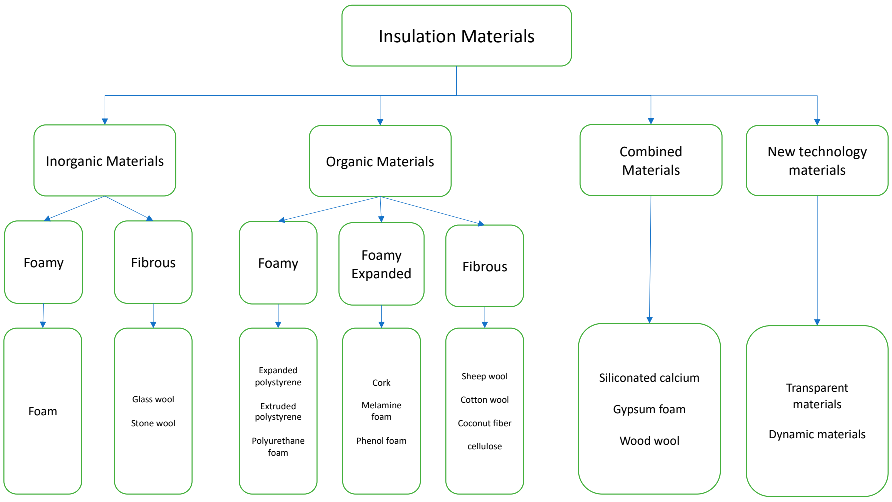

Figure 1. Classifications of insulation materials. Data adapted from [21].

Globally, the most used insulation materials are made of mineral wool (MW), including, glass wool, stone wool, and fibreglass, and of plastic foams (PFs) such as expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR). In 2015, MW dominated the market with just over 50% of the market share, and PFs accounted for 41% of the market share. The share of PFs will continuously grow because the demand for PFs is growing faster than for the other insulation materials [22]. MW is derived from inorganic minerals and PFs are derived from organic fossil fuels. Both feature a high level of embodied carbon due to an intensive material production process and impactful raw material extraction [23]. Furthermore, their carbon emissions are much higher than those of organic plant/animal or innovative insulation materials. Natural insulation materials are competitive alternatives because they contain a high percentage of renewable embodied carbon and they can store carbon. Hemp has the advantages of both low embodied carbon and low GHG emissions [21].

Hemp is acknowledged worldwide as one of the most used vegetal materials in building and construction in forms of fibres and hurds. HIMs have comparable thermal properties and behavior to MIMs, and they have better environmental performance [24]. However, the application of hemp for building and construction in Canada is still in its infancy. Although Canada is currently the largest hemp producer in the world, the focus is on hemp oilseed. The recent publications regarding hemp in Canada are largely focused on the impact of legalising marijuana and the popularisation of hemp health products and cannabidiol (CBD) [25]. There is a lack of studies regarding the potential of using hemp as a sustainable alternative to reduce the GHG emissions of Canadian buildings on a holistic scale.

This paper attempts to examine the extent to which HIMs can replace MIMs in Canadian residential buildings. The potential carbon mitigation from 2025 to 2050 at different levels through HIM substitution is measured and compared to the business-as-usual scenarios. The suitability of HIMs for Canadian private dwellings and the feasibility of implementing HIM substitution is discussed. The purpose of the work is to show the holistic impact that hemp could achieve in reducing emissions from the building sector. It will support further research, such as investigation of an integrated hemp supply chain to bring hemp from the farm to a completely hemp-insulated home and re-evaluate the potential of HIM substitution by using the dynamic life cycle assessment method.

The literature review is focused on the following research aims. First, the basic information of hemp, such as its botany, history, utilisation, cultivation, and politics, and the feasibility of large-scale hemp cultivation in Canada, is reviewed to identify why hemp is considered a sustainable option. Then, the scope is narrowed down to the use of hemp as a building material. The forms of hemp building materials, their applications, the development of hemp in building and construction, the comparison of mechanical properties, the environmental impact of HIMs and MIMs, and the structural types of Canadian private dwellings are reviewed to evaluate the suitability of HIMs for Canadian residential buildings. Then, the research gap between HIMs and Canadian residential buildings is identified. The literature review funnel chart is shown in Figure 2.

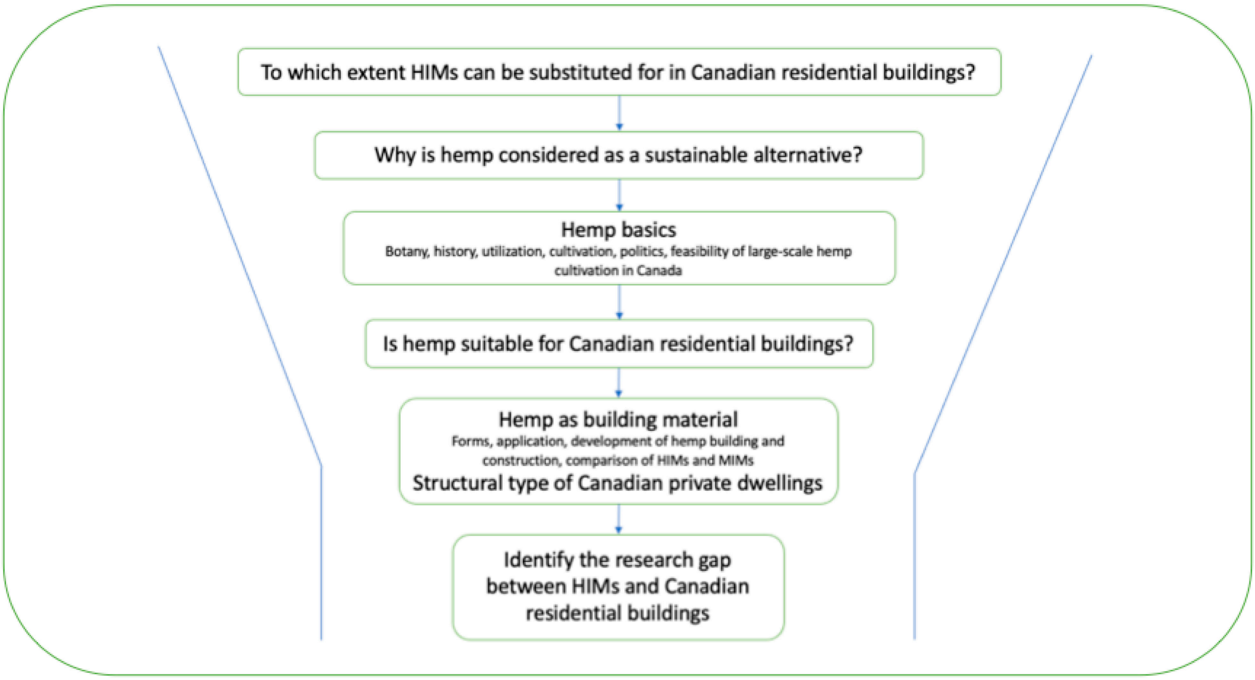

Figure 2. Literature review funnel chart.

2. Material Substitution

Hemp, or industrial hemp (*C. sativa* L.), is an annual C3 herbaceous plant in the Cannabis genus, a species of the Cannabaceae family [24]. The Cannabis genus includes three subspecies as shown in Figure 3a: *C. sativa* L., hemp; *C. ruderalis*, a wild form; and *C. indica* L., which features a high content of tetrahydro-cannabinol (THC), the principal cannabinoid content of hemp [26]. Cannabis is classified as hemp (the source of grain and fibre) if its THC content is below 0.3% and as marijuana (the source of medical and recreational use) if its THC content is above 0.3%; this level can cause hallucinations. Hemp and marijuana have a high level of genetic variability and heterozygosity, which is rare in other plants [27]. However, they are different [28]. Depending on its purpose, hemp has different varieties as shown in Figure 3b: low-density narcotic, low-density oilseed, very-high-density fibre, moderate-density dual purpose, and moderate-density early-maturing oilseed [28].

Figure 3. (**a**) Subspecies of Cannabis genus [29]. (**b**) Different varieties of hemp based on their purpose [28].

Hemp is considered one of the most ancient crops. It originated in central Asia about 10,000 years ago. A continuous record of hemp cultivation dating from 6000 years ago to the present can be found in China [30]. Hemp migrated to Europe between 1000 and 2000 BC, to South America in 1545, and to North America in 1606. Hemp was the leading cordage fibre in North America from 1840 to 1938, when hemp cultivation was prohibited. This is because hemp was a controversial plant due to the loosely interchangeable use of its common names, i.e., hemp and marijuana. The same reason has caused hemp to be banned in other places around the world over the last century [28]. Encouraged by the success of hemp legalisation in Western Europe, Canada, and the U.S. legalised hemp cultivation in 1994 and 2018, respectively. Hemp became a modern commodity crop in North America [31].

Hemp is one of the fastest-growing plants, typically planted in May and harvested in August. It can grow up to 1.5–4 m, depending on variety, in about 4 months. Grown hemp needs very little or no pesticides, herbicides, or fungicides. Its strong taproots can penetrate the soil up to 2–3 m, ventilating the soil while building soil aggregates and preventing erosion. It is an excellent rotation crop for winter wheat and soybean. Increases in the yield of wheat and soybean cultivated after hemp have been observed [32]. Hemp also has significant environmental benefits. It can remediate contaminated soils through phytoremediation, convert atmospheric CO_2 to biomass through bio-sequestration, and use hemp biomass for bioenergy production [33].

Hemp is widely adapted to different environments, from the equator to about 60° N latitude in the northern hemisphere, and most of the southern hemisphere [24]. The ideal temperature for growing hemp is 14 °C, and 5.6–27.5 °C is tolerable. Hemp requires 500–700 mm of available moisture for optimum yield. However, modern techniques can produce 15 t of hemp dry matter with only 250–400 mm water. Hemp, like corn and wheat, prefers loamy soil containing rich organic matter. Hemp is sensitive to photoperiods and not very tolerable to frost [34]. In general, Canada has an ideal geographic location, temperature, precipitation, and soil to develop hemp cultivation [35]; hemp has been cultivated in Canada from its eastern to its western regions [36].

