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DEPARTMENT OF BUILT ENVIRONMENT

Master's thesis

ENVIRONMENTAL IMPLICATIONS OF USING BIO-BASED MATERIALS IN NEW CONSTRUCTION IN AALBORG, DENMARK

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Abstract

This report aimed to identify the environmental implications of mineral-based construction, timber-based construction, and bio-based construction in four case buildings: single-family house, terraced house, multi-story building, and office buidling. In order to get the results, multiple methods were used such as interviews, LCA calculation with the use of LCAbyg, and carbon storage calculations. The research showed that mineral-based construction has the highest Global Warming Potential, meanwhile, bio-based construction consisting of timber structure and meadow grass insulation has consequently the lowest impact. The results indicated that in order to build only with the bio-based construction, Aalborg would require 85 411 m^3 of timber per year, which is equivalent to a yearly harvest of 3.95 km^2 of the forest or 197.5 km^2 during 50 years for the sustainable cycle. Moreover, the results showed that building with bio-based construction could store 56 513 tonnes of CO_2 equivalents from yearly construction. It was concluded that bio-based materials are a promising solution for lowering the environmental impact and sequestering carbon, however, they require changes to more sustainable sourcing methods.

Keywords: carbon sequestration, carbon emissions, bio-based materials, timber, wooden construction

Contents

Chapter 1

Introduction

1.1 Background

The construction industry is one of the major contributors to carbon emissions and the production of large amounts of greenhouse gases, which aggravates the average global temperature [Labaran et al., 2022]. As reported by the United Nations Environment Program, 37 percent of the world's carbon emissions come from the building industry [United Nations, 2023]. It is critical to address these problems linked to building practices as cities continue to expand and more buildings are being built. One of the main reasons for these significant contributions to carbon emissions is due to the industry's conventional way of constructing with the reliant use of mineral-based materials such as concrete and steel [Mathur et al., 2021]. Wherein, the manufacturing of these building products accounts for 14 percent of CO_2 emissions globally [United Nations, 2023]. Therefore, it is essential to use alternative materials that might help mitigate the environmental impacts of the industry. An alternative solution is to use bio-based materials in new constructions. These materials come from renewable sources such as plants, agricultural byproducts, or agricultural waste and they are not as notoriously carbon-intensive to produce compared to concrete or steel [Yadav and Agarwal, 2021].

To quantify the environmental impacts of bio-based materials and to differentiate it from mineral-based materials a Life Cycle Assessment was carried out. A Life Cycle Assessment (LCA) is the process of assessing the environmental effects of a product across its whole life cycle [Muralikrishna and Manickam, 2017].

EN 15978 outlines a systematic approach for evaluating the environmental performance of buildings, taking into account all stages of a building's life cycle. The assessment considers the raw material extraction, manufacturing, and transportation of construction products which is part of the product stage (A1-A3), the construction phase (A4-A5), the building maintenance and operation (B1-B7), and its end-of-life processes (C1-C4), such as demolition and waste management [Dansk Standard, 2012]. This provides a comprehensive analysis of sustainability factors such as energy consumption, carbon emissions, and resource depletion.

Additionally, only recently a life cycle assessment is a part of the new climate requirements for Denmark's building regulation BR18, as a means to reduce CO_2 emissions from new constructions [Building Regulations, 2023]. Wherein, there is now a limit on carbon emission corresponding to 12 kg CO_2-equivalent per m^2 of new constructions over 1 000 m^2 [Videncenter om Bygningers Klimapåvirkninger, b].

The new LCA requirement may shift Denmark's building industry in methods, practices, and materials used. To provide a context, building with timber is not the conventional construction method in Denmark, it is estimated that only 10 percent of the buildings are made with timber as the primary material (Appendix B). Therefore, deciding on materials with reduced CO_2 emissions, such as bio-based materials, is a convenient choice to consider.

1.2 Bio-based materials

Using bio-based materials for construction is not a revolutionary building technique. However, using these materials corresponds to an essential progressive approach to lowering the environmental impact of the construction industry [Pomponi et al., 2020]. These materials have gained recognition not only for their structural and thermal qualities but also for their dynamic ability to function as carbon sinks [Akiner et al., 2022]. Unlike conventional mineral-based building materials, which emit CO_2 due to their heat-intensive processes during their manufacturing stage, bio-based materials absorb CO_2 and store it for an extended length of time [Bourbia et al., 2023].

Numerous cases have shown that timber has a lower carbon emission than concrete during its production stage [Liang et al., 2020]. This is because concrete production involves high-temperature kilns, which use considerably more energy [García-Gusano et al., 2015], whereas timber processing is typically less energy-intensive [Bergman et al., 2014]. Moreover, using timber in construction may contribute to reducing the emissions to the target of 0.4 kg CO_2-eq./m^2 per year by the year 2030 [Reduction Roadmap, 2022]. Furthermore, since the goal of Denmark is to raise the forest area from 15% to 20-25% by the year 2100, increased usage of timber and therefore a bigger forest area could be a step in this direction [Einfeldt, 2018].

This research led to a case study of 25 best practice cases in Denmark with the lowest carbon footprint which indicated that most of the buildings were constructed with bio-based materials [Garnow et al., 2023]. This correlation between low carbon emissions and bio-based construction highlights the importance of bio-based materials.

Furthermore, bio-based materials have a unique ability that allows for carbon sequestration which is the capture, and storage of carbon dioxide from the atmosphere [Correa de Melo et al., 2023]. However, the amount of carbon that is sequestered depends on the density and the age of the plant. Subsequently at the end of the material's life, when the materials are either burnt or landfilled the carbon that has been captured will be released back into the atmosphere [Skog and Nicholson, 1998]. This can be visible in LCAbyg since it uses the -1/+1 approach. This approach considers both the biogenic uptake and release as well as the transfer of biogenic carbon between different systems. During the production phase, the CO_2 emissions are negative due to the CO_2 uptake during the forest growth, consequently, in its end-of-life stage, the carbon is released back into the atmosphere resulting in positive emissions [Hoxha et al., 2020].

Correspondingly, it is important to consider the sources where these bio-based materials are obtained to minimize a negative environmental impact in terms of deforestation and the disruption of the ecosystem as well as limiting the potential of the forests to sequester carbon. Therefore it is important to source materials that are PEFC (Programme For The Endorsement Of Forest Certification) or FSC (Forest Stewardship Council)-certified. Their purpose is to ensure forest-based products are sourced from sustainably managed forests. Sustainable forest management as stated by UN FAO (Food and Agricultural Organization) is the forests and land that are used in a way that still maintains their biodiversity, and regeneration capacity and should be used so that it is possible to support ecological, economic, and social functions without disrupting the ecosystem [United Nations, 2020]. Moreover, the European Resolution outlines six criteria for sustainable forest management such as the maintenance of resources and their contribution to the global carbon cycle, which provides a framework for sustainable sourcing practices [MCFA, 1998].

1.3 Literature review

It is important to find a solution for the reduction of high greenhouse gas emissions caused by the building industry to achieve the goal of the Paris Agreement by 2050 in the Danish context [Danish Ministry of Climate, Energy and Utilities, 2020]. Many recent studies have focused on the environmental impact of substituting traditional building materials with bio-based materials.

Both Buchanan and Levine [1999] and Amiri et al. [2020] discussed the environmental advantages of using timber in the building industry. However, Buchanan and Levine [1999] focused on the relation between increased amount of timber and reduction in overall greenhouse gas emissions, meanwhile Amiri et al. [2020] concentrated on the carbon storage in timber, highlighting that it mostly depends on the amount of wood used in the building instead of the wood type or type of buildings. On the other hand, Peng et al. [2023] presented the opposite results, claiming that wood is not as environmentally friendly as many researchers think, which is based on a different approach to carbon accounting. The study suggests that replacing steel or concrete with wood could have lower emissions only under specific conditions, including reduced meat consumption in high-income countries, increased crop, and reduced farmland use.

Moreover, Hansen et al. [2023] discussed the environmental consequences of changing from conventional construction to wood. The results showed that timber-based multi-story buildings have a lower environmental impact compared to the mineral materials in both 60 and 100 reference periods due to the usage of steel in the mineral scenario, meanwhile, in the single-family house case and the office building, the timber-based construction has a higher impact. Furthermore, Hansen et al. [2023] also highlights that changing to wood on a big scale may result in indirect consequences such as land use change (LUC) which causes a lot of CO_2 emissions, and the conversion of natural forests into productive forests, resulting in variation of the CO_2 stored. Moreover, Hansen et al. [2023] also mentioned consequences such as a bigger impact on biodiversity while increasing the use of timber in construction. Additionally, the research revealed that results without indirect land use change and forest modeling have a significantly lower impact when shifting to the timber-based scenario.

Fast-growing bio-based materials such as straw or hemp have also been analyzed when it comes to their environmental capabilities. One research showed that carbon storage in fast-growing bio-based materials is more effective than carbon storage in timber due to their regrowth time [Pittau et al., 2018]. Another research showed that to achieve the goal of the Paris Agreement by 2050, it is necessary to use bio-based materials with a very fast regrowth time due to their capability of removing carbon from the atmosphere in a very short time [Carcassi et al., 2019].

While there has been much research on the influence of bio-based materials on the environment, few researchers have performed a comparison on case buildings instead of pure LCA and carbon storage calculations. Buchanan and Levine [1999] looked into single-story industrial buildings, five-story office buildings, a six-story hostel building, and residential single-family houses in New Zealand. To get the results they created two scenarios for each type of building: construction with the use of traditional materials and bio-based materials. On the other hand, another research performed a comparison based on the case building of a hypothetical building block located in Stockholm, Sweden [Peñaloza et al., 2016]. To get the results, they compared three different scenarios: concrete structure, CLT structure, and structure with increased bio-based materials. Furthermore, Hansen et al. [2023] looked into a single-family house, a multi-story building, and an office building in Denmark.

While all of the researchers provide valuable results, the Buchanan and Levine [1999] research was performed in New Zealand, and therefore there are different wood species and other bio-based products available locally. Even though the research made by Peñaloza et al. [2016] was located near Denmark, they used the boreal forest as their wood source which has a regrowth time of 80 years, meanwhile spruce available locally in Denmark has a regrowth time of 50 years. Moreover, the research made by Hansen et al. [2023] was conducted in Denmark, however, it used 88 years of a rotation period of trees and cellulose wood. In addition, none of the researchers compared the carbon stored in the wooden construction with the emissions from the population of the city in which the buildings are being built.

These variations in the wood species, location, and rotation period led to the decision to work with the simplified EN LCA methods with the desired study parameters.

1.4 Project formulation

The building industry's notable use of concrete and steel has had a negative impact on the environment. The production of these elements involves high emissions, which contrasts with bio-based materials which not only is a viable alternative for reduced emissions but also it functions as a potential carbon sink. However, the challenge is to comprehend the scope of using timber and bio-based materials as alternatives in construction. This involves investigating not only their immediate benefits but also their long-term impact on carbon reduction and environmental sustainability. Wherein, the renewability of resources, the environmental footprint throughout the life cycle, and the compatibility with environmental goals are taken into consideration.

This thesis aims to explore the potential of utilizing bio-based materials, primarily timber in building construction to serve as carbon sinks in the city of Aalborg, Denmark. Moreover, this study aims to explore the reduction of carbon emissions in buildings and potentially offsetting the emitted CO_2 with the use of alternative construction materials. In this regard, it gives insights into the following key investigation points.

1. Impact on carbon emissions while using bio-based materials. The first goal of this investigation is to identify and compare the environmental impacts of using timber and bio-based insulation with typical mineral-based products. The goal is to identify the changes in carbon emissions when new buildings are built with bio-based materials, and how it can contribute to Aalborg's overall carbon reduction goals.

2. Timber consumption for new construction. The next point leads to the evaluation of the quantity of wood needed to build all new structures in Aalborg in the most timber-centric way. This study looks into the environmental impact of using wood as a principal building material in the city.

3. The effect on forests. When the amount of materials has been determined, this leads to examining the environmental effect by calculating the area of the forest necessary for wood production. This paper investigates the trade-offs between the renewable nature of bio-based materials and the amount of timber consumed.

4. Carbon sequestration potential. Lastly, the potential of new bio-based construction to sequester carbon is determined and scaled into the city of Aalborg. This then leads to identifying the capacity of a city to offset CO_2 emissions through sustainable construction techniques, which aligns with Aalborg's objective of lowering greenhouse gas emissions by 70 percent by 2030.

In order to answer the problem formulation questions, four different case buildings in Denmark were investigated: three residential buildings and one non-residential case. For each case building, three different scenarios were explored. The first one is the primary use of mineral-based materials, the second is the use of timber-based materials and the last scenario is a bio-based construction.

Chapter 2

Methodology

2.1 Data gathering

As a first step, building statistics were analyzed, which provided an exact number of square meters of different types of new buildings every year from 2006 to 2022 in Aalborg. Forest management in Denmark was also analyzed to get information about the number of forests in Denmark, the percentage of different tree species in the forests, the amount of wood harvested every year, and lastly how the wood is used after it is harvested (including the proportion allocated to the building industry).

