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The Potential of Bio-based Building Materials to Contribute to Reducing Global Warming

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Abstract

This study investigates how bio-based materials influence the climate impact of buildings compared with conventional and alternative material choices. The analysis focuses on Danish single-family houses and evaluates construction scenarios representing different building technologies: a bio-based scenario using exclusively bio-based material; a mineral-based scenario reflecting conventional constructions with mineral-based materials; a hybrid scenario combining bio-based and mineral-based materials; and an optimized mineral-based scenario employing low-impact, production-optimized mineral-based materials. All scenarios are assessed using both static and dynamic Life Cycle Assessment approaches, with Global Warming Potential as the primary indicator. The dynamic Life Cycle Assessment results show that bio-based materials can substantially reduce the climate impact of buildings in the short to medium term due to the temporary storage of biogenic carbon. Fast-growing biomass species exhibit the highest mitigation potential. In contrast, materials with longer rotation periods are more sensitive to methodological assumptions. The static approach aggregates emissions over the entire life cycle and considers biogenic carbon uptake as climate neutral, leading to differences in the resulting impact estimates. Despite the methodological differences, both approaches consistently indicate significant climate benefits of bio-based materials compared with mineral-based alternatives.

Keywords: *Bio-based materials · Static Life Cycle Assessment · Dynamic Life Cycle Assessment · Global Warming Potential · Biogenic carbon sequestration*

1.0 Background

Climate change is intensifying, and the world is increasingly experiencing floods, droughts, and extreme weather events, which are attributable to global warming. The year 2024 was the warmest on record, and the likelihood of limiting the increase in global average temperature to 1.5 °C by 2050, as stipulated in the Paris Agreement, is now considered low [1]. The construction sector plays a significant role in climate change and is among the largest contributors to global CO_2 emissions. The sector contributes both directly, through material production and construction activities, and indirectly, through energy consumption [2]. According to the United Nations Environment Programme, the construction sector accounts for 37% of global emissions [3]. Of this total, approximately 23% can be attributed to the production and transportation of construction materials, with more than half of these emissions originating from the production of steel and cement [4].

Historically, efforts to reduce the climate impact of buildings have primarily focused on the operational phase, through measures such as improved energy efficiency and the use of renewable energy sources [5]. However, more recent studies emphasize the need to address additional phases of the building life cycle in order to achieve substantial reductions in CO_2 emissions and meet the climate targets [4]. Consequently, increasing attention is being directed towards alternative material choices [5]. In this context, bio-based materials have emerged as a key area of focus, as their use can reduce carbon emissions associated with material production by relying on renewable sources and by sequestering CO_2 doing growth [6].

Bio-based materials are derived from biological organisms such as trees and plants. These materials include, among others, fast-growing crops such as hemp and straw, slow-growing tree species, and marine plants such as seaweed and eelgrass [6]. Bio-based materials can largely meet the same functional requirements as mineral-based materials, including load-bearing capacity, fire resistance, durability, and thermal performance [7]. A key advantage of bio-based materials is their ability to capture and store carbon from the atmosphere [8].

During growth, bio-based materials absorb carbon through the process of photosynthesis and typically consist of approximately 50% carbon by mass [6]. Of the sequestered carbon, approximately 50-65% is stored in the stem, while 20-30% is retained in the root system [9]. The carbon stored in bio-based materials contributes to climate change mitigation by delaying the release of CO_2 into the atmosphere while simultaneously promoting the regrowth of new plants and trees. Over time, this system can be considered nearly carbon-neutral, provided that forest management practices are sustainable [10]. In this way, the progression of climate change is delayed, creating time for transition until more permanent carbon storage solutions become feasible [7]. The rate at which CO_2 is removed from the atmosphere depends on the growth rate of bio-based materials. Regrowth periods range from less than one year for certain agricultural crops to 45-120 years for trees [7]. In Danish constructions, spruce and pine are primarily used, with rotation periods of approximately 60 years [11]. In conventional constructions, the majority of carbon emissions occur during the production phase (A1-A3) [12], as materials such as cement, metals, and glass require large amounts of energy or release carbon through chemical processes, for example during steel production [13]. In contrast, for bio-based materials, most carbon emissions occur at the end of the material life cycle (C3-C4), when the stored carbon is released through decomposition or combustion [12]. In addition, many bio-based materials can be utilized for energy recovery through combustion [12].

2.0 Goal and Scope

In recent years, the primary focus has been on reducing operational carbon emissions, as these constitute the majority of the total emissions from the construction sector [3]. However, the proportion of emissions associated with construction materials is expected to increase in the coming years, as electricity grids transition to renewable energy and building operations become more efficient [3]. Consequently, greater attention should be directed towards reducing the climate impact at the construction stage.

