The Global Warming Impact of Applying Bio-Based Insulation Materials in Residential High-Rises in Amsterdam

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ABSTRACT

In light of the changing climate and the need for urban densification in the Netherlands, this study analyzes the potential global warming impact (GWI) of implementing bio-based insulation materials (BBIMs) in high-rises in Amsterdam. A literature and market review led to the identification of straw, grass, hemp, flax, wood-fiber, and cellulose insulation as the most relevant BBIMs in the Dutch context because of local availability and potential scalability. From an expert interview on fire-safety constraints of BBIMs, it was concluded that a 12 mm layer of gypsum fiberboard is needed to ensure fire safety in high-rise buildings for insulation materials which do not meet fire-safety class A1/A2. The GWI of the BBIMs was compared with stone wool, glass wool, expanded polystyrene (EPS) and extruded polystyrene (XPS) through a dynamic Life Cycle Assessment (LCA). The results consistently demonstrated optimal GWI performance for the plant-based BBIMs, while XPS and cellulose typically had the highest GWI. In a building case study, cumulative radiative forcing values between 1.61e−8 W m^{-2} yr (cellulose) and −1.66e−8 W m^{-2} yr (straw) were found in 2222. For the insulation of all 97.500 residential high-rise buildings which are to be built in Amsterdam until 2050, these values were 2.50e−6 W m^{-2} yr (XPS) and −2.59e−6 W m^{-2} yr (straw). Annual emissions savings of up to 587 tons of CO_2-equivalents were projected when switching from XPS to straw insulation. In working towards its 2050 climate neutrality goals, the city of Amsterdam is advised to stimulate the implementation of BBIMs in all buildings, focusing on straw, grass and hemp in prefabricated façades.

Keywords — bio-based, insulation, high-rise, global warming impact, dynamic LCA

Contents

Glossary

Abbreviations

BBIM	Bio-based insulation material
BENG	Bijna energieneutrale gebouwen (nearly energy-neutral buildings)
DLCA	Dynamic Life Cycle Assessment
EOL	End-of-life
EPBD	Energy performance of buildings directive
EPD	Environmental product declaration
EPS	Expanded polystyrene
GHG	Greenhouse gas
GWP	Global warming potential
GWI	Global warming impact
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
KBOB	Coordination Conference of Building and Property Bodies of Public Sector Developers
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
PCR	Product category rule
ROW	Rest-of-world
UNFCCC	United Nations Framework Convention on Climate Change
XPS	Extruded polystyrene

Mathematical symbols

a_{GHG}	Radiative forcing per unit mass	$\mathrm{W\,m^2\,kg^{-1}}$
I	Thickness	m
R	Rotation period	yr
-	Radiative forcing (cumulative)	$\mathrm{W\,m^{-2}\,yr}$
-	Radiative forcing (instantaneous)	$\mathrm{W\,m^{-2}}$
T	Temperature	K
q	Heat flow	W
λ	Thermal conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
μ-value	Diffusion resistance factor	-

1
Introduction

Climate change is widely recognized as one of the defining issues of our time. To decrease anthropogenic impacts on global warming, there is a need for transitioning to a carbon neutral society. The 2022 IPCC report identifies the built environment as one of the focal points in climate change mitigation as building construction and operations amount to almost 40% of global energy-related CO_2 emissions (Pörtner et al., 2022). As energy efficiency requirements for new buildings are becoming stricter and national energy supplies are decarbonized, reducing the embodied impacts of construction materials is increasingly important. Embodied emissions in buildings are those that result from energy use during the harvesting and processing of construction materials. Operational emissions result from the energy requirements of buildings for heating, cooling and power. To reduce emissions related to the built environment, two important factors are: making buildings more energy efficient, and implementing more efficient construction processes and materials with lower embodied emissions.

The current share of embodied CO_2 emissions in a building's total life-cycle emissions can range between 10% to 80%, being highly dependent on the operational energy efficiency of the building (Röck et al., 2020). Reductions in construction and demolition waste, and enhancements of material efficiency could reduce construction emissions by up to 50% (Carcassi, Habert, et al., 2022). However, as a result of energy-intensive manufacturing processes and emissions from necessary chemical reactions, mineral materials like concrete cannot become totally emission-free (Carcassi, Habert, et al., 2022).

In contrast, bio-based materials present considerable potential for reducing embodied emissions of the built environment due to their renewable nature and the carbon sequestration during their growth. Renewable materials play a key role in the development of a circular economy, which could reduce the greenhouse gas (GHG) emissions of western European countries up to 70% (Wijkman & Skånberg, 2015). The biogenic carbon capture in plant-based materials means that their implementation in the building stock can result in temporary net negative CO_2-emissions as a result of carbon storage. The amount of captured CO_2 which is re-emitted into the atmosphere is highly dependent on the end-of-life (EOL) disposal strategy (Pittau et al., 2019). EOL-strategies for bio-based materials include landfilling, recycling and incineration with energy recovery. For example, in the case of energy recovery through incineration, the fixed CO_2 is released when the material is burnt in a waste incineration plant at the EOL. Although the CO_2 is re-emitted, the produced energy negates the need for some other form of energy generation and some avoided emissions can be attributed to this process. Additionally, the biogenic CO_2 stored in buildings is only emitted after the product lifespan, which can range between 50-75 years for products in residential buildings (Göswein et al., 2021; Hoxha et al., 2020; Levasseur et al., 2010). Although there is no scientific consensus yet on how to discount postponed emissions, pushing emissions into the future may provide an important contribution to reaching the Paris Agreement goal of limiting global warming by 2050 to 1.5°C (Brandão et al., 2013; Hoxha et al., 2020; United Nations Framework Convention on Climate Change [UNFCCC], 2015).

Aiming towards the sustainable development goals set at the Paris agreement, European countries are undergoing a renovation wave to meet energy performance standards, and the requirements for new construction are becoming more strict through the European Union's Energy Performance Buildings Directive (EPBD) (Council of European Union, 2010; European Commission, n.d.). Therefore, despite promising applications for bio-based materials in structural elements, this study specifically focuses on the carbon reduction potential of transitioning from conventional to bio-based insulation materials (BBIMs). Insulation materials based on plant fibers and timber-based structural elements provide different opportunities and qualities. Although this study considers new construction only, the possibility of implementing BBIMs in both existing and new buildings provides a large potential for biogenic carbon capture. Furthermore, bio-based insulation material crops like hemp, flax and straw provide significantly shorter rotation periods than the timber used for structural elements, as many wood species are harvested only after around 75 years of biomass growth (Göswein et al., 2021; Peñaloza et al., 2016). As a result, production of bio-based insulation materials can be scaled up more quickly, thereby presenting opportunities to offset ongoing carbon emissions in working towards the 2050 climate goals.

When compared with conventional insulation materials, bio-based options can provide similar thermal performance with significantly lower embodied emissions (Carcassi, Habert, et al., 2022). Conventional insulation materials include glass wool, stone wool and EPS (Expanded Polystyrene), while BBIMs are made from fibrous parts of trees or plants like hemp, flax and straw. With recent increases in energy prices, strong thermal performance is essential for insulation materials to be adopted. Concurrently, the increasing energy prices present opportunities for competitive pricing for materials with lower embodied energy in the production process. Germany is one of Europe's leaders in the implementation of BBIMs and saw a market share of 9% for BBIMs in 2020 (Geß et al., 2021; Künzel, 2022). Increasing the market share of BBIMs could significantly reduce embodied carbon in the construction sector. Additionally, when compared to conventional insulation materials, hygrothermal properties of BBIMs stabilize indoor temperature changes and can improve indoor climate (Lafond & Blanchet, 2020; Palumbo et al., 2016). However, some downsides to the use of BBIMs still exist. Firstly, to achieve sufficient fire and mold resistance, some materials should be treated with chemical additives, reducing their circularity potential by impeding alternative recovery routes (Rabbat et al., 2022). Additionally, the novelty of some BBIMs and their relatively low market-share limits their price-competitiveness.

1.1 Problem statement

The Netherlands is in need of a sustainable densification of its urban areas. To resolve the ongoing housing crisis, the Dutch national government aims to build 961.300 houses by 2030 (Figure 1.1). Although the Netherlands ranks second in terms of population density within the European Union (EU27), the most densely populated local administrative unit in the Hague has a population density 1/8th of its Parisian counterpart (Eurostat, n.d., 2023). The combination of the Netherlands' high population density with its relatively low urban density signifies a large potential for densification in its urban regions. Figure 1.1 clearly shows that the largest housing developments are all planned in urban areas. Of all the Dutch municipalities, Amsterdam has been developing the most housing for the past years (Centraal Bureau voor de Statistiek [CBS], 2023a). Densification is a significant part of Amsterdam's housing plan, in which the city aims to construct 73.660 houses by 2028 and 150.000 houses by 2050 (Gemeente Amsterdam, n.d.-a, n.d.-b). Considering the need for sustainable densification of the residential building stock in the Netherlands, evaluating the potential applications and environmental impacts of bio-based materials in high-rise construction is essential.

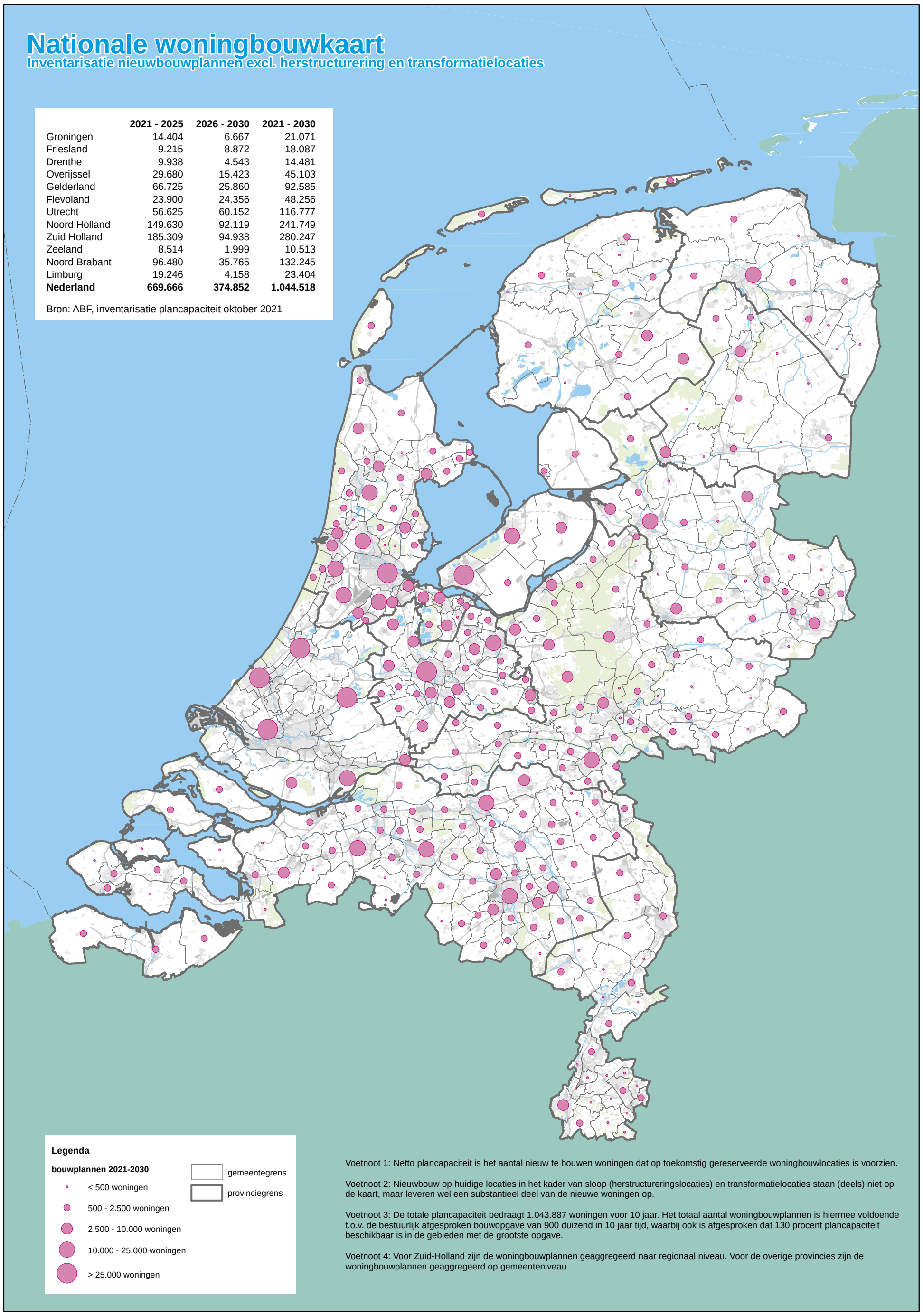


Figure 1.1: Planned construction locations in the Netherlands between 2021-2029 (Rijksoverheid, 2021)

In addition to the reduced embodied carbon BBIMs provide when compared to conventional insulation materials, the implementation of BBIMs could also reduce nitrogen emissions. As livestock farms disproportionally contribute to nitrogen emissions, farmers transitioning from holding livestock to growing crops could reduce their nitrogen emissions, especially with crops like flax, hemp and cereals which require little fertilizer (Leendertse et al., 2020; Righton & Damen, 2022). The failure of the Netherlands to meet national and European nitrogen emission regulations has resulted in construction delays. The adoption of more BBIMs could thus improve the speed of construction in the Netherlands (Rijksoverheid, 2022; van der Wal-Zeggelink, 2022). Given the large need for housing in the Netherlands and the ongoing climate crisis, the global warming impact of applying bio-based insulation materials in high-rise buildings in Amsterdam should be evaluated.

1.2 Research question

Although research has shown the potential of bio-based materials for insulating buildings and providing biogenic carbon capture, the potential global warming impact of applying bio-based insulation materials in high-rise buildings in Amsterdam is insufficiently understood. Therefore, a case study of high-rise building *The Ensemble*[1] in Amsterdam is performed and extrapolated to the scale of Amsterdam to answer the following question:

> *What is the global warming impact of implementing bio-based insulation materials in residential high-rise buildings in Amsterdam?*

To answer this question, the following three sub-questions are defined:

1. Which bio-based materials can be implemented for façade insulation in high-rise buildings in Amsterdam?
2. What is the global warming impact of applying bio-based insulation materials in high-rise building *The Ensemble*?
3. What is the global warming impact of applying bio-based insulation materials in new residential high-rise buildings in Amsterdam until 2050?

[1] More information on this building in Section 4.2

1.3 Research methods

A review of scientific literature and market reports is performed to analyze the properties of currently available BBIMs. This review results in a list of material properties for BBIMs which are currently available in the Netherlands. To evaluate the applicability of these materials in high-rise buildings, the fire-safety implications of implementing BBIMs in this context are investigated through an expert interview. In the interview, a rule of thumb is formulated for the required amount of fire-resistant material to implement BBIMs in high-rise buildings with sufficient fire safety.

This result is used to generate building scenarios with BBIMs for high-rise building *The Ensemble* which provides fire-safety equivalent to the original building plans with conventional insulation materials. The building plans are analyzed for the choice of materials, the area of insulated façade and the required thermal resistance. For each of the materials resulting from the analysis in sub-question 1, the amount of material necessary to provide identical thermal resistance and fire safety is calculated. For each of the material scenarios a dynamic Life Cycle Assessment (DLCA) model is applied to compare the global warming impact (GWI) related to the material choice.

The DLCA model considers the emissions of CO_2, CH_4, N_2O and CO following a life-cycle approach over life-cycle stages A1-A5 (Product), B4 (Renovation), C1-C4 (End-of-life) & D (Benefits beyond life). It models the atmospheric decay of the different greenhouse gas (GHG) emissions and considers biogenic carbon capture through the regrowth of plant-based materials. The model outputs the resulting instantaneous and cumulative radiative forcing values over time for each scenario. These describe GWI as a change in the atmospheric energy flux in $\mathrm{W\,m^{-2}}$. The influence of EOL decisions is modeled by comparing incineration and anaerobic digestion scenarios for the BBIMs.

Following the building case-study, the DLCA model is applied to the scale of Amsterdam to evaluate the GWI of applying BBIMs in all residential high-rise developments in the city. The required amount of material is based on case-study parameters and policy documents which describe the amount of planned construction in Amsterdam. The modeled results are synthesized with the answers to the other sub-questions into a conclusion on the potential global warming impact of applying bio-based insulation materials in high-rises in Amsterdam.

1.4 Outline

Following the introduction, Chapter 2 covers background on insulation materials, high-rise buildings, the life-cycle approach, and methods for GWI assessment. In Chapter 3, related work is synthesized to provide the scientific context for this study. Following this, Chapter 4 describes the methods used to answer each of the research questions. The results in Chapter 5 are divided into the three sub-questions. These answers are synthesized and contextualized in the discussion in Chapter 6 and the study is finalized with a conclusion in Chapter 7.

2
Background

2.1 Thermal insulation materials

Thermal insulation materials are used in construction to reduce the heat transfer between the outside and the inside of the building envelope. The three types of heat transportation are convection, conduction and radiation (Venkateshan, 2021). Figure 2.1 shows the heat flow (q) over the wall from a temperature T_0 to T_1 with the influence of convection and radiation outside of the wall, and conduction inside the wall.