Hemp is primarily an important fibre plant [30]. As one of the strongest and stiffest natural fibres, hemp fibre is very suitable for textiles, paper, composite products, automotive and construction materials, and many new environmentally friendly products [37]. Hemp seeds can be used for food, cosmetics, energy, etc.; hemp hurds, the waste by-products, can also be used for animal bedding and construction. As a versatile crop, hemp has been the source of more than 25,000 hemp products for centuries. Many fossil-fuel-based materials and applications can be replaced by hemp-based materials. The modern use of hemp is listed in Figure 4 [38].

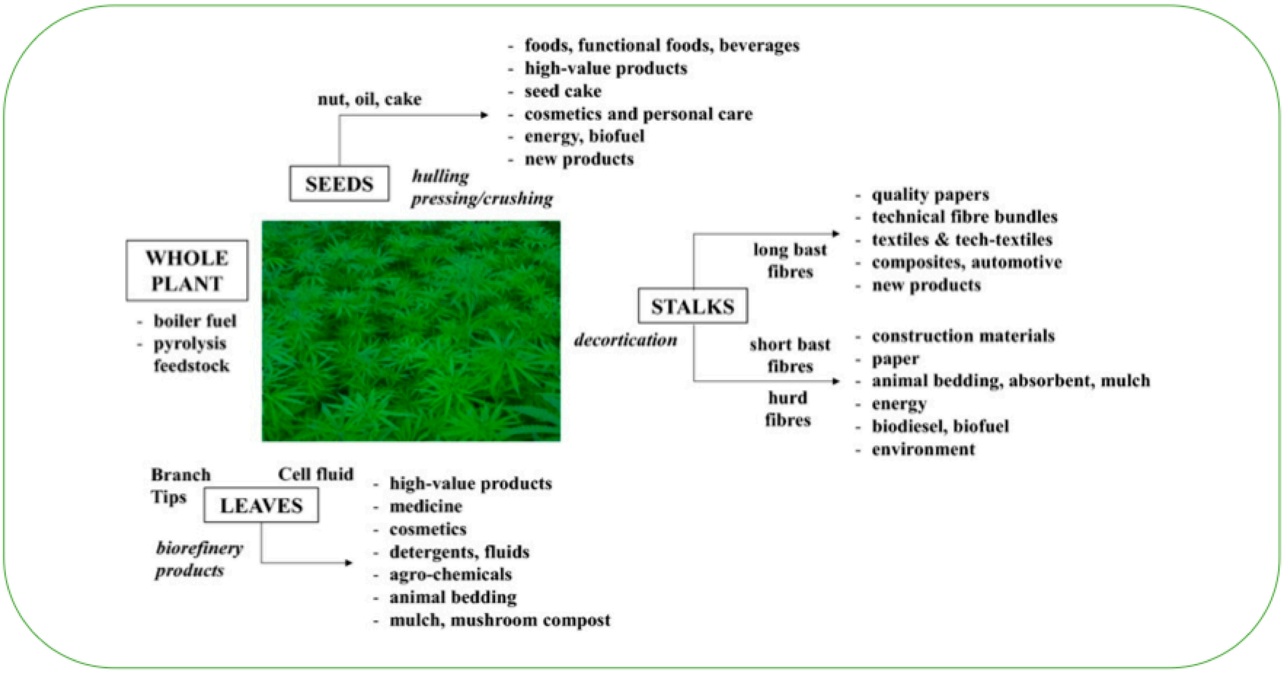

Figure 4. The modern use of hemp [38].

The application of hemp in construction and building can be traced back to 500 AD, when an ancient stone bridge was built with mortar made of hemp (more than 10% hemp) by Merovingians in France. Thanks to the permeability of hemp mortar, the bridge has been in place for centuries [39]. Mr. Nakamura's hemp house, built in 1698 in Miasa Mura, Japan, is a hemp museum today [40]. The modern use of hempcrete as an alternative to replace wattle and daub infills of timber stud walls started in the 1980s in France. It was used for first time in the renovation of the Maison de la Turquie by Charles Rasetti. Since the advancement of hempcrete building technologies and the availability of hempcrete, thousands of hemp buildings have been built in Europe for residential, commercial, and public use [41]. However, hemp building is still in its infancy in North America. The first hemp house in the U.S. was built in 2010 [42]; the first hemp house in Canada was built in 2002 [43]; and the first institutional hemp building was just finished in the UBC Vancouver campus, Canada [44]. The examples of hemp building and construction around the world in different periods are shown in Figure 5.

Hemp stalk contains hemp fibre and a woody core (also known as shives or hurds), which can be used to produce different construction materials. Hemp fibres are used to replace synthetic fibres to produce insulation. The hurds are used primarily to produce light and super-light concretes and mortars, as well as infills for cavities and under floors. Typical commercial hemp-based construction products are shown in Figure 6. Today, over 100 hemp-based construction products are available on the market [26].

Figure 5. Hemp buildings and construction. Source of photos: (**a**) [39], (**b**) [40], (**c**) and (**d**) [42], (**e**) [43], (**f**) [44].

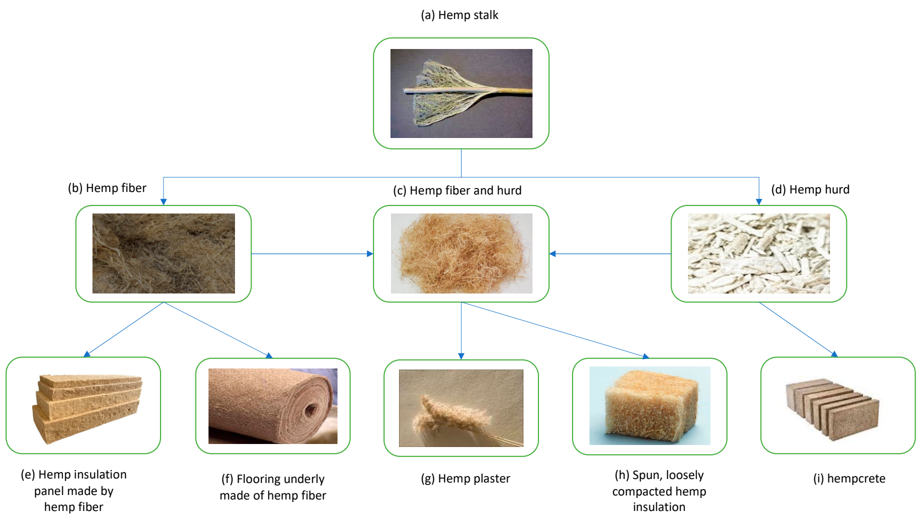

Figure 6. Typical commercial hemp-based construction products. Source of photos: (**a**) [42], (**b**) [45], (**c**,**d**,**i**) [46], (**e**,**f**) [47], (**g**) [48], (**h**) [28].

The porous structure of bast fibres enables hemp fibre to be suitable for thermal insulation, and its thermal conductivity is compatible with that of conventional insulations [49]. Attributed to the CO_2 uptake associated with hemp plant photosynthesis and fibre biodegradability, HF enables comparable thermal insulation performance with much higher levels of environmental compatibility [50].

HC, also known as hemp concrete or lime hemp concrete (LHC), is a biocomposite mix made of hemp hurds and lime [51]. A lime-based binder is chosen because of its abundance and the low emissions from its manufacture [52]. HC can be used for roofs, walls, and floors with adjusted composition through casting, spraying, or pre-casting [51]. However, HC cannot be used as a direct load-bearing material because of its low compressive strength and modulus of elasticity. HC has good thermal and acoustic insulation properties and can passively regulate humidity in a built environment [53]. The thermal properties and behavior of an HC wall were found experimentally to be virtually identical to those of a commonly used lightweight concrete insulation material with a similar density [54]. Thanks to the CO_2 uptake associated with hemp plant photosynthesis and the negative GHG emissions from its manufacture and installation, HC is carbon negative [55].

HC is very durable, resistant to freeze–thaw salt exposure, mould, and insects [56]. These properties are very desirable due to Canada's freezing cold winter [57] and more frequent floodings caused by climate change [58]. Furthermore, the heat resistance of hempcrete is better than that of conventional insulation materials due to its permeability. Flame tests have also proven that hempcrete is non-flammable [59]. Those features make HIMs a better choice than MIMs to combat extreme natural disasters, such as wildfire. Currently, forest fires are happening across Canada with more frequency and intensity; the spread of extreme forest fires caused by climate change has been increasing since 1980 and will continue to worsen until 2090 [60].

The thermal quality of hemp-based materials is the core value to a building's users [61]. Thermal conductivity, the measure of heat flow that passes through a specific type of material, is the main parameter used to express the thermal performance of an insulation material [62]. The thermal conductivity of commercially available hemp insulation is within the range of all generic groups of insulation and is compatible with those of other fibrous insulation materials [63].

In Canada, MIMs include fibreglass, rock wool, slag wool, cellulose, and spray foam used for attics and wall cavities. XPS, EPS, PIR, and PUR are used for both continuous sheathing and under-slab applications [64]. MW includes fibreglass, rock wool, and slag wool [23]. In 2016, the market share of the top three insulation materials was 44.3% mineral, 23.5% EPS, and 16.7% PIR/PUR [65]. Overall, insulation materials based on MW and PFs are dominant in Canada, with more than 80% of the market share.

To evaluate the environmental performance of HIMs and MIMs, the Construction Calculator (EC3) was applied to collect embodied carbon data. EC3 is an open access database of construction Environmental Production Declarations (EPDs), with a matching building impact calculator for use in the design and material procurement. EPD, a standardised and LCA-based tool, was developed to enable better comparability of the environmental performance of products [66]. The process of data collection is shown in Figure 7.

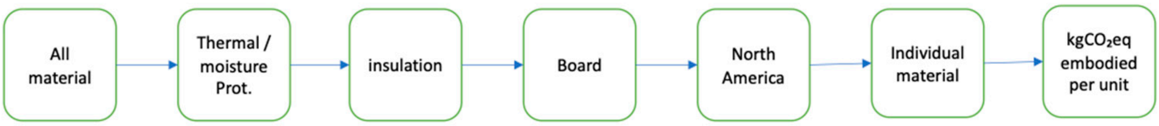

Figure 7. The selection of category in EC3.