The aim of this study is to investigate the extent to which bio-based constructions can reduce climate impact compared with traditional and alternative building methods. The analysis focuses on Danish single-family houses, including detached-, terraced-, chain-, and semi-detached houses. According to data from JAJA-Architects and Realdania, single-family houses account for approximately 29% of total new constructions by floor area [14]. Calculations in this study are primarily presented for detached houses, while results for other housing types are provided in Appendix J and K.

3.0 Method

3.1 Workflow

The methodology of this study is structured in several steps. First, construction requirements as well as material property requirements are analyzed. Based on this analysis, relevant materials are selected for an in-depth assessment, focusing on their Global Warming Potential. The results of the material assessment then serve as the basis for modelling four construction scenarios. These scenarios are subsequently used to evaluate and compare the environmental impact of the buildings from both a static Life Cycle Assessment perspective and a dynamic Life Cycle Assessment approach. A visualization of the workflow is presented in Figure 1.

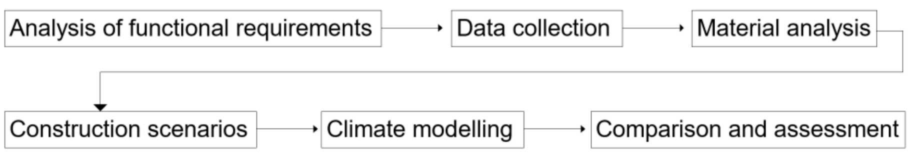


Figure 1 Workflow visualization

3.2 Subject of methodology

The following scenarios are examined and compared in this study:

1. **Scenario 1**: **Traditional** Mineral-Based Construction
   This scenario represents conventional building practices using mineral-based materials.

2. **Scenario 2**: **Optimized** Traditional Mineral-Based Construction
   Based on the traditional design, this scenario incorporates climate-optimized materials to reduce the building's environmental footprint.

3. **Scenario 3**: **Hybrid** Construction
   This scenario combines both mineral-based and bio-based materials

4. **Scenario** 4: **Bio-Based** Construction
   This scenario consists entirely of biobased materials

3.3 Life Cycle Inventory

The purpose of the Life Cycle Inventory is to collect and quantify data on resource use and emissions throughout the product's life cycle, providing the basis for the Life Cycle Assessment. Data for the Life Cycle Inventory were obtained from research articles, reports, manufacturer datasheets, and Environmental Product Declarations. These data are used to analyze and compare selected materials, with a focus on their individual climate impacts. All Environmental Product Declarations used in this study are listed in Appendix A.

Materials were selected based on a review of available bio-based and mineral-based products with Environmental Product Declarations prepared in accordance with DS/EN15804 [15]. The review covers all components included in the primary building elements. Fasteners are excluded, in accordance with BR18, Annex 2, Table 6.

Each material is assessed based on its climate impact per m^2. Service lives are defined, as specified in BUILD's service life table [16]. Transport emissions (A4) were calculated using the distance-based approach [17]. Further details are provided in Appendix B. This method was chosen because transport emissions reported in Environmental Product Declarations can be difficult to compare due to varying assumptions and calculation methods, for example regarding distances and modes of transport [18]. Transport distances were therefore determined from nearest production site to Aarhus to establish a common reference point, ensuring a consistent calculation method.

To ensure comparability between materials, functional requirements for insulation materials were set at a minimum of 0,12 W/m^2K. Load-bearing solid elements were assessed based on structural requirements, while framed constructions were evaluated according to insulation criteria, meaning that dimensions of comparable materials may vary. All other materials were compared on a one-to-one basis. In the final material selection, additional considerations regarding functional requirements on the construction level were also taken into account.

The applied standards for construction and construction products, including EN15978 and EN15804 prescribe a specific method for accounting for carbon, as defined in DS/EN16449 [19]. In accordance with these standards, the -1/+1 method is used to handle biogenic carbon. This means that biogenic CO_2 absorbed during forest growth is recorded as a negative emission in module A, while its release at the building's end-of-life is recorded as a positive emission in module C. The overall biogenic carbon balance is therefore considered neutral [4].

The material assessment encompasses the life cycle from cradle to grave and includes the following phases, selected in accordance with the applicable climate requirements in the building regulations:

- Production phase (A1-A3)
- Construction phase (A4-A5)
- Replacement (B4)
- End-of-life (C3-C4)

Operational energy use (B6) is not included, as the focus is solely on material-related impacts.