As the next step, interviews were arranged to provide a better understanding of the approach towards using timber in buildings in Denmark. The first interviewee was the expert in the field of the Building Department in Aalborg who gave an overview of sustainability, current trends, and future plans of the construction sector in Aalborg. Moreover, a member of the organization supporting the wood industry in Denmark and a wood distributor were also interviewed. It helped with understanding how timber is managed in Denmark, and what the current regulations and the trends of usage of timber in Denmark are.

2.2 Case buildings

After finishing the research, case buildings were necessary to do the investigation. Four types of buildings constructed with mineral materials were selected to be analyzed: a single-family house, a terraced house, a multi-story building, and an office building. A single-family house case was taken from a consultancy company, however, an NDA was signed and therefore drawings and details may not be further discussed. When it comes to all the other building types, the buildings were randomly chosen from the case library of Denmark [Videncenter om Bygningers Klimapåvirkninger, a]. Due to the limited amount of available cases for some types of buildings, there were situations where one of the building parts was made with timber materials. In this case, this timber part was changed into the desired material to get the representative building scenario.

2.3 Scenarios

Each of the case buildings had its own three construction scenarios: Mineral-based construction, timber-based construction, and bio-based construction. Mineral-based construction means the traditional way of building. It is characterized by using mineral materials, such as concrete, steel, and mineral insulation. Next, timber-based construction is a mix of mineral and bio-based construction. In this scenario, all the external walls, internal walls, roofs, floor partitions, columns, and beams are changed to timber. Moreover, the floor slab on the ground floor is also changed into timber, however, any construction below the ground level stays the same. Lastly, bio-based construction is the same as timber-based construction but with the addition of changing the mineral insulation into bio-based insulation. The table below shows the chosen materials for each category:

	Mineral-based	Timber-based	Bio-based
External walls	Concrete and steel	CLT	CLT
Load-bearing internal walls	Concrete and steel	CLT	CLT
Non-load-bearing internal walls	Concrete	Timber frame	Timber frame
Roof	Concrete and steel	Timber frame	Timber frame
Floor partitions	Concrete and steel	CLT	CLT
Groundfloor slab	Concrete and steel	Timber	Timber
Construction below the ground level	Concrete and steel	Concrete and steel	Concrete and steel
Structural elements (columns, beams)	Concrete and steel	CLT	CLT
Insulation	Mineral wool	Mineral wool	Bio-based insulation

TABLE 2.1: Materials in three scenarios

To change the materials from one scenario to another, no change in the U-value had to be ensured so the "energy consumption and supply" in LCAbyg stays the same. Therefore based on the mineral-based construction, the U-values of different parts of a building envelope were calculated. And afterward, timber-based and bio-based scenarios had to follow the same U-values.

2.4 Life Cycle Assessment

As a next step, a life cycle assessment for all different scenarios was calculated with the use of LCAbyg. It gave the result of the global warming potential for each scenario and the precise weight of all the materials.

2.5 Forest area

The amount of wood was calculated for each scenario, and then subsequently converted into the necessary forest area in Aalborg. This was achieved by dividing the required amount of timber by the density of the forest obtained from the forest statistics [Kofod, 2018]. The density of the forest was calculated as the amount of wood in Denmark divided by the hectares of Danish forests. Afterward, the forest area was multiplied by 50 years in order to determine an area required to have a sustainable forest cycle. The area was drawn on top of the map of Aalborg, which provided a visualization of the needed space.

2.6 Carbon sequestration

Lastly, the CO_2 storage of timber and bio-based materials was calculated with the following formula based on the DS/EN 16449:2014 standard [Dansk Standard, 2014], which shows the number of kilograms of carbon stored in one m^3 of wood for its whole life.

$$\text{CO}_2 \text{ storage} = \frac{\text{Amount of wood * density}}{1 + \text{moisture content}} = \frac{3.67}{2} \tag{2.1}$$

Moreover, in order to present the dynamics of the biogenic carbon uptake and release in timber, the following formula was applied [Resch et al., 2021]. The result will show how much carbon is stored in wood every year after being harvested. This means that the graph will start with year 0, which is the year the wood was harvested. Afterward, the tree will start to regrow and the carbon uptake will be presented.

$$f_{CR}(y) = kpe^{-kp}(1 - e^{-kp})^{p-1} \tag{2.2}$$

$$f_{bio,i}(y) = m_{CO2,i} * f_{CR}(y) / \sum_{y=0}^{TH} * f_{CR}(y) \tag{2.3}$$

where

k	growth rate of the trees
p	catabolism of the trees
i	inventory of the product
TH	time horizon
m_{CO_2}	content of biogenic CO_2

Chapter 3

Case Study Method

3.1 New buildings in Aalborg

Data from the building statistics from 2006 to 2022 in Aalborg were gathered [Danmarks Statistik, 2023]. As visible in the graph below, the area of constructed buildings each year varied by a fair amount, especially in the multi-dwelling houses.

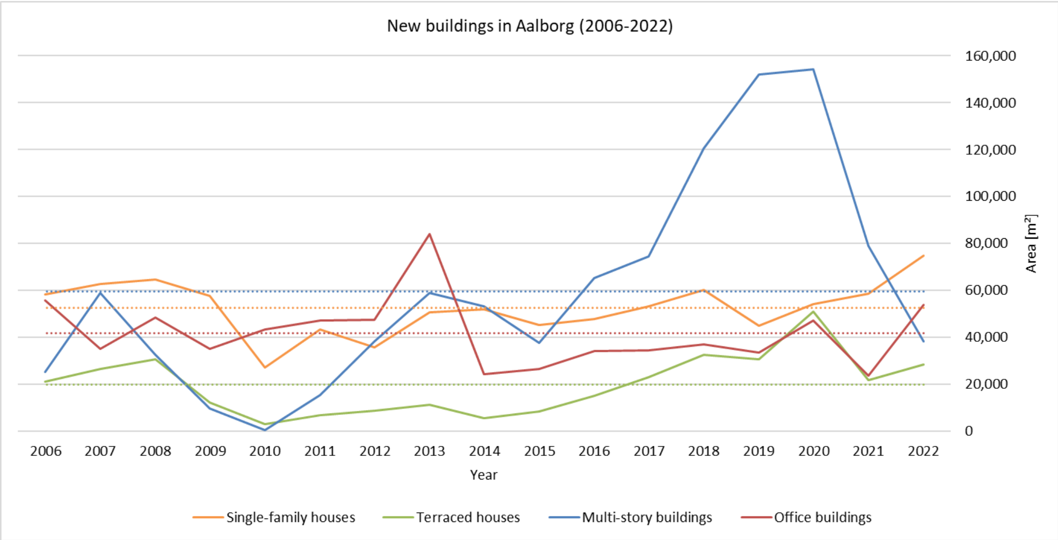


FIGURE 3.1: New buildings in Aalborg per year

To find the values for further calculation, the average yearly area was calculated based on the data from all the available years.

Type of building	**Average area of new buildings per year in Aalborg [m²]**
Single-family house	52 488
Terraced house	19 864
Multi-story building	59 734
Office building	41 877

TABLE 3.1: Average area of constructed buildings per year in Aalborg

3.2 Case scenarios

Three different construction scenarios were subjected to the four case buildings that are shown in the following sub-chapter. The three scenarios allow for comparisons and understanding of the environmental implications of the different construction methods and materials. The first scenario is the mineral-based construction, which will serve as a baseline for comparisons and is the current method of construction of the four chosen case buildings. The next scenarios are the timber-based and the bio-based construction. To ensure a fair comparison among the scenarios, the thermal transmittance (U-value) of the building envelope remains the same to not alter the building's energy frame. The scenarios primarily focus on substituting the external walls, internal walls, roof, partition floors, and insulation materials. The basement walls, floors, and foundations however are not changed.

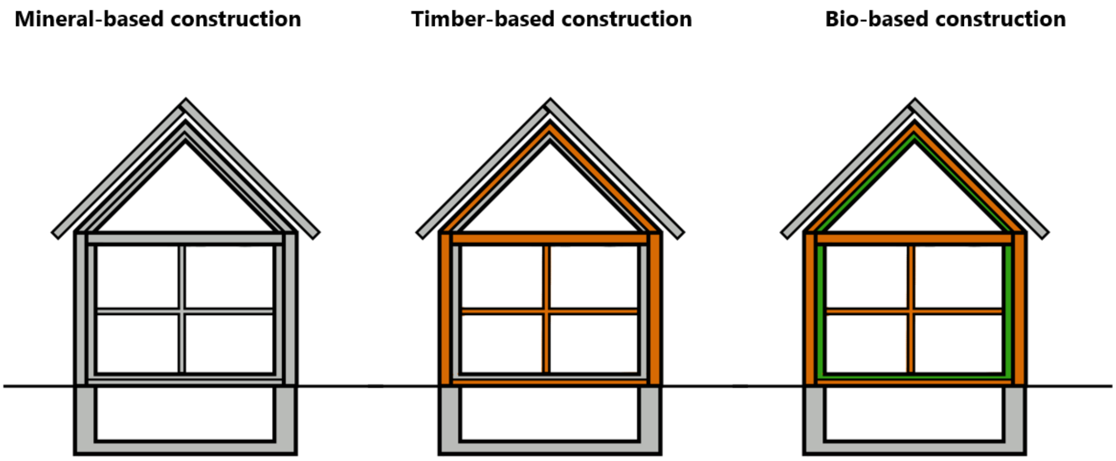


Figure 3.2: Three case scenarios

The mineral-based construction represents the conventional way of building with the use of concrete and/or steel. However, the single-family house, which originally featured a roof with wooden rafters, was modified to incorporate a flat concrete roof, while still implementing the same U-value to keep the scenario coherent.

The timber-based construction features the use of CLT as the structural element as a substitute for the concrete/steel walls, beams, and columns. While the non-load-bearing interior walls are substituted with timber framing. The cross-laminated timber was chosen for this scenario due to numerous reasons. Firstly, CLT is known for its structural integrity exhibiting a high load-bearing capacity that makes it possible to be used for tall buildings [Kuilen et al., 2011]. Furthermore, it is chosen for its versatility and ease of installation, comparable to that of a prefabricated concrete element where both elements are easy to install on the construction site but the CLT element is much lighter.

Moreover, CLT is a reliable material when it comes to its fire performance, wherein when exposed to fire it has a predictable charring rate which provides insulation to the inner layers and maintains structural integrity [Klippel et al., 2014].

Lastly, the decision was made to use spruce wood for the project. This choice was made because of the renewability of spruce, along with its relatively rapid growth of 50 years, compared to the other types of wood that have a growth rate of 100 years [Einfeldt, 2008]. Moreover, it is available locally in Denmark [Kofod, 2018].

The bio-based construction scenario is similar to the timber-based approach but it takes a step further in using bio-based material wherein the mineral insulation was switched to Gramitherm meadow grass insulation. Meadow grass was chosen because of its thermal performance, sound absorption, and growth factor while potentially capturing CO_2. Its thermal conductivity (lambda-value) is 0.04 W/mK while mineral wool varies from 0.032-0.04 W/mK (see Appendix C). The mineral and bio-based insulation are quite similar in terms of their thermal properties but different in terms of their environmental impact. Additionally, this bio-based insulation is just harvested grass waste where 1 acre of its land produces 200 m^3 of insulation and 1 kg of the insulation can capture 1.5 kg CO_2-eq. (Appendix C).

The external walls constructed with brick and concrete are changed to a timber and bio-based solution. An example of the changes in different scenarios is shown in figure 3.3.

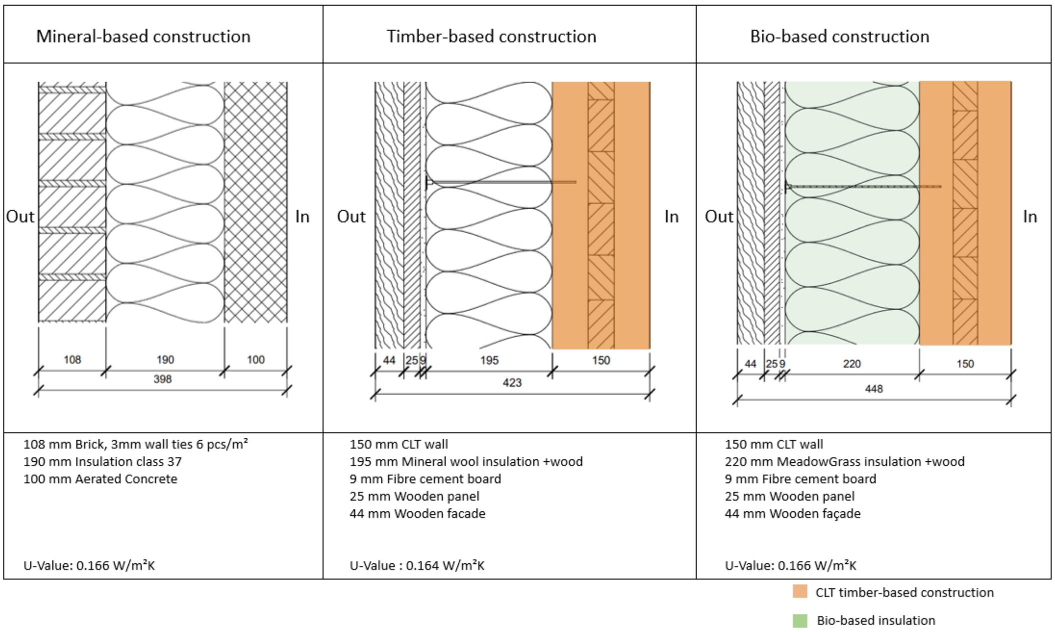


FIGURE 3.3: External walls of the different scenarios in the terraced house

The mineral-based scenario of the roof construction is a ventilated warm roof that is built with a concrete deck and mineral wool insulation on top, it is similar among all the case buildings. Furthermore, the solution of the roof for the timber and bio-based construction was taken from Taasinge Elementer, a company in Denmark that produces prefabricated wooden construction elements. This solution is used for all four different case buildings and was chosen due to its prefabricated nature as well as its thermal transmittance matching the reference construction.