Thermal insulation materials in buildings are mostly used to reduce the conduction of heat inside walls. Thermal conductivity (λ) is a material property which denotes the amount of heat which flows through a layer of material with a thickness of 1 m and a surface area of 1 m^2 at a temperature difference of 1 K ($W\,m^{-1}\,K^{-1}$) (van der Linden et al., 2011). The R-value ($m^2\,K\,W^{-1}$) measures thermal resistance in the construction industry and is related to the thermal conductivity (λ) and material thickness (I) as follows:

$$R = \frac{I}{\lambda} \tag{2.1}$$

The hygrothermal performance of an insulation material describes its interactions with water vapour, and is another factor in the thermal performance of buildings as well as indoor air quality and hygienic conditions (Pavlík & Černý, 2009). The diffusion resistance factor (μ-value) describes

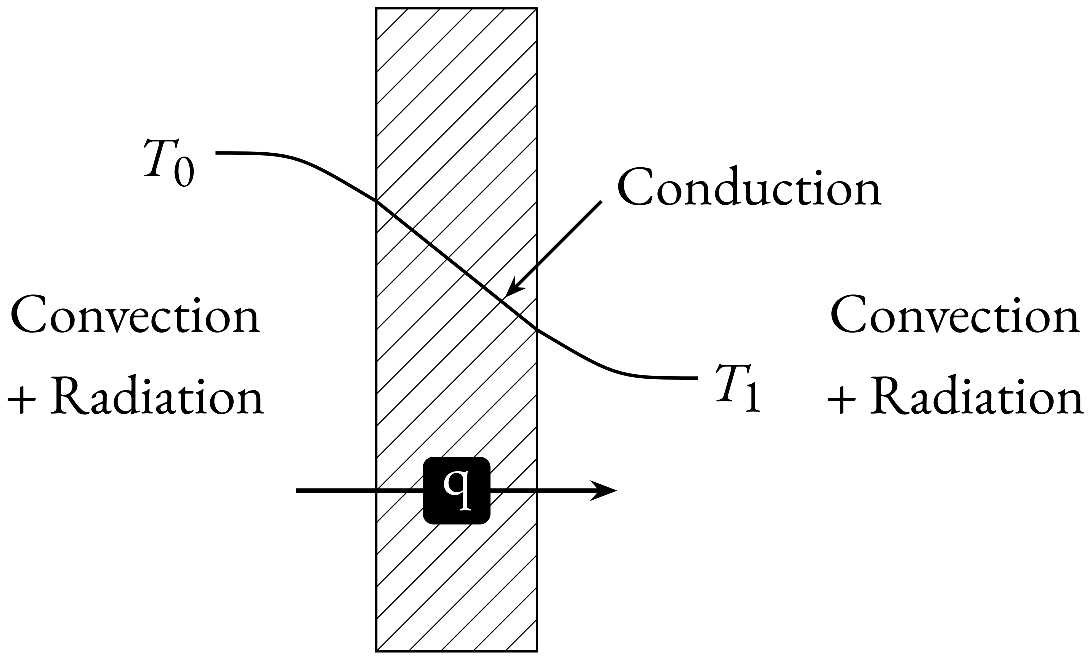


Figure 2.1: Heat flow across a wall, adapted from Venkateshan (2021)

the hygrothermal performance of a material by measuring the impedance of vapor diffusion in the material as compared to air (Koh et al., 2022). Materials with a high water vapor permeability (low μ-value) and a high moisture storage capacity present opportunities to buffer moisture levels. Reducing daily changes in relative humidity limits energy consumption and maintains hygrothermal comfort in buildings Bennai et al. (2022). The indoor humidity is closely related to health problems and the energy consumption of buildings.

This study compares the global warming impact of conventional and bio-based insulation with different material properties. The conventional materials considered here are stone wool, glass wool, expanded polystyrene (EPS), extruded polystyrene (XPS) (Geß et al., 2021). Because of their affordability and low thermal conductivity, mineral wools (stone and glass wool) and organic foamy materials (EPS, XPS) accounted for 60% and 27% of the insulation material market in 2005 respectively (Papadopoulos, 2005). More recently, a study of raw materials used for insulation materials in Germany in 2019 showed a 43% and 48% share of mineral and fossil materials respectively, the remaining 9% being bio-based (Geß et al., 2021).

Bio-based insulation materials are a renewable alternative to their conventional counterparts. Although these materials do not provide the same thermal conductivity as novel materials like vacuum insulated panels (VIPs), their performance can compete with conventional options (Grazieschi et al., 2021; Lafond & Blanchet, 2020; Rabbat et al., 2022). Additionally, BBIMs are renewable and can provide lower environmental impacts and better hygrothermal performance (Chang & Kim, 2015; Jensen et al., 2020; Pittau et al., 2019; Rabbat et al., 2022). Only plant-based BBIMs are considered here as there are renewable and, especially when using short rotation-period crops, highly scalable (Kośny & Yarbrough, 2022). These materials also benefit from capillary active systems which can act as a moisture buffer (Chang & Kim, 2015; Jensen et al., 2020). In some cases, this hygrothermal behavior can result in better insulating properties despite higher thermal conductivity values (Palumbo et al., 2016).

Although many relevant parameters exist, for the sake of simplicity thermal insulation materials in this study are compared on properties:

1. Thermal Conductivity
2. Fire-safety
3. Global warming impact

2.2 High-rise buildings

The definition of high-rise buildings is highly context dependent. This study follows the definition used by the municipality of Amsterdam of a minimum height of 30 meters (Gemeente Amsterdam, 2011). Although high-rise construction in the Netherlands is relatively moderate, it is an integral part of Amsterdam's vision to realize urban densification. In Amsterdam and the Netherlands most high-rise buildings fall within the medium-rise category, ranging between 30 m and 70 m, as building taller often means higher construction, exploitation and maintenance costs (Gemeente Amsterdam, 2011; Soeters, 2018).

High-rise construction is subject to specific building requirements for fire-safety, where the regulations serve 4 purposes (R. van Herpen, personal communication, April 21, 2023):

1. Preventing the spread of fire to neighboring plots
2. Ensuring the integrity of structural elements
3. Limiting the spread of fire and smoke by compartmentalization
4. Ensuring the accessibility of escape and attack routes

In the context of this study on high-rise façade insulation, assuming non-load bearing façades, points 1 and 3 are most relevant. The distance to neighboring plots in high-rise buildings is generally sufficient such that the spread of fire is unlikely, except for in the bottom floor which may accommodate storefronts. The Dutch building code requires façade elements at a height up to 2.5 m or above 13 m to achieve fire class B, as evaluated through a single burning item test (SBI) following EN13823:2002 (Comité Européen de Normalisation [CEN], 2002; Rijksoverheid, 2012b). The regulation up to 2.5 m aims to protect the building from outside fires which occur close to the façade, while the regulations above 13 m reduce the fire spread over the surface of the façade. Although Dutch building code prescribes fire safety only on the façade-element level, the EU also requires testing of fire-safety of construction products on the product level (Table 2.1).

Table 2.1: Fire classification of construction products according to EN13501-1 (CEN, 2007)

Class	Reaction to fire
A1	No contribution to fire
A2	No significant contribution to fire growth
B	Very limited contribution to fire growth
C	Limited contribution to fire growth – Flashover after 10 minutes
D	Contribution to fire – Flashover after 2-10 minutes
E	Significant contribution to fire – Flashover before 2 minutes
F	No performance determined

As the façade is an adjoining part of construction, which could short-circuit other fire compartmentalization measures if it is combustible, the fire safety of a façade is highly relevant in high-rise buildings. The required time of resistance to fire spread for façades above 13 m is 60 minutes, as opposed to 30 minutes for lower façades (Rijksoverheid, 2012c).

Buildings above 70 m form a separate category in the Dutch building code with respect to fire safety (Rijksoverheid, 2012a). However, the fire-safety requirements for these buildings are not explicitly stated. Instead, local governments evaluate each individual project to ensure that it provides equivalent fire safety to that of medium-rise buildings with the aid of an independent advisory committee (Adviescommissie toepassing en gelijkwaardigheid bouwvoorschriften., n.d.; Rijksoverheid, 2012a; V2BO Advies, 2003).

Typical additional measures for these buildings include the installation of a sprinkler system and pressurized escape routes (Unica Fire Safety, 2018, R. van Herpen, personal communication, April 21, 2023). In the context of this study the fire-safety regulations for buildings with a height between 30-70 m are assumed since they represent most high-rise buildings in Amsterdam.

2.3 Life cycle approach

Life Cycle Assessment or Life Cycle Analysis (LCA) is a widely applied and standardized methodology for analyzing the environmental impact of a product through different life-cycle stages. Life Cycle Assessment is a method that allows the estimation of the potential environmental impacts and resources used throughout a product's life cycle. It considers the product from raw material acquisition, through the production and use stages, to waste management (Finnveden et al., 2009; International Organization for Standardization [ISO], 2006). The system perspective to environmental impact provided by an LCA ensures the consideration of trade-offs between impacts during different life-cycle stages. Its standardization is designed to provide comparability between different studies, so that different product impacts can properly be weighed. An LCA study consists of four phases (Finnveden et al., 2009):

1. Goal and Scope Definition
2. Life Cycle Inventory Analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

While this study does not apply a standardized LCA method, it employs a Life-Cycle approach. Where a typical LCA measures environmental impacts over 15 environmental impact categories like eutrophication, ozone depletion and acidification, this study focusses on the climate change impact category (Rosenbaum et al., 2018). This measures the GHG emissions over the product lifespan in CO2-equivalents (Ecochain, 2023). The current LCA practice is to express this in terms of global warming potential with a timeframe of 100 years (GWP100), which is the cumulative radiative forcing of a GHG emission relative to a CO2 emission of the same mass over a 100 years (Levasseur et al., 2010). This study employs a dynamic LCA model to show the impact on global warming as a function of time (see Section 4.2.1).

The considered impacts are measured over different stages of the product life cycle. Figure 2.2 shows these stages as applied to products in buildings. The application of LCAs in the construction sector is standardized through EN15978 (CEN, 2011). Typically the scope of an LCA study covers one of the following approaches to define the system boundaries:

1. A1 – A3 (cradle-to-gate)
2. A - C (cradle-to-grave)
3. A - D (cradle-to-cradle)

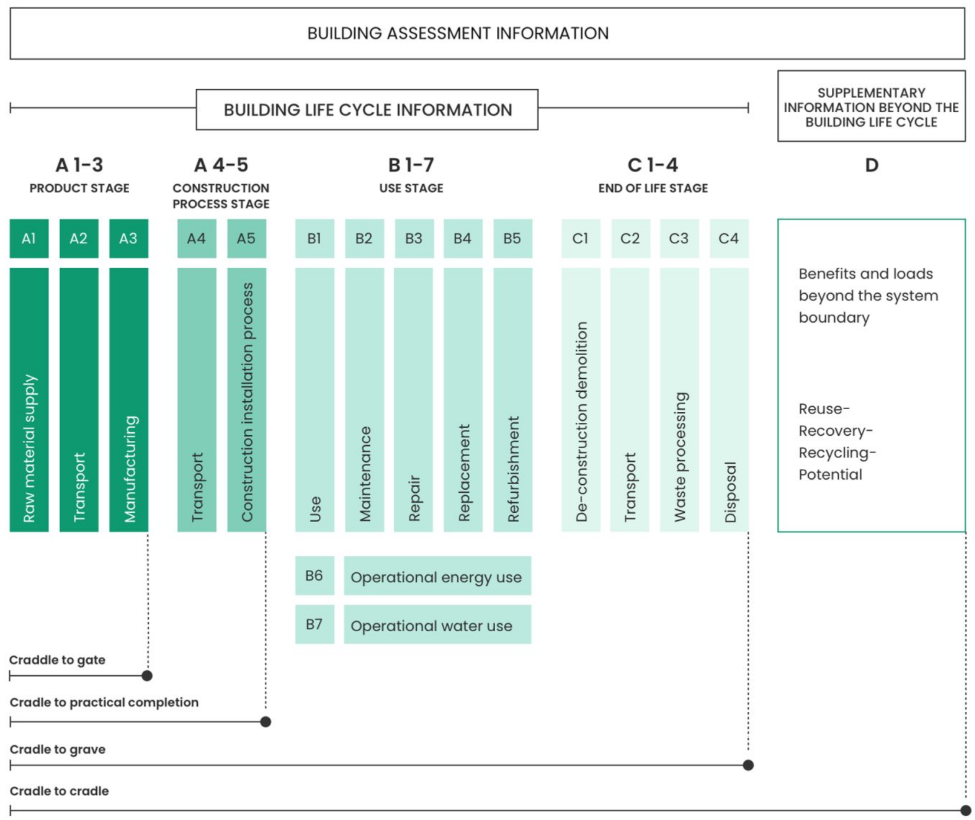


Figure 2.2: LCA stages (OneClickLCA, 2023)

In the construction sector, LCAs are often standardized into Environmental Product Declarations (EPDs), which report the environmental impacts of a product following EN15804 (CEN, 2012). The standardization through EN-15804 and product category rules (PCRs) ensure consistency and comparability of LCA results for different products (CEN, 2012; Hoxha et al., 2020). Recently, the original EN15804+A1 has been revised, resulting in EN15804+A2 (CEN, 2019). Some important revisions include updated impact categories, mandatory declaration of stages C1-C4 and D which were previously optional, and reporting biogenic carbon capture.

2.4 Global warming impact methodologies

Various methods exist for counting global warming impacts from GHG emissions. The most common measure, which is also used in the LCA climate change impact category and is adopted by the United Nations Framework Convention on Climate Change (UNFCCC), is the global warming potential (GWP). For an emission of a given GHG, the GWP index represents the global warming impact (GWI) of that emission relative to an emission of CO2, in kg CO2-equivalents. This is done by dividing the cumulative radiative forcing (W m^{-2} yr) caused by an emission of mass C_0 of that GHG over a time horizon (TH) by the cumulative radiative forcing caused by an emission of CO2 of the same mass over the same time horizon (Equation 2.2) (Brandão et al., 2013). Here a_{GHG} and $\gamma_{GHG}(t)$ denote the GHG's instantaneous radiative forcing per unit mass (W m^2 kg^{-1}) and atmospheric decay function respectively.

$$\mathrm{GWP}_{\mathrm{TH}_{\mathrm{GHG}}} = \frac{C_0 \int_0^{TH} a_{GHG} \cdot \gamma_{GHG}(t)\, dt}{C_0 \int_0^{TH} a_{CO_2} \cdot \gamma_{CO_2}(t)\, dt} \tag{2.2}$$

Due to the different atmospheric decay functions for different GHGs, the choice of time horizon will strongly influence the relative importance of different GHGs. Typically, the GWP value in LCA studies is calculated over a time horizon of 100 years and different GHGs (Equation 2.3) (Brandão et al., 2013).

$$\mathrm{GWP}_{100} = \sum_{\mathrm{GHG}} \mathrm{GWP}_{100_{\mathrm{GHG}}} = \sum_{\mathrm{GHG}} \frac{C_0 \int_0^{100} a_{GHG} \cdot \gamma_{GHG}(t)\, dt}{\int_0^{100} a_{CO_2} \cdot \gamma_{CO_2}(t)\, dt} \tag{2.3}$$

Three points of critique of GWP100 pointed out by Brandão et al. (2013) are that it does not account for carbon sequestration during biomass growth, it disregards the timing of emissions, and it requires the arbitrary choice of a time horizon. Before the adoption of EN15804+A2, following the 0/0 approach, most LCA studies ignored biogenic carbon under the assumption that the sequestration of carbon from biomass growth equals the emission of biogenic carbon at the EOL. Under EN15804+A2, LCAs are required to report biogenic carbon sequestration and emissions, and apply the -1/+1 approach. Negative CO2-emissions are counted in life-cycle stage A which are re-emitted in stage C, although emission timings are still disregarded. As a result, there is no added benefit of temporary carbon storage. A risk of the -1/+1 methodology is that some LCAs exclude the EOL phase and only count the negative emissions in stage A, resulting in a misleading GWP (Arehart et al., 2021; Hoxha et al., 2020).

2.4.1 Crediting methods

Alternative methods have been proposed which account for biogenic carbon sequestration and emission timing. Brandão et al. (2013) cover the Moura Costa, Lashof, PAS2050, and ILCD[1] methods. These methods define the GWP for products with biogenic carbon as the difference between the impact from the biogenic CO2 pulse emission GWP_{bp}, and the credit GWP_c, gained from storing the biomass for a number of years (Equation 2.4) (Guest et al., 2013). Cherubini et al. (2011) add the consideration of crop rotation periods to the calculation of GWP in their GWP_{bio} index, and Guest et al. (2013) develop this index further. Nevertheless, these methods are still dependent on the choice of an arbitrary time horizon.

$$\mathrm{GWP} = \mathrm{GWP_{BP}} - \mathrm{GWP_C} \tag{2.4}$$

2.4.2 Dynamic LCA for GWP calculation

The dynamic LCA (DLCA) approach proposed by Levasseur et al. (2010) addresses carbon sequestration, crop rotation periods and emission timings without the need for selecting an arbitrary time horizon. Instead, it dynamically models global warming impact (GWI) as a function of time. Although this method is applicable across different LCA impact categories, this study specifically applies it for global warming. In the approach, a dynamic Life-Cycle Inventory is computed which considers emissions as they occur in time. In the dynamic Life-Cycle Impact Assessment, dynamic characterization factors are applied to result in real-time impact scores which do not require the choice of an arbitrary time horizon (Levasseur et al., 2010). Different studies compared DLCA with other methods of accounting for biogenic carbon emissions and show that DLCA is a robust method to consistently assess global warming impact (Hoxha et al., 2020; Levasseur et al., 2010).

The details of the DLCA implementation of this study are described in Section 4.2.1. For each GHG, dynamic characterization factors (DCFs) are defined which express the atmospheric radiative forcing t years after the emissions of 1 kg of GHG ($\mathrm{W\,m^{-2}\,kg}$). The instantaneous GWI in year t is calculated by applying the DCFs to a dynamic LCI, which contains a yearly overview of GHG emissions. It expresses the radiative forcing ($\mathrm{W\,m^{-2}}$) in year t as a result of the emissions in the dynamic LCI. The cumulative GWI ($\mathrm{W\,m^{-2}\,yr}$) in year t sums over the instantaneous GWIs from year 0 to year t to describe the cumulative radiative forcing effect. Both the instantaneous and cumulative GWI can be graphed for all years t in the time horizon to show the dynamics of the global warming impact.