Published EPDs contain discrepancies and inaccuracies due to the multiple methods of assessment [67]. The achievable value is picked for comparison because it represents the low value of the category, where more than 20% of products are better than the required specification [68]. Board-type insulation materials are considered because these are where most EPDs are found, and the *GWP* values under the board type come with a minimum 50-year lifespan, while the boundary of the other types, such as blanket, foam in place, and blown, is cradle-to-gate only without consideration of the lifespan [69]. The *GWP* values of each insulation material vary depending on its application; the weighted average values for different intended uses—walls and general, exterior walls, roofs, below grade, duct, and others—are taken for comparison. The expression of the formula is:

$$GWP_{wa} = \frac{\sum_{i=1}^{n} GWP_{iu} \times N_{iu}}{\sum_{i=1}^{n} N_{iu}} \quad (1)$$

where:

GWP_{wa} = weighted average *GWP*

GWP_{iu} = *GWP* for the intended uses

N_{iu} = number of declared EPDs for intended uses

The *GWP* values of HC and HF are not available in EC3. Moreover, the availability of HIMs in the market is limited. Therefore, the *GWP* values from the EDPs of a typical HF panel made in Canada by Natur-Chanv/hemp™ and an HC block made in Belgium by IsoHemp were picked for comparison. The functional unit (FU) for comparison was 1 m^2 of insulation material with a thickness that provides an average thermal resistance RSI = 1 $m^2 \cdot K/W$ with a minimum 50-year lifespan. The lifespan of HF is 75 years because no 50-year lifespan is available. Polyiso is used to represent PUR and PIR because both PIR and PUR are produced from the chemical reaction between polyol and isocyanate, with different ratios of isocyanate and different processes [62].

The comparison of thermal conductivity and *GWP* values of HIMs and MIMs, shown in Figure 8 (the relevant calculation in Appendix A), shows that the thermal conductivity of HF and HC is compatible with that of MIMs. HC is the only insulation with a negative environmental impact; HF is the second-lowest-emission insulation material. Therefore, HIM substitution can significantly reduce GHG emissions while maintaining the comparable thermal performance of buildings.

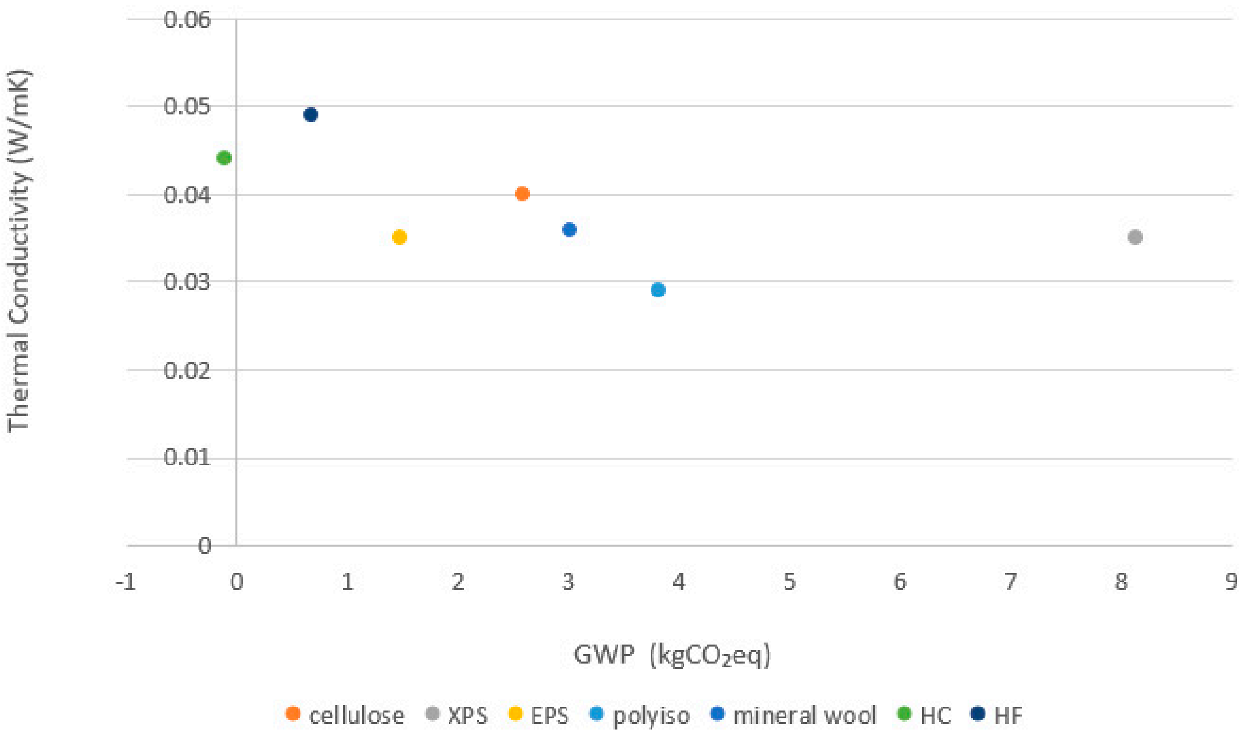

Figure 8. Comparison of GWPs and thermal conductivities of HIMs and MIMs. Data of thermal conductivities adapted from [62].

3. Methodology

Material flow analysis (MFA) systematically assesses the state and changes in the flows and stocks of materials within a system defined in space and time [70]. It is the primary methodology framework for environmental assessment and is widely implemented in environmental accounting and systems analysis [71]. Life cycle assessment (LCA) is a well-defined methodology used to assess the environmental impact of a product, process, or activity over its entire life cycle. It is frequently applied to evaluate the environmental impact of building construction [72]. For example, D'Amico et al. (2020) combined MFA and LCA across both spatial and temporal dimensions to evaluate their carbon mitigation by replacing concrete floors with steel cross-laminated timber [73]. Considering the similarity of evaluating the environmental impact through building material substitution, MFA and LCA were adopted to evaluate the potential carbon reduction achieved via substituting MIMs with HIMs for Canadian residential buildings from 2025 to 2050.

To assess the *GHG* mitigation derived from gradual HIM substitution, the annual *GHG* emissions in year t are expressed as the dot product between two vectors, $\overline{M}$ and $\bar{e}$ [74].

$$GHG^t(u) = \overline{M}^t(u) \cdot \bar{e} \tag{2}$$

The first vector, $\overline{M}$, is the material mass quantity in the given year t; another vector, $\bar{e}$, contains the corresponding carbon coefficients (CC), representing the amount of *GHG* (CO_2eq) emitted to the atmosphere per unit mass of material. The factor u, ranging from 0 to 100%, represents the percentage of MIMs to be replaced by HIMs at the end of reference period, 2025–2050. The vectors of the chosen materials and corresponding CC are:

$$\overline{M}\ (\mathrm{u}) = \begin{bmatrix} M_{mim}(u) \\ M_{him}\ (u) \end{bmatrix};\ \bar{e} = \begin{bmatrix} e_{mim}\ (u) \\ e_{him}\ (u) \end{bmatrix} \tag{3}$$

where:

M_{mim} = material mass quantity of MIM
M_{him} = material mass quantity of HIM
e_{mim} = carbon coefficients of MIM
e_{him} = carbon coefficients of HIM

The amount of HIMs needed for substitution in the given year t is subject to the area suitable for HIMs application and the percentage of MIMs to be replaced by HIMs. The *GHG* emitted into the atmosphere per unit of mass are assumed to be the same from 2025 to 2050. The process to identify the carbon mitigation by hemp substitution is explained in Figure 9:

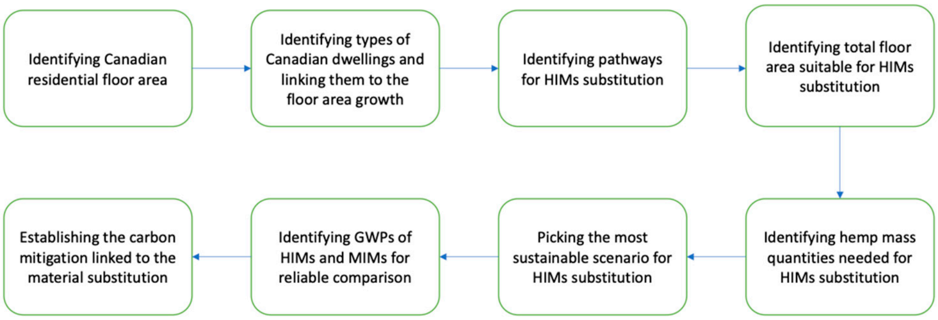

Figure 9. Process of data identification and assembly.

4. Results

4.1. Projection of Canadian Residential Floor Area from 2025 to 2050

To forecast future demand of HIMs for substitution, the residential floor area (Λ^t_{res}) in the given year t needs to be projected first. As the entire floor area is not suitable for HIM substitution, the percentage (ρ) of area suitable for HIM substitution (Λ^t_{him}) also needs to be identified. The projection is expressed as:

$$\Lambda^t_{\mathrm{him}} = \rho \Lambda^t_{\mathrm{res}} \tag{4}$$

Along with population growth, the Canadian residential floor space has increased from 1499 million square meters in 2000 to 2158 million square meters in 2018, which is a 2% compound annual growth rate (CAGR), the mean annual growth rate [11]. As the Canadian population will continue to grow at a moderate rate over the next 50 years [74], the assumption was made that the Canadian residential floor area will continue to increase at a 2% CAGR in the period of 2025–2050. The residential floor area in the given year t is expressed as:

$$\Lambda^t_{res} = (1 + 2\%) \Lambda^{t-1}_{res} \tag{5}$$

where Λ^{t-1}_{res} represents the floor area in the year before the given year t.

The value of the 2018 residential floor area is used as the starting year to project the 2025−2050 residential floor area [11].