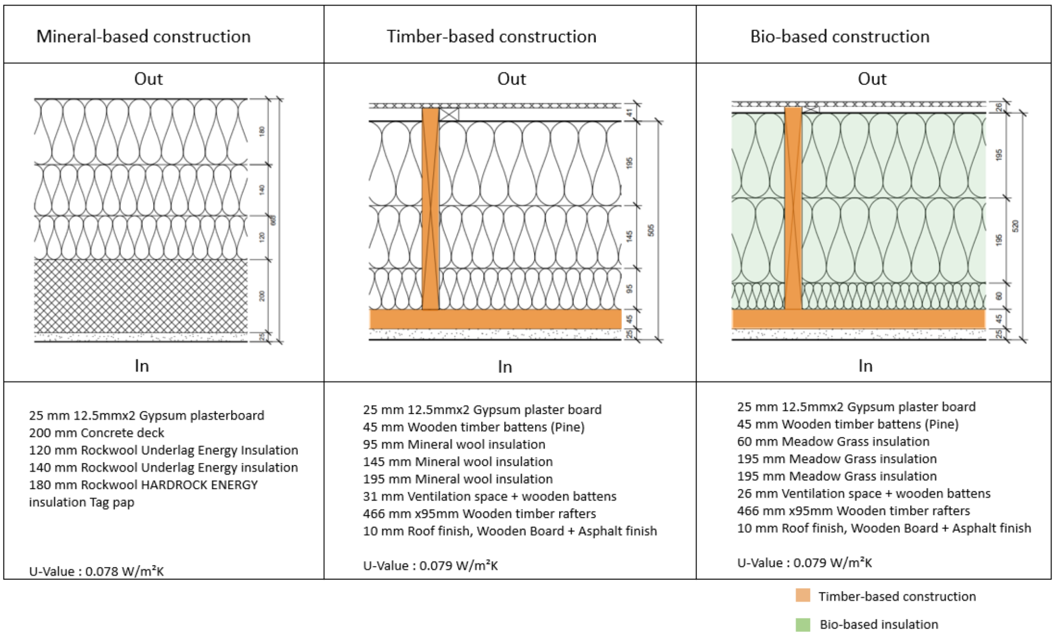


FIGURE 3.4: Roofs of the different scenarios in the terraced house

The timber and bio-based floor solutions are made with wooden rafters as their structural components and their only differences are the insulation material used. While the mineral-based floors are the conventional concrete floors with polystyrene insulation.

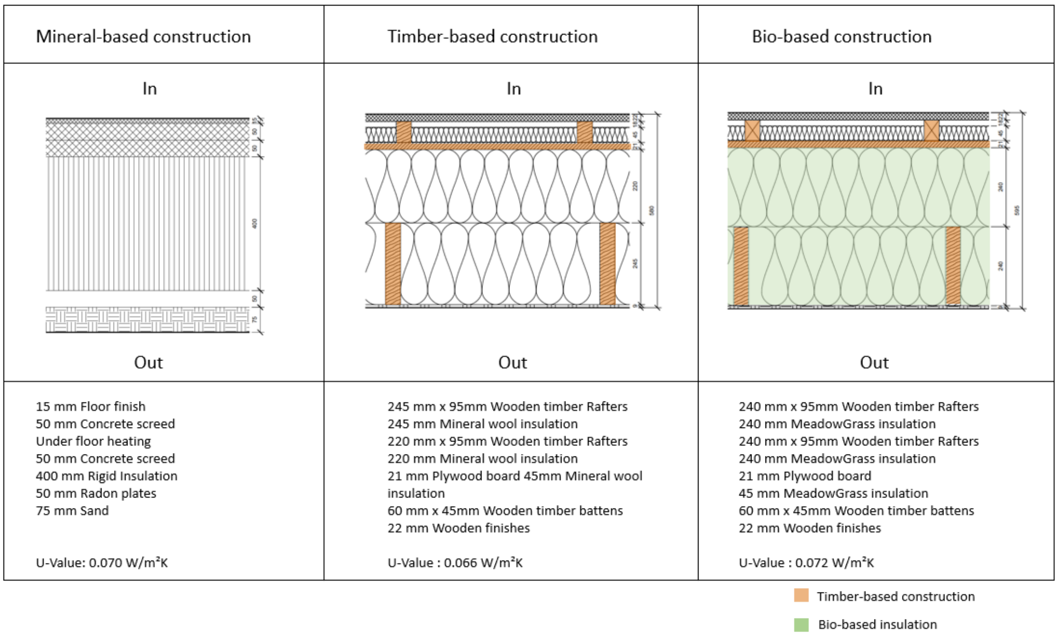


FIGURE 3.5: Floors of the different scenarios in the terraced house

The scenarios provide insights into the alternative materials each aimed at contributing to carbon sequestration possibilities and reduction of CO_2 emissions. Notably, the alterations of the building elements are not exaggerated for enhanced carbon sequestration and CO_2 reduction. They are simply switched to match the U-value and to ensure structural coherence.

The timber and bio-based scenario exhibits significant potential for optimizing the GWP and their carbon sequestration. However, it is important to note that these findings represent a comparative analysis of various building methods and use of materials. The GWP can potentially be further reduced, but evaluating this would require a separate study.

3.3 Case source

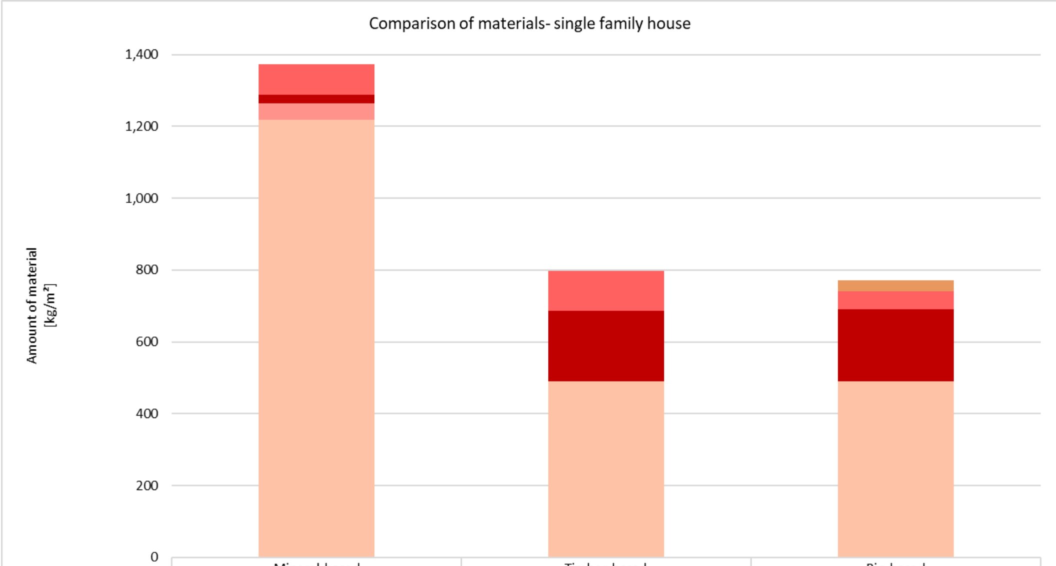
Four case studies were chosen to investigate the influence of bio-based materials: three residential buildings and one non-residential building. The buildings were randomly chosen and the only criterion was that they should be constructed with traditional construction materials. The buildings were assumed to be the typical, representative buildings of Denmark. Moreover, all of the chosen buildings were finished in 2022.

3.3.1 Single-family house

The first residential building case was a single-family house. The selected single-family house case study covers an area of 165 m^2, additionally, the average area of single-family houses constructed annually in Aalborg is 52 488 m^2, translating to approximately 300 new houses each year in the city.

The building structure is based on external load-bearing walls made out of brick and concrete. Internal walls are made out of aerated concrete. The GWP is 11.67 kg CO_2 eq./m2 per year and the energy demand of the building is 34.8 kWh/m^2/year. Due to the signed non-disclosure agreement, the drawings of the building may not be revealed.

As shown in the figure 3.6, the amount of concrete used in the mineral-based construction of the single-family house is 1 218 kg per m^2, equivalent to 201 tons of concrete comprising approximately 75 percent of the construction, and significantly drops in the timber and bio-based construction when substituting the materials to timber and bio-based insulation. Since the foundation was not altered this results in a percentage of concrete remaining.



	Mineral-based	Timber-based	Bio-based
Bio-based insulation	0.00	0.00	30.64
Mineral insulation	85.42	111.98	50.44
Wood	23.46	195.54	200.11
Steel	45.03	1.85	1.85
Concrete	1,218.88	488.93	488.93

FIGURE 3.6: Materials used in the single-family house

Moreover, the use of mineral wool insulation in the timber-based scenario slightly increased due to the requirement of matching the U-value to the reference case having to add more insulation. The amount of wood used in bio-based construction remains almost similar to timber-based buildings adding 30.64 kg/m² of meadow grass insulation and reducing the mineral wool use by half.

3.3.2 Terraced house

The second residential building case was a terraced house. The two-story building is in a group of ten slightly different terraced houses that together have 5402 m² of heated floor area, resulting in an average area of 540 m² per building. While the average amount of terraced houses built in Aalborg every year is 19 864 m². The building has a climate impact of 9.44 kg CO_2 eq./m2 per year. The load-bearing structure consists of external walls that are made out of brick and concrete, and the load-bearing internal walls are made out of aerated concrete and silka block. The sloped roof is made out of timber. The energy demand of the building is 35.47 kWh/m²/year.

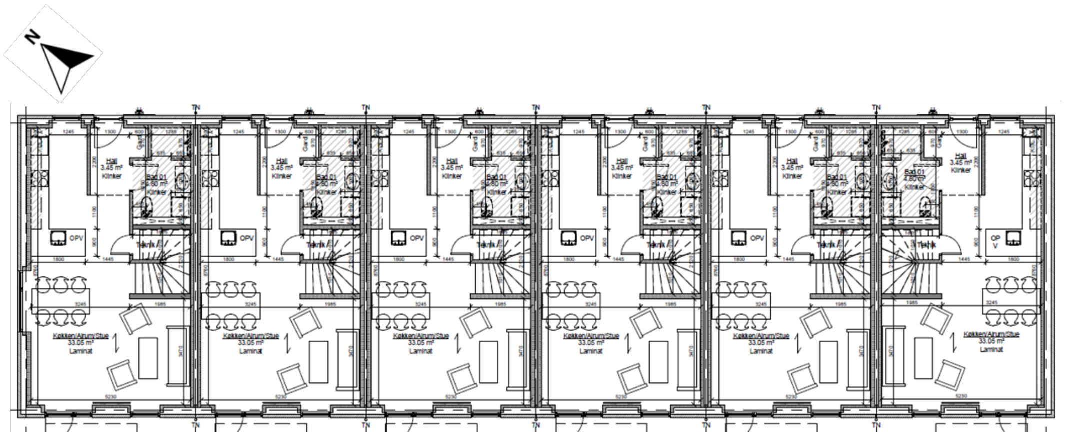
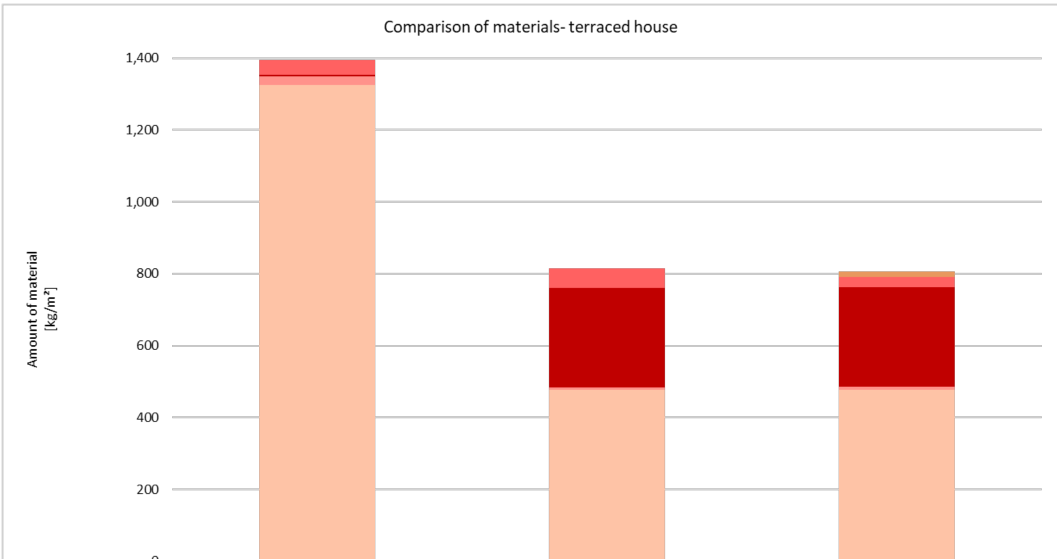


FIGURE 3.7: Teglsoerne building

FIGURE 3.8: Teglsoerne building

Additionally, the amount of concrete used in the reference scenario/mineral-based construction is 1 324 kg/m^2 which translates to 7 152 tons of concrete used for this building while the amount of wood used is only 3.06 kg/m^2. For timber-based construction, the use of wood increases to 275.08 kg/m^2, and the amount of concrete is lowered to 476.61 kg/m^2. In the bio-based construction, the amount of wood slightly increases from the timber-based scenario to 277.59 kg/m^2 and the addition of 15 kg/m^2 of meadow grass substituting approximately 52% of the mineral wool insulation, while the amount of concrete remains the same.