[1] International Reference Life Cycle Data System

3
Related work

This study is contextualized by previous works which applied DLCAs to evaluate global warming impact. Pittau et al. (2019) apply a DLCA to forecasted renovation projects on a European scale. Their work shows that fast-growing biogenic materials have a significantly larger carbon reduction potential than materials from plants with larger rotation periods. The study also shows the influence of different EOL scenarios on the global warming impact. Göswein et al. (2021) apply a material flow analysis and a DLCA to three renovation scenarios for a Lisbon neighborhood. Similar to Pittau et al. (2019), their straw- and wood-based renovation system results in the lowest cumulative radiative forcing. Zieger et al. (2020) show the modeling differences in CO2-equivalent emissions between GWP100, GWP500 and DLCA for a concrete wall with mineral wool insulation and a wooden wall with bio-based insulation. The authors show that static LCAs are not properly able to count the benefits of biogenic carbon storage. Additionally, Göswein et al. (2021) show that their results are in line with with those of Pittau et al. (2019) and Zieger et al. (2020). Although Negishi et al. (2019) also apply a DLCA to residential buildings in France and show the benefits of bio-based insulation, they count the negative emissions of carbon sequestration before plant material is harvested which makes their results less comparable with previous works (Göswein et al., 2021; Peñaloza et al., 2016).

This study adds to the existing body of scientific literature in multiple ways. Firstly, the analysis focuses on the global warming impact of insulation materials which play a critical role in the transition towards carbon neutral buildings. The dynamic LCA allows for a robust demonstration of global warming impact of different material scenarios over time. The results can therefore be used to assess the influence of material choice on climate goals for different time frames. Additionally, the use of BBIMs from short-rotation period crops can be scaled up more quickly than bio-based materials like mass timber. Furthermore, this study complements existing work on global warming impact from renovation by analyzing new construction (Göswein et al., 2021; Pittau et al., 2019). The impact is calculated in the context of high-rise buildings in Amsterdam through the use of a case-study. Considering the large construction demand in the Netherlands and the ongoing climate crisis the findings this study produces are socially and scientifically significant.

4
Methods

A schematic overview of the research methods is shown in Figure 4.1. The following three sections cover the methods used for answering each of the sub-questions.

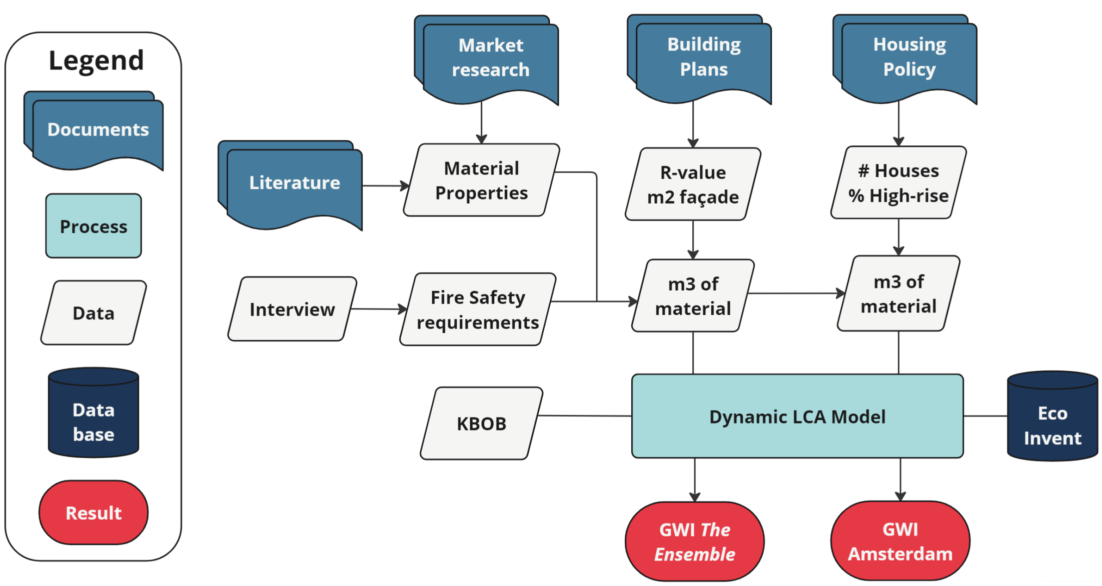


Figure 4.1: Schematic overview of the methodology

4.1 Insulation materials applicable in high-rises in Amsterdam

First, a structured literature review is performed to retrieve a list of relevant bio-based insulation materials. To cover a wide range of publications, the literature review is specifically aimed at review articles, using the filter in the "Web of Science" database. The database is searched with search terms "(ALL=Thermal insulation material) AND ALL=(Building)". From these, the 50 most cited articles are analyzed for material properties. A paper is included if it specified thermal conductivity (λ) values. Lastly, two reports and one paper which were already included in other sections of this study are added as they included further material information (Hedde et al., 2022; Papadopoulos, 2005; van Dijk et al., 2022).

Material information from these reports is noted for all high performing thermal insulators, following the thermal conductivity threshold of 0.05 $W\,m^{-1}\,K$ (Asdrubali et al., 2015). Limiting the list of materials to the scope of the research, only conventional and plant-based insulation materials are included. As an example, hemp fibers are included while recycled cotton, sheep wool and aerogels are excluded. Materials which are not currently grown in the Netherlands were removed, to focus on those that are relevant in the context of Amsterdam (CBS, 2023b). From different straw types, only wheat straw is included as it is the most prevalent in The Netherlands.

As thermal conductivity values vary quite significantly in the scientific literature, thermal conductivity values from EPDs are used to represent values realistic in practice. A material is excluded from the analysis when no EPDs are available for it. Through the openly accessible Eco Platform, the following collection of EPD databases is consulted for EPD availability (ECO Platform, n.d.):

FDES	(France)
EPD Norge	(Norway)
IBU	(Germany)
PEPecopassport	(France)
International EPD	(SE/ANZ/TU/LA)
MRPI	(Netherlands)
ITB	(Poland)
BRE EN 15804 EPD	(UK)
EPD Ireland	
EPD Italy	
ECO Platform small programs	

As fire safety is a common concern for BBIMs and high-rise construction has additional fire-safety requirements, the fire-safety class of each material is noted (van Dijk et al., 2022). To evaluate the conditions under which different BBIMs meet fire-safety regulations when implemented in an element, an interview is conducted with an expert in the field of fire-safety engineering. The advised safety measures, like adding a fireproof gypsum board, are included in the scenarios in the following sub-questions to ensure that the compared scenarios provide equivalent fire-safety.

4.2 Global warming impact of using bio-based insulation materials in the ensemble

The global warming impact of different insulation materials is first evaluated through a cast study of high-rise building *The Ensemble*. At the time of writing the building is being constructed on the Karspeldreef 14-16 in Amsterdam. It consists of two adjoined towers with 592 apartments and utility functions on the lower floors. The building is seen as representative for future high-rise construction as it meets the extralegal BENG[1] energy-efficiency requirements proposed by the municipality of Amsterdam (Table 4.1) (Gemeente Amsterdam, 2021). The R-value of the thermal insulation in *The Ensemble* is calculated using the thickness of insulation and the thermal conductivity of the insulation material from the building plans, as provided by the architect. For this calculation, only the residential part of the building is considered. For each of the materials resulting from sub-question 1, the required material thickness for an equivalent R-value is calculated. Thermal conductivity ratios and the total amount of insulation material used in the building plans are used to calculate the volume of insulation needed per material. For each material, the required amount of fire proofing is added to calculate the total material requirements for an equivalent building.

Table 4.1: BENG requirements for energy efficiency of a building

	Description	Unit	National requirement	Amsterdam requirement
BENG 1	Energy requirement	$\mathrm{kW\,h\,m^{-2}\,yr^{-1}}$	<65	<60
BENG 2	Fossil energy requirement	$\mathrm{kW\,h\,m^{-2}\,yr^{-1}}$	<50	<20
BENG 3	Renewable energy share	%	>40	>70

[1] Bijna Energieneutrale Gebouwen (nearly energy-neutral buildings)

4.2.1 Dynamic life cycle assessment model

A Dynamic Life Cycle Assessment (DLCA) model is implemented following Levasseur et al. (2010) to calculate the global warming impact related to the choice of insulation material over a 200 year timeframe. Emissions are modeled in Python[2] to generate a dynamic inventory which considers the timing of GHG emissions and biogenic carbon sequestration following examples from the literature (Göswein et al., 2021; Hoxha et al., 2020; Pittau et al., 2019).

The modeled life-cycle stages are as follows:

1. Production (A1-A5[3]): Extraction, transportation, production and transportation to the building site
2. Use (B4): Replacement of products at end of lifespan and carbonization process in lime-based products
3. End-of-life (C1-4[4]): Demolition, transportation, waste treatment and disposal
4. Additional loads and benefits (D): Material recycling and energy recovery

The four different greenhouse gasses (GHGs) taken into account over the different life-cycle stages are CO2, CH4, N2O and CO as these contribute most to radiative forcing. The atmospheric decay of the different GHGs is approximated using Fuctions 4.1 and 4.2, following Hoxha et al. (2020):

$$C_{CO_2}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot e^{\frac{-t}{\tau_i}} \tag{4.1}$$

$$C_{CH_4,N_2O}(t) = e^{\frac{-t}{\tau}} \tag{4.2}$$

In Function 4.1, a_i are the coefficients which model the fractions of CO2 remaining in the atmosphere. Their values are: $a_0 = 0.217, a_1 = 0.259, a_2 = 0.338, a_3 = 0.186$. The perturbation times τ_i have the values: $\tau_1 = 172.9, \tau_2 = 18.5, \tau_3 = 1.186$. For CH4 and N2O the perturbation times are $\tau = 12$ and $\tau = 114$ respectively. CO is expected to rapidly oxidize into CO2 and is therefore modeled as an emission of CO2 by applying the molecular mass conversion factor $\frac{44.01}{28.01}$.

The dynamic characterization factor is calculated using the atmospheric decay function $C_{GHG}(t)$ and impact factor a_{GHG} (Equation 4.3). Note that $C_{GHG}(t)$ corresponds to $\gamma_{GHG}(t)$ from

[2] See https://github.com/Jonasvdham/BBIMs/

[3] Depending on data availability, see 4.2.2

[4] See note 3

Equation 2.2 but $C_{GHG}(t)$ is used here for consistency with the original authors (Levasseur et al., 2010). $DCF_{GHG}(t)$ returns the impact on atmospheric radiative forcing from an emission of 1 kg of GHG after t years ($\mathrm{Wm^{-2}kg}$).

$$DCF_{GHG}(t) = \int_{t-1}^{t} a_{GHG} C_{GHG}(t)\, dt \tag{4.3}$$

The impact factors a_{GHG} are the radiative forcing per unit mass values. For CO2, CH4 and N2O these are: a_{CO_2} = 1.76e−15 W m^{-2} kg^{-1}, a_{CH_4} = 1.28e−13 W m^{-2} kg^{-1}, a_{N_2O} = 3.90e−13 W m^{-2} kg^{-1} (Hoxha et al., 2020). The instantaneous GWI ($\mathrm{Wm^{-2}}$) for year t is then calculated as follows:

$$\mathrm{GWI}(t) \;=\; \sum_{GHG} \mathrm{GWI}_{GHG}(t) \;=\; \sum_{GHG} \sum_{j=0}^{t} g_{GHG_j} \cdot \; DCF_{GHG}(t-j) \tag{4.4}$$

For each GHG a sum over the years 0 to t counts the current GWI as a result of the historical emissions of GHG, where g_{GHG_j} are the emissions of GHG in year j. Summing over the different GHGs results in the GWI. Finally, the cumulative GWI in year t is calculated by summing of the instantaneous GWIs from year 0 to t:

$$\mathrm{GWI}_{cumg}(t) = \sum_{i=0}^{t} \mathrm{GWI}(i) \tag{4.5}$$

4.2.2 Dynamic life cycle inventory

In the DLCA model a dynamic LCI is generated using data of GHG emissions over the life-cycle stages considered from the ecoinvent database (Wernet et al., 2016). Appendix A provides an overview of the used ecoinvent processes. When available, land transformation processes on the insulation material level are used for data on the emissions which occur in the production and construction phases (life-cycle stages A1-A5). These emissions are modeled at the time of construction. For BBIMs which are not in the ecoinvent database, ecoinvent data for the raw agricultural product is used. A required transport to the manufacturing location of 50 km by truck is assumed, while the emissions from the manufacturing and construction processes are assumed to be negligible.

For bio-based materials, carbon sequestration is modeled for 1 rotation period (R) under the assumption of linear regrowth after the harvesting of biomass (Peñaloza et al., 2016). That is, for R years after construction a negative emission of $\frac{CO_{2bio}}{R}$ is modeled. For seasonal crops, a rotation period of 1 year is assumed. Carbon sequestration is not considered for recycled materials to avoid double counting of the biogenic CO_2. The biogenic carbon content of different crops is taken from KBOB (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren [(KBOB)], n.d.).

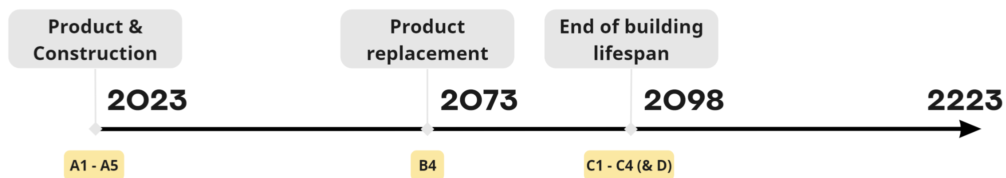


Figure 4.2: Timeline of modeled emissions

Figure 4.2 shows a timeline of the modeled emissions for the construction of a building in 2023. In sub-question 3, where the gradual construction of multiple buildings is modeled, each building starts a new timeline of modeled emissions shifted to year t of construction. The emissions from stage B4 related to the replacement of products are modeled after the lifespan of the product, which was assumed to be 50 years for all of the products. For insulation materials which have a suitable waste scenario modeled in ecoinvent this process is used (Appendix A). These processes typically include emissions from dismantling, handling, transport and final disposal (stages C1-C4). For the bio-based options, incineration and anaerobic digestion scenarios are compared, as EOL scenarios can have a significant impact on LCA results (Pittau et al., 2019). For cellulose and wood-fiber insulation, only the incineration scenario is modeled as these materials are not suited for anaerobic digestion. The incineration scenario models the emission of all biogenic CO_2 content and disregards other GHGs. The emissions resulting from anaerobic digestion are taken from ecoinvent. In this process biogas is generated which can be used to replace another fuel source. This replacement is seen as a benefit in stage D and therefore the emissions of burning the biogas are not included. EOL emissions are modeled both after the lifespan of the product (50 years) and the building (75 years). As this study focusses on fossil and biogenic emissions, direct and indirect land-use impacts are out of the scope.

4.3 Global warming impact of using bio-based insulation in high-rises in Amsterdam

The case-study results are generalized to evaluate the carbon-saving potential of implementing BBIMs on the scale of Amsterdam. The city of Amsterdam intents to build 150.000 houses until 2050 (Gemeente Amsterdam, n.d.-b). Documents internal to the municipality of Amsterdam suggest that a reasonable assumption for the share of new construction taller than 30 m is 65%. Following this, the number of high-rise dwellings to be constructed in Amsterdam until 2050 is assumed to be 97.500. Assuming a linear trend in the number of residential high-rise dwellings constructed per year, the annual number of constructed houses is calculated as follows:

$$\frac{97500}{(2050-2023)} \approx 3611$$

The m^2 of façade per dwelling which needs to be insulated is taken from the case study by dividing the total m^2 of installed insulation by the number of dwellings in *The Ensemble*:

$$\frac{4494.6}{592} \approx 7.6\,\mathrm{m}^2$$

The insulation thickness that was applied in the case study is assumed for the construction of houses until 2050.

5
Results

5.1 Insulation materials applicable in high-rise buildings in Amsterdam

A structured literature review was performed as described in Section 4, to arrive at a list of insulation materials which are relevant to the scope of this study (Figure 5.1). The initial search resulted in 278 review papers. The 50 most cited papers were searched for material properties, which resulted in the inclusion of 14 papers. After adding 3 market reports with material properties, the structured literature review resulted in 17 publications.

From the 17 publications, 176 material-citation combinations were collected, covering 50 unique materials. After excluding materials which are not conventional[1], not plant-based or do not meet the thermal conductivity criterion, 120 material-citation combinations over 32 unique materials were left. After reducing the scope to Amsterdam by removing materials which are not grown in the Netherlands and limiting to one type of straw, 85 total entries were left over, covering 14 unique materials.

[1] Included conventional materials are stone wool, glass wool, EPS and XPS

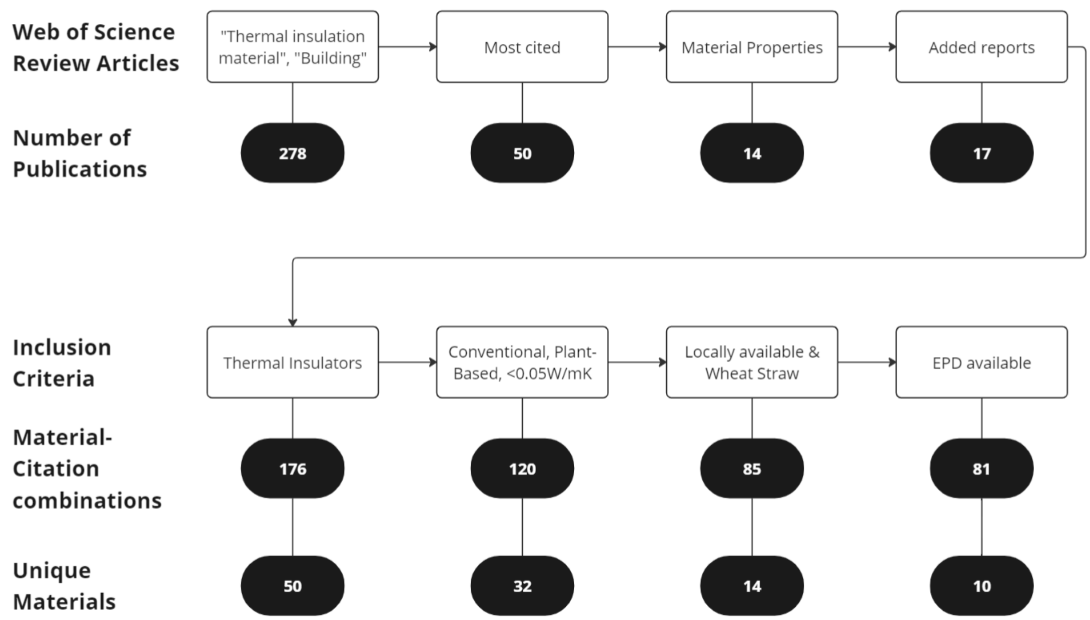


Figure 5.1: Schematic overview of the structured literature review

Tables 5.1 and 5.2 show the thermal conductivity and material density values for these 14 materials. Since the values were taken from a large number of sources, they include considerable ranges. Outlier values from experimental studies may be included which are not representative of the material properties for marketed products. Therefore, market-representative thermal conductivity and density values were taken from EPDs. The lack of EPD availability for the materials in Table 5.1 resulted in the exclusion of these materials in the DLCA model. The marketed materials in Table 5.2, which have EPDs available, are assumed to be the most import in the Dutch context because of their availability.