The material assessment and the final evaluation serve as the basis for modelling the construction scenarios. The four scenarios include all primary building envelope components (roof, exterior walls, and ground floor slab). The analysis is limited to the building envelope, as these components account for the largest material consumption and, consequently, the most significant climate impact [20]. The total area of each building component was calculated based on area factors per heated floor area, derived from the Energy Performance Certificate Database. For further details see Appendix C.

The reference period for the building's life cycle is set at 50 years, while the climate impacts are calculated over a 100-year time horizon. This approach ensures comparability with the method described in EN15978 and with the climate requirements of the building regulations.

3.4 Life Cycle Impact Assessment

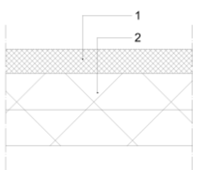
The purpose of the Life Cycle Impact Assessment is to evaluate how the use of bio-based materials influences the overall climate footprint of buildings.

The four selected scenarios form the basis for the final comparison and assessment of the impact of bio-based materials. All scenarios are based on widely recognized construction methods that comply with current functional requirements for moisture (SBI279), fire safety (according to guidance for pre-approved solutions for single-family houses), U-value (in accordance with building regulations), and structural performance (based on supplier calculations as well as calculations conducted for this study). A detailed list of relevant functional requirements is included in Appendix D.

The scenarios are presented below:

Ground Floor Slab

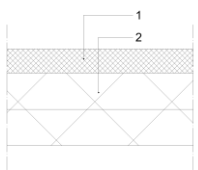
Scenario one:
Mineral-based



1: 100mm concrete IBF
2: 300mm EPS Sundolitt

Thickness: 400 mm
U-Value: 0,13 W/m² K

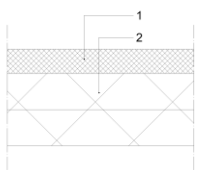
Scenario two:
Mineral-based Optimized



1: 100mm concrete Futurecem
2: 300mm EPS BEWI

Thickness: 400 mm
U-Value: 0,13 W/m² K

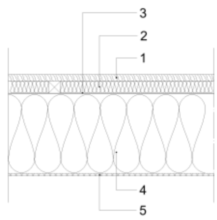
Scenario tree:
Hybrid



1: 100mm concrete Futurecem
2: 300mm EPS BEWI

Thickness: 400 mm
U-Value: 0,13 W/m² K

Scenario four:
Bio-based

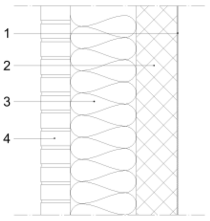


1: 25mm Spaandex subfloor
2: 45mm battens
Incl. hemp insul. – c/c 600mm
3: vapor barrier
4: 45 x 300mm construction wood
incl Hamp insul. – c/c 600mm
5: 9mm fiber cement

Thickness: 381 mm
U-Value: 0,13 W/m² K

External Wall

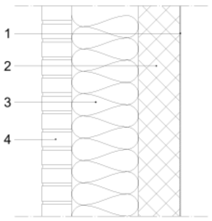
Scenario one:
Mineral-based



1: 3mm multi-coat plaster
2: 100mm H+H multiblock
3: 245mm Rockwool insulation
4: 108mm Wienerberger brick EW2440

Thickness: 506 mm
U-Value: 0,12 W/m² K

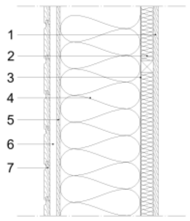
Scenario two:
Mineral-based Optimized



1: 3mm multi-coat plaster
2: 100mm Baurock multiblock
3: 245mm Rockwool insulation
4: 108mm Wienerberger brick EW494 LESS

Thickness: 506 mm
U-Value: 0,12 W/m² K

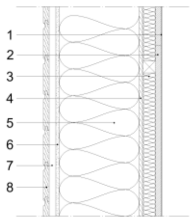
Scenario tree:
Hybrid



1: Int. wood cladding
2: 45 x 45 mm battens
Incl glasswool insul. - c/c 600mm
3: Vapor barrier
4: 45 x 295mm construction wood
incl. glasswool insul. c/c 600mm
5: 12mm Hunton Windtight (wood)
6: 25mm imp. battens c/c 600mm
7: 21mm cedar

Thickness: 419 mm
U-Value: 0,11 W/m² K

Scenario four:
Bio-based

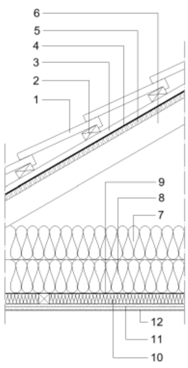


1: 3mm clay plaster
2: 22mm hemp board
3: 45 x 45 mm battens
Incl. hemp Iso - c/c 600mm
4: 15mm OSB4 (vapor retarder)
5: 45 x 345mm construction wood
Incl. hemp insul. – c/c 600mm
6: 12,5mm Wind board (Gypsum)
7: 25mm imp. vent. battens
c/c 600mm
8: 21mm Cedar