4.2. Structural Type of Canadian Dwellings

To define the percentage of the residential floor area suitable for HIM substitution, the types of Canadian dwellings need to be identified to assess if HIM substitution is applicable. Dwellings in Canada are divided broadly into two types: private and collective. A private dwelling refers to a separate set of living quarters with a private entrance either from outside the building or from a common hall, lobby, vestibule, or stairway inside the building. Collective dwelling refers to a dwelling of commercial, institutional, or communal nature in which a person or group of persons reside or could reside. According to the 2016 Census, 98% of Canadians resided in private dwellings and 2% lived in collective dwellings [75]. For this paper, HIM substitution is limited to private dwellings only. Structural types of private dwellings are classified into nine categories as shown in Figure 10: single-detached house, semi-detached house, row house, apartment or flat in a duplex, apartment in a building that has five or more storeys, apartment in a building that has fewer than five storeys, other single-attached home, mobile home, and other movable home [76].

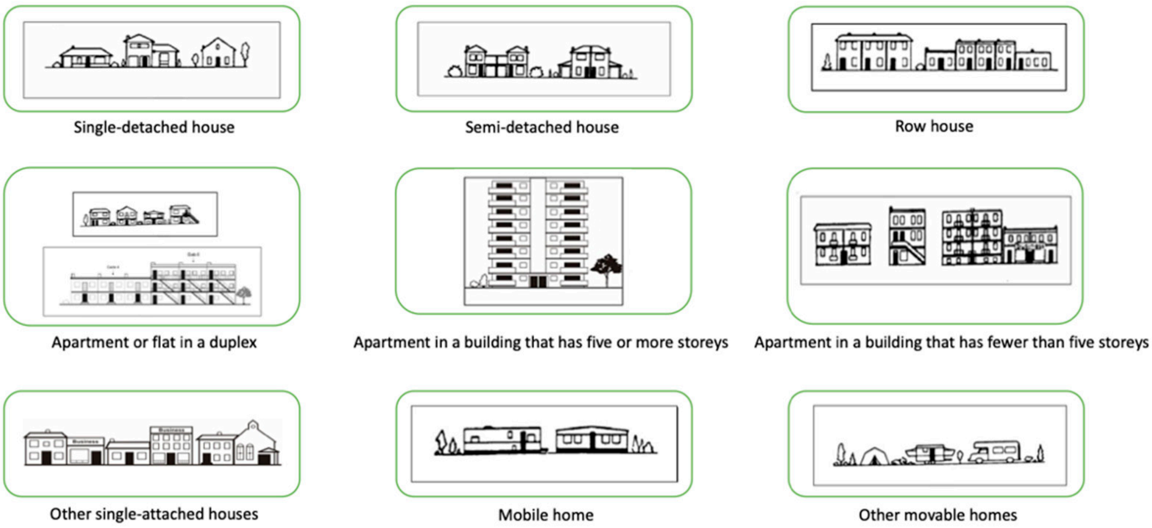

Figure 10. Structural type of Canadian private dwellings [76].

As HIMs are suitable to form envelopes in most low-rise constructions up to six storeys [77], all dwelling types, except apartments in a building that has five or more storeys ($\Lambda^t_{\geq 5s}$), are considered suitable for HIM application. The percentage (ρ) of space suitable for HIM substitution (Λ^t_{him}) in a given year t is expressed as:

$$\rho = \frac{\Lambda^t_{res} - \Lambda^t_{\geq 5s}}{\Lambda^t_{res}} \tag{6}$$

Based on the Canadian Residential Housing Stock and Floor Space issued by Natural Resources Canada [11], HIMs can be applied in 81% of the existing Canadian residential floor space.

4.3. Pathways for HIM Substitution

When modelling the quantities of HIMs needed for substitution, both the new added floor area ($\Lambda^t_{new\ add}$) and the retrofit floor area (Λ^t_{retro}) need to be included.

4.3.1. New Added Floor Area Suitable for HIM Substitution

The new added floor area in the given year *t* is expressed as:

$$\Lambda^{t}_{new\ add} = \Lambda^{t}_{him} - \Lambda^{t-1}_{him} \tag{7}$$

where Λ^{t-1}_{him} represents the floor area suitable for HIM substitution in the year before the given year *t*.

4.3.2. Retrofit Floor Area Suitable for HIM Substitution

The energy retrofitting of existing buildings has become a common climate action initiative around the world in response to a more stringent energy performance standard [78]. Canadian provincial and territorial governments have committed to expand efforts to retrofit existing buildings by supporting energy efficiency improvement. Deep and major retrofits involve large-scale changes; for example, different building envelopes and heating equipment can reduce energy use by 45–60% [79]. Retrofits also provide social and economic benefits [80]. However, a homeowner's decision to retrofit depends on many factors, such as the evaluation of the current efficiency and durability, the cost of the retrofit, the benefit of the retrofit, and the government's incentives. As a result, less than 20% homeowners have implemented the retrofit recommended by the government [81]. The 2015 Survey of Household Energy Use showed that only about 6% of improvements in building insulation in the past five years had been for the basement and roof, and 3% for any exterior walls [82]. Therefore, the assumption was made that annual insulation retrofit is 3% of the total floor area suitable for HIM replacement. The expression of the retrofit of the floor area in the given year *t* is:

$$\Lambda^{t}_{retro} = 3\%\ \Lambda^{t}_{him} \tag{8}$$

4.4. Projection of Total Floor Area Suitable for HIM Substitution

4.4.1. Projection of Roof Area Suitable for HIM Substitution

HIMs can be applied to the roof, wall, and floor [51]. Therefore, the roof (Λ^{t}_{roof}) and wall (Λ^{t}_{wall}) area in given year *t* should also be taken into consideration. According to the building code, ceiling insulations must be applied to cathedral and flat roofs, skylight shafts, and ceilings below attics [83]. The assumption was made that the ceiling area needs to be insulated to the same degree as the floor area.

$$\Lambda^{t}_{roof} = \Lambda^{t}_{him} \tag{9}$$

4.4.2. Projection of Wall Area Suitable for HIM Substitution

The wall area suitable for HIM substitution in given year *t* depends on the wall-to-floor ratio (r_w), which is related to the fenestration- and door-to-wall ratio (FDWR) and ceiling height (h_c). The expression of wall space (Λ^{t}_{wall}) suitable for HIM substitution is:

$$\Lambda^{t}_{wall} = r_w\ \Lambda^{t}_{him} \tag{10}$$

The FDWR for different climate zones varies according to the Canada National Building Code, from a maximum of 40% for the warmer-climate zones to 20% for the coldest zones [84]. The weighted average FDWR (r_f) of different zones was used for the wall area calculation. The expression of r_f is:

$$r_f = \frac{\sum_{i=1}^{3} \mu_i \Lambda_{th} \gamma_i}{\Lambda_{th}} \tag{11}$$

where μ_i represents the percentage of the total heated area (Λ_{th}) permitted for FDWR (γ_i).

Based on the 2015 Survey of Household Energy Use (SHEU-15), 53% (μ_1) of the total heated area of dwellings (Λ_{th}) was within the maximum 40% FDWR (γ_1), 41% (μ_2) was within the maximum 33% FDWR (γ_2), and 7% (μ_3) was within the maximum 20–27% FDWR (γ_3) [85]; the weighted average FDWR (r_f) was 37%.

The minimum ceiling height required by the Canada National Code is 2100 mm [86]. Standard 8-foot (2438 mm) ceilings prevail in post-war North American homes [87]. Therefore, the ceiling height (h_c) was assumed to be 2438 mm.

When ceiling height is defined, the wall-to-floor ratio (r_{wi}) depends on the length (l_i) and width (w_i) of a certain floor area (Λ_i). The expression of r_{wi} is:

$$r_{wi} = \frac{(l_i + w_i) \times 2 \times h_c \times \left(1 - r_f\right)}{\Lambda_i} \tag{12}$$

The average size of the Canadian house unit in 2018 was 137 m^2 [12]. The diagrams of the structure types of dwellings, used by trained emulators to collect information on dwellings for the Census, show that mainstream Canadian house units are either rectangle or square shapes [88]. Therefore, two assumptions were made for the shape of the average size of a Canadian house unit: rectangular and square. The average of r_{w1}, derived from a rectangular shape, and that of r_{w2}, derived from a square shape, was labelled r_w and used for the wall area calculation. The formula is:

$$r_w = \frac{\sum_{i=1}^{2} r_{wi}}{2} \tag{13}$$

4.4.3. Total Area Suitable for HIM Substitution

The summary of the total area suitable for HIM substitution (Λ^t_{total}) in a given year t can be expressed as:

$$\Lambda^t_{total} = \Lambda^t_{new\ add} + \Lambda^t_{retro} + \Lambda^t_{roof} + \Lambda^t_{wall} \tag{14}$$

Overall, the projection of the Canadian residential floor area and the total area suitable for HIM substitution from 2025 to 2050 is shown in Figure 11 (the relevant calculation in Appendix B).

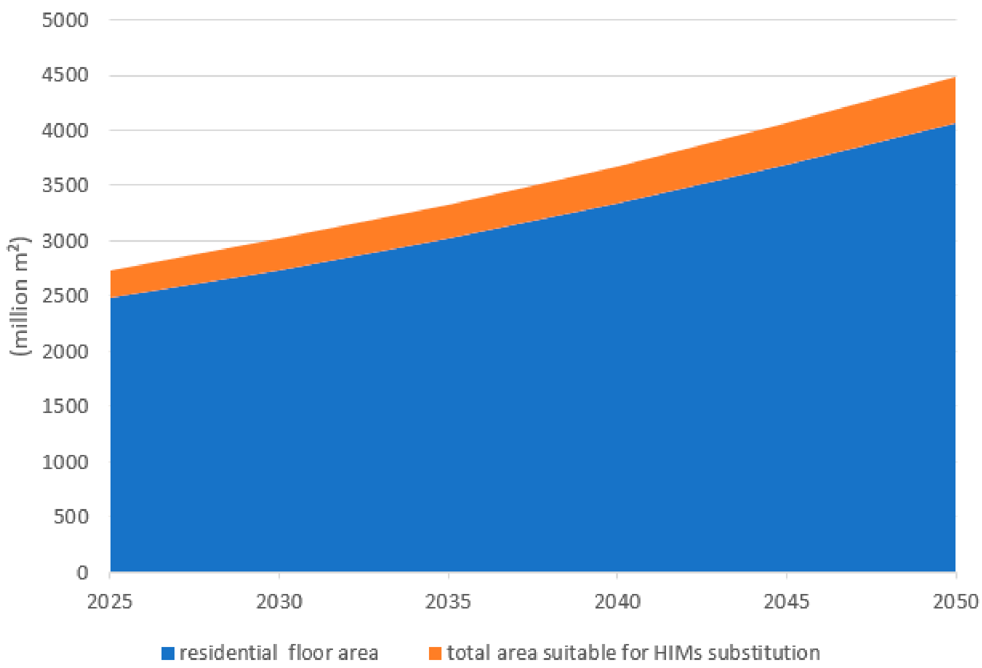

Figure 11. Projection of Canadian residential floor area and total area suitable for HIM substitution (million m^2).