Table 5.1: Material properties from literature with limited data availability

Material	**Density**	**λ**	**EPD λ**	**EPD Density**	**Fire safety class**
Unit	(kg/m^3)	$(Wm^{-1}K)$	$(Wm^{-1}K)$	(kg/m^3)	-
Barley + Corn starch	108	0.042	-	-	-
Cornstalk block	-	0.045 - 0.055	-	-	-
Hay	30-65	0.04	-	-	-
Sunflower	36-152	0.039 - 0.05	-	-	-

Table 5.2: Material properties from literature for materials included in the DLCA model

Material Unit	Density (kg/m^3)	λ ($Wm^{-1}K$)	EPD λ ($Wm^{-1}K$)	EPD Density (kg/m^3)	Fire safety class -
Stone wool	5 - 300	0.03 - 0.07	0.036	29.5	A1
Glass wool	10 - 100	0.03 - 0.05	0.036	22	A1
EPS	15 - 50	0.029 - 0.041	0.031	20	E
XPS	-	0.025 - 0.041	0.033	30	E
Cellulose	30 - 80	0.037 - 0.055	0.038	52	B - E
Flax	20 - 100	0.035 - 0.075	0.038	40	E
Grass fiber	40	0.04 - 0.041	0.04	40	D - E
Hemp	20 - 90	0.0339 - 0.06	0.041	36	E
Wheat straw	50 - 150	0.038 - 0.072	0.044	100	E
Wood fiber	29 - 270	0.036 - 0.051	0.038	47.5	D - E

5.1.1 Fire-safety of bio-based insulation materials

The fire-safety class of the materials from the literature ranges from A1 to E (Table 5.2). The best fire-safety class of A1 is obtained by glass and stone wool. All of the other materials typically have a fire-safety class rating of E, showing little variation in the fire-safety of different BBIMs. Moreover, except for glass and stone wool, the BBIMs also obtain ratings equal to that of EPS and XPS.

The application of BBIMs in high-rise façades requires them to meet the fire-safety regulations, as described in Section 2.2. The most important requirements for high-rise building façades are fire-safety class B and resisting fire spread between fire compartments for at least 60 minutes (Rijksoverheid, 2012b, 2012c). Although these measures suffice for high-rises up to 70 m, for taller buildings additional measures like a sprinkler installation and pressurized flight routes would likely be needed. The additionally required measures are determined on a case-by-case basis.

Expert interview

To assess the conditions under which BBIMs can be applied in high-rise façades with equivalent fire-safety to conventional insulation materials a fire-safety expert interview was performed with Ruud van Herpen[2] (full interview transcript is presented in Appendix B). The interview resulted in points of attention for the application of BBIMs in high-rise construction.

[2] Fellow in Fire Safety Engineering at Eindhoven University of Technology

Firstly, in high-rise construction the Dutch building code requires fire-safety class B on the level of the façade element. Combining different materials layers in the façade can deteriorate fire-safety, thus including an insulation material of fire-safety class B does not guarantee fire-safety class B for the façade element. Conversely, the disconnect between the product and the element fire-safety class means that, with sufficient measures, insulation materials of fire-safety class E could be implemented in a façade element with fire-safety class B.

Secondly, margins exist within the different fire-safety classes. Fire-safety class F includes the largest margins of performance as it includes highly-flammable materials and materials which have not been tested for fire-safety. Most BBIMs in Table 5.2, as well as EPS and XPS, have a fire-safety class of E. Despite this poor fire-safety class, EPS and XPS are commonly applied in high-rise construction in sandwich panels. The application of these materials, interposed between inflammable metal films, demonstrates the possibility of applying insulation materials with fire-safety class E in high-rise construction, given the correct implementation.

Thirdly, in developed fires the supply of heat is large enough that flammable materials of fire-safety classes B-F will likely ignite. Although the speed of fire spread will differ between these categories, only the inflammable materials of fire-safety class A1-A2 will prevent ignition. Consequently, there is no distinction in the fire-safety precautions required in combination with insulation materials of fire-safety class B-F to provide equivalent fire-safety to façades which implement insulation materials of fire-safety class A1-A2. In all of the classes B-F, the insulation material should be sufficiently shielded from heat sources so that it does not contribute to the development of a fire. In line with the regulations which limit fire spread between fire compartments, the insulation material should be shielded from exposure to fire for 60 minutes.

Lastly, as there are limited chances of ignition from outside sources in a high-rise façade, fire resistant material should be applied on the inside of the façade to shield insulation material from exposure to fire for 60 minutes. Typical fire resistant materials include gypsum boards, silicate plates, or a plaster layer. A double gypsum board of 2 x 12mm can provide around 60 minutes of fire-resistance. As fire-resistant insulation materials are also covered by some plate material for finishing purposes, a single gypsum board is counted as additional material requirement in scenarios with BBIMs of fire-safety class B-F in the following sub questions.

5.2 Global warming impact of insulating the ensemble

To model the potential reductions in GWI of implementing BBIMs in high-rise building *The Ensemble*, different material scenarios which meet the insulation requirements for this building were compared. Table 5.3 shows the insulation material parameters taken from the building plans.

Table 5.3: Parameters taken from *the Ensemble*

Parameter	**Value**	**Unit**
Façade surface area	4494.6	m^2
R-value	3.5	m^2KW^{-1}
Material	EPS	-

Using the λ-value for EPS of 0.035 from Table 5.2, the thickness of insulation applied is calculated using Equation 2.1. For the EPS used in the building, the material thickness is calculated as follows:

$$3.5 \cdot 0.035 = 0.1225\,\text{m}$$

This thickness is multiplied with the façade surface area to result in the volume of EPS required to insulate the whole building:

$$4494.6 \cdot 0.1225 = 550.59\,\text{m}^3$$

Replacing the thermal conductivity of EPS ($\lambda = 0.035$) with the thermal conductivities from Table 5.2 results in the different volumes of material required to provide equivalent insulation for *The Ensemble* (Table 5.4). For the materials with a fire-safety class other than A1/A2, a 12 mm layer of gypsum board is added to the material volume to provide equivalent fire-safety. Applying the 12 mm gypsum layer over 4494.6 m^2 of façade results in the need for 53.94 m^3 of gypsum board. The resulting material volumes are taken as input volumes for the dynamic GWP model to calculate the GWI of the different material scenarios for *The Ensemble*.

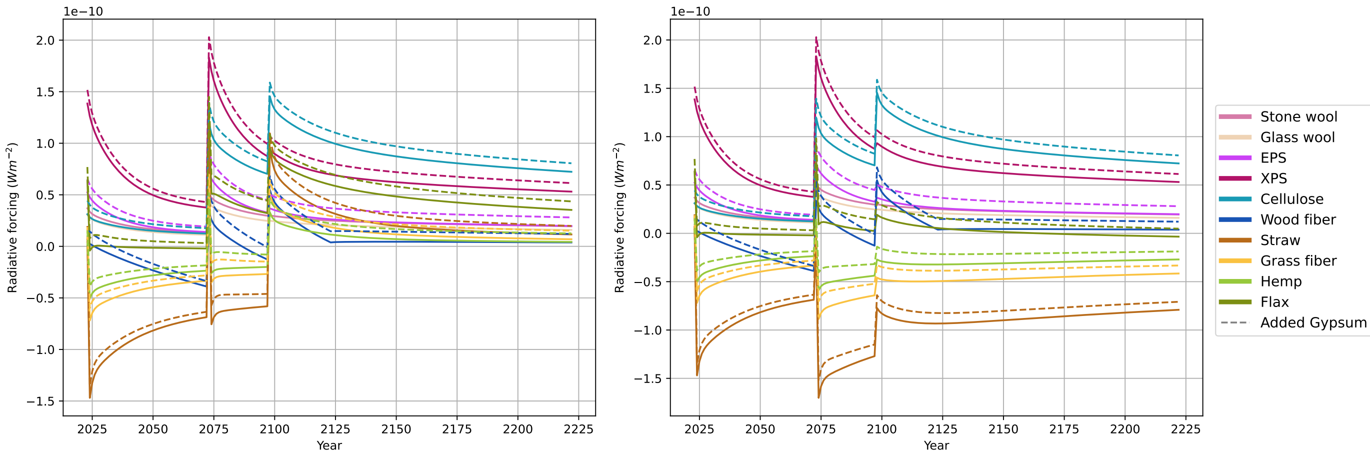
Table 5.4: Material properties for materials included in the DLCA model

Material	**λ**	**Thickness**	**Volume**	**Mass**	**Rotation period**	**Fire safety class**	**Gypsum board**
Unit	($Wm^{-1}K$)	(m)	(m^3)	(kg)	(yr)	-	(m^3)
Cellulose	0.038	0.133	597.78	31084.56	-	B	53.94
EPS	0.035	0.1225	550.59	16517.7	-	E	53.94
Flax	0.041	0.1435	644.98	25799.2	1	E	53.94
Glass wool	0.036	0.126	566.31	12458.82	-	A1	0.0
Grass fiber	0.040	0.14	629.24	25169.76	1	E	53.94
Hemp	0.041	0.1435	644.97	23218.92	1	E	53.94
Stone wool	0.036	0.126	566.31	16706.145	-	A1	0.0
Wheat straw	0.044	0.154	692.16	69216	1	E	53.94
Wood fiber	0.045	0.1575	707.90	24422.55	50	D-E	53.94
XPS	0.033	0.1155	519.13	20765.2	-	E	53.94

Figure 5.2 shows the instantaneous radiative forcing as a result of the GHG emissions during the life cycle of *The Ensemble* for different insulation materials. The left plot assumes incineration of the bio-based materials at the EOL while the right assumes anaerobic digestion to generate biogas for all BBIMs except cellulose and wood-fiber insulation. For materials with fire-safety class B-F, the dashed line represents the GWI with the addition of a required gypsum board. Both plots show the instantaneous GWI in terms of radiative forcing, or the change in energy flux in the atmosphere in $W\,m^{-2}$. The instantaneous GWI at time t shows the global warming impact in year t as a result of all emissions up to year t.

Both Figures 5.2a and 5.2b clearly show the GWI related to the production and construction phases (A1-A5) of the materials in the year of construction (2023). In this year, XPS has the largest GWI[3] ($1.52e{-}10\,W\,m^{-2}$) while hemp has the smallest GWI ($1.56e{-}11\,W\,m^{-2}$). After 1 year, the short rotation-period BBIMs have a large negative spike in GWI as a result of the carbon sequestration from biomass growth. Note that the biogenic carbon sequestration can have a larger absolute value than the emissions related to the production and installation of the materials. This effect is especially visible for the straw insulation as it is applied at a significantly higher density than the other BBIMs and therefore sequesters more carbon during its regrowth. As a result of its longer rotation period, the decrease in GWI of the wood-fiber insulation is slower than that of the other BBIMs. Following the initial construction, the replacement of the materials in 2073 and the end of the service life of the building in 2098 are two considerable emission pulses (Figure 5.2).

[3]When applicable, denoted values include the influence of the required gypsum fiberboard



(a) Incineration

(b) Anaerobic digestion

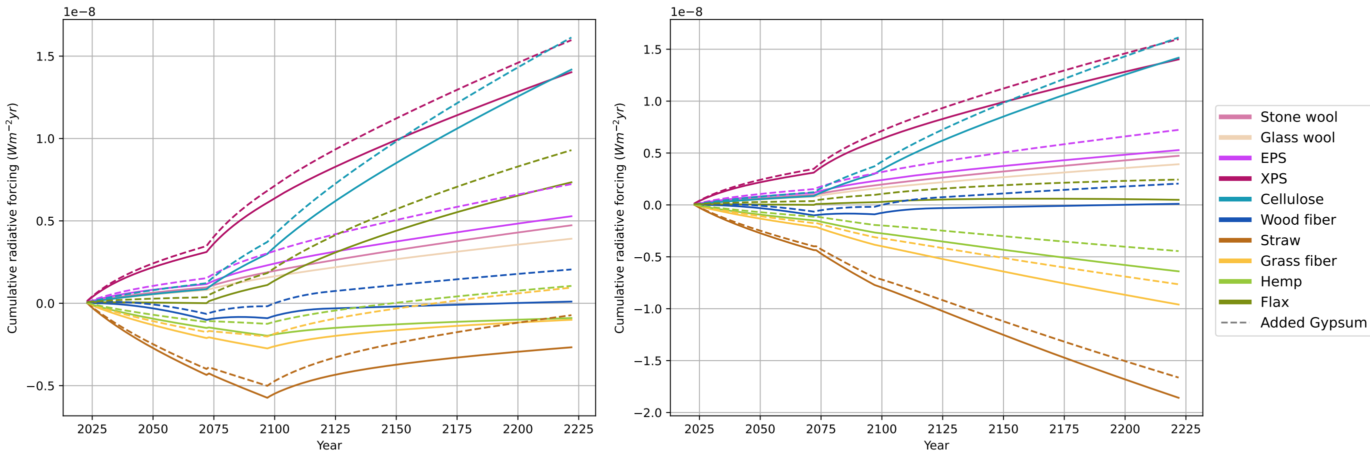
Figure 5.2: Instantaneous global warming impact for The Ensemble

The carbon sequestration as a result of the regrowth of straw results in the largest negative peaks of $-1.35\text{e}{-10}\ \text{W m}^{-2}$ in 2024 and $-1.52\text{e}{-10}\ \text{W m}^{-2}$ in 2074 in GWI in the incineration and anaerobic digestion scenarios respectively. The largest positive peak in radiative forcing results from the concurrent EOL impacts of the materials which are to be replaced and production impacts of the replacement materials for XPS in 2073. The radiative forcing amounts to $2.03\text{e}{-10}\ \text{W m}^{-2}$ in both cases as the EOL for XPS is consistent between the two graphs. For the BBIMs, material replacement in 2073 also results in a GWI peak but this is quickly reduced as a result of the carbon sequestration from the replacement materials.

Generally speaking, the instantaneous GWI of the BBIMs is lower than that of the conventional insulation materials. However, after the end of the building lifespan, the instantaneous GWI is highest for cellulose. Although EPS and XPS clearly have a higher GWI than all other bio-based materials, after the end of the building lifespan stone and glass wool perform very comparable to the BBIMs. At this point stone and glass wool even outperform flax[4]. Straw, grass and hemp are the materials which most clearly benefit from their biogenic carbon sequestration in terms of GWI. Looking at the anaerobic digestion scenario, all plant-based BBIMs outperform the conventional insulation materials. Stone wool, glass wool and EPS still outperform cellulose as biogenic carbon sequestration benefits are not counted for cellulose to avoid double counting. The conventional materials also benefit from lower EOL emissions than cellulose, for which incineration is assumed.

[4]The geographical scope of the life-cycle data for flax may affect its GWI, see Section 6.2.1

The significant decrease in radiative forcing at the EOL for plant-based materials in the anaerobic digestion scenario demonstrates the benefits of this EOL strategy. Unlike with incineration, in the case of anaerobic digestion the biogenic carbon in the plant-based materials is not fully re-emitted.



(a) Incineration

(b) Anaerobic digestion

Figure 5.3: Cumulative global warming impact for The Ensemble

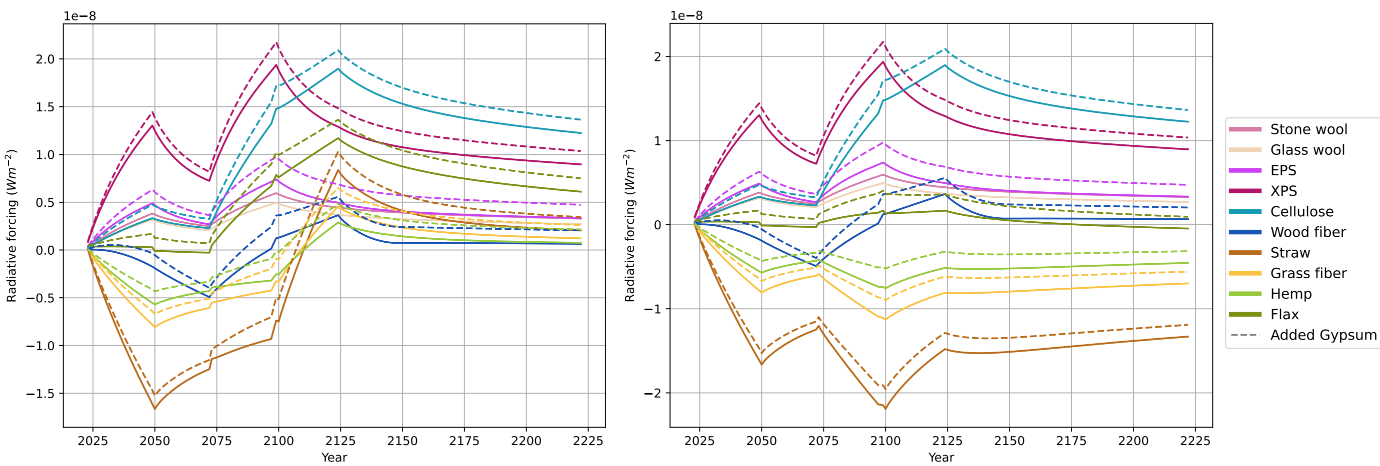
The cumulative GWI graphs in Figure 5.3 show the long-term effect of the different material scenarios on the radiative equilibrium of the atmosphere. These graphs compound the effects observed in the instantaneous GWI graphs while the influence of short-term peaks is reduced. In the incineration EOL scenario only straw results in a negative cumulative radiative forcing effect at the end of the time horizon. When excluding the required gypsum board layer, the same holds for grass and hemp. In the anaerobic digestion scenario, straw, grass and hemp all result in negative cumulative GWIs. Cellulose ($1.61\text{e}{-8}\ \text{W}\,\text{m}^{-2}\,\text{yr}$) and XPS ($1.59\text{e}{-8}\ \text{W}\,\text{m}^{-2}\,\text{yr}$) clearly show the highest cumulative GWI, followed by flax and EPS. Stone and glass wool perform relatively moderate, outperforming flax in the incineration scenario, but being outperformed by all plant-based BBIMs in the anaerobic digestion scenario. In the incineration scenario, the minimum cumulative GWI ($-5.01\text{e}{-9}\ \text{W}\,\text{m}^{-2}\,\text{yr}$) is reached by straw just before the incineration of the material at the end of the building lifespan in 2097. In the anaerobic digestion scenario the cumulative GWI for straw keeps decreasing, with a slowly decreasing slope, and results in a finale cumulative radiative forcing of $-1.66\text{e}{-8}\ \text{W}\,\text{m}^{-2}\,\text{yr}$ in 2022. The difference in the EOL scenarios again clearly shows for the plant-based materials which, except for flax, all result in negative cumulative radiative forcing.