	Mineral-based	Timber-based	Maximum bio-based
Bio-based insulation	0.00	0.00	15.69
Mineral insulation	42.77	55.95	29.28
Wood	3.06	275.08	277.59
Steel	24.87	7.83	7.88
Concrete	1,324.62	476.61	476.61

FIGURE 3.9: Materials used in the terraced house

3.3.3 Multi-story building

The third residential building was a multi-story building. The seven-story building has a heated floor area of 4280 m². Additionally, in Aalborg, there is an average of 59 734 m² of multi-story buildings being constructed annually. The building has a climate impact of 9.34 kg CO_2 eq./m2 per year. The load-bearing structure consists of external walls made out of brick and concrete, meanwhile, the load-bearing internal walls and the roof are made out of concrete. The energy frame of this building is 26.3 kWh/m²/year.

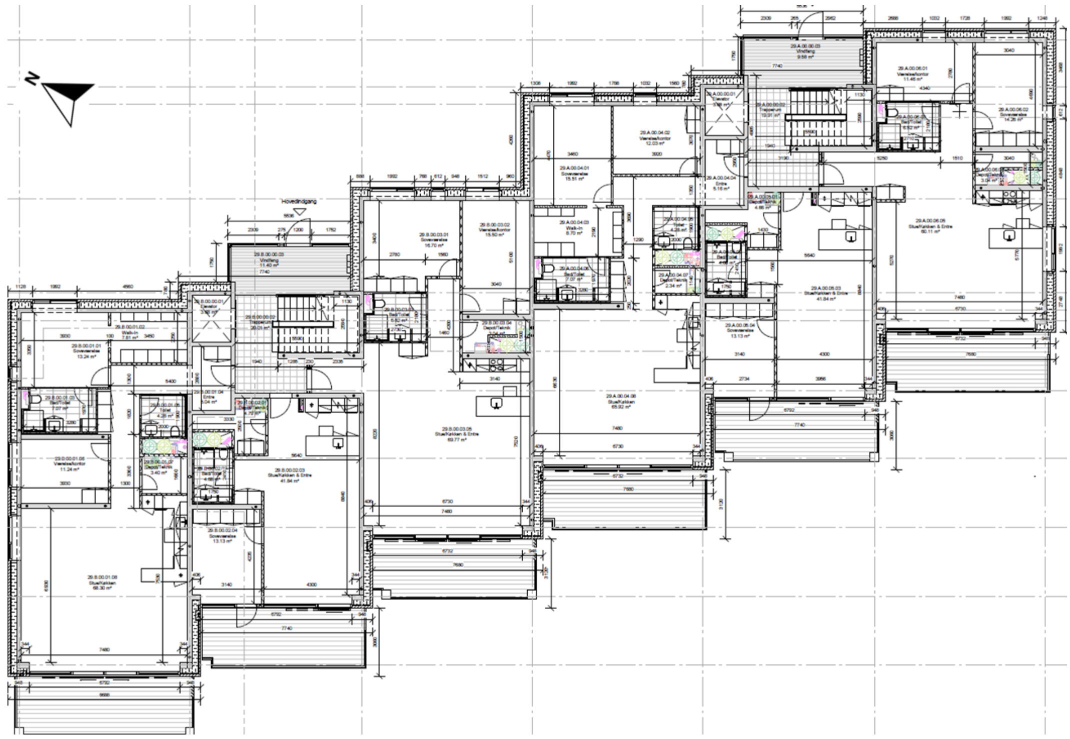


Figure 3.10: Kongebrohuset building

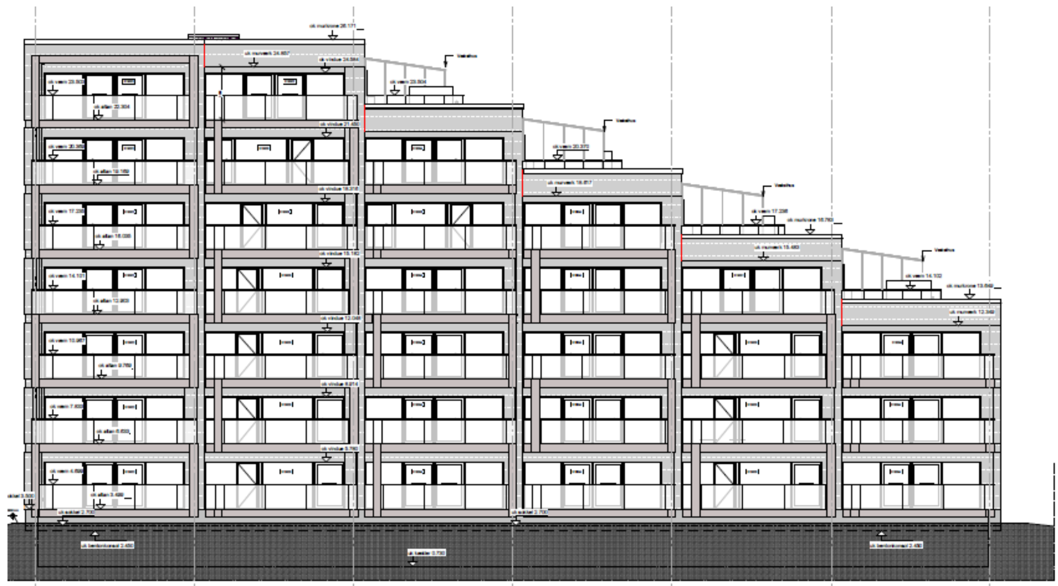
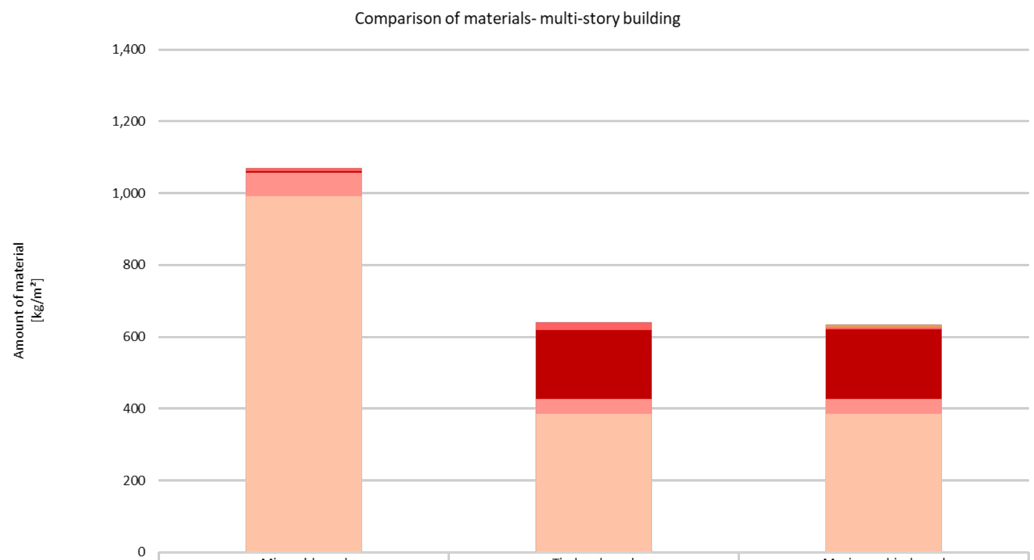


Figure 3.11: Kongebrohuset facade

The amount of concrete used in the mineral-based scenario of the multi-story building is 992.52 kg/m² which comprises 77% of the entire building and it has 4.61kg/m² of wood that is mainly just used for the finishes of the building components. The timber-based construction uses 191.21 kg/m2 of wood and it still has 386.11 kg/m2 of concrete. lastly, the bio-based scenario consists of 192.04 kg/m² of timber which is only 0.8 kg/m² more than that of the timber-based construction, and lastly the addition of 9.73 kg/m² of meadow grass insulation.



	Mineral-based	Timber-based	Maximum bio-based
Bio-based insulation	0.00	0.00	9.73
Insulation	8.57	21.51	4.96
Wood	4.61	191.21	192.04
Steel	64.62	42.51	42.51
Concrete	992.52	385.11	385.11

FIGURE 3.12: Materials used in the multi-story building

3.3.4 Office building

Lastly, the chosen non-residential building is a three-story office. The building has a heated floor area of 9478,4 m² and on average there are 41 877 m² of office buildings built per year in the city of Aalborg. It has a climate impact of 13.4 kg CO_2-eq./m² per year. The load-bearing system consists of concrete and steel beams, concrete columns, external walls made out of concrete, brick, and steel, and load-bearing internal walls made out of concrete elements. The energy frame of the building is 33.1 kWh/m²/year.