4.5. Hemp Quantities Needed for HIM Substitution

The quantity of hemp (M_{hemp}) needed for HIM substitution in a given year t depends on the thickness (ι), proportion, and density of HF and HC used for HIM substitution (Λ^t_{total}). It is expressed as:

$$M_{hemp} = \iota\, \rho_{hf} \Lambda^t_{total} d_{hf} + \iota\, \rho_{hc} \Lambda^t_{total} d_{hc} \tag{15}$$

where:

ρ_{hf} = proportion of HF for substitution
ρ_{hc} = proportion of HC for substitution
d_{hf} = density of hemp fibre, average 35 kg/m^3 [63]
d_{hc} = density of hempcrete, average 350 kg/m^3 [89]

4.5.1. Thickness of HIMs

The minimum R-value needed to meet code requirements varies between different areas in Canada and is very variable for different parts of the house. R-43 is the minimum average according to the Insulation Building Code requirements of 2021 [90]. Hemp insulation is relatively unknown and not commonly used in North America. R-3.5 per inch of thickness, the same as for other fibrous materials, is suggested by the U.S. Department of Energy [91]. Based on that, a thickness (ι) of 30 cm is needed for HIMs to meet the R-43 requirement.

4.5.2. Scenarios for Hemp Material Usage

To identify the appropriate proportion of HF and HC used for HIM substitution, sustainability is the priority. The goal is to maximise hemp product utilisation and minimise the impact on the environment. The hemp economy and the allocation of hemp mass were also considered.

Hemp is traditionally grown for its fibre. Hemp hurds are the byproduct [92]. The potential to use hempcrete is huge due to the availability of hemp hurds [51]. However, only 25.9% of hemp fibre and 15% of hurds were used for insulation in Europe in 2010 [63]. The mass allocation of 1 ton of hemp typically contains 75% hurds, 20% technical fibre, and 5% dust [93]. Therefore, three scenarios were assumed in Table 1 to identify the most sustainable combination of HF and HC for HIM substitution.

Table 1. Scenarios of hemp material usage.

	Ratio of HF	Ratio of HC	Reason
Scenario 1	20%	80%	All hemp fibre used for insulation
Scenario 2	10%	90%	Half of hemp fibre used for insulation
Scenario 3	5%	95%	Existing portion of hemp fibre used for insulation in EU where modern hemp building is originated and most developed

The comparison of different scenarios, shown in Figure 12 (the relevant calculation in Appendix C), shows that hemp production is more sensitive to the proportion of HF than that of HC. Every 5% increase in HF proportion requires about double the hemp production to support it. However, every 5% increase in HC proportion only requires approximately 6% more hemp production. Based on the assumption that all extra hemp fibre produced from HIM substitution will be fully absorbed by hemp fibre's traditional and innovative applications, the HIM replacement fulfilled by 5% HF and 95% HC is the most sustainable scenario because it will maximise the utilisation of hemp production and minimise resource waste.

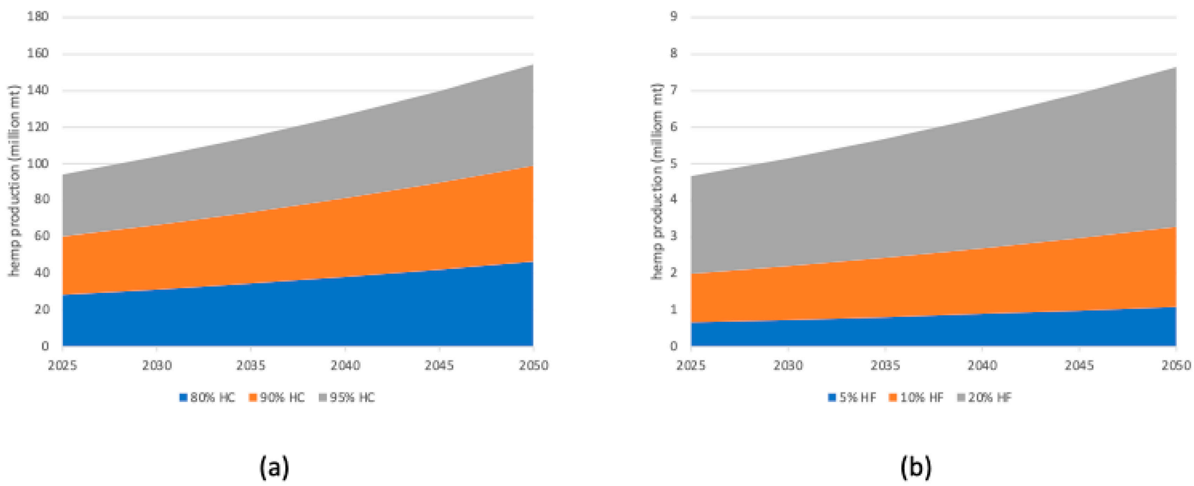

Figure 12. Hemp production needed under different scenarios of HIM substitution. (**a**) Hemp production to meet demand for hemp hurds for HIM substitution. (**b**) Hemp production to meet hemp fibre demand for HIM substitution.

4.6. Cumulative Carbon Mitigation by HIM Substitution

To compare the environmental impact of HIMs with that of MIMs, the quantity of *GHG* emitted into the atmosphere due to the use of different insulation materials in a given year t is needed, and is related to the *GWP* value per function unit (FU) of different insulation materials, the total floor area suitable for HIM substitution, and the quantity of FU to achieve an average that meets the R-43 building code requirement. The expression is:

$$\overline{GHG}_i^t = \overline{GWP}_i^t \times \Lambda_{total}^t \times \overline{n}_i \tag{16}$$

$$\overline{n}_i = \frac{l_{iR43}}{l_{iR1}} \tag{17}$$

where:

$\overline{GHG}_i^t$ = *GHG* emissions by given insulation i in given year t.
$\overline{GWP}_i^t$ = *GWP* value of given insulation i per FU.
Λ_{total}^t = total area suitable for HIM substitution in given year t.
$\overline{n}_i$ = quantity of FU to achieve R-43, which can be expressed as:
l_{iR43} = thickness to achieve R-43 of given insulation i.
l_{iR1} = thickness of a FU to achieve R-1 of given insulation i.
The following assumptions are made:

- Full HIM substitution means that the total floor area suitable for HIM substitution is fulfilled by 5% HF and 95% HC.
- Business as usual (BAU) means that the total floor area suitable for HIM substitution is fulfilled by MIMs composed of 50% MW and 50% PFs.
- The average *GWP* values of EPS, XPS, and Polyiso are applied to PFs.
- The thickness of 1 m^2 insulation to achieve the R-1 of different insulations is the same.

The result, shown in Figure 13 (the relevant calculation in Appendix D), shows that full HIM substitution would emit -1.43 $MtCO_2eq$ *GHGs* into the atmosphere from 2025 to 2050. If BAU, 142.42 $MtCO_2eq$ *GHGs* will be emitted into the atmosphere in the same period. Therefore, HIM substitution would mitigate 101% GHG of the emissions of BAU from 2025 to 2050.

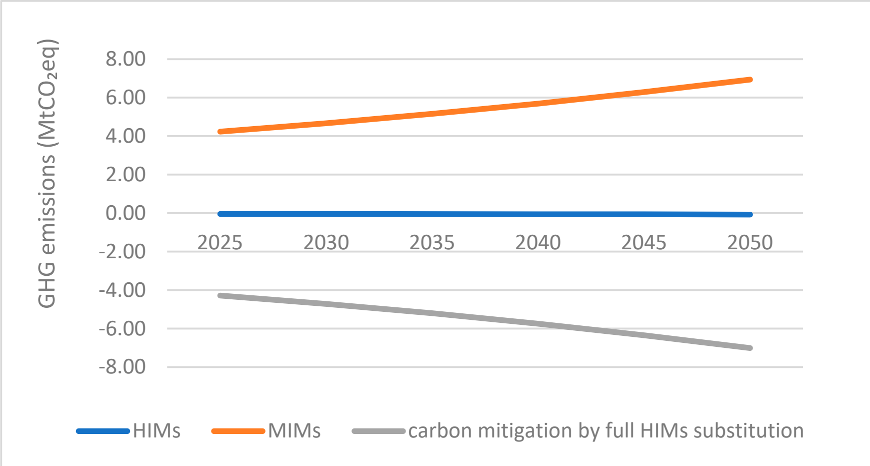

Figure 13. Comparison of *GHG* emissions in full HIM substitution to BAU scenario.

4.7. Impact on Net Zero Emissions by 2050

In 2020, Canadian buildings emitted 88 $MtCO_2eq$ into the atmosphere [94]. To achieve the net zero carbon target in 2050, the annual *GHG* emissions need to be reduced at a CAGR of −13.9%. We projected the ratio (r_i) of *GHG* emissions from full HIM substitution and business-as-usual scenarios toward target emissions (GHG_{target}) to achieve net zero emissions in 2050 to examine the impact of the HIM substitution on the net zero carbon goal.

$$r_i = \frac{GHG_i}{GHG_{target}} \tag{18}$$

where:

GHG_i = *GHG* emissions from different scenarios

GHG_{target} = target emissions to achieve net zero emissions in 2050

The result, shown in Figure 14 (the relevant calculation in Appendix E), shows that full HIM substitution can positively contribute a 7.38% reduction in the target emissions to achieve net zero emissions by 2050. However, BAU will generate 700% of the target emissions, which will require extra efforts to offset it to achieve net zero carbon by 2050.