Finally, the two cumulative graphs clearly show the value of the DLCA methodology. The difference between comparing the cumulative GWI for straw in Figures 5.3a and 5.3b in for instance

2100 and 2200 is significant. In 2100 the difference between the incineration scenario ($-4.72e{-9}\ \mathrm{W\,m^{-2}\,yr}$) and the anaerobic digestion scenario ($-7.19e{-9}\ \mathrm{W\,m^{-2}\,yr}$) is relatively limited. However, in 2200 the values for incineration ($-1.18e{-9}\ \mathrm{W\,m^{-2}\,yr}$) and anaerobic digestion ($-1.50e{-8}\ \mathrm{W\,m^{-2}\,yr}$) approximately differ by a factor of 10. This demonstrates that the choice of an arbitrary time horizon like 50 or 100 years, as is required for calculating the GWP, has a large impact on the results. Using a static approach conceals the real-world dynamics of GWI which is undesirable if an objective interpretation of the data is to be made.

5.3 Global warming impact of insulating high-rises in Amsterdam until 2050

The same dynamic LCA which was applied to the case study is used to model the global warming impact of applying BBIMs in all residential high-rises in Amsterdam until 2050. For the construction of 97.500 high-rise dwellings, the set of insulation materials from Table 5.4 is compared under incineration and anaerobic digestion EOL scenarios.



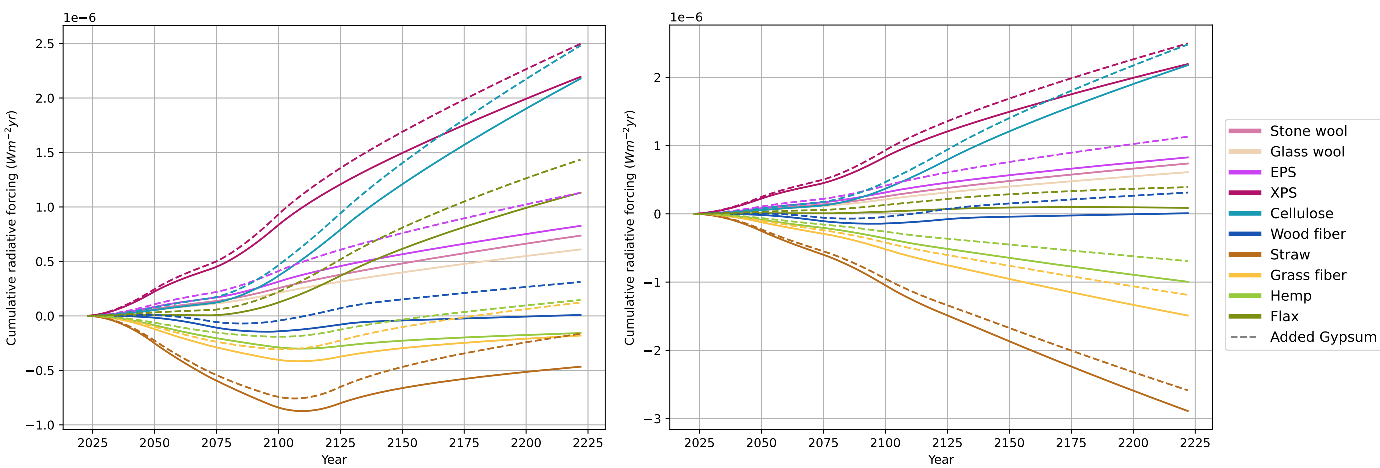
(a) Incineration

(b) Anaerobic digestion

Figure 5.4: Instantaneous global warming impact for high-rise dwellings built in Amsterdam until 2050

The modeling results for the scale of Amsterdam show the same general trends as the case study, although the gradual construction of new houses dampens some of the peaks in GWI. Looking at the instantaneous GWI in Figures 5.4a and 5.4b, the differences in GWI start to increase as more houses are constructed towards the 2050 goal for both EOL scenarios. After 2050 no new construction is taken into consideration and the GWI values slowly tend towards 0 as a result of atmospheric decay of the emitted GHGs. After material replacements are performed on houses with a lifetime of 50 years, starting with the first constructed houses in 2073, the difference between the two EOL scenarios starts showing. The benefit of anaerobic digestion shows for all the plant-based materials but most clearly for those with high biogenic carbon content like straw, grass and hemp. In comparison with the case study (Figures 5.2a and 5.2b) the peaks are less pronounced as a result of the gradual construction of houses. While in the incineration scenario the GWI increases for all materials between 2073 and 2098, in the anaerobic digestion scenario the GWI for straw, grass and hemp decreases in this period. The decrease can be explained by the biogenic carbon sequestration in the replacement material and the relatively low emissions from the anaerobic digestion process.

In accordance with the case study, the largest positive peak in instantaneous radiative forcing of $2.18\mathrm{e}{-8}\ \mathrm{W\,m^{-2}}$ is caused by the EOL of XPS. Due to the gradual construction of houses this peak occurs in 2099, as opposed to 2073 in the case study. The largest negative peaks both result from carbon sequestration by straw and amount to $-1.53\mathrm{e}{-8}\ \mathrm{W\,m^{-2}}$ and $-1.96\mathrm{e}{-8}\ \mathrm{W\,m^{-2}}$ for the incineration and anaerobic digestion scenarios respectively. The low emissions from anaerobic digestion are apparent as they further reduce the negative peak in 2050 in the incineration scenario down until 2100.



(a) Incineration

(b) Anaerobic digestion

Figure 5.5: Cumulative global warming impact for high-rise dwellings built in Amsterdam until 2050

The cumulative GWI results on the scale of Amsterdam are highly comparable with those for the case study. For straw, Figure 5.5a shows a turning point in 2110 comparable to the one in 2098 in the case study (Figure 5.3a). The effect is slightly delayed as the number of houses at their end of life gradually increases. As a result, the turning point of the graph is also less sharp. Except for the slight delay in turning points and the smoothing of the graphs there are no discernible differences with the trends shown in Figure 5.3a. Similarly, the trends shown in the cumulative graphs for the anaerobic digestion scenario are also highly comparable between Figure 5.5b and Figure 5.3b.

6 Discussion

This study applied a dynamic LCA to evaluate the potential GWI of implementing bio-based insulation materials in residential high-rise buildings in Amsterdam. To answer the main research question, a list of BBIMs applicable in the Dutch high-rise context was generated. These materials were compared with conventional insulation materials on their GWI with the use of a case study, and in the context of Amsterdam's housing plans projected up until 2050.

The BBIMs which were found to be applicable in the Dutch context are cellulose, flax, hemp, wheat-straw and wood-fiber insulation. Typically all of these materials have fire-safety class E, with the exception of some wood-fiber insulation products, and cellulose when applied with a thickness of above 100 mm. The Dutch building code requires a resistance of fire spread between compartments for at least 60 minutes in high-rise buildings. To limit the spread of fire through the façade when insulation materials of fire-safety class other than A1/A2 are used, an additional 12 mm gypsum board was applied.

To evaluate the GWI of using different materials in a high-rise building, a DLCA was applied to high-rise building the Ensemble. The GWI scores for stone and glass wool were relatively comparable with most BBIMs while XPS and cellulose typically had the highest GWI and straw had the lowest GWI. The cumulative GWI compounded these trends and again showed the highest GWI for XPS and the lowest GWI for straw.

The trends in the GWI for the DLCA model which was applied on the scale of Amsterdam were very comparable with those of the case-study. The gradual construction of more houses dampened and delayed some peaks in the data but general trends were persistent. Although the radiative forcing values were of another order of magnitude, the relative differences between materials did not change.

6.1 Materials applicable in high-rise buildings

The performed literature review resulted in a set of materials which were included in the analysis. Only the 50 most cited articles from the Web of Science database were included in the study. Including more literature databases, articles or further search terms could have resulted in more materials being added to the analysis. Furthermore, the application of the material inclusion criteria resulted in a set of relatively common BBIMs. Although this step was necessary to arrive at a set of materials with sufficient data availability, it prevented the inclusion of innovative bio-based materials like barley and cornstarch, cornstalk, and sunflower insulation. It should be noted that when life-cycle emissions data becomes available they can easily be compared with the BBIMs in this study using the openly available DLCA model[1].

As a result of lacking comparable data with respect to hygrothermal performance, this material property was not taken into account, despite its influence on the insulating qualities of a material. Cost was another factor which was disregarded in the analysis as a result of lacking data availability. Cost is related to thermal conductivity since the thickness of the insulation layer and the extra gypsum layer influence the wall thickness and the gross floor area. This is especially relevant in high-rise buildings, where the influence of wall thickness on gross floor area is multiplied by the number of stories which may result in significant differences for the business case of a project developer. To support the implementation of BBIMs these effects should be further investigated.

With respect to fire safety, it was concluded that there was no significant difference between fire-safety classes B-E in a developed fire. Assuming equal fire safety between materials with fire-safety class A1/A2 and materials with fire-safety classes B-E with the addition of a gypsum board allowed for the comparison of the different materials. This simplification disregards the complex definitions of different fire-safety classes for the sake of analysis. In practice, materials with fire-safety classes B-E would likely contribute differently to the development of a fire. The 60 minutes of fire resistance provided by the gypsum layer would ensure sufficient time for evacuation of the building but it is unclear how the combination of a flammable insulation material with a gypsum layer influences the likelihood of a full burnout. Similarly, it was assumed that in case of a developed fire, the available heat would result in little practical difference between the fire-safety of materials of classes

[1] https://github.com/Jonasvdham/BBIMs

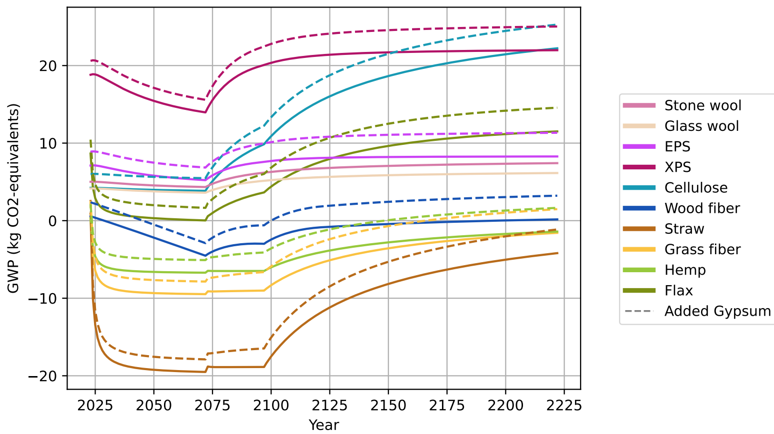
B-E. The difference in fire safety between these materials in a less developed fire scenario was not considered.

Lastly, it should be noted that after the Grenfell Tower incident in London, Dutch fire-safety regulations may be subject to change (BBC, 2019). Other European countries have already instated stricter fire-safety regulations for high-rise buildings (van de Leur & van Mierlo, 2021). In an advisory report for the Dutch ministry of internal affairs and kingdom relations, van de Leur and van Mierlo (2021) also suggest stricter regulations like fire-safety class A2 for façades above 50 meters. Alternatively, Ruud van Herpen[2] suggests higher requirements could be set for the installation of sprinkler systems and the fire protection ability of the façade (K-factor), as requiring fire class A2 would hinder innovations like bio-based construction materials (R. van Herpen, personal communication, April 21, 2023).

6.2 Dynamic life cycle assessment

The dynamic LCA results were considered within the scientific context to verify their validity. Although no studies directly comparable to this were found, some related work has applied DLCAs to bio-based materials. Similar to this study, other studies showed increasing GWI values for straw, hemp, mineral wool and EPS respectively (Carcassi, Minotti, et al., 2022; Göswein et al., 2021; Pittau et al., 2019). Radiative forcing values cannot directly be compared with other studies as renovation and construction scenarios were considered at different scales. Göswein et al. (2021) do provide a functional unit for comparison by modeling the dynamic GWP for the renovation of 1 m^2 of façade. Following Göswein et al. (2021), the dynamic GWP of a scenario was defined as its global warming impact relative to the GWI of a 1 kg pulse emission of CO_2 in year 0 (Equation 6.1). This definition uses the definition of GWI from Equation 4.4 and the resulting graph for 1 m^2 of façade insulation is shown in Figure 6.1. Although Göswein et al. (2021) only consider life-cycle stages B4 & B5 (renovation), the GWP values for the renovation of 1 m^2 of façade fall within a range which is very comparable with this study, especially when considering the graph for straw. In this study the GWP values for straw insulation range between -18 and 2.5 while the values from Göswein et al. (2021) range between approximately -25 and 10. The higher initial peak of 10 kg CO_2-equivalents found by Göswein et al. (2021) can be explained by the fact that their scenario also includes mineral coating, a timber beam and oriented strand board (OSB). The lower minimum GWP value in their study may result from the assumed lifespan of 60 years of their retrofit system, which provides more time for the GWP to decrease.

[2] Fellow in Fire Safety Engineering at Eindhoven University of Technology



$$\mathrm{GWP}_{dyn}(t) = \frac{\mathrm{GWI}(t)}{C_0 \int_0^t a_{CO_2} \cdot \gamma_{CO_2}(t)\, dt} \qquad (6.1)$$

Figure 6.1: Dynamic GWP of $1\mathrm{m}^2$ of façade insulation

The inclusion of emissions from the fire-resistant layer required to provide equivalent fire safety between different material scenarios in this study is novel. As discussed in the results, the inclusion of the gypsum fiberboard resulted in negative cumulative GWI values turning positive in some cases (e.g. for hemp and wood-fiber insulation in Figure 5.3a). Nevertheless, with the exception of temporary differences, the relative ranking of the materials was consistent whether the gypsum fiberboard was included or not. Consequently, although the inclusion of this fire-resistant layer in this study did ensure the most representative GWI values, recommendations on material use made in other studies which disregarded fire-safety are likely still valid.

6.2.1 Assumptions in the modeled data

Some assumptions in the input data were made in this study which may influence the validity of the results. An overview of the ecoinvent processes used to generate the GHG emissions related to the production of the different insulation materials can be found in Appendix A. ecoinvent processes were readily available for stone wool, glass wool, EPS, XPS, cellulose, and the gypsum fiberboard. For the other materials, ecoinvent processes for production of comparable materials or for the cultivation of raw biomass were used. For the raw biomass processes, the emissions related to 50 km of transportation by truck were added to account for the transportation to the construction site, but the emissions related to the processing of the raw biomass into insulation materials were assumed to be negligible and were ignored. This assumption potentially favors the plant-based insulation materials in terms of their GWI. Furthermore, as no ecoinvent data on wood fiber insulation was available and wood wool was assumed to have comparable emissions, it was modeled instead. Similarly, no data was available for the cultivation of hemp and the cultivation of maize seed was modeled instead, following (Pittau et al., 2019) and (Zampori et al., 2013). Data on the cultivation of flax was only available under the rest-of-world (RoW) geographical scope which likely negatively influenced the GWI of the flax insulation material, as agricultural efficiency is likely higher in the western-European context.