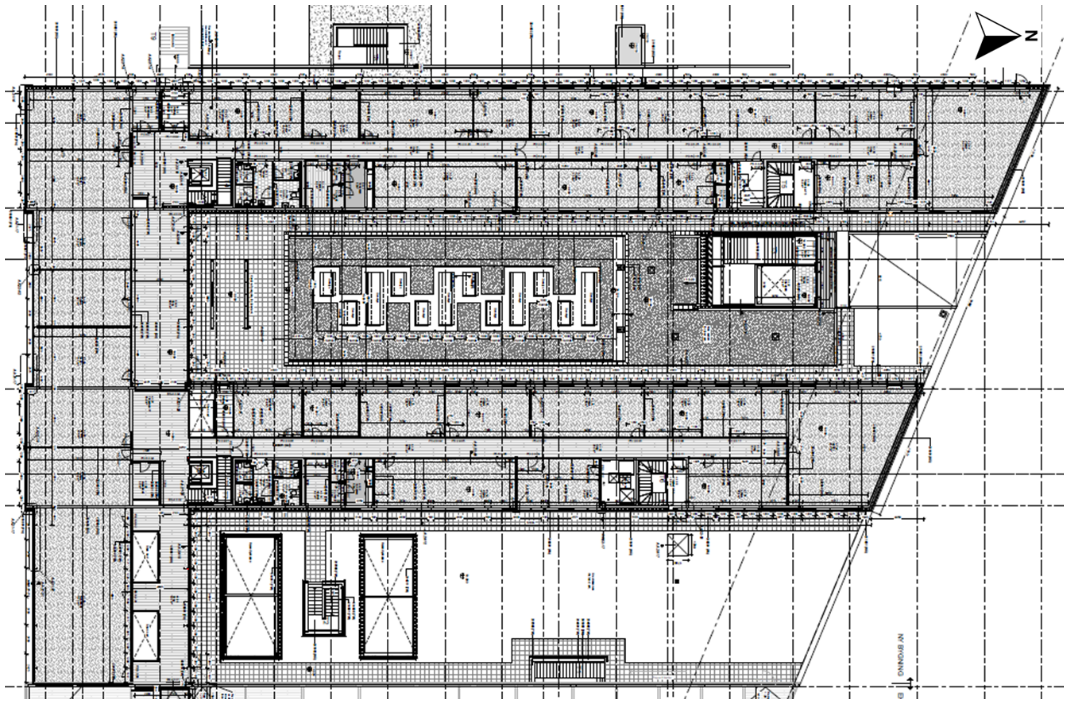


FIGURE 3.13: Jysk building

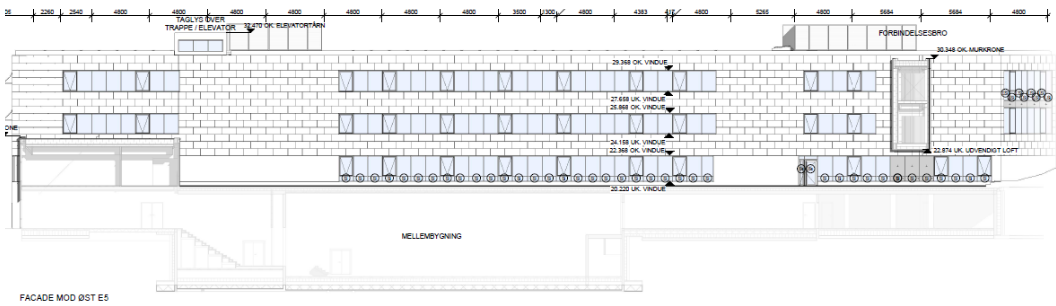
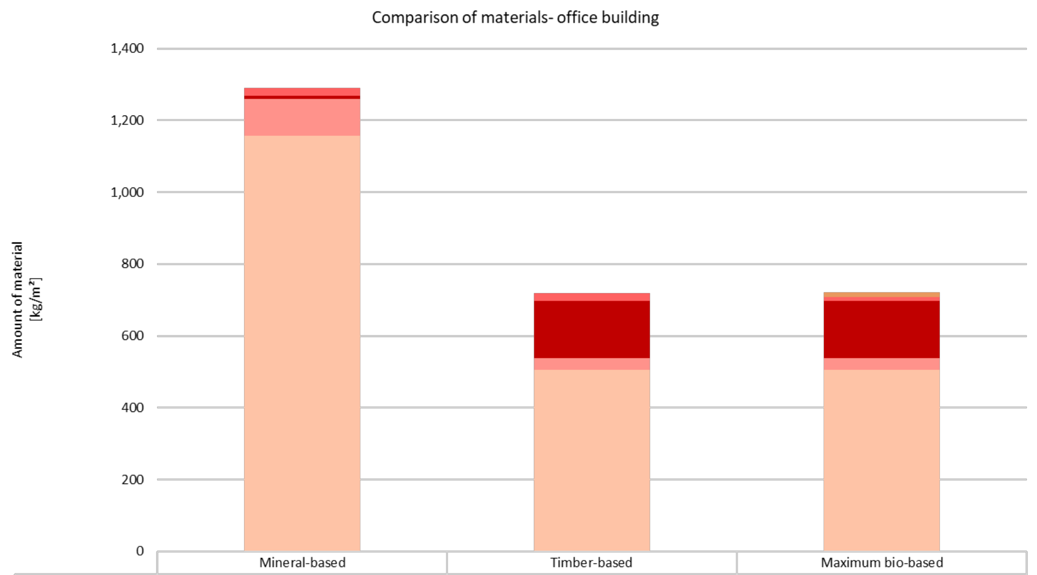


FIGURE 3.14: Jysk building

The concrete used for the mineral-based office building is 1 157 kg/m^2, that is 10 966 tons of concrete used for this building alone and only uses 8.4 kg/m^2 of wood for the building finishes such as the floor tiles.



	Mineral-based	Timber-based	Maximum bio-based
Bio-based insulation	0.00	0.00	13.37
Insulation	21.12	23.07	10.19
Wood	8.40	158.63	159.41
Steel	103.13	32.06	32.06
Concrete	1,157.37	505.48	505.48

FIGURE 3.15: Materials used in the office building

The timber-based scenario lowers the concrete usage by 652 kg/m^2 while the use of wood increases to 158.63 kg/m^2. The same goes for the bio-based construction the amount of wood used is nearly identical with just a difference of 0.78 kg/m^2 but has an addition of 13.37 kg/m^2 of meadow grass insulation and the mineral wool is reduced to 10.19 kg/m^2. The reason why there is still mineral wool insulation in the bio-based construction is because the floors and walls that are in the basement that use this insulation were not replaced.

Chapter 4

Results and Analysis

This chapter presents the assessment of carbon emissions for each scenario of the four case buildings in Denmark, highlighting the quantified reduction in carbon emissions from mineral-based to bio-based construction and showing the environmental consequences of the materials used.

Additionally, this chapter shows the amount of CO_2 that the building can sequester when constructed with timber and bio-based insulation.

Lastly, the quantity of wood in cubic meters and hectares of trees that will be used for one year of construction in Aalborg when opting for the timber-based or bio-based construction method is determined.

4.1 Carbon emissions of the different scenarios

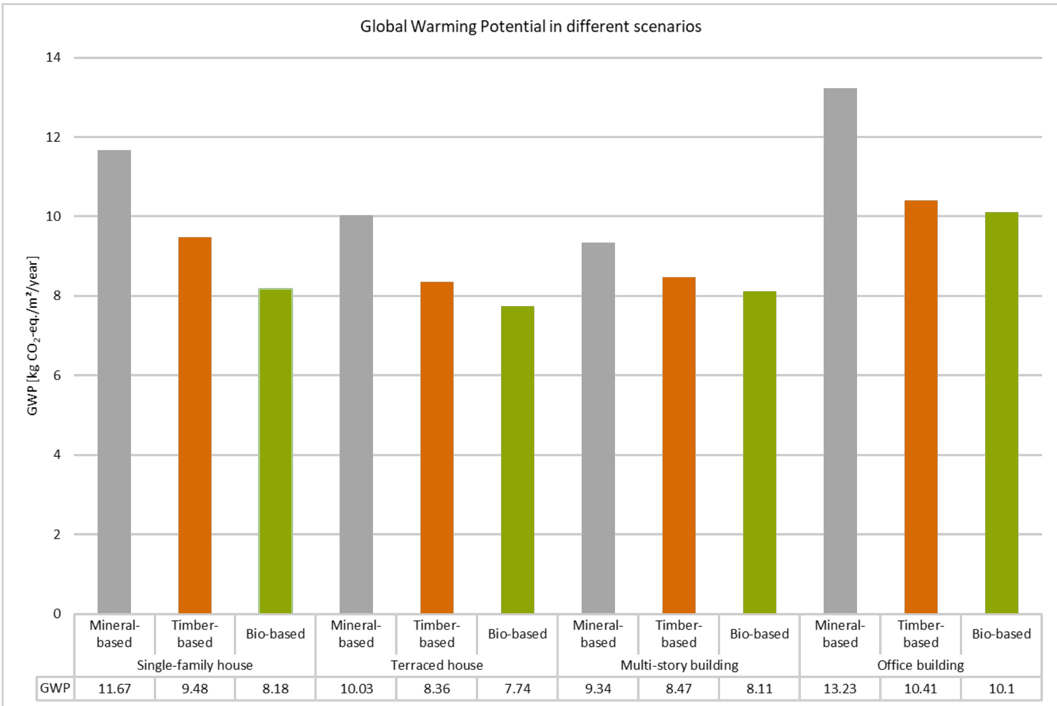


FIGURE 4.1: GWP in different scenarios

The values in figure 4.1 show the carbon emissions per square meter for each construction scenario and reveal distinctive trends and differences across mineral-based, timber-based, and bio-based constructions.

The mineral-based construction, as assumed, exhibits the highest GWP value among the three different scenarios while timber and bio-based buildings consistently have lower GWP values than mineral-based constructions across all case buildings.

Bio-based buildings slightly outperform timber-based constructions by just replacing mineral wool insulation with meadow grass insulation, showing the potential to cut carbon emissions more.

The difference between timber-based construction and bio-based construction was the biggest in the single-family house where it was 1.3 kg CO_2-eq./m^2/year, meanwhile, the smallest difference was in the office building (0.31 kg CO_2-eq./m^2/year).

To quantify the carbon emissions and CO_2 sequestration of the buildings in the city of Aalborg, interpolation was done based on the size of the case study buildings and scaled to the average area of the type of building constructed in the city based on the available building statistics.

4.1.1 Single-family house

As visible in figure 4.2, the GWP of the single-family house decreases significantly in the production phase (A1-A3) when switching from traditional materials to bio-based ones. However, the GWP from the usage phase slightly increases. Moreover, GWP in the end-of-life phase also increases due to the methodological approach used by the LCAbyg which is -1/+1. GWP beyond the building life cycle has the lowest value in the bio-based solution.

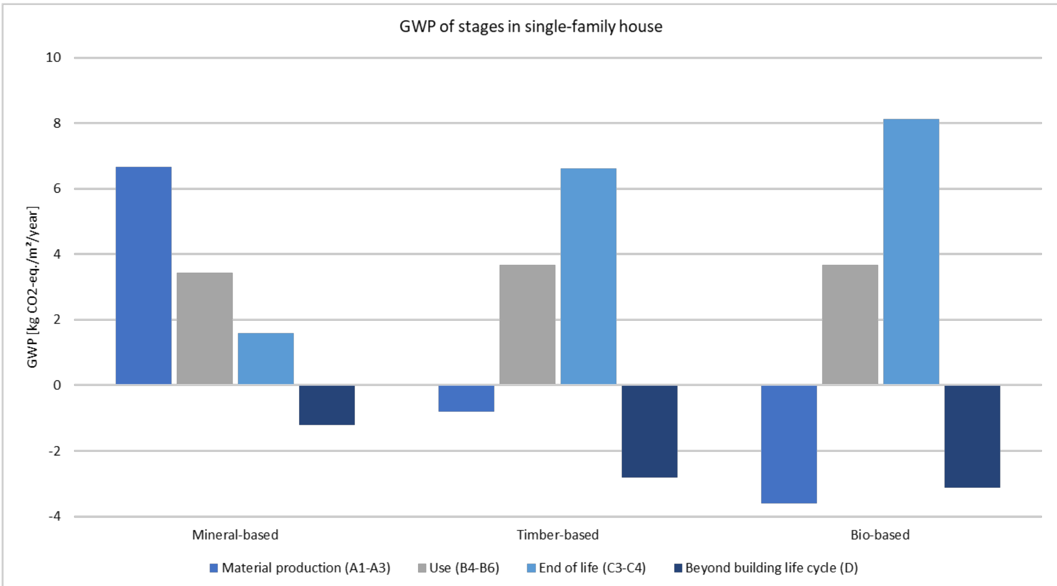


FIGURE 4.2: GWP of different stages in single-family house

As shown in figure 4.3 an increased quantity of bio-based materials used corresponds to a higher potential for sequestration.

The mineral-based single-family house uses 9.7 m^3 of wood in its construction and can sequester 6.34 tons of CO_2 while a timber-based family house uses 80.66 m^3 of timber and has the potential to store 52.86 tons of CO_2, and when scaled to one year's worth of single-family house constructions in Aalborg it will result in storing 16 816 tons of CO_2 while using 25 658 m^3.

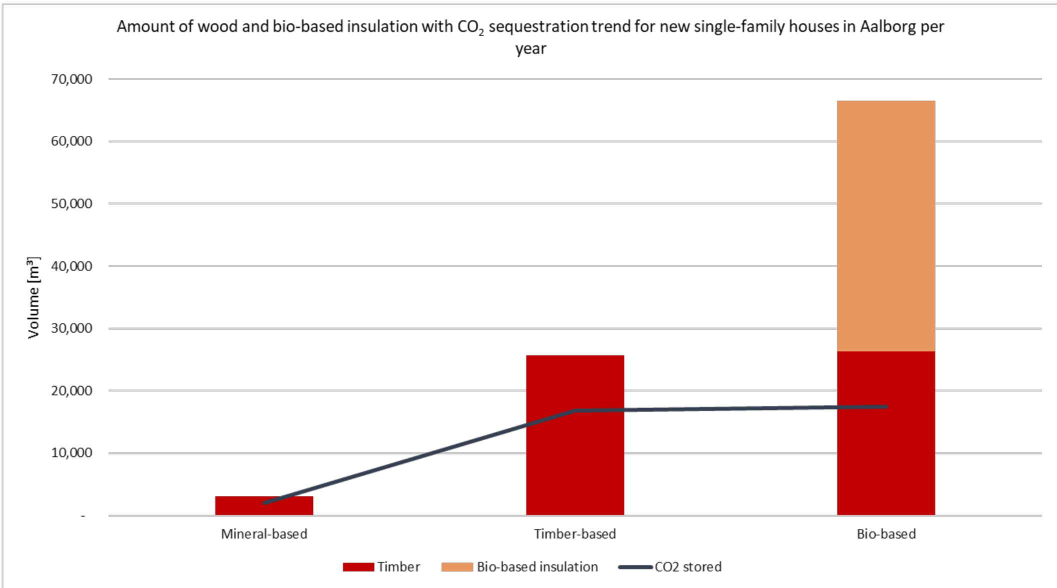


Figure 4.3: Amount of wood and bio-based insulation with CO_2 sequestration for all new single-family houses

With the replacement of the mineral wool with meadow grass insulation for the bio-based scenario, a single-family house increased the CO_2 sequestration potential to 55 tons with 82.54 m^3 of wood and 126.4 m^3 of meadow grass insulation used. Furthermore, when scaled to the city of Aalborg the CO_2 stored for a was 17 492 tons of stored CO_2 while using 26 258 m^3 of wood and 40 208 m^3 (Appendix E). Although a significant volume of bio-based insulation is used, its impact on carbon sequestration is not at all substantial. Nevertheless, it still enhances the potential for sequestration by 282 tons and demonstrates a more postive environmental impact.

4.1.2 Terraced house

The chosen case building has an area of 5402m^2 that consists of 10 separate buildings, moreover, the total annual construction of new terraced houses in Aalborg sums up to 19,864 m^2.

As visible in figure 4.4, the GWP in the production phase decreased, GWP at the end-of-life phase highly increased, meanwhile, GWP in the use phase slightly increased while substituting the mineral-based materials with the bio-based ones. Moreover, the GWP beyond the building life cycle decreased.