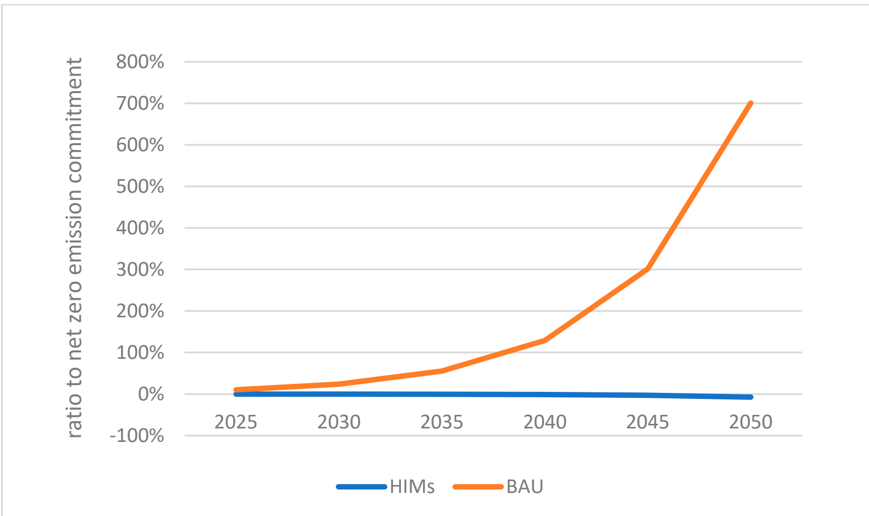

Figure 14. Comparison of the impact of full HIMs substitution and BAU scenarios towards net zero commitment by 2050.

4.8. Resource Availability to Achieve full HIM Substitution

To evaluate the resource availability for full HIM substitution, the area of farm in Canada suitable for hemp cultivation is the primary consideration. The expression of hemp acreage needed for HIM substitution is:

$$A^t_{hemp} = \frac{P^t_{hemp}}{y} \quad (19)$$

where:

A^t_{hemp} = acreage of hemp cultivation in given year t

P^t_{hemp} = production of hemp in given year t

y = the yield of hemp fibre for HIM substitution

The yield of hemp stem dry matter fluctuates, ranging from 7 t to 19 t per ha, which heavily depends on the cultivar, temperature, water, and fertilisation [95]. An average hemp fibre yield of 14 tons per ha was observed in Italy [96]. We assumed a yield of 15 t per ha because it is technically achievable even with less-than-normal precipitation [34].

Meanwhile, a projection of Canadian area of farm from 2025 to 2050 was established to investigate the land availability for HIM substitution. Historic data of the Census of Canadian agriculture show that the area of farm has deceased by 2% every 5 years from 2011 to 2021 [97]. Such a trend is most likely to continue through to 2050 due to massive urbanisation and the booming population [98]. Therefore, the assumption was made that the area of farm in Canada will continue to shrink at a rate of 2% every 5 years until 2050.

The comparison, shown in Figure 15 (the relevant calculation in Appendix F), shows that there is enough area of farm for hemp cultivation in Canada to satisfy the demand for full HIM substitution. The percentage of hemp acreage to total area of farm will grow from 3.67% in 2025 to 6.67% in 2050 due to the increase in hemp cultivation and shrinking of farmlands.

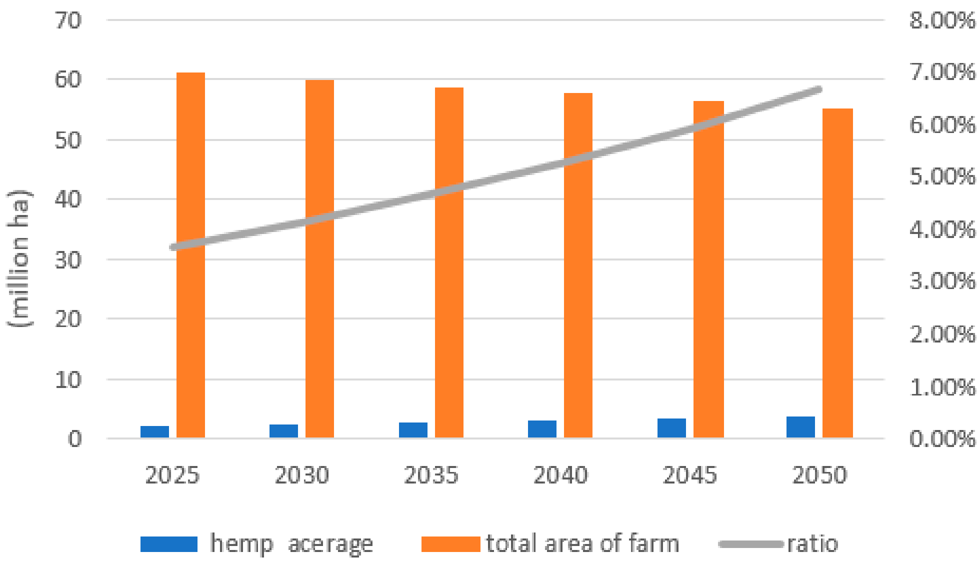

Figure 15. Ratio of hemp acreage for full HIM substitution vs total farmland in Canada.

5. Discussion

Existing studies show that wood, bamboo, and straw clay can replace conventional building materials such as concrete, aluminium, and bricks with comparable mechanical properties and significant carbon mitigation [99]. The comparison of the GWP reduction caused by substitution with hemp and other natural building materials, shown in Table 2, shows that hemp substitution can mitigate more GWP than other natural materials substitution. Hemp substitution can sequester carbon instead of emitting carbon.

Table 2. Comparison of the environmental impact of natural materials substitution. Data adapted from [100].

Article	Conventional Building Material	Natural Material Substitution	LCA Phase	GWP Reduction
[101]	Concrete masonry wall	Natural cob	Cradle to site	−75%
[102]	Wood wall	Wood wall with light straw clay and cob	Manufacturing	−92%
[73]	Concrete	Cross-laminated timber	Whole-life carbon	−2%
[100]	Insulation panel	Granule plaster	Cradle to processing	−36%
[103]	Concrete	Timber	Whole-life carbon	−37%
[104]	Aluminium	Medium-density fibreboard	Cradle to gate	−68%
		Oriented strand board		−91%
		plywood		−74%
[105]	Bricks and concrete	Bamboo glue laminate	Cradle to use	−80%
	Bricks	Bamboo glue		−70%
	Concrete hollow	Bamboo		−50%
	MIMs	HIMs	Whole-life carbon	−101%

Although there is plenty of farmland in Canada available for hemp cultivation, and Canada is the largest hemp producer, with 555,853 ha hemp acreage in 2018 [34], the primary focus of hemp cultivation in Canada is currently the hemp seed, because it is more profitable. Most Canadian hemp seeds are exported to the U.S. Furthermore, unlike many other mature crops subject to substantial research in genetic optimisation, product applications, and equipment design, fibre hemp needs a lot more study to make it competitive alongside other commodities [25]. Economic consideration is the bottom line for farmers. The estimated return of grain hemp is slightly positive, but that of fibre hemp is now negative [106]. Therefore, it is a significant challenge to realise mass fibre hemp production in Canada in the short term to meet the requirements for full HIM substitution. The chance to import hemp from other countries is also rare because the overall market size is too small [34]. However, the increase in global hemp cultivation in the long term is optimistic. Industrial hemp is emerging as a highly successful commercial crop due to its low carbon footprint, efficient land use, and multiple uses [107]. China, a historically dominant hemp grower and exporter, has committed to substantially increase hemp acreage [108]. The hemp production in Europe has increased by 70% from 2013 to 2018, driven by emerging demand from industrial textile fibre applications [109]. The U.S., as the largest importer of hemp products, is turning from a net hemp importer into a hemp producer. The hemp acreage has increased from 0 in 2013 to over 90,000 acres (or 36,421 ha) in 2018. The rapid growth in hemp production in the U.S. will significantly impact the global hemp supply [110], particularly in Canada, the major exporter of hemp products to the U.S. [25].

HIMs have been officially approved for use in the construction industry in Europe. HC is commonly used in France, England, Germany, Ireland, Belgium, Luxembourg, and Switzerland [39]. In October 2022, hemp–lime construction was approved for U.S. residential construction. It is limited to the non-structural, solid infill mix of hemp hurds and their binder in between or around the wall framing [111]. In Canada, Quebec is the leader and pioneer of hemp construction [39]. Residential hemp construction projects are permissible under Section 9 of the Ontario Building Code [112]. However, hemp building has not officially been approved by the National Building Code and the rest of the provinces yet.

In Canada, most hemp stems are burned by farmers due to the lack of decortication equipment to separate the fibre and hurds. The hurds used in Canada for HC are imported from Europe and China [113]. There is a lack of fine varieties of the hemp cultivar, state-of-the-art techniques to support high-yield cultivation, processing capacity, industrial standards, and coordination between planting and processing [25]. An integrated hemp supply chain is essential to popularise hemp cultivation and utilisation in Canada.

Furthermore, the current comparison of carbon mitigation is based on the GWP values from traditional LCA results. No time-related conditions were considered, although the impact of releasing the same quantity of pollutant at one time or at a small rate over time is generally different. Dynamic LCA was primarily developed to improve the accuracy of LCA by addressing the inconsistency of temporal assessment [114]. Therefore, re-evaluating the potential carbon mitigation using dynamic LCA may provide a valuable comparison to the current paper.

6. Conclusions

Hemp-based insulation materials have comparable thermal properties to those of MIMs, with much better environmental performance. HIM substitution can be applied to 81% of existing Canadian homes. The unique properties of HIMs, such as durability, resistance to freeze–thaw and salt exposure, antimould properties, resistance to fire, and non-flammability, are significantly important for combating extreme weather events and natural disasters caused by climate change. The environmental benefit of hemp substitution is superior to that of other natural materials' substitution. Full HIM substitution with 5% HF and 95% HC would mitigate a total pf of 1.43 MtCO_2eq of GHG emissions from 2025 to 2050, which is 143.92 MtCO_2eq less than that in a BAU scenario. Although Canada has sufficient land to cultivate hemp for full HIM substitution, it is a significant challenge to increase hemp production in the short term because hemp is a still a new crop in North America. There is a lack of hemp fibre cultivars, equipment, techniques, and expertise to pursue large-scale fibre hemp cultivation and processing. Meanwhile, hemp fibre is not economically competitive compared to other traditional commodity crops. Furthermore, hemp as a building material has not been widely accepted by Canadian building codes. These barriers need to be addressed first. Recommendations for future research include the integration of a hemp supply chain to support mass HIM production and the re-evaluation of the potential of HIM substitution from a dynamic LCA perspective.