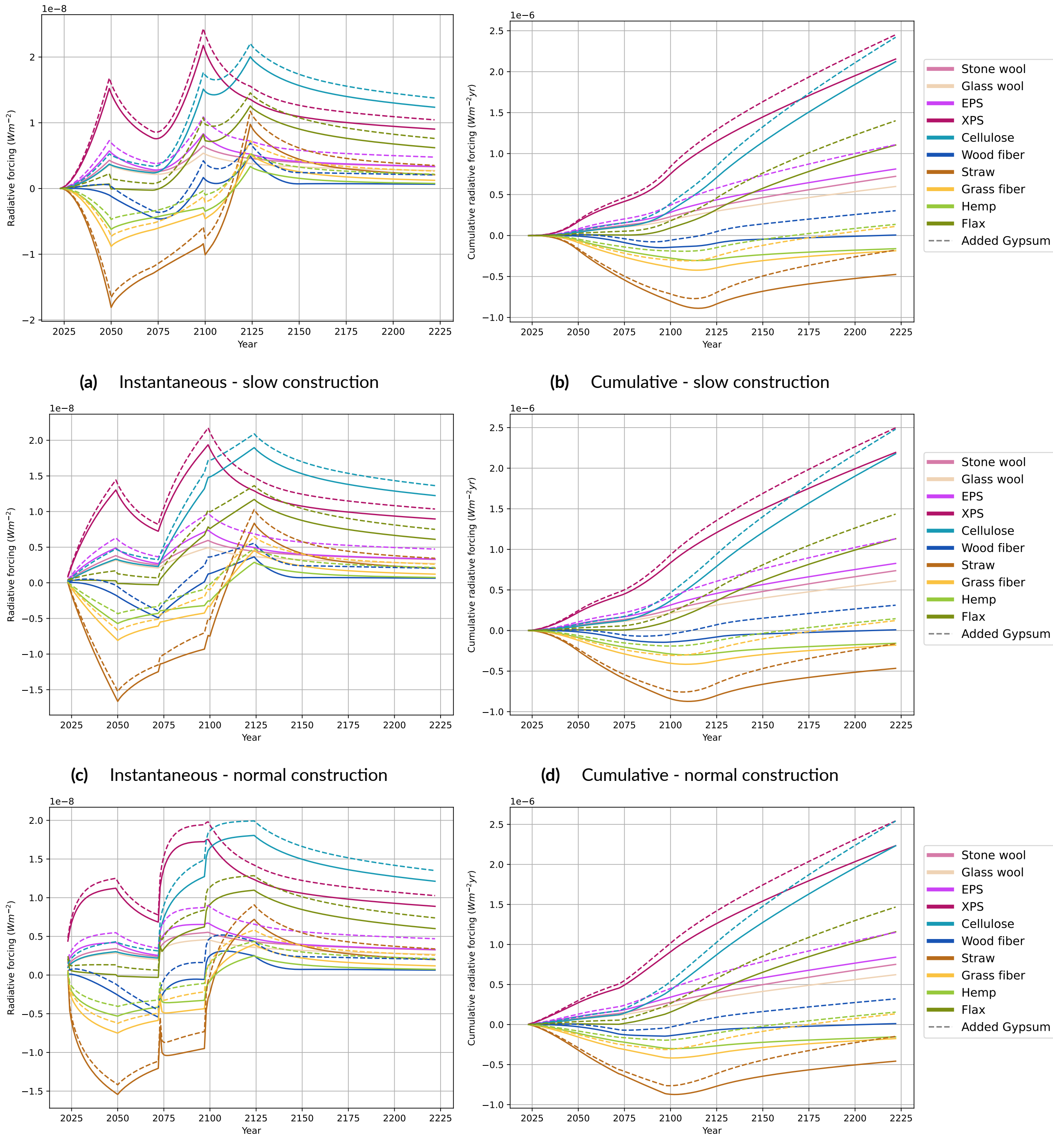
Lastly, the assumed material properties (Table 5.4) for each of the insulation materials also influenced the results. As the structured literature review resulted in considerable thermal conductivity and density ranges, EPDs were consulted to provide market-representative values. Nevertheless, for some materials multiple EPDs were available and a relatively arbitrary choice for average values had to be made which influenced the results.

6.2.2 Modeling assumptions

An incineration and an anaerobic digestion scenario were modeled to evaluate the impact of different EOL scenarios. For the incineration scenario the simplifying assumption was made that all biogenic carbon, but no other GHGs, would be emitted. In addition to ignoring the dynamics of incineration, no energy recovery or emission capturing was assumed, which is unrealistic in the Dutch context. The GWI of the plant-based materials resulting from the EOL should therefore be interpreted as a worst-case scenario when incineration was modeled. Furthermore, the same anaerobic digestion EOL scenario was applied to all BBIMs except wood fiber and cellulose. This simplifying assumption disregards the efficiency of anaerobic digestion depending on the type of material which it is applied to. Further, the modeled EOL scenarios are consistent for all building deconstruction. There is no consideration of possible EOL innovations which may lead to lower emissions.

As mentioned in Section 4.3, a linear interpolation was assumed for the construction of 97.500 high-rise dwellings by 2050. To evaluate the influence of this assumption, two different building scenarios were modeled to show the impact of proactive and reactive construction strategies on the GWI. The proactive and reactive scenarios are based on a quadratic and square root interpolation respectively, such that the total number of houses in 2050 is 97.500, i.e. $H_i(2050 - 2023) = H_i(27) = 97.500$. The number of houses constructed per year for the fast and slow scenarios is retrieved by integrating over the respective functions:

$$H_{slow}(t) = \frac{97.500}{27^2}t^2 \qquad H_{fast}(t) = \frac{97.500}{27^{0.5}}t^{0.5} \qquad H_{total_i}(t) = \int_{t-1}^{t} H_i(t)dt$$



(a) Instantaneous - slow construction

(b) Cumulative - slow construction

(c) Instantaneous - normal construction

(d) Cumulative - normal construction

(e) Instantaneous - fast construction

(f) Cumulative - fast construction

Figure 6.2: Instantaneous and Cumulative GWI under different construction scenarios

Figures 6.2a, 6.2c and 6.2e show the instantaneous GWI with incineration at the EOL for the slow, normal and fast construction scenarios respectively. The speed of construction is clearly visible in the peaks in the instantaneous GWI plots. However, these differences do not result in notable differences in the cumulative GWI plots (Figures 6.2b, 6.2d, 6.2f). Therefore the effect of different construction scenarios was deemed to be negligible and only the linear interpolation scenario was considered in the results.

The only LCA impact category considered in this study was climate change. As different impact categories were not taken into account, no holistic recommendations on the use of materials can be made. Although straw was generally the best performing material in terms of GWI, it may be outperformed by other materials in different impact categories.

Finally, similar to Pittau et al. (2019), this study assumed that replanting crops would fully regenerate harvested biomass. As pointed out by Pittau et al. (2019), this does not account for any crop rotations which might be necessary to ensure sufficient soil quality. Additionally, the dynamics of carbon cycles in forests and soil were not considered as only the biogenic carbon was modeled.

6.2.3 Recommendations for future research

Based on the limitations of this study, future research is recommended to further elaborate on various aspects. Firstly, improving the data sources will lead to stronger results. For this study, data on GHG emissions were derived from the ecoinvent database, where estimates are presented as average values of coarse geographical scopes. Further studies can focus on gathering LCA data for specific geographical scopes, and could perform complete LCA studies following ISO standard requirements for the insulation materials which lack representative data. While the results of this study focus solely on a handful of available BBIMs, further research could use the list of materials resulting from the literature review as a reference for materials which show potential for climate change mitigation strategies.

Moreover, future studies are advised to include hygrothermal performance as a parameter to more accurately model insulating properties of materials. The inclusion of this property could influence material requirements for a given thermal performance. This affects cost effectiveness, which is another potential avenue for further research.

The large impact of EOL scenarios on GWI motivates the need for further research into EOL options. Recycling and landfilling are relevant options for all materials, while pyrolysis is a promising options which could be explored for bio-based materials (Werner et al., 2018).

Lastly, the scalability of the bio-based materials analyzed in this study can be studied by examining agricultural production in the Netherlands. This could contribute to contextualizing BBIMs in the insulation material market, and shed light on the potential for BBIM cultivation to contribute to reducing nitrogen emissions from the agricultural sector.

6.3 Results in the context of amsterdam

By interpreting the results in the Amsterdam context, practical implications of the results can be formulated. Firstly, given sufficient fire-proof material, façade elements with BBIMs can meet the fire-safety requirements for high-rise buildings. As these requirements are stricter than those for façades below 13 meters, BBIMs can be adopted more easily in low-rise buildings. If more BBIMs are implemented in low-rise buildings, practical experience on the fire-safety of prefabricated façades with BBIMs can be transferred to high-rise construction. Permorming costly single-burning-item (SBI) tests on prefabricated façades with BBIMs would be especially beneficial. In doing so, façade elements with BBIMs which meet fire-safety class B can be implemented on a large scale. Examples of prefabricated elements with BBIMs like straw already exist[3] which can directly be implemented as load-bearing façades for low-rise buildings up to 3 building layers. With additional constructional elements, the manufacturer claims no height limitations for their implementation.

The results of this study are highly relevant in view of Amsterdam's policy goals of becoming climate neutral by 2050[4]. The results show that the global warming impact (GWI) of BBIMs is generally lower than that of their traditional counterparts, even when additional fire-proof material is required. Thus, the fire-safety constraints are not a limiting factor for high-rise applications of BBIMs from a climate change perspective.

The best performing materials from a GWI perspective are straw, hemp and wood-fiber insulation respectively. To relate different materials' GWI to the scope of Amsterdam, the dynamic GWP of implementing them in all residential high-rises in Amsterdam is plotted in Figure 6.3, using Equation 6.1 as described in Section 6.2. In terms of GWP in 2050 the best and worst performing materials are straw ($-7.26e+6$ kg CO_2-equivalents) and XPS ($7.88e+6$ kg CO_2-equivalents) respectively.

The absolute difference in GWP between using straw or XPS for insulating all residential high-rises until 2050 is $1.59e+7$ kg CO_2-equivalents. This amounts to potential annual emissions savings of $5.87e+5$ kg CO_2-equivalents when switching from XPS to straw insulation, the equivalent of

[3] https://www.strotec.nl/

[4] https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/duurzaamheid/klimaatneutraal/

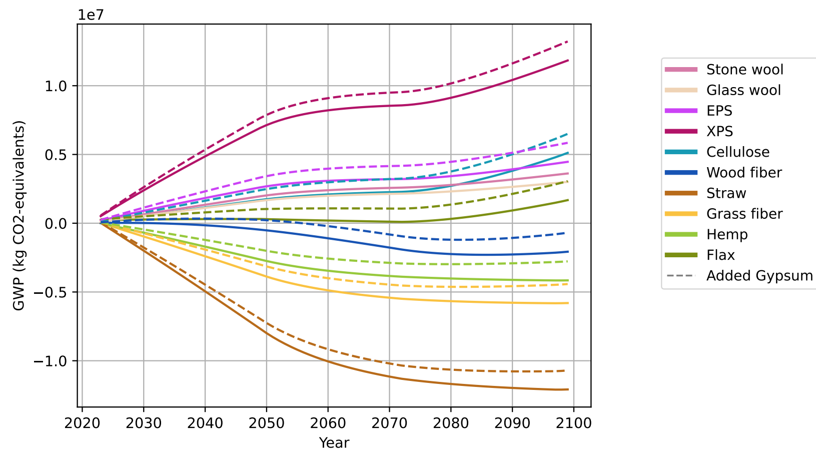


Figure 6.3: Dynamic GWP of insulating 97500 houses until 2050

approximately 1482 one-way flights from New York to Helsinki[5] (Baumeister, 2017). Relating to the local context, the 'Roadmap Amsterdam Climate Neutral' shows that Amsterdam's built environment was responsible for the emission of 1.25e+9 kg CO2-equivalents in 2017 (Gemeente Amsterdam, 2020). Consequently, switching from XPS to EPS in high-rises alone could reduce the CO2-equivalent emissions from Amsterdam's built environment by up to 0.047%:

$$\frac{5.87 \cdot 10^5}{1.25 \cdot 10^9} = 4.7 \cdot 10^{-4} = 0.047\%$$

Amsterdam's climate policy aims for a 5% reduction in CO2-emissions by 2025 (Gemeente Amsterdam, 2020). In light of this, the potential emission reductions offered by BBIMs are highly valuable, especially considering the fact that insulation materials represent only 0.5% (0.52/104 Mt) of the total mass of housing construction materials in The Netherlands (Copper8, 2023).

[5] 6750 km flight, depending on numerous variables (Baumeister, 2017)

7
Conclusion

This study evaluated the potential global warming impact (GWI) of implementing bio-based insulation materials in residential high-rise buildings in Amsterdam through a dynamic Life Cycle Assessment. A comprehensive literature review indicated that straw, grass, hemp, flax, wood-fiber and cellulose are the most applicable bio-based insulation materials (BBIMs) in the Netherlands. From an expert interview, it was concluded that a 12 mm layer of gypsum fiberboard is needed to ensure fire safety in high-rise buildings for insulation materials which do not have fire-safety class A1/A2.

The GWI of the BBIMs was compared with glass wool, stone wool, expanded polystyrene (EPS) and extruded polystyrene (XPS) insulation through a dynamic LCA. For the insulation of high-rise building *The Ensemble*, cumulative radiative forcing values between 1.61e−8 W m^{-2} yr for cellulose and −1.66e−8 W m^{-2} yr for straw were found in 2222. For the insulation of all 97.500 residential high-rise buildings which are to be built in Amsterdam until 2050, these values were 2.50e−6 W m^{-2} yr for XPS and −2.59e−6 W m^{-2} yr for straw in 2222. To contextualize the results, dynamic global warming potential (GWP) values were calculated. For the insulation of 1 m^2 of façade, dynamic GWP values ranged between −20 and 30 kg CO_2-equivalents for different materials over a 200 year time frame.

In general, the materials with high biogenic carbon content and low production emissions performed the best, while materials without biogenic carbon content scored poorly in terms of GWI. In all cumulative GWI graphs straw had the lowest GWI, resulting in global cooling. It was followed by grass, hemp and wood-fiber insulation, while XPS and cellulose typically had the highest GWI.

Stone and glass wool performed moderately well, although they were generally outperformed by all BBIMs except cellulose.

Although improvements can be made in the comparability of the input data, the results were consistent with other research literature. The results indicate that the application of straw, grass and hemp insulation is a promising climate change mitigation strategy as they can result in net cooling. As the GWI of stone and glass wool is relatively moderate, these materials can be applied when a high level of fire safety is required. When only GWI and fire-safety are considered, the use of EPS, XPS and cellulose insulation is advised against.

In the context of Amsterdam, the GWI reduction of implementing BBIMs in residential high-rises is significant. While insulation materials represent only 0.5% of the total mass of housing construction materials, annual emissions savings of up to 587 tons of CO_2-equivalents when switching from XPS to straw insulation were projected. This number equates to approximately 1482 one-way flights from New York to Helsinki, or 0.047% of Amsterdam's built-environment related emissions.

Thus, on the basis of the present study, it is advised to quickly scale up the implementation of BBIMs, focusing on the materials with the best GWI performance. While this can most easily be done for low-rise buildings, further development of prefabricated façades with BBIMs should also increase adoption rates for high-rise buildings. The city can stimulate the adoption of BBIMs through grants and experiments to reduce the built-environment emissions and work towards its goal of becoming climate neutral by 2050.

A

Ecoinvent processes

Transport emissions

"Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| market for | Cut-off, S"

Gypsum fiberboard

Production: "Gypsum fibreboard {CH}| production | Cut-off, S"

Produced 100% from natural gypsum (no FGD). Energy consumption is extrapolated from production of solid gypsum board (incl. drying).

End-of-life: "Waste gypsum plasterboard {CH}| treatment of, sorting plant | Cut-off, S"

The waste contains 1kg gypsum (GSD=100%). Waste density is 1000 kg/m3. Includes energy for dismantling, particulate matter emissions from dismantling and handling, machines for handling in sorting plant, electricity demand for sorting plant, transport to dismantling facilities, final disposal of waste material.

Cellulose

Production: "Cellulose fibre, inclusive blowing in {CH}| production | Cut-off, S"

This dataset represents the production of 1 kg of cellulose fibre from waste paper. This cellulose fibre is intended for use as a thermal insulation material in buildings. For this application, the fibres are blown into cavities, e.g. between two planks of a wall. Cellulose fibre in this type of application has a density of 50 kg/m3 and a thermal conductivity of 0.04 W/mK when applied. Cellulose fibres are treated with borax and boric acid to enhance fire retarding properties. The activity starts when the raw materials enter the process. This activity ends with the production of 1 kg of cellulose fibre made out of waste paper. The dataset includes the input energy and materials to the production processes, as well as the process emissions (only heat waste from electricity use). Also included is the packaging and the energy for the application of the fibres as insulation materials in buildings.

End-of-life: "incineration"

Flax

Production: "Fibre, flax {RoW}| fibre production, flax, retting | Cut-off, U"

The product 'flax plant, harvested' is a grain. It is an annual crop.

End-of-life (1): "incineration"
End-of-life (2): "Biowaste {CH}| treatment of biowaste by anaerobic digestion | Cut-off, S"

Biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, comparable waste from food processing plants, it also includes forestry or agricultural residues and manure. It does not include sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood. The anaerobic digestion treatment is a collection of processes by which microorganisms break down biodegradable material in the absence of oxygen. The treatment process produces biogas (a mixture of mainly methane and carbon doxide) and residual products called solid and liquid digestate.

Hemp

Production: "maize seed production, Swiss integrated production, at farm"

The product 'maize seed, Swiss integrated production, at farm' is a seed. It is an annual crop. Swiss integrated production refers to agriculture meeting the ecological requirements (ökologischer Leistungsnachweis, ÖLN) defined by the Swiss regulation on direct payments to agriculture (Direktzahlungsverordnung).

End-of-life (1): "incineration"
End-of-life (2): "Biowaste {CH}| treatment of biowaste by anaerobic digestion | Cut-off, S"

> Biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, comparable waste from food processing plants, it also includes forestry or agricultural residues and manure. It does not include sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood. The anaerobic digestion treatment is a collection of processes by which microorganisms break down biodegradable material in the absence of oxygen. The treatment process produces biogas (a mixture of mainly methane and carbon doxide) and residual products called solid and liquid digestate.

Wood fiber

Production: "Wood wool {RER}| production | Cut-off, S"

> The product 'wood wool' represents wood shavings which are 0.03 to 0.5 mm thick and usually 2 mm wide. Wood wool has a water content (water in wet mass [kg] / dry mass [kg]) of 0.2. Wood wool is produced mainly from spruce by machines similar to planing machines. The input wood has to be dry (u<20-30%) and its length usually is around 50 cm. Wood wool is mainly used as packing material and as raw material for wood wool boards.

End-of-life: "incineration"

Grass fiber

Production: "Grass, organic CH| grass production, permanent grassland, organic, intensive | Cut-off, S"

> The product 'grass, Swiss integrated production' is a grain. It is an annual crop. Swiss integrated production refers to agriculture meeting the ecological requirements (ökologischer Leistungsnachweis, ÖLN) defined by the Swiss regulation on direct payments to agriculture (Direktzahlungsverordnung).

End-of-life (1): "incineration"

End-of-life (2): "Biowaste {CH}| treatment of biowaste by anaerobic digestion | Cut-off, S"

Straw

Production: "Straw {CH}| wheat production, Swiss integrated production, extensive | Cut-off, S"

> This dataset represents the cultivation of wheat on an area of 1 ha producing the co-products wheat grain and straw. The yield of wheat grain is 5305 kg/ha at a moisture content at storage of 15%, the yield of straw is 3232 kg/ha at a moisture content of

15%. This activity starts after the harvest of the previous crop. The inputs of seeds, mineral fertilisers and pesticides are considered. Farm manure as an organic fertiliser is only accounted for in terms of direct field emissions; all pre-processes are included in the animal production systems. The dataset includes all machine operations and corresponding machine infrastructure and sheds. Machine operations are: soil cultivation, sowing, fertilisation, weed control, pest and pathogen control, combine-harvest, transport from field to regional processing centre (10 km) and drying of grains. Further, direct field emissions are included. This activity ends after drying of grains at the regional processing centre.