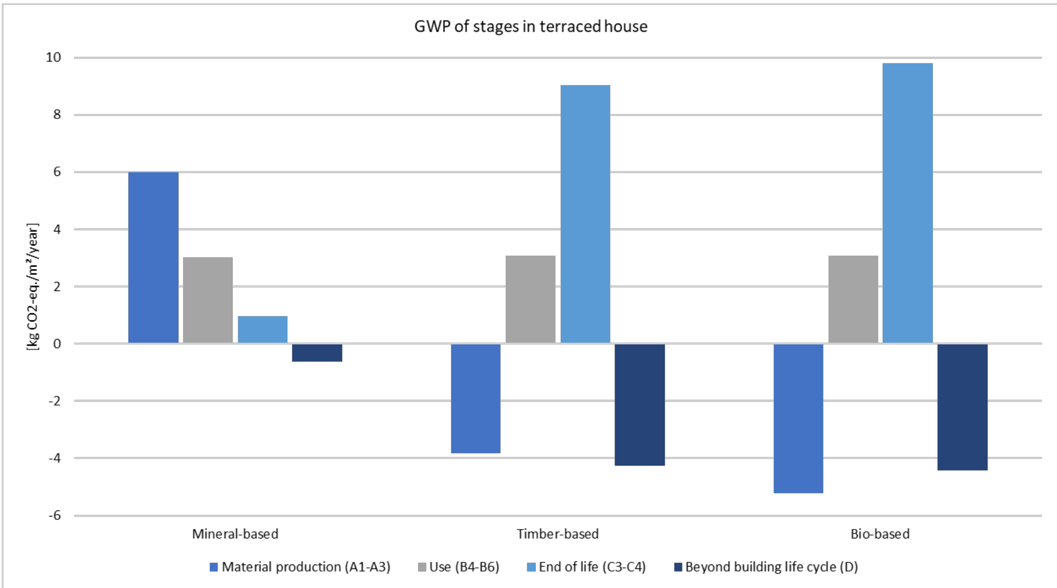


FIGURE 4.4: GWP of different stages in terraced house

The timber-based approach for the terraced house demonstrates its capacity as a carbon sink, utilizing 3 715 m^3 of wood and effectively sequestering 2 434 tons of CO_2 when scaled to the average amount of wood used and CO_2 sequestered in new terraced houses built per year it captures 8 952 tons of CO_2 and uses 13 660 m^3 of timber. This highlights the substantial carbon storage potential achievable through timber-centric construction methods. Comparatively, the mineral-based method, with minimal use of 41 m^3 of wood primarily in the finishes of building components, can sequester a modest 27 tons of CO_2. Correspondingly, the bio-based scenario presents a notable environmental impact. By integrating 3 749 m^3 of wood and 2 119 m^3 of meadow grass insulation, the construction contributes significantly to the sequestration of 2 471 tons of CO_2. This showcases the effect of incorporating bio-based materials, emphasizing the role of both wood and sustainable insulation in enhancing carbon sequestration in building practices.

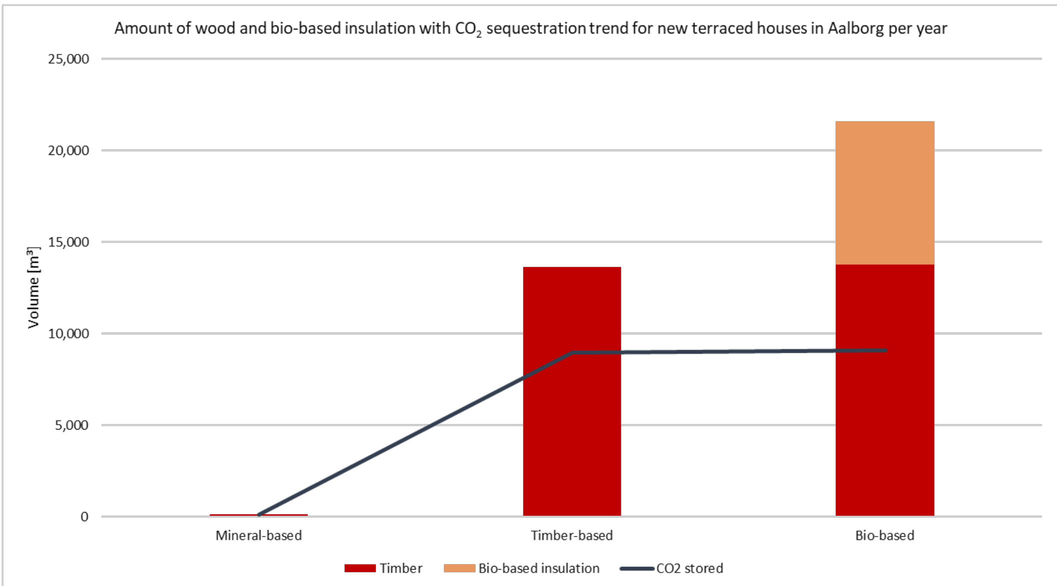


FIGURE 4.5: Amount of wood and bio-based insulation with CO_2 sequestration for all new terraced houses

When extrapolated to determine the required amount of wood it takes to build new terraced houses in Aalborg for one year, along with their carbon sequestration potential, the timber-based construction uses 26 659 m^3 of wood, resulting in a storage of 8 952 tons of CO_2. In comparison, the bio-based construction employs 26 258 m^3 of wood and 7 794 m^3 of bio-based insulation achieving sequestration of 9 089 tons throughout its life cycle, demonstrating a notable environmental impact. For a large amount of bio-based insulation utilized it only added to 55 tons of CO_2 sequestered. However, the sequestration of a small amount of carbon is still impactful.

4.1.3 Multi-story building

As visible in figure 4.6, the same trend appeared as before. An increase in GWP was observed in the usage phase (B4-B6) and at the end of life phase (C3-C4), meanwhile, a decrease in GWP was found in the production phase (A1-A3) and beyond the building life cycle (D).

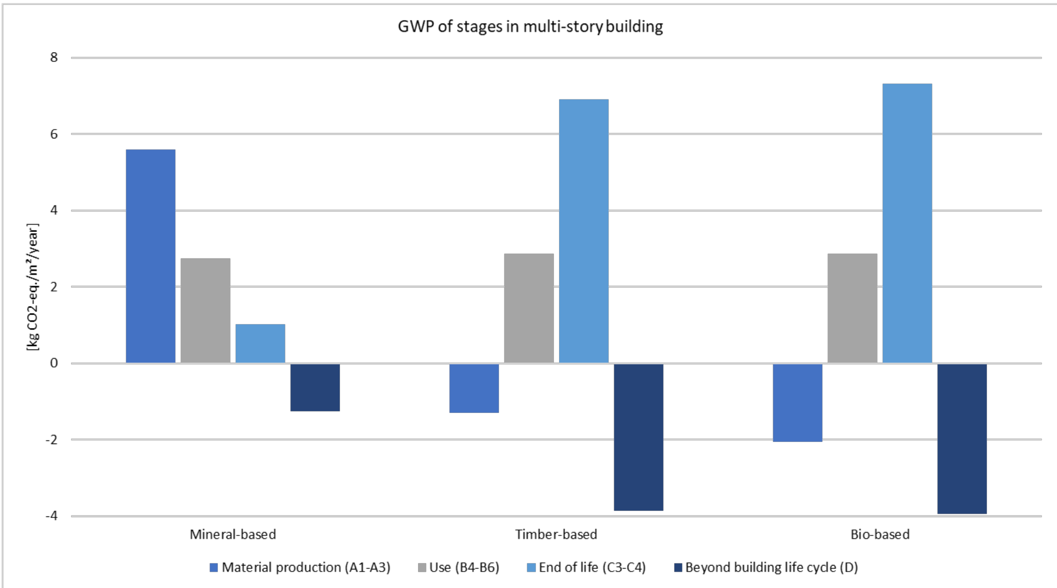


FIGURE 4.6: GWP of different stages in a multi-story building

In the context of constructing multi-story buildings in Aalborg within one year, the mineral-based construction utilizes 689 m^3 of wood, contributing to the storage of 451 tons of CO_2. In contrast, the timber-based approach requires a significantly larger volume of wood, totaling 28 554 m^3, and it yields a notable increase in carbon sequestration, storing 18 713 tons of CO_2 during its lifetime. The bio-based construction, employing 28 678 m^3 of wood, and 14 531 m^3 of meadow grass insulation demonstrates a slightly higher wood usage than the timber-based scenario and a significant use of bio-based material. Meanwhile, it contributes to a similar amount of carbon sequestration from timber-based construction, storing 18 896 tons of CO_2 with the addition of the meadow grass which only added a carbon sequestration potential of 102 tons of CO_2.

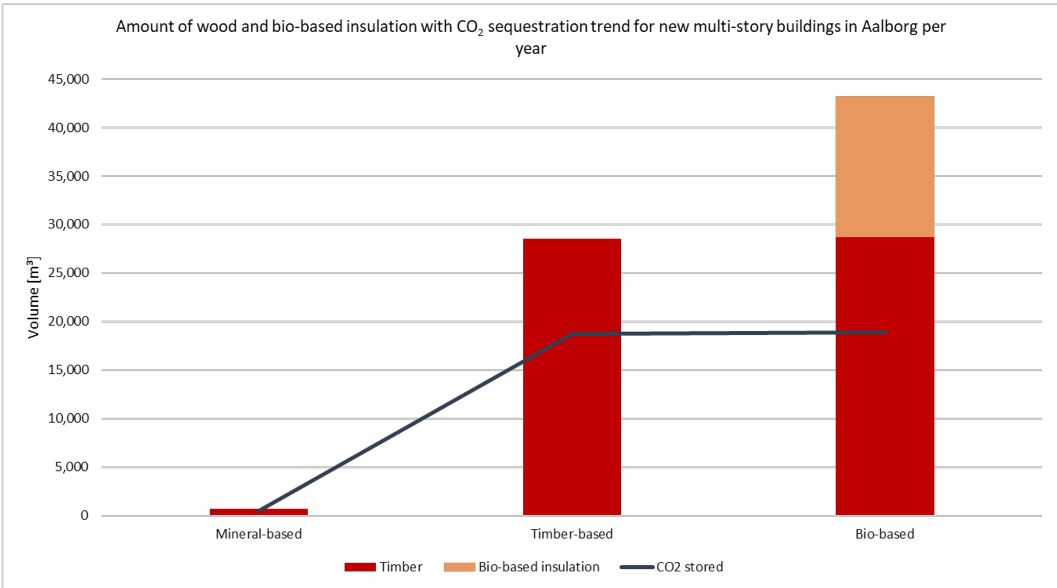


FIGURE 4.7: Amount of wood and bio-based insulation with CO_2 sequestration for all new multi-story buildings

4.1.4 Office building

As visible in figure 4.8, the trend of overall increase and decrease in GWP was similar to the figures before. However, it can be observed that the GWP in the usage phase (B4-B6) did not increase as much as before. Moreover, the GWP value in the production phase (A1-A3) is positive in the timber-based solution, while in other case buildings, this number was always negative. This is possible due to the large amount of wood and using the -1/+1 approach in the LCAbyg, therefore it can be observed that the bio-based solution has the highest C3-C4 value due to the same reason.

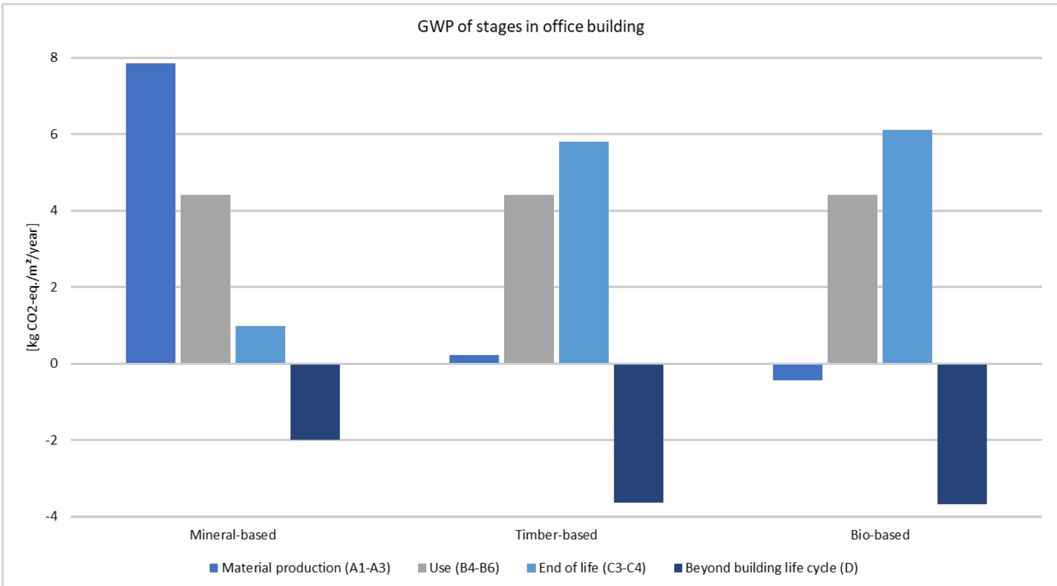


FIGURE 4.8: GWP of different stages in office building

In timber-based construction, a volume of 3 758 m^3 of wood is employed, allowing for the sequestration of 2 463 tons of CO_2. Similarly, the bio-based construction utilizes a comparable amount of wood, totaling 3 777 m^3, leading to a CO_2 sequestration of 2 475 tons. Notably, the inclusion of meadow grass in the bio-based scenario contributes an additional 22 kg of CO_2 sequestration, using 3 167 m^3 of this renewable insulation.