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Abbreviations

Greenhouse gases (GHGs); Carbon dioxide (CO_2); Hemp insulation materials (HIMs); Mainstream insulation materials (MIMs); Hemp fibre insulation (HF); Hempcrete (HC); Mineral wool (MW); Plastic foams (PF); Expanded polystyrene (EPS); Extruded polystyrene (XPS); Polyisocyanurate (PIR); Polyurethane (PUR); Carbon coefficient (CC); Functional unit (FU); Business as usual (BAU); Compound annual growth rate (CAGR).

Appendix A

Appendix A.1 The Average Thermal Conductivities

$$\lambda^i_{average} = \frac{\lambda^i_{min} + \lambda^i_{max}}{2} \tag{A1}$$

where:

$\lambda^i_{average}$ = average thermal conductivity of certain insulation material i
λ^i_{min} = minimal thermal conductivity of certain insulation i
λ^i_{max} = maximum thermal conductivity of certain insulation i

Table A1. Comparison of thermal conductivities of HIMs and MIMs.

Insulation	MW	Cellulose	XPS	EPS	Polyiso	HC	HF
Thermal conductivity (W/mK)	0.036	0.040	0.035	0.035	0.029	0.044	0.049

Data adapted from [63]. Original thermal conductivity values are given in ranges. The average of the min and max thermal conductivity values are picked for comparison.

Appendix A.2 The Weighted Average GWP Values

$$GWP_{wa} = \frac{\sum_{i=1}^{n} GWP_{iu} \times N_{iu}}{\sum_{i=1}^{n} N_{iu}} \tag{A2}$$

where:

GWP_{wa} = weighted average GWP
GWP_{iu} = GWP for the intended uses
N_{iu} = the number of declared EPDs for all intended uses

Table A2. Comparison of GWPs of HIMs and MIMs.

Insulation	MW	Cellulose	XPS	EPS	Polyiso	HC	HF
Achievable $kgCO_2$ per 1 m^2 RSI	3.01	2.59	8.14	1.47	3.81	−0.106	0.684

Appendix B

Appendix B.1 Calculation of Compound Annual Growth Rate (CAGR) of Canadian Residential Floor Area Based on Natural Resource Canada 2020′s Statistic of Residential Floor Space from 2000 to 2018

$$CAGR = \left(\frac{\Lambda_{2018}}{\Lambda_{2000}}\right)^{1/t} - 1 \tag{A3}$$

where:

Λ_{2018} = residential floor area of 2018
Λ_{2000} = residential floor area of 2000

t = time of period.

Table A3. CAGR of Canadian residential floor area from 2000 to 2018.

Year	2000	2018
Floor area (million m^2)	1500	2163
CAGR		2%

Appendix B.2 Projection of Residential Floor Space from 2020 to 2050

$$\Lambda_{res}^{t} = (1 + 2\%)\Lambda_{res}^{t-1} \tag{A4}$$

where:

Λ_{res}^{t} = floor area in given year t

Λ_{res}^{t-1} = floor area in the year before the given year t

The value of the 2018 residential floor area is used as the starting value to project the 2020−2050 residential floor area.

Table A4. Projection of Canadian residential floor area.

Year	2025	2030	2035	2040	2045	2050
Floor area (million m^2)	2479	2737	3022	3336	3683	4067

Appendix B.3 Percentage of Residential Floor Area Suitable for HIM Replacement

$$\rho = \frac{\Lambda_{res}^{t} - \Lambda_{\geq 5s}^{t}}{\Lambda_{res}^{t}} \tag{A5}$$

where:

ρ = percentage of total residential floor area suitable for HIM replacement

Λ_{res}^{t} = total residential floor area

$\Lambda_{\geq 5s}^{t}$ = total residential floor area more than five storeys (not suitable for HIM replacement).

Table A5. Floor area suitable for HIM substitution.

Year	2025	2030	2035	2040	2045	2050
Total floor area (million m^2)	2479	2737	3022	3336	3683	4067
Floor area more than 5 storeys (million m^2)	466	515	568	628	693	765
Floor area suitable for HIM replacement (million m^2)	2012	2222	2453	2709	2990	3302
Percentage suitable for HIM replacement	81%	81%	81%	81%	81%	81%

Appendix B.4 New Added and Retrofit Floor Space for HIM Replacement

$$\Lambda_{new\ add}^{t} = \Lambda_{him}^{t} - \Lambda_{him}^{t-1} \tag{A6}$$

$$\Lambda_{retro}^{t} = 3\%\ \Lambda_{him}^{t} \tag{A7}$$

where:

$\Lambda_{new\ add}^{t}$ = new added floor area suitable for HIM replacement

Λ_{him}^{t} = floor area in given year t
Λ_{him}^{t-1} = floor area in the year before the given year t
Λ_{retro}^{t} = retrofit floor area in given year t
Λ_{him}^{t} = floor area suitable for HIM replacement in given year t

Table A6. New added and retrofit floor area.

Year	2025	2030	2035	2040	2045	2050
New added floor area (million m^2)	39	44	48	53	59	65
Retrofit floor area (million m^2)	60	67	74	81	90	99

Appendix B.5 Projection of Roof and Wall Area for HIM Replacement

Appendix B.5.1 Roof Area Suitable for HIM Replacement

$$\Lambda_{roof}^{t} = \Lambda_{him}^{t} \tag{A8}$$

where:
Λ_{roof}^{t} = roof area suitable of HIM replacement in given year t;
Λ_{him}^{t} = floor area suitable for HIM replacement in given year t.

Appendix B.5.2 Wall Area Suitable for HIM Replacement

$$\Lambda_{wall}^{t} = r_w \, \Lambda_{him}^{t} \tag{A9}$$

$$r_f = \frac{\sum_{i=1}^{3} \mu_i \Lambda_{th} \gamma_i}{\Lambda_{th}} \tag{A10}$$

$$r_{wi} = \frac{(l_i + w_i) \times 2 \times h_c \times \left(1 - r_f\right)}{\Lambda_i} \tag{A11}$$

$$r_w = \frac{\sum_{i=1}^{2} r_{wi}}{2} \tag{A12}$$

where:
Λ_{wall}^{t} = wall area suitable for HIM replacement in given year t;
Λ_{him}^{t} = floor area suitable for HIM replacement in given year t;
r_f = weighted average FDWR
Λ_{th} = total heated area
γ_i = permitted FDWR
μ_i = percentage of total heated area in permitted FDWR
r_{wi} = wall-to-floor ratio under different assumptions
l_i = length of the floor under different assumptions
w_i = width of the floor under different assumptions
h_c = ceiling height
Λ_i = floor area under different assumptions
r_w = wall-to-floor ratio.

Table A7. Roof and wall area suitable for HIM replacement.

Year	2025	2030	2035	2040	2045	2050
Roof area (million m^2)	100	110	122	134	148	164
Wall area (million m^2)	54	60	66	73	80	88

Appendix B.6 Projection of Total Area Suitable for HIM Replacement

$$\Lambda^t_{total} = \Lambda^t_{new\ add} + \Lambda^t_{retro} + \Lambda^t_{roof} + \Lambda^t_{wall} \quad (A13)$$

where:

Λ^t_{total} = total area suitable for HIM replacement
$\Lambda^t_{new\ add}$ = new added floor area suitable for HIM replacement
Λ^t_{retro} = retrofit area suitable for HIM replacement
Λ^t_{roof} = roof area suitable for HIM replacement
Λ^t_{wall} = wall area suitable for HIM replacement

Table A8. Total area suitable for HIM replacement.

Year	2025	2030	2035	2040	2045	2050
New added floor area (million m^2)	39	44	48	53	59	65
Retrofit floor area (million m^2)	60	67	74	81	90	99
Roof area (million m^2)	100	110	122	134	148	164
Wall area (million m^2)	54	60	66	73	80	88
Total area (million m^2)	254	280	309	341	377	416

Appendix C

$$M_{hemp} = \iota\, \rho_{hf} \Lambda^t_{total} d_{hf} + \iota\, \rho_{hc} \Lambda^t_{total} d_{hc} \quad (A14)$$

where:

M_{hemp} = quantity of hemp needed for HIM replacement
ι = thickness to achieve desired R-value
ρ_{hf} = proportion of HF used for HIM substitution
ρ_{hc} = proportion of HC for substitution
d_{hf} = density of HF, average 35 kg/m^3 [91]
d_{hc} = density of HC, average 350 kg/m^3 [92]

Table A9. Quantity of hemp needed for HIM replacement under different scenarios.

Year	Hemp Production (Million mt)					
	5% HF	95% HC	10% HF	90% HC	20% HF	80% HC
2025	0.666	33.726	1.331	31.951	2.663	28.401
2030	0.735	37.273	1.470	35.277	2.940	31.357
2035	0.811	41.112	1.623	38.949	3.246	34.621
2040	0.896	45.391	1.792	43.002	3.584	38.224
2045	0.989	50.116	1.978	47.478	3.957	42.203
2050	1.092	55.332	2.184	52.420	4.368	46.595

Appendix D

Appendix D.1 GHG Emissions by HIM Replacement and Business as Usual

$$\overline{GHG}^t_i = \overline{GWP}^t_i \times \Lambda^t_{total} \times \overline{n}_i \quad (A15)$$

$$\overline{n}_i = \frac{l_{iR43}}{l_{iR1}} \quad (A16)$$

where:

$\overline{GHG}_i^t$ = the GHG emission by certain insulation i in given year t

$\overline{GWP}_i^t$ = the GWP of certain insulation i per FU

Λ_{total}^t = the total area suitable for HIM substitution in given year t

$\overline{n}_i$ = number of FU to achieve R-43

l_{iR43} = thickness to achieve R-43 of certain insulation i

l_{iR1} = thickness of 1 m^2 insulation to achieve R-1 of certain insulation i

Appendix D.2 Cumulative Carbon Mitigation by Full HIM Replacement

$$\overline{GHG}_{c/hims}^t = \sum_{t=2025}^{2050} \overline{GHG}_{hims}^t \quad \text{(A17)}$$

where:

$\overline{GHG}_{c/hims}^t$ = cumulative GHG emission by full HIM replacement in given year t

$\overline{GHG}_{hims}^t$ = GHG emission by full HIM replacement in given year t.