End-of-life (1): "incineration"

End-of-life (2): "Biowaste {CH}| treatment of biowaste by anaerobic digestion | Cut-off, S"

Biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, comparable waste from food processing plants, it also includes forestry or agricultural residues and manure. It does not include sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood. The anaerobic digestion treatment is a collection of processes by which microorganisms break down biodegradable material in the absence of oxygen. The treatment process produces biogas (a mixture of mainly methane and carbon doxide) and residual products called solid and liquid digestate.

Glass wool

Production: "Glass wool mat {CH}| production | Cut-off, S"

This module can be used for all different kind of glass wool mats. The density of the glass wool mat used as basis for the study is 40 kg/m3. The original dataset from ecoinvent v2 has been amended with CO_2 and NO_x emissions. Included processes: melting, fibre forming & collecting, hardening & curing and internal processes (workshop, etc.). Additionally, energy carrier for furnace, packing and infrastructure are included. The activity ends with the product being ready to be shipped.

End-of-life: "Waste mineral wool {Europe without Switzerland}| treatment of waste mineral wool, sorting plant | Cut-off, S"

Stone wool

Production: "Stone wool {CH}| stone wool production | Cut-off, S"

This product is not available on the market as it is not packed. It has been defined for internal use in this database as input for the packaging module. Inputs and outputs are not balanced in the unit process since some are included in the unit proces 'rock woll, packed, at plant'. This dataset is not to be used to describe rock wool in other inventories. Included processes: melting, fiber forming & collecting, hardening & curing furnace, and internal processes (workshop, etc.). Transport of raw materials and energy carrier for furnace are also included. Not included are administration, packing and infrastructure.

End-of-life: "Waste mineral wool {Europe without Switzerland}| treatment of waste mineral wool, sorting plant | Cut-off, S"

EPS

Production: "Polystyrene foam slab {CH}| production, 45% recycled | Cut-off, S"

Combination of material and processing module. EPS foam slab has a density of 28 kg/m3 and a thermal conductivity of 0.036 W/mK. Includes grinding and thermo-forming processes

End-of-life: "Waste polystyrene {Europe without Switzerland}| treatment of waste polystyrene, sanitary landfill | Cut-off, S"

Inventoried waste contains 100% PS. Waste composition (wet, in ppm): upper heating value 38.88 MJ/kg; lower heating value 38.67 MJ/kg. Share of carbon in waste that is biogenic 0%.

XPS

Production: "Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Cut-off, S"

This dataset can be used in the construction building sector. The cutting of the extruded polystyrene blocks is not included in the process. Blowing agent is CO_2 (50.7% w/w). Co-blowing agent is acetone (49.3% w/w). Process emissions are 25% (w/w) for acetone. The dataset describes the production of extruded polystyrene. Included processes are the melting of polystyrene pearls in the extruder, the discharge through a slot die, as well as the cooling with water.

End-of-life: "Waste polystyrene {Europe without Switzerland}| treatment of waste polystyrene, sanitary landfill | Cut-off, S"

B

Fire Safety Interview – Ruud van Herpen

Date:	June 22, 2023
Length:	37m 1s
Interviewer:	Jonas van der Ham

6:46

Ham, Jonas van der: Oké, Ik wil eerst even een verificatie doen van een stukje wat ik al heb geschreven nu ik je toch aan de lijn heb. Dus ik kijk inderdaad naar het toepassen van bio-based isolatie in hoogbouw. Klopt mijn aanname dat vanaf de façade hoogte boven 13 m de fire safety class B vereist wordt op het element niveau.

7:05

Herpen, Ruud van: Ja hoor, ja dat klopt dus voor dat deel van de gevel hoger dan 13 m, maar ook het deel van de gevel van nul tot 2,5 meter.

7:09

Ham, Jonas van der: Ja ja, en dus voor laagbouw is dat deel van 0 tot 2,5 relevant.

7:24

Herpen, Ruud van: Ja precies ja.

7:27

Ham, Jonas van der: OK.

7:27

Herpen, Ruud van: Dus het onderste deel is vooral relevant om te voorkomen dat een brand buiten makkelijk de gevel zou kunnen aansteken en het bovenste deel is met name relevant voor branduitbreiding vanuit gevel openingen. [In dat bovenste deel] is van buitenaf natuurlijk niet zo heel veel risico meer. Dat gaat het vooral om de interne risico's.

7:34

Ham, Jonas van der: Ja precies. En klopt het dat het in Nederland op productniveau, dus als ik bijvoorbeeld alleen naar isolatie kijk, geen eisen worden gesteld, maar enkel op element niveau.

7:57

Herpen, Ruud van: Ja, de eisen in het bouwbesluit zijn product onafhankelijk. Daarom noemen we ze ook prestatie eisen. Ze hebben betrekking op constructiedelen als geheel, hè. Dus een samengestelde constructie.

7:59

Ham, Jonas van der: Ja precies.

8:13

Herpen, Ruud van: Dus dat is inderdaad heel verwarrend, hoor, want veel mensen denken nou, dit materiaal is toch brandklasse A of brandklasse B, maar dat kan niet. Het gaat om de totale constructie die getest wordt om een bepaalde brandklasse te realiseren. Dus daar speelt niet alleen de oppervlakte een rol, maar ook de achterliggende constructie. Vandaar dat je ziet dat constructies met spouwen erin vaak veel ongunstiger presteren (...) dan constructies waar de spouw niet in voorkomt.

8:19

Ham, Jonas van der: Ja precies.

8:45

Herpen, Ruud van: Dus dat is echt een constructie kenmerk en zo hebben we onze regelgeving ook opgesteld. Ja.

8:51

Ham, Jonas van der: En nou geld er voor een vloer boven verblijfsgebied op hoogte van 13 m, dus de brandklasse B voor de façade. Dan is er de eis weerstand tegen branddoorslag en brandoverslag tussen brandcompartimenten, dat is 60 minuten.

9:07

Herpen, Ruud van: Ja. In de nieuwbouw? Ja.

9:09

Ham, Jonas van der: En dan hebben we ook nog de tijdsduur van de brandwerendheid met betrekking tot bezwijken 120 minuten. Ik vroeg me af of dat ook geldt voor een façade en ook voor een bijvoorbeeld een niet dragende façade.

9:22

Herpen, Ruud van: Nee, aan een gevel zijn geen eisen met betrekking tot brandwerendheid te stellen, want die eisen die worden alleen gesteld als invulling van wat we dan noemen de WBDBO: Weerstand tegen branddoorslag en brandoverslag, en die eis geldt alleen tussen ruimten, hè? Dus tussen brandcompartimenten of tussen brandcompartimenten en vluchtroute. Maar die eis geldt niet tussen brandcompartiment en buitenlucht. Buitenlucht is geen ruimte, hè, dus gevels kunnen in principe zonder brandwerendheid toegepast worden. Meestal in Nederland zijn gevels niet dragend dus is er ook geen eis om een dragende functie brandwerend te maken. Dus dat wil zeggen, en dat zie je ook, de eisen aan brandklasse die we hebben aangegeven zijn puur bedoeld om branduitbreiding en het aansteken van de gevel te vermoeilijken maar uiteindelijk kan die gevel wel gewoon branden. Ja, en kan die brand ook gewoon naar binnen gaan, dat is allemaal toegestaan.

10:17

Ham, Jonas van der: Ja. En als er dan 60 minuten voor brand doorslag wordt geëist, en ik heb twee woningen naast elkaar, wordt het dan 60 plus 60 minuten dus 120? Omdat het een soort van twee aanliggende muurtjes zijn of is het gewoon 60 minuten voor de overslag.

10:31

Herpen, Ruud van: Nee, nee, het blijft 60 minuten. Alleen van de ene woning naar de andere woning is het dan 60 minuten in de ene richting en vice versa is er dan dus ook 60 minuten in de andere richting, hè? Dus die 60 minuten geldt twee richtingen op als het tussen brandcompartimenten is. Als het tussen een brandcompartiment is en een vluchtroute die buiten een brandcompartiment ligt, dan noemen we dat een extra beschermde vluchtroute. Daarin veronderstellen we dat geen brand ontstaat, dan geldt die eis maar in één richting namelijk alleen van brandcompartiment naar de vluchtroute.

10:42

Ham, Jonas van der: Ja ja.

11:02

Herpen, Ruud van: En dan denk je, ja wat een geneuzel, maar dat kan wel eens verschil maken hè? Dus dat kan wel eens handig zijn om dat te weten.

11:07

Ham, Jonas van der: Ja, duidelijk dankjewel. En die klasse B, die wordt dus geëist boven 13 m. Jij zegt dus dat als er toegevoegde extra maatregelen zijn, zoals een sprinklerinstallatie, de k factor die voldoende is, en vluchtroutes met overdruk, dan is het ook mogelijk toereikend voor hoogbouw boven de 70 m.

11:34

Herpen, Ruud van: Die eisen aan de gevel, bedoel je?

11:36

Ham, Jonas van der: Ja.

11:37

Herpen, Ruud van: Die brandklasse B ja.

11:38

Ham, Jonas van der: Ja.

11:41

Herpen, Ruud van: Nou ja, kijk de brandklasse B geld voor de gevelconstructie, gezien vanaf de buiten oppervlakte en de sprinkler zit aan de binnenkant, hè? Dus daar kun je nog wel over twisten of die sprinkler daar enige waarde heeft voor de brandklasse eisen van de gevel. Want de sprinkler beheerst alleen een brand binnen en niet een brand die van buiten naar binnen gaat. Die kan een sprinkler niet beheersen, dus ik denk eigenlijk dat daarvoor dezelfde brandklassen eis zou moeten gelden als in de ongespoten situatie. Dus als we nu zeggen, voor hoge gebouwen gaan we straks in BBL zeggen dat moet brandklassen A zijn. Hè, dus we gaan worden strenger. Dat komt een beetje door het Grenfall [tower] incident. Dan zou dat dus voor de gesprinklerde situatie ook zo gelden. Het enige wat je nog zou kunnen zeggen is dat bij een succesvolle sprinkler beveiliging we geen uitstaande vlammen krijgen uit gevelopeningen en dan hebben we wel een belangrijk deel van de kans dat een gevel wordt aangestoken weggenomen. En dan zou je kunnen zeggen, oké, dan zouden we zelfs bij hoge gebouwen misschien toch met dezelfde brandklasse als bij lage gebouwen kunnen volstaan, omdat we het risico toch gereduceerd hebben door die sprinkler, omdat we de uitslaande vlammen kwijt zijn, dan blijft eigenlijk alleen nog het risico van buitenaf over hè? Van een buitenbrand.

13:00

Ham, Jonas van der: Ja, en die is dan weer op die hoogte, waarschijnlijk niet zo aannemelijk.

13:03

Herpen, Ruud van: Nee op die hoogte, niet zo aannemelijk nee. Je zou ook nog kunnen zeggen, nou doe dan ook bij gesprinklerde gebouwen de onderste 2,5 m wel en als het een schoolgebouw is misschien een wat strengere brandklasse, maar daarboven ja is die noodzaak veel minder aanwezig omdat de kans bijna nihil geworden is dat daar nog iets aangestoken kan worden van die gevel.

13:23

Ham, Jonas van der: Ja. De k factor, die verwijst naar de Fire Protection Ability.

13:31

Herpen, Ruud van: Ja ja.

13:31

Ham, Jonas van der: Ik heb op Wikipedia verwarrende dingen gelezen, nou geloof ik helemaal niet per se wat er op Wikipedia staat, maar ik wilde toch even verhelderen. Daar hadden ze namelijk over de volumetric flow rate van de sprinkler. Is dat de ook een k factor?

13:43

Herpen, Ruud van: Nee, dat is een andere k factor, dat is ook een k factor. Dat is een kleine k en dat is eigenlijk de hoeveelheid water, de volumestroom water die bij de druk over de sprinkler kop naar buiten geperst kan worden. Voor standaard sprinklers hanteren we ja, dat noemen we dan K 80 of zo, daar zijn standaard waardes voor. Maar dat heeft niks met de gevel te maken. Bij de gevel kennen we ook een k factor. Volgens mij is dat een hoofdletter K en dat noemen we Protection Ability Index volgens EN 13501-1 reaction to fire. En wat die k factor eigenlijk doet is [vragen] van ja, wat is eigenlijk het vermogen hè? Van de buitenste laag van de gevel om de rest van de gevel te beschermen tegen hoge temperaturen of tegen brand van buitenaf. En dat heeft eigenlijk te maken met ja, laat maar zeggen de warmtecapaciteit van die materialenlaag, dus de soortelijke massa en de soortelijke warmte van die materiaal laag. Je kunt je voorstellen als ik veel massa heb, dus veel gewicht heb, dat ik veel meer warmte kan opslaan in dat laagje voordat het wordt doorgegeven naar de achterconstructie, dan wanneer ik heel weinig massa heb, waarbij het laagje meteen opgewarmd is. Dus die heeft een hele lage k factor. We sturen dat in Nederland niet aan, in de meeste West Europese landen niet. De k factor is wel populair In de Oost-Europese landen. En ik vind dat een hele verstandige factor eigenlijk omdat die veel meer wat zegt over het vermogen van de gevel om weerstand te bieden tegen de bedreiging door brand dan de brandklasse.

15:19

Ham, Jonas van der: Ja.

15:21

Herpen, Ruud van: Wat ik ook jammer vind is dat nu voor hoge gebouwen wordt gedacht van ja, die brandklasse B hè? Dat is de discussie die geweest is. Die is eigenlijk vrij kleinschalig getest. Die is eigenlijk bedoeld voor binnenbranden. We passen hem ook toe op de gevel. We hanteren daar dezelfde classificatie voor, maar eigenlijk is de testmethode niet zo geschikt voor die gevel, dus laten we voor de zekerheid een stapje strenger maken, ook weer ingegeven door Grenfall [tower] natuurlijk. Laten we hem klasse A maken, ja.

15:47

Ham, Jonas van der: Ja.

15:49

Herpen, Ruud van: Daarmee wordt het zeker beter, dus dat bestrijd ik niet. Maar ik denk dat het misschien veel slimmer was geweest om hem gewoon een brandklasse B te houden en daarnaast een eis te stellen aan de fire Protection Ability Index hè? Dus de k- factor.

16:00

Ham, Jonas van der: Ja. Ja.

16:02

Herpen, Ruud van: Niet te verwarren met de k-factor van de sprinklerinstallatie.

16:04

Ham, Jonas van der: Nee precies ja, nou ja, dat wilde ik inderdaad even ophelderen. En je zegt dat hij naar brandklasse A gaat, die geveleis voor hoogbouw. Is dat al vastgelegd, of is dat nog in gesprek?

16:16

Herpen, Ruud van: Ja, oh, dat weet ik eigenlijk niet helemaal zeker. Ik krijg gelukkig af en toe wel mee wat onze wetgever allemaal doet, maar eigenlijk interesseren de regels mij iets minder dan de doelgerichte brandveiligheid. Dus ik weet niet zeker of er ja.. Echte zekerheid kan ik je niet geven. Of dat al geaccepteerd is en dadelijk in BBL zo vast ligt. Bij mijn weten eigenlijk wel, maar ja, durf ik niet helemaal te zeggen.

16:23

Ham, Jonas van der: Ja nou, dat is goed even checken. Volgens mij heb ik al eerder genoemd, dat als een paneel opgebouw is uit verschillende onderdelen met klasse B dat het element zelf niet per definitie klasse B haalt, hè?

17:03

Herpen, Ruud van: Nee over het algemeen slechter is dan klasse B hè? Want de klasse B is zeg maar een soort van snelheid waarmee de brand uitbreidt. Als je stelt dat je dat per materiaal laag weet in elke materiaal laag. Als ik parallellen uitbreidingstrajecten heb, zal dat de snelheid alleen maar vergroten en nooit vertragen, hè dus klasse B plus klasse B plus klasse B geeft uiteindelijk een lagere brandklasse.

17:24

Ham, Jonas van der: Ja. En dus het feit dat het element niveau los staat van de productklasse, zeg maar, dat betekent ook dat een product met bijvoorbeeld klasse E wel op element niveau klasse B kan halen.

17:32

Herpen, Ruud van: Ja ja, zeker zeker. Dat zie je natuurlijk bij sandwichpanelen, hè? Dus dat zijn kunststof schuimen die eigenlijk een hele slechte brandklasse hebben. Maar doordat ze in een sandwich constructie zitten als element best goed kunnen presteren.

17:51

Ham, Jonas van der: Ja ja, dat is bijvoorbeeld bij EPS en XPS hè? Isolatie dan, die scoren allebei D of E. Meestal E waarschijnlijk. Zitten er binnen die klassen, dus bijvoorbeeld een klasse E, zit daar nog veel ruimte tussen verschillende materialen die allebei klasse E scoren. Of zijn die wel echt vergelijkbaar?

17:55

Herpen, Ruud van: Nee, het is een soort classificering hè, dus daar zit zeker ruimte tussen. En klasse E is al een hele slechte klasse eigenlijk. Ja, als ze niet getest zijn is volgens mij klasse F, dat is de het laagste niveau. Natuurlijk [heeft klasse F] daarmee uiteraard de grootste bandbreedte, dus daar kunnen zelfs licht ontvlambare materialen in zitten, zal ik maar zeggen. Dat kan in klasse E nog niet hè? Dus daar zitten natuurlijk wel grenzen aan, maar ja, als je kijkt bijvoorbeeld naar naaldhout, dat zal vaak klasse D halen, zeg maar als geheel. Maar soms ook klasse E en dan zie je dat er een heel groot verschil is tussen naaldhout of EPS, dat kun je wel voorstellen hè, dus die bandbreedte is behoorlijk groot.

18:53

Ham, Jonas van der: Ja. Dus In het voordeel van naaldhout, zeg maar...