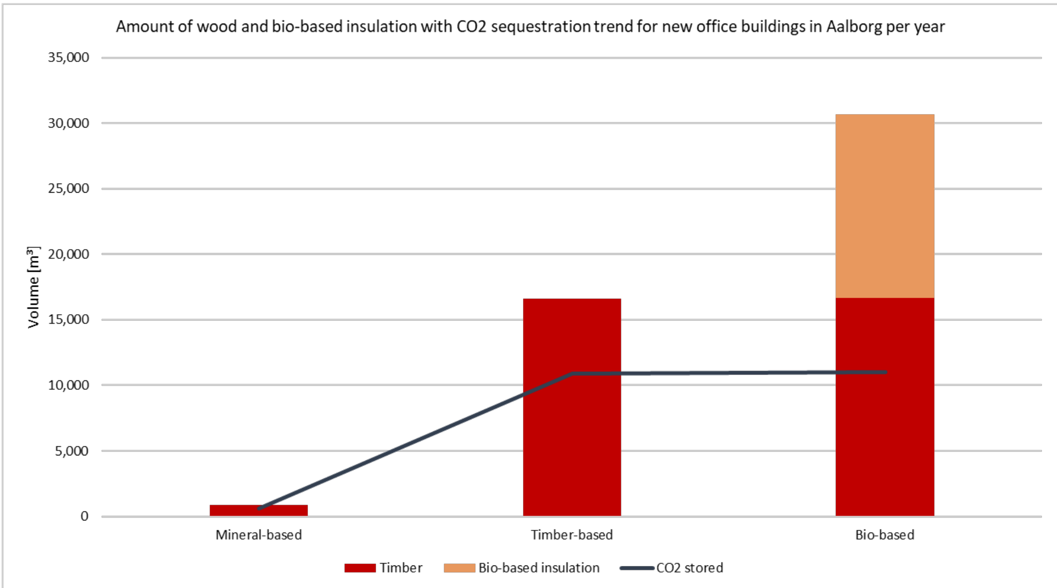


FIGURE 4.9: Amount of wood and bio-based insulation with CO_2 sequestration for all new office buildings

When scaled to the average amount of wood used in new office buildings built per year in the city of Aalborg, the estimated amount of wood used for the conventional way of construction is 880 m^3 which results in a potential to sequester 576 tons CO_2. The timber and bio-based construction uses 16 607 m^3 and 16 689 m^3 respectively. However, the bio-based construction uses 13 996 m^3 which makes this method sequester a little more carbon dioxide. timber-based scenario potentially can sequester 10 883 tons of CO_2 while bio-based construction sequesters 10 937 tons of CO_2 from timber and 98.45 tons from the meadow grass insulation.

4.2 Total results

4.2.1 Carbon sequestration

Based on the patterns observed in the results of different scenarios of the case buildings, an increase in the use of wood, as a substitute for concrete, corresponds to a decrease in Global Warming Potential (GWP), as well as enhancing the potential for carbon sequestration significantly. In addition, the amount of bio-based insulation, relative to its carbon sequestration potential, is comparatively low. Nevertheless, it still effectively sequesters carbon, making it a sustainable option worth considering.

The contrast in carbon sequestration potential between mineral-based and bio-based structures emphasizes the crucial role of construction materials in influencing the environmental footprint of both residential and non-residential buildings.

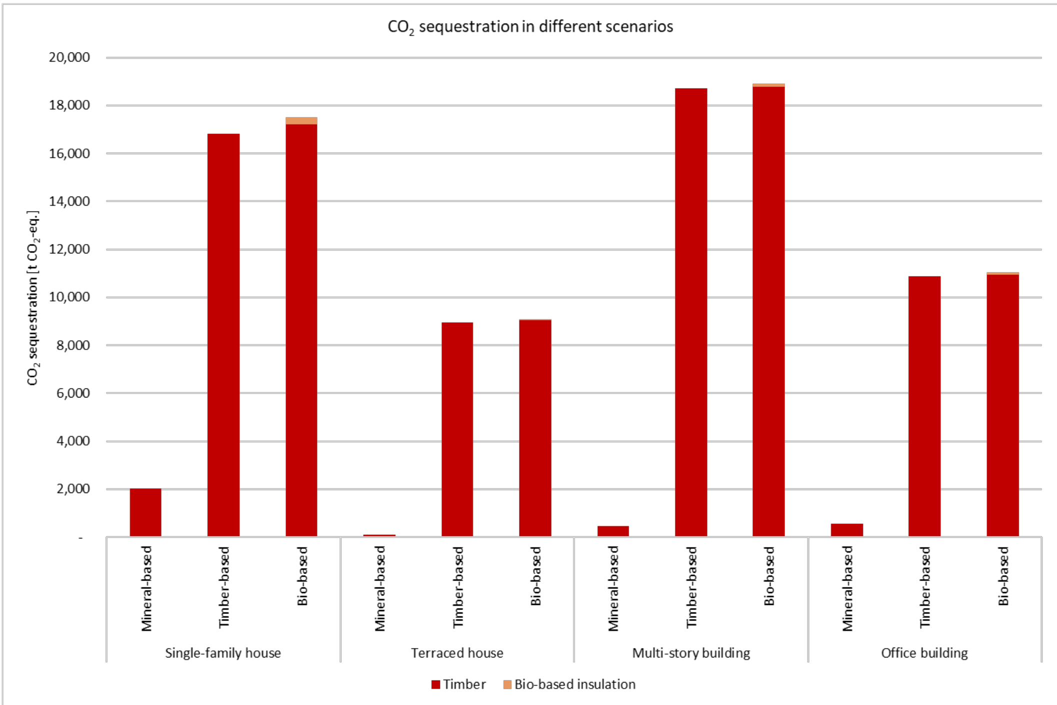


FIGURE 4.10: CO_2 sequestration of different construction scenarios

To illustrate the relation between storage and emissions from different materials, the graph below was created. To get the value of the emissions, the GWP of timber was multiplied by 50 years so it is comparable to the storage for its whole life span. As visible in figure 4.11, which represents storage and emissions from using timber in all new construction built in Aalborg during 50 years, timber stores approximately 6 times more carbon dioxide than what is needed to produce it. Constructing single-family houses with wood could already store above 17 000 tons of CO_2 which is equivalent to the yearly emissions from 5 666 Danes.

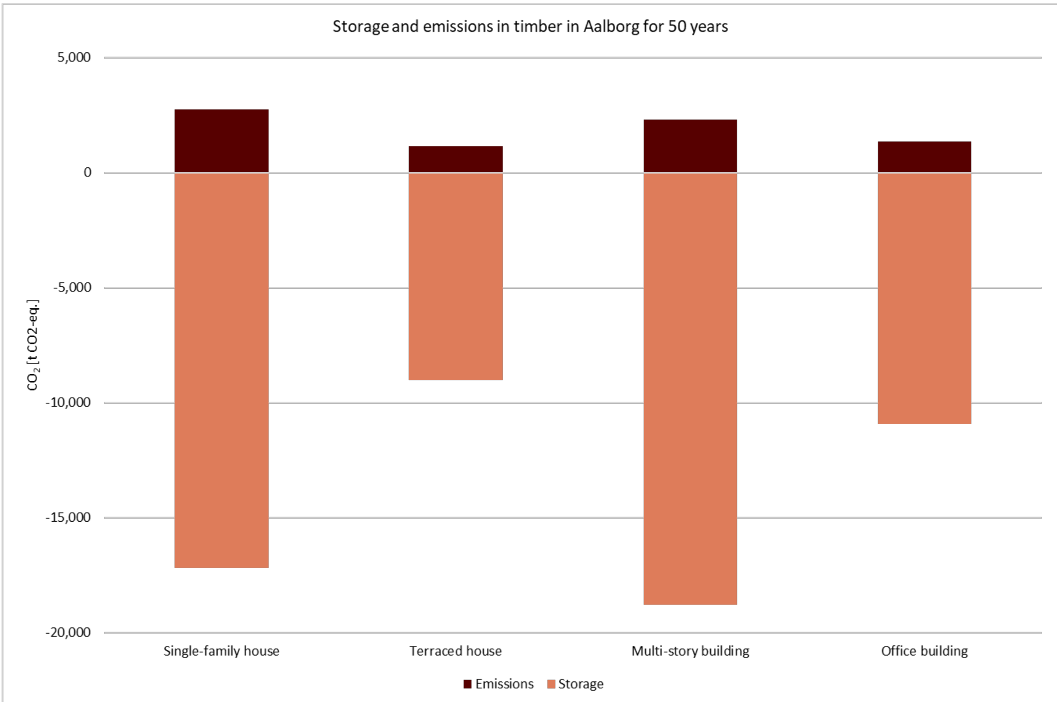


FIGURE 4.11: Storage and emissions in timber

On the other hand, as visible in figure 4.12 which represents storage and emissions from meadow grass insulation in all new construction built in Aalborg for 50 years, CO_2 emitted from producing the insulation is higher than the CO_2 it can store. However, it stores around 85% of the CO_2 it produces, meanwhile, mineral insulation has no carbon sequestration properties.

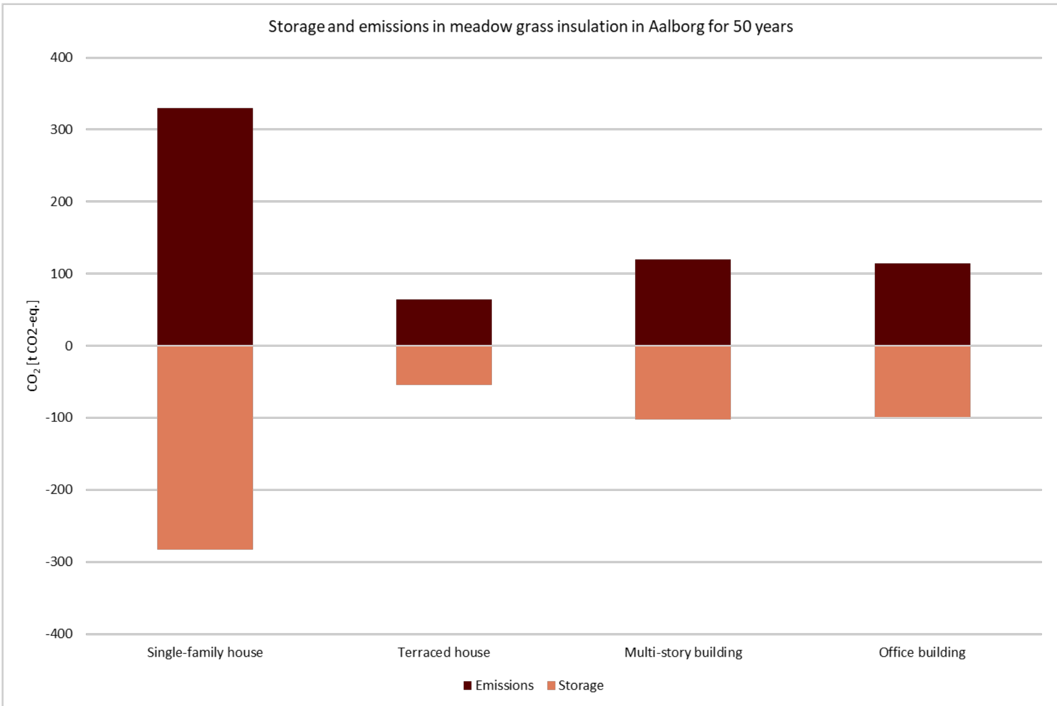


FIGURE 4.12: Storage and emissions in the meadow grass insulation

Each person in Denmark emits on average 3 tons of CO_2 equivalents per year [Erdes, 2022]. When multiplying it with Aalborg's population of 222 571 people [Danmarks Statistik, 2023], it gives the result of 667 713 tons of CO_2 equivalents in Aalborg per year.

If all the new single-family houses, terraced houses, multi-story buildings, and office buildings were built according to the bio-based scenario, they would store 56 513 tons of CO_2 equivalents, which is equivalent to yearly emissions of 18 837 Danes which is 8.4% of Aalborg population.

The large amount of use of timber in the timber and bio-based structures is balanced by their significantly greater potential for carbon sequestration. This underscores the significance of choosing construction materials with a comprehensive consideration of both their environmental impact and their ability to capture carbon throughout their life cycle. This approach aligns with sustainable construction practices and efforts to mitigate climate change.

4.2.2 Timber consumption and its effect on forest

Denmark harvests 3.1 million m^3 of wood annually, and around 10 percent of the harvested wood is used in the construction industry, leaving it at 310 000 m^3/year. Furthermore, out of the wood that is used in the building industry, 28% is spruce wood that can be used for CLT and the timber framing in the scenarios [Kofod, 2018].