Appendix D.3 Cumulative Carbon Saving by HIM Replacement Compared to Business as Usual

$$\overline{GHG}_{c/saving}^t = \sum_{t=2025}^{2050} \left(\overline{GHG}_{hims}^t - \overline{GHG}_{mims}^t\right) \quad \text{(A18)}$$

where:

$\overline{GHG}_{c/saving}^t$ = cumulative carbon saving in given year t

$\overline{GHG}_{hims}^t$ = GHG emission by full HIM replacement in given year t

$\overline{GHG}_{mims}^t$ = GHG emission by MIMs in given year t.

Table A10. Cumulative carbon mitigation by HIMs and MIMs.

	Area for HIM Substitution (Million m^2)	5% by HF (Million m^2)	GWP of HF ($kgCO_2eq$)	95% by HC (Million m^2)	GWP of HC ($kgCO_2eq$)	Total GWP by HIMs ($MtCO_2eq$)	50% by Mineral Wool (Million m^2)	GWP of Mineral Wool ($kgCO_2eq$)	50% by Plastic Foams (Million m^2)	GWP of Plastic Foam ($kgCO_2eq$)	Total GWP by MIMs ($MtCO_2eq$)	GWP Saving HIMS vs. MIMs ($MtCO_2eq$)
2025	254	13	69.496	241	−114.077	−0.045	127	1704.924	127	2531.897	4.237	−4.281
2026	259	13	70.862	246	−116.323	−0.045	130	1738.486	130	2581.738	4.320	−4.366
2027	264	13	72.230	251	−118.568	−0.046	132	1772.047	132	2631.578	4.404	−4.450
2028	269	13	73.598	256	−120.814	−0.047	135	1805.609	135	2681.419	4.487	−4.534
2029	274	14	74.996	260	−123.059	−0.048	137	1839.170	137	2731.259	4.570	−4.619
2030	280	14	76.608	266	−125.754	−0.049	140	1879.444	140	2791.068	4.671	−4.720
2031	286	14	78.250	272	−128.449	−0.050	143	1919.718	143	2850.877	4.771	−4.821
2032	291	15	79.618	276	−130.695	−0.051	146	1953.279	146	2900.717	4.854	−4.905
2033	297	15	81.259	282	−133.389	−0.052	149	1993.553	149	2960.526	4.954	−5.006
2034	303	15	82.901	288	−136.084	−0.053	152	2033.827	152	3020.334	5.054	−5.107
2035	309	15	84.542	294	−138.779	−0.054	155	2074.101	155	3080.143	5.154	−5.208
2036	315	16	86.184	299	−141.473	−0.055	158	2114.375	158	3139.952	5.254	−5.310
2037	322	16	88.099	306	−144.617	−0.057	161	2161.361	161	3209.728	5.371	−5.428
2038	328	16	89.741	312	−147.312	−0.058	164	2201.634	164	3269.537	5.471	−5.529
2039	335	17	91.656	318	−150.456	−0.059	168	2248.621	168	3339.314	5.588	−5.647
2040	341	17	93.298	324	−153.151	−0.060	171	2288.894	171	3399.122	5.688	−5.748
2041	348	17	95.213	331	−156.294	−0.061	174	2335.880	174	3468.899	5.805	−5.866
2042	355	18	97.128	337	−159.438	−0.062	178	2382.867	178	3538.676	5.922	−5.984
2043	362	18	99.043	344	−162.582	−0.064	181	2429.853	181	3608.452	6.038	−6.102
2044	369	18	100.958	351	−165.726	−0.065	185	2476.839	185	3678.229	6.155	−6.220
2045	377	19	103.147	358	−169.319	−0.066	189	2530.537	189	3757.974	6.289	−6.355

Table A10. *Cont.*

	Area for HIM Substitution (Million m^2)	5% by HF (Million m^2)	GWP of HF ($kgCO_2eq$)	95% by HC (Million m^2)	GWP of HC ($kgCO_2eq$)	Total GWP by HIMs ($MtCO_2eq$)	50% by Mineral Wool (Million m^2)	GWP of Mineral Wool ($kgCO_2eq$)	50% by Plastic Foams (Million m^2)	GWP of Plastic Foam ($kgCO_2eq$)	Total GWP by MIMs ($MtCO_2eq$)	GWP Saving HIMS vs. MIMs ($MtCO_2eq$)
2046	384	19	105.062	365	−172.463	−0.067	192	2577.523	192	3827.750	6.405	−6.473
2047	392	20	107.251	372	−176.056	−0.069	196	2631.222	196	3907.495	6.539	−6.608
2048	400	20	109.440	380	−179.649	−0.070	200	2684.920	200	3987.240	6.672	−6.742
2049	408	20	111.629	388	−183.242	−0.072	204	2738.618	204	4066.985	6.806	−6.877
2050	416	21	113.818	395	−186.835	−0.073	208	2792.317	208	4146.730	6.939	−7.012
total						−1.426					142.417	−143.916

Note: (1) The quantities of FU to achieve R-43: HF/8, HC/4.46, mineral wool/4.46, plastic foams/4.46. (2) GWP values (kg CO_2eq): HF/0.684, HC/-0.106, mineral wool/3.01, plastic foams/4.47.

Appendix E

Appendix E.1 Projection of GHG Emissions from Building Sector from 2020 to 2050

Appendix E.1.1 CAGR of Carbon Emissions to Realise Net Zero Emission in 2050

$$AGR = \left(\frac{GHG_{2050}}{GHG_{2020}}\right)^{1/t} - 1 \tag{A19}$$

where:

GHG_{2050} = GHG emissions in 2050
GHG_{2020} = GHG emissions in 2020
t = time of period.

Table A11. CAGR of Carbon Reduction to Achieve Net Zero by 2050.

Year	2020	2050
GWP ($MtCO_2eq$)	88	0
CAGR	−13.9%	

Appendix E.1.2 Impact of Different Scenarios towards Net Zero Emission in 2050

$$r_i = \frac{GHG_i}{GHG_{target}} \tag{A20}$$

where:

r_i = ratio towards net zero emissions
GHG_i = GHG emissions from different scenarios
GHG_{target} = target GHG emissions to achieve net zero by 2050

Table A12. Impact of Different Scenarios towards Net Zero Emission by 2050.

Year	HIMs Emissions ($MtCO_2eq$)	MIMs Emissions ($MtCO_2eq$)	Net Zero Target Emissions ($MtCO_2eq$)	Ratio HIMs	Ratio BAU
2025	0.045	4.237	41.64	0.11%	10.17%
2030	0.049	4.671	19.70	0.25%	23.17%
2035	0.054	5.154	9.32	0.58%	55.30%
2040	0.060	5.688	4.41	1.36%	128.98%
2045	0.066	6.289	2.09	3.17%	300.89%
2050	0.073	6.939	0.99	7.38%	700.91%

Appendix F

Appendix F.1 Convert Demand for Hemp Needed for HIM Substitution into Hemp Acreage

$$A^t_{hemp} = \frac{P^t_{hemp}}{y} \quad \text{(A21)}$$

where:

A^t_{hemp} = acreage of hemp cultivation in given year t
P^t_{hemp} = production of hemp in given year t
y = the yield of hemp fibre for HIM substitution (15 t/ha).

Table A13. Conversion of hemp demand in tonnage to acreage.

Year	Quantity of Hemp Needed for HIMs (Million mt)	Equivalent Hemp Acreage (Million ha)
2020	30.547	2.036
2025	33.726	2.248
2030	37.273	2.485
2035	41.112	2.741
2040	45.391	3.026
2045	50.116	3.341
2050	55.332	3.689

Appendix F.2 Projection of Canada Farmland

Appendix F.2.1 CAGR of Canada Farmland from 2011 to 2021

$$CAGR = \left(\frac{FL_{2021}}{FL_{2011}}\right)^{1/t} - 1 \quad \text{(A22)}$$

where:

FL_{2021} = farmland in 2021
FL_{2011} = farmland in 2011
t = time of period.

Table A14. CAGR of farmland from 2011 to 2016.

Year	2011	2016	2021
Farmland (million ha)	64,813	64,233	62,195
CAGR			−0.4% annual or −2% every 5 years

Appendix F.2.2 Projection of Canada Farmland from 2020 to 2050

$$\Lambda^t_{fl} = (1 + 2\%)\Lambda^{t-1}_{fl} \quad \text{(A23)}$$

where:

Λ^t_{fl} = farmland in given year t
Λ^{t-1}_{fl} = farmland in the year before the given year t

Table A15. Projection of Canadian farmland from 2025 to 2050.

Year	2025	2030	2035	2040	2045	2050
Farmland (million ha)	61.195	59.971	58.772	57.596	56.444	55.316

Appendix F.3 Percentage of Hemp Acreage vs. Total Farmland

$$r^t = \frac{\Lambda^t_{hp}}{\Lambda^t_{tfl}} \quad \text{(A24)}$$

where:

r^t = ratio of hemp acreage to farmland in given year t;
Λ^t_{hp} = hemp acreage in given year t;
Λ^t_{tfl} = total farmland in given year t.

Table A16. Percentage of hemp acreage vs total farmland.

Year	Hemp Acreage (Million ha)	Total Farmland (Million ha)	Ratio
2020	2.036	62.444	3.26%
2025	2.248	61.195	3.67%
2030	2.485	59.971	4.14%
2035	2.741	58.772	4.66%
2040	3.026	57.596	5.25%
2045	3.341	56.444	5.92%
2050	3.689	55.316	6.67%

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