19:01

Herpen, Ruud van: Ja naaldhout presteert wel beter, maar zou dan toch net door die classificeringsgrenzen, valt die soms in klasse D, soms in klasse E, dus die valt dan waarschijnlijk net in klasse E. Dus aan de gunstige kant hè? Terwijl EPS bijvoorbeeld aan een veel ongunstigere kant zit. En nou ja, als je je dat voorstelt, dan kan iedereen zich ongeveer wel voorstellen dat het brandgedrag heel verschillend is van EPS en naaldhout.

19:03

Ham, Jonas van der: Ja. Ja precies ja. En toch worden die EPS en XPS in sandwichpanelen in de hoogbouw toegepast.

19:33

Herpen, Ruud van: Ja, ja, maar in sandwichpanelen kan het heel lang goed gaan en zeker als die panelen goed gevuld zijn. Goed luchtdicht zijn, zeg maar. En dan kun je je voorstellen dat dat EPS eigenlijk de kans niet krijgt om vloeibaar te worden en te vergassen, want dan moet het uitzetten en dat wordt tegengehouden door die staalplaten aan weerszijden. Waardoor het gedrag ook veel beter is dan gewoon naakte EPS, hè. En ja, daarnaast al zou het gaan vergassen. Ja, gaat het element misschien een beetje vervormen, maar als het er binnen blijft, als het maar niet uitkomt, doet het niet mee aan de brand en dus ook niet aan de branduitbreiding. Dus dat is geen voordeel van EPS op zich maar dat is een voordeel van de constructie.

20:08

Ham, Jonas van der: Ja, van het sandwich paneel.

20:17

Herpen, Ruud van: Ja hoe die leveranciers die sandwichpanelen gemaakt hebben, ja.

20:19

Ham, Jonas van der: Ja. In de data die ik in de literatuur vind, gaat het over PUR echt brandklasse E tot F. Echt slechtste klasse die er zijn, is dat ook jouw ervaring?

20:29

Herpen, Ruud van: Ja. Ja, kijk PUR en PIR (en PIR heeft een betere brandgedrag dan PUR) dat noemen we dan thermoharders, dus dat zijn kunststof schuimen die vergassen bij verhitting. EPS is een thermoplast, hè, dus dat is een kunststof schuim die vloeibaar wordt bij verhitting en daarna pas vergast, dus die kent extra faseovergang. En de temperatuur grens bij EPS is ook veel lager dan bij PUR. Dus ik vind eerlijk gezegd even los van de brandklasse, EPS veel vervelender brandgedrag hebben we dan PUR. Omdat het eerder vloeibaar wordt, of verweekt, zal ik dan maar zeggen, al bij 150 graden. En nou ja, laat maar zeggen bij 180 graden of zo aangestoken wordt.

21:21

Ham, Jonas van der: Ja.

21:22

Herpen, Ruud van: Maar het verplaatst zich dus ook, het materiaal blijft niet op één plek en dat maakt het super onvoorspelbaar. Wat dat betreft is PUR en PIR veel fijner. Want dat materiaal blijft op zijn plek zolang het in vaste toestand is en als het vergast, ja, dan doet het of mee aan de brand of die gassen stromen naar buiten weg. Dus even los van de brandklassen, je ziet dus ook dat er veel meer aspecten dan alleen de brandklassen een rol spelen. Dat is wat ik net ook al zei over die k factor, hè? Dat is eigenlijk ook best een slimme factor. [Het is zo dat de] focus veel te erg op die brandklassen ligt en dat die brandklassen eigenlijk geen recht doen aan het echte brandgedrag van materialen in de gevel.

21:48

Ham, Jonas van der: Ja Ja, en toch is het wat er vereist wordt.

22:03

Herpen, Ruud van: Ja, ja, regelgeving denkt simpel hè.

22:07

Ham, Jonas van der: Dat is politiek natuurlijk, hè?

22:11

Herpen, Ruud van: Ja ja, ook dat ja ja.

22:07

Ham, Jonas van der: En, wordt PIR en PUR naar jouw weten in hoogbouw als isolatie toegepast in de gevel.

22:20

Herpen, Ruud van: Nee PUR kan ik me niet voorstellen. PIR misschien wel weer daarvan hebben leveranciers ook langere tijd beweerd dat dat klasse A2 zou kunnen halen eigenlijk dus moeilijk brandbaar, zal ik maar zeggen. Bijna vergelijkbaar met steenwol. Maar dat is natuurlijk niet het geval. Dat is alleen het geval bij lage temperaturen en bij een lokale vlam, Maar als een heel compartiment in brand staat, dan is die thermische belasting zo hoog en zo lang dat alle brandbare materiaal heus wel gaat meedoen, ongeacht de brandklassen. En dan zie je echt het voordeel tussen brandbare materialen en echt onbrandbare materialen.

22:53

Ham, Jonas van der: Ja. Ja precies.

22:58

Herpen, Ruud van: En de PIR industrie zegt dan weer ja, maar steenwol is ook niet echt onbrandbaar, want er zit bindmiddel in om die vezels op één plek te houden en dat is brandbaar. Dat klopt, dat is ongeveer ja, ik weet niet precies, één of twee massa procenten, hè. Dus daar hebben ze gelijk in. Dat is niet helemaal onbrandbaar en op het moment dat het bindmiddel verbrandt, hè, dan ben je je stabiliteit van je steenwol kwijt, dan valt het uit elkaar, dus natuurlijk, daar zit ook wel wat in. Maar toch, in essentie brandt het niet en is de hoeveelheid brandbaar product erin echt veel minder dan wanneer ik een kunststof schuim heb. Wat dat ook is of het nou EPS is of PIR of PUR.

23:35

Ham, Jonas van der: Ja duidelijk. Nou om dus de brandklasse op element niveau te verbeteren kan je materiaal toepassen. Wat zijn de typische materialen die toegepast worden om dit te verbeteren?

23:53

Herpen, Ruud van: Nou ja, we hebben net al even de sandwichpanelen genoemd, hè, dus dat is staal.. Maar dat is een onbrandbaar materiaal. Dat is natuurlijk altijd gunstig. En ja, dat soort dingen wordt ook wel geprobeerd met bijvoorbeeld aan de gevel in ieder geval cementgebonden vezelplaten. Dat is nou ja, gips ook, maar gips is echt een binnen toepassing, dus dat lukt buiten niet. Dus in plaats van gips gebruiken we als buitentoepassing dan cement. Wat ook goed werkt is als je, en dat is voor bio-based materialen interessant, je materiaal isolatiemateriaal zodanig mengt met een onbrandbaar materiaal dat er weliswaar brandbaar materiaal in zit, maar dat je het gewoon niet aangestoken krijgt.

24:24

Ham, Jonas van der: Ja. Ja precies. Van die boor zouten of zo?

24:48

Herpen, Ruud van: Nou, ja, Ik heb dat een keer gezien bij kalk hennep gevels, hè, dus Dat is eigenlijk een een soort in-situ, denk ik tenminste, in-situ laag aan de buitenzijde die ja gewoon een mortel van kalk met hennep is, die redelijk goed isoleert en niet aangestoken kan worden, onmogelijk.

24:52

Ham, Jonas van der: Ja precies ja.

25:11

Herpen, Ruud van: Hè, dus dat kan ook... En wat jij zegt, hè, dan gaat het echt om brandwerende producten. Dus dat kunnen silicaat platen zijn of er zitten inderdaad van die zouten in, die dan in feite heel erg brandvertragend reageren en daarmee het gedrag van de brandbare component afremmen.

25:17

Ham, Jonas van der: Ja precies. Precies, zodat het eigenlijk niet bij het isolatiemateriaal kan komen of langdurig tijd niet.

25:33

Herpen, Ruud van: Ja precies, ja.

25:38

Ham, Jonas van der: Er is dus een onderscheid tussen extra materiaal toevoegen aan de buitenzijde van de gevel en aan de binnenzijde. Maar is dat aan allebei de kanten vereist als je tot die 60 minuten wil komen? Of kan aan een van de twee kanten genoeg zijn, zodat je niet de doorslag door de gevel.

25:55

Herpen, Ruud van: Ja, kijk aan de gevel hebben we geen eisen, zeiden we net, hè. Dus ik moet eigenlijk alleen aan de brandklasse voldoen hè. Dus ik heb eigenlijk geen brandwerendheid eis voor dat laagje aan de buitenzijde en de binnenzijde, maar op het moment dat je dat niet hebt en je brandbare laag in de gevel loopt door over de verdiepingsvloer naar het compartiment erboven, dan heb ik eigenlijk opeens wel een eis gekregen, want ik wil niet dat die aangestoken wordt, want dan sluit ik mijn brandcompartimentering kort via mijn gevel. En dat speelt vooral bij een brand binnen. Dus dan zou je eigenlijk willen dat een volledig ontwikkelde brand binnen niet het brandbare materiaal in de gevel kan aansteken. Of je staat dat wel toe, maar dan moet ik bij elke verdiepingsvloer, en ook bij elke brandwand verticaal, een soort firestop maken. Dus de laag gaan onderbreken met een onbrandbare laag om dan te zorgen dat die brand niet doorloopt naar het volgende compartiment.

26:51

Ham, Jonas van der: Ja, en dat gaat toch weer veel eisen van de constructie vooraf.

26:55

Herpen, Ruud van: Ja, precies. Ik vind dat zelf wel het meest zuivere, want dan heb je de brandscheidingen precies zitten op de plek waar je ze [nodig] hebt. Je kunt je voorstellen dat als je de hele binnenkant van de gevel brandwerend maakt, dat je altijd problemen krijgt bij daglicht openingen. Hoe weet ik nou zeker dat dat goed gaat? Wat gebeurt er als het glas eruit knapt, heb ik dat nog steeds voldoende zekerheid dat mijn brandbare laag niet aangestoken wordt? Met andere woorden, de faalkans daarvan is denk ik groter dan wanneer je een firestop zou toepassen, maar een firestop is lastig detailleren, en ga je misschien aan de buitenzijde ook zien. Dat wil een architect natuurlijk weer niet. Dus ja, daar zijn voors en tegens maar allebei kan in theorie hè? Allebei is mogelijk.

27:28

Ham, Jonas van der: Ja. Dan denk ik dat het voor mij om een soort aanname te maken eigenlijk het makkelijkste is om te focussen op plaatmateriaal aan de binnenkant.

27:47

Herpen, Ruud van: Ja ja, want als we een brandwerendheid eisen, dan zal die vooral aan de binnenkant zijn. Bij een buitenbrand kun je je voorstellen, als een auto bij de gevel staat te branden of een vuilcontainer, dat dat ook wel een serieuze thermische belasting is en dat die brandklasse daar ook niet genoeg over zegt. Daar ben ik het mee eens, maar als die hele gevel in brand gaat, ja, dan wil ik eigenlijk toch in ieder geval [brandcompartimentering]. En mocht dat [bij het aanbrengen van brandwerend materiaal aan de binnenkant] gebeuren, dan zou je in ieder geval willen dat de woningen of in ieder geval de compartimenten zo lang mogelijk beschermd zijn tegen die brand. Dus enerzijds vanwege het aansteken zou die brandwerende binnenplaat gunstig kunnen zijn, maar ook vanwege een eenmaal brandende gevel om de weerstand naar binnen zo groot mogelijk te houden, dus vluchttijd zo lang mogelijk te houden, is dat ook wenselijk, hè? Zowel aan de bron zijde als aan de respons zijde, zou je kunnen zeggen.

28:47

Ham, Jonas van der: Ja. Maar ik kan me voorstellen dat het dan sowieso voor de onderste bijvoorbeeld 2,5 meter of waar van buitenaf risico's zijn dan beide kanten brandveiligheid te garanderen, dat dat boven minder belangrijk is.

28:54

Herpen, Ruud van: Ja, jazeker echt de onderste plint hè? De onderste verdieping van een gebouw is altijd belangrijker aan de buitenzijde, want daar gebeurt nog wel eens het een en ander.

29:01

Ham, Jonas van der: Ja en dus voor het vanuit de binnenkant brandveilig maken, kan ik een met een vuistregel komen die ik als aanname kan gebruiken in mijn onderzoek? Waar ik zeg "Ik heb isolatiemateriaal van klasse E, maar ik wil het vergelijken met steenwol, dus ik vroeg zoveel centimeter extra stuc toe of ik voeg zoveel plaatmateriaal toe"

29:28

Herpen, Ruud van: Ja, en kijk, de klasse maakt niet eens uit het onderscheid zit hem in, is het brandbaar of niet brandbaar? Kan het aangestoken worden of niet, hè? De klasse geeft nog een klein beetje tijdvertraging, zou je kunnen zeggen, een betere brandklasse betekent dat het iets meer energie nodig heeft om het aan te steken. Maar als ik eenmaal een volledig ontwikkelde compartimentsbrand heb, zit daar zoveel energie in dat die tijdsvertraging eigenlijk verwaarloosbaar is. Dus het gaat vooral om brandbaar of niet brandbaar en als ik dan brandbaar isolatiemateriaal heb in de gevel en dat wil ik beschermen. Ik wil niet dat die laag doorloopt naar een ander compartiment, ik noem maar even wat, hè? Dan denk ik van ja, hoeveel zou ik die willen beschermen? Nou eigenlijk net zo goed als de brandscheiding zelf, hè? Dus 60 minuten. En dan ja, dan moet je denken aan nou.., dan kun je wel diverse handboeken vinden. Kijk een zeg maar een 10 mm gipsplaat presteert ongeveer 20 minuten brandwerendheid hè, dus die zou hier al aan 30 mm moeten denken. Nou ik denk dat het iets minder kan, dan nemen we een gewapende gipsplaat hè, dus met glasvezeltjes erin, dan blijft het gips langer op zijn plek. Misschien dat je met een dubbele gipsplaat 2 keer 12 mm die 60 minuten ongeveer kunt halen. Aan dat soort diktes moet je ongeveer denken. En als het steenwol is, heb ik in principe voor de voor de branduitbreiding niks nodig, hè? Dus ja, ik moet natuurlijk ook een binnenafwerking hebben, want ik kan niet tegen de steenwol aankijken. Dan heb ik allerlei bouwfysische problemen, allerlei condens problemen dus die zou je dan met een enkele plaat afwerken, als je dat met gips zou doen. Dus ja, het kost je een extra gipsplaat.

30:49

Ham, Jonas van der: Oké. Nee precies ja ja.

31:10

Herpen, Ruud van: Valt op zich nog mee, dus dat.

31:11

Ham, Jonas van der: Ja precies dat vind ik inderdaad nog te overzien en dan dus binnen de.. Als ik naar Bio-based isolatie kijk. Die zijn dus allemaal brandbaar. Ga ik even vanuit.

31:13

Herpen, Ruud van: Ja.

31:22

Ham, Jonas van der: Dan maakt het dus binnen die categorieën niet uit of ze nou klasse D of E hebben, Dat is allemaal hetzelfde.

31:24

Herpen, Ruud van: Nee eigenlijk niet, nee. Dat klopt ja. Nee dus, daarvoor hoef je niet een goede brandklassen te halen hè? Dus puur als je het materiaal onafgewerkt zou willen gebruiken, ja, dan krijg ik opeens een brandklasse eis omdat het niet te makkelijk aangestoken mag worden.

31:37

Ham, Jonas van der: Ja, Ja precies. Maar dat willen we sowieso niet. We willen wel iets mooiere muur hebben.

31:47

Herpen, Ruud van: Nee ja. Oké.

31:50

Ham, Jonas van der: Ik heb ergens een publicatie gelezen waar ze ook zeggen, dus iets Amerikaans, waarin één inch stuclaag ook een uur aan brandveiligheid op het oppervlak ongeveer kan garanderen.

32:02

Herpen, Ruud van: Ja.

32:05

Ham, Jonas van der: Klinkt dat realistisch?

32:05

Herpen, Ruud van: Ja, dat kan, ja, dat is zeker realistisch, dat kan wel en we hebben dat. Je kunt je voorstellen dat bij renovatie van woongebouwen met houten vloeren, hè? Die veel voorkwamen, zeg maar in de jaren 40-50. Voordat we naar het betonnen vloeren toe gingen dat we dan brandwerende plafonds moesten maken, of dat we zeiden, oké, er zit een plafond. Het is gips op riet, dus stuc op riet. Dat zijn de oude stucplafonds van vroeger. Hoe moeten we die nou waarderen? Waarderen we ook ongeveer op die manier. Als je ongeveer 20 mm, ja vaak is bij ons, in de renovatie 30 minuten voldoende als brandwerendheid tussen woningen, hè, dus dan zitten we op 15 milimeter ofzo, dus dit klinkt realistisch hè, dat je dan voor een uur een inch.

32:49

Herpen, Ruud van: Dat is een inch bijna 30 mm, toch of zo?

32:51

Ham, Jonas van der: Ja. Zo, ja, ik denk zoiets, zal ik het snel opzoeken.

32:55

Herpen, Ruud van: Ja ja ja, Ik weet het ook niet.

32:58

Ham, Jonas van der: Ja, 2,5 cm.

33:00

Herpen, Ruud van: Ja twee ja nou ja, dat kan dat kan. Nee, dat klinkt realistisch zeker ja.

33:10

Ham, Jonas van der: OK. Dus nog een keer in renovatieproject was 30 minuten geëist, dus dan was 15 mm genoeg.

33:11

Herpen, Ruud van: Ja ja, in Nederland vaak wel. In Nederland hebben we dan de verbouw eisen en dan eisen we 30 minuten. En in nieuwbouw eisen we altijd 60 minuten.

33:19

Ham, Jonas van der: En dat 30 minuten is het 15 mm.

33:21

Herpen, Ruud van: Ja zoiets

33:22

Ham, Jonas van der: Nieuwbouw dan 30.

33:30

Herpen, Ruud van: Ja in die orde dus die 25 kan ook goed hoor, maar ergens tussen 25-30 en dan kan ik het in mijn stuclaag halen. Waar ik altijd zelf een beetje bang voor ben is, ja blijft de stuc wel zitten of gaat het eraf vallen? Ja, dat maar goed ja.

33:38

Ham, Jonas van der: Ja ik ga ook zeker geen garanties doen, hoor binnen mijn onderzoek, maar dan heb ik wel een materiaal hoeveelheden waar ik mee kan werken. Dat is fijn.

33:45

Herpen, Ruud van: Ja ja ja.

33:47

Ham, Jonas van der: Nou ja, Dat was het van mijn kant eigenlijk.

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