When the wooden components of the building were analyzed, it resulted with the following numbers as shown in figure 4.13, indicating that the building component that tends to use the largest quantity of timber is the floor deck which is 41% of the entire building followed by the internal walls with 25% and then external walls with 24%. All the other values are below 5%.

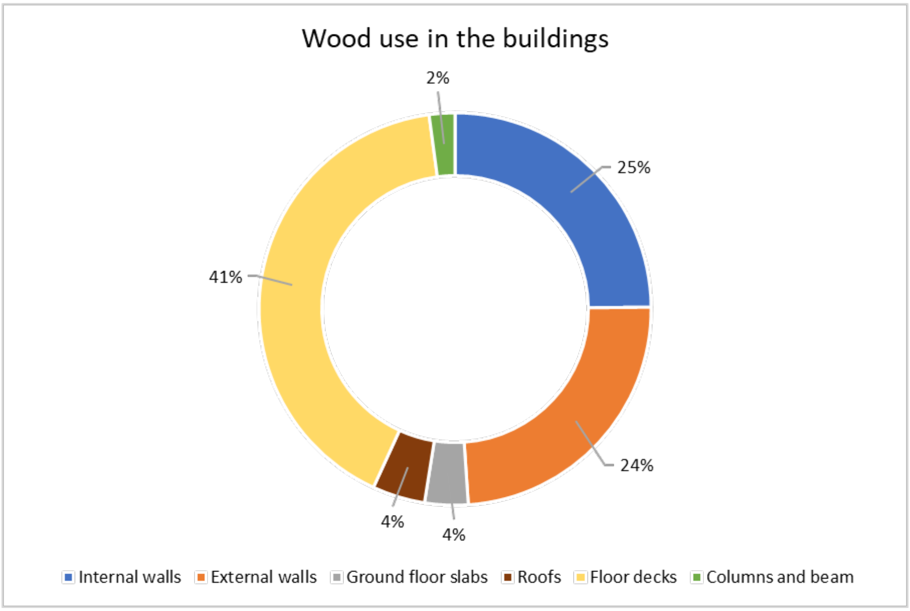


FIGURE 4.13: Percentage of wood used of each building component

In terms of carbon sequestration and wood consumption, this information implies that the floor deck and walls are significant contributors to the overall timber consumption in the building. Additionally, it suggests that these components likely play a crucial role in carbon sequestration.

If Aalborg constructs all new residential buildings and offices with wood for a year it will use an estimated 85 411 m^3 of timber which is equivalent to 3.95 km^2 of spruce trees forests harvested or 395 hectares, which is the size of 533 football fields.

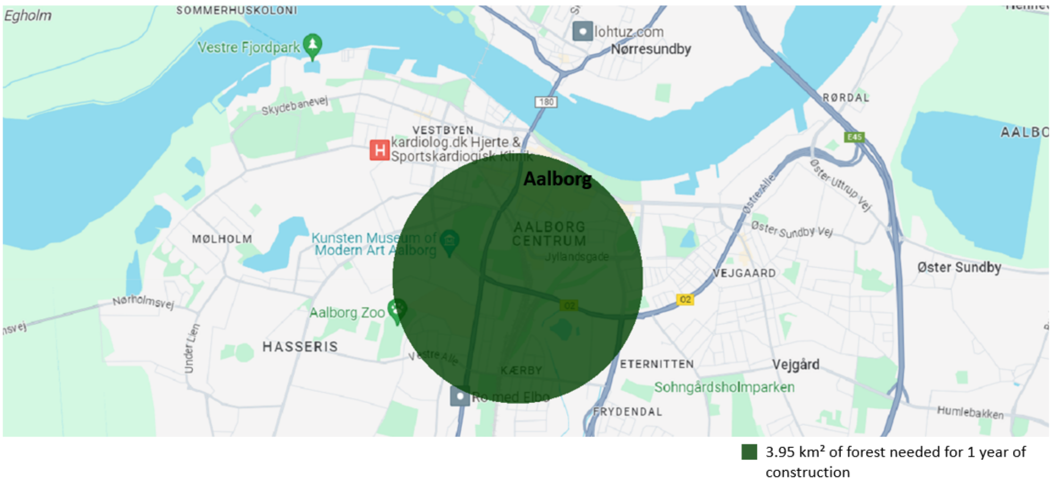


FIGURE 4.14: Map of the necessary forest area to build with wood for the bio-based scenario for 1 year

Furthermore, planting a forest as the only source for bio-based construction would require 197.5 km^2 of forest, which is about 4 times bigger than the city of Aalborg, which is visible in figure 3.1. This calculation required multiplying the necessary yearly forest area by 50 years in order to ensure a sustainable cycle. As visible in the figure, the dark green represents 1/50th of the area reflecting the possibility of planting this much of a forest every year for 50 years.

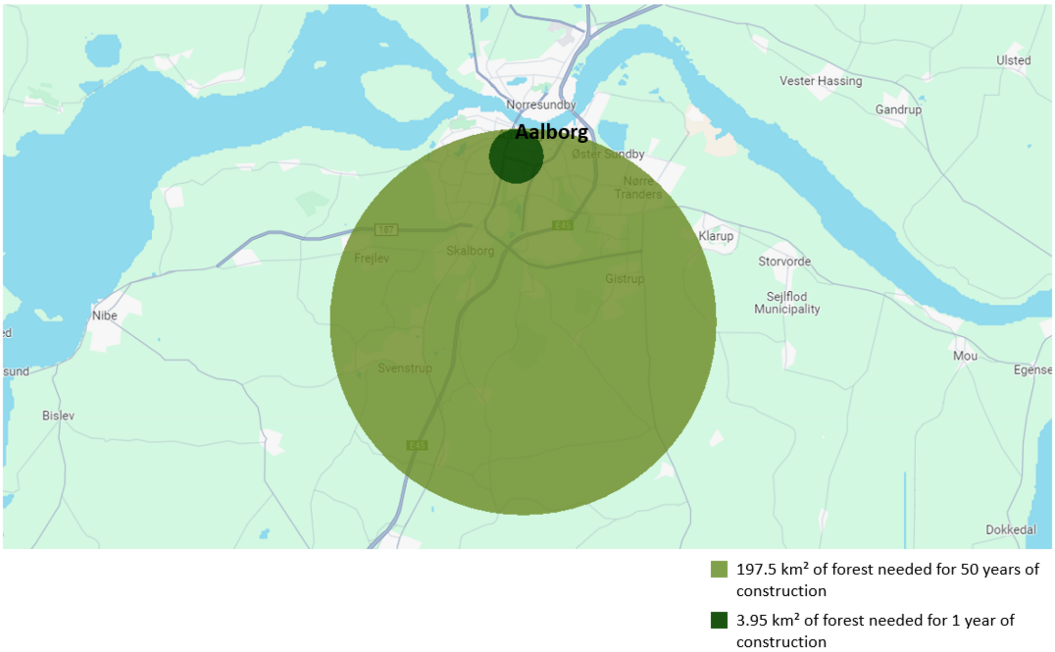


FIGURE 4.15: Map of the necessary forest area to build with wood for the bio-based scenario for 50 years

Lastly, the final figure 4.16 shows the necessary area for 50 years on a scale of the whole of Denmark.

FIGURE 4.16: Map of the necessary forest area to build with wood for the bio-based scenario

Chapter 5

Discussion

The outcome of this research has provided insight into the differences in the carbon footprint of mineral-based construction, timber-based construction, and bio-based construction. The first goal was to find a difference in the environmental impact between different materials. Results indicated that bio-based construction has the lowest Global Warming Potential in every case building, meanwhile, the highest GWP was in mineral-based construction. Moreover, data suggests that if all the new buildings were built with the bio-based solution instead of the mineral-based construction, they could save 10.14 kg CO_2-eq./m^2/year.

The second goal of this research was to find the quantity of wood necessary to build all the new buildings with the bio-based solution. Results indicated that the necessary amount of wood to build all new residential buildings and offices with bio-based construction, which has the highest amount of wood out of the three scenarios, is around 85 411 m^3.

The third goal was to find the necessary forest area and the different approaches to wood sourcing. Data suggests that Aalborg would need 3.95 km^2 of spruce forest per year. To have a sustainable cycle, it would require to have 197.5 km^2 of forest area, which is four times bigger than the whole city.

Due to the large amount of timber needed for Aalborg, three solutions for solving this issue were analyzed. The first solution is to locally source wood and limit it to only the amount of wood available in Aalborg, which is approximately 6 200 m^3/year (Appendix D). This amount of wood is enough to build approximately 74 single-family houses in bio-based construction. This means that the rest of the buildings would be built using mineral building materials.

The second solution is afforestation which means planting an enormous forest of 197.5 km^2 for Aalborg and using it as the only source of wood. This solution would provide the city with a renewable and sustainable supply of wood. Moreover, it would be a step towards increasing the forest area in Denmark, wherein the goal is to increase Denmark's forest area from 15% to 20-25% by the year 2100 [Einfeldt, 2018].

Lastly, the third solution is a combination of local and imported wood using all of the available wood in Aalborg and importing the rest from the nearby countries. It would ensure that the local needs are met while the local wood supply is limited.

There is no ideal solution in and of itself because each has its own drawbacks. The first solution requires building almost only with mineral construction materials, which means higher environmental impact, and therefore taking no action in fighting the climate crisis. Meanwhile, the second one requires changing the whole area around Aalborg. While planting more forests is a great idea, doing it in a very short time on a very big scale requires a lot of thought and high-skilled planning not to cause any disruptions to the ecosystem. One of the methods for increasing the forest area could be planting 1/50 of the required forest area every year, and gradually reaching the desired amount in 50 years. However, even in the gradual approach, it will take 50 years from the time the trees were planted until they can be harvested. Furthermore, it can be a valid solution for a city scale, but it would be difficult to scale it to a country level since it would require a drastic change in the whole landscape of Denmark. Lastly, the third solution, which is used today, seems like the best choice out of the three, however, the drawback is that it adds CO_2 emissions to the atmosphere from transportation.

Therefore, after an analysis, the chosen method of sourcing timber is a mix of second and third solutions. Afforestation should be done by Aalborg to have more locally sourced wood, however, it does not need to cover 100% of the demand. This mix of solutions would lower the environmental impact of transportation and simultaneously capture more CO_2 from the atmosphere.

The last goal was to determine the amount of carbon that can be sequestered while building with the bio-based solution. If all the newly analyzed residential buildings and office buildings were built using bio-based construction, which means using timber as a structural material, and meadow grass as an insulation material, they could store 56 513 tons of CO_2 equivalents. The study shows that it could cover yearly emissions of approximately 8% of Aalborg's population.

The reliability of the results is limited by the lack of structural analysis, which was not done due to the limited time. Instead, the structural sizes of the non-load-bearing mineral materials were also used for the timber and bio-based construction. When it comes to the load-bearing construction parts, the chosen sizes of timber were based on other building cases that had similar structural systems. Therefore future studies should take into account the sizes of the structural materials while changing scenarios from mineral-based to timber.

Moreover, due to the lack of data regarding the economic value, the research cannot indicate the feasibility of the construction choice. For that reason, further research is needed to establish the economic values of different materials.

Furthermore, it is crucial to acknowledge that in order to get the timber-based and bio-based scenarios, the mineral materials were simply substituted with the bio-based ones and adjusted to have the same U-value without any optimization. Optimization could significantly lower the global warming potential in all case buildings, however, it was not the main focus of this study. Therefore, future studies are necessary to investigate the maximal possibilities of lowering the environmental impact of bio-based construction.

Chapter 6

Conclusion

In conclusion, this research examined the environmental impact of four case buildings with three different scenarios- mineral-based, timber-based, and bio-based construction. The findings show that the mineral-based construction had the highest Global Warming Potential in all four case buildings. Meanwhile, bio-based construction which uses timber as a structural material and meadow grass as an insulation, consistently had the lowest environmental impact.

Another data found was that the amount of wood required for building new structures in Aalborg with bio-based construction would require 85 411 m^3 per year. This amount of wood used would require 3.95 km^2 of spruce forest harvested per year or 197.5 km^2 for 50 years in order to maintain a sustainable cycle.

This led to analyzing three different wood sourcing methods to fulfill the amount of wood required in Aalborg. While the first solution (locally sourced wood) leads to limited use of timber construction and enforces the conventional way of building, the second and third methods (afforestation and combination of local and imported wood) ensure that the amount of wood required for building new construction with timber is fulfilled. However, each solution independently, has its own drawbacks, such as an extended timeline to observe the desired effect or additional emissions from transportation.

Considering the drawbacks, a combination of afforestation (second solution) and importing the remaining wood (third solution) is suggested. This hybrid solution lowers the environmental impact of transportation, while actively acting on Denmark's goal of increased forest area.

The research also looked into the carbon sequestration potential of building with bio-based materials. Results showed that when changing from mineral materials to bio-based materials, new construction in Aalborg within a year can sequester 56 513 tons of CO_2.

Nevertheless, the study needs to acknowledge its limitations. A lack of structural and economic analysis narrows the study down to only the environmental aspects. Therefore, future studies should look into those two aspects to get a full overview of the implications when substituting mineral-based construction with bio-based materials.

In summary, bio-based materials promise a lower environmental impact and high carbon sequestration but require a large amount of timber resulting in new sustainable sourcing methods.

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