Thickness: 436 mm
U-Value: 0,11 W/m² K

Roof (ventilated attic)

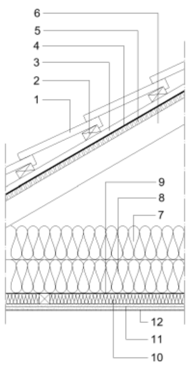
Scenario one:
Mineral-based



1: Roof tile - Højslev
2: 38mm battens c/c 600mm
3: 25mm imp. battens c/c 600mm
4: Roofing felt
5: 22mm plywood
6: 45 x 195mm rafter
c/c 600mm
7: 95 mm glasswool insulation
8: 45 x 195 mm ceiling joist
Ickl. glasswool insul. - c/c 600mm
9: Vapor barrier
10: 45 x 45 mm battens
Incl. glasswool insul. - c/c 600mm
11: 25mm Gyproc Normal (2stk)
12: 3mm multi-coat plaster

U-Value: 0,12 W/m² K

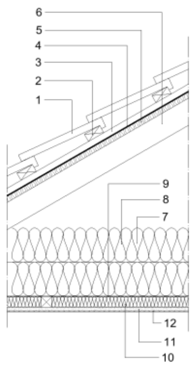
Scenario two:
Mineral-based optimized



1: Roof tile -Højslev
2: 38mm battens c/c 600mm
3: 25mm imp. battens c/c 600mm
4: Roofing felt
5: 22mm plywood
6: 45 x 195mm rafter
c/c 600mm
7: 95 mm glasswool insulation
8: 45 x 195 mm ceiling joist
Incl. glasswool insul. - c/c 600mm
9: Vapor barrier
10: 45 x 45 mm battens
Incl. glasswool insul. - c/c 600mm
11: 25mm Gyproc ErgoLite (2stk)
12: 3mm multi-coat plaster

U-Value: 0,12 W/m² K

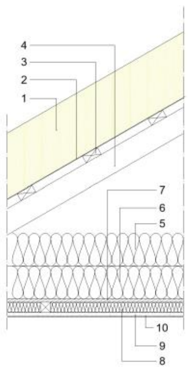
Scenario tree:
Hybrid



1: Roof tile -Højslev
2: 38 x 73mm battens c/c 600mm
3: 25mm Imp. battens c/c 600mm
4: Roofing felt
5: 22mm plywood
6: 45 x 195mm rafter
c/c 600mm
7: 95 mm hemp insulation
8: 45 x 195 mm ceiling joist
Incl. hemp insul. - c/c 600mm
9: Vapor barrier
10: 45 x 45 mm battens
Incl. hemp insul. - c/c 600mm
11: 22mm hemp board
12: 3mm clay plaster

U-Value: 0,12 W/m² K

Scenario four:
Bio-based



1: 300mm hatched roof
2: Glass-fiber mat
3: 38mm battens c/c 600mm
4: 45 x 195mm rafter
5: 95 mm hemp insulation
6: 45 x 195 mm ceiling joist
Incl. hemp Isul. - c/c 600mm
7: 15mm OSB4 (Vapor retarder)
8: 45 x 45 mm battens
Incl. hemp insul. - c/c 600mm
9: 22mm hemp board
10: 3mm clay plaster

U-Value: 0,12 W/m² K

The traditional scenario is modelled using only conventionally applied materials, while the remaining scenarios are designed to minimize climate impact. However, there are some deviations from the overall construction principles due to applicable requirements.

In the bio-based scenario, a mineral-based wind barrier is included to satisfy fire safety requirements. Additionally, a plastic vapor barrier is used in the floor construction to comply with the required Z-value.

In the hybrid scenario, glass wool insulation is employed, despite not having the lowest Global Warming Potential. However, its non-compostable properties allow the use of less fire-retardant materials for interior cladding and the wind barrier. Consequently, the choice of glass wool can indirectly reduce the climate impact of other building components. For detailed material properties see Appendix E.

This study focuses exclusively on Global Warming Potential, measured in kg CO_2e, as this is considered the most direct and quantifiable indicator of climate impact. All other environmental impact indicators are therefore omitted.

The analysis of the scenarios' climate impacts incorporates both static-, and Dynamic Life Cycle Assessment. Static Life Cycle Assessment quantifies the total climate impacts over the entire life cycle of the product, whereas dynamic Life Cycle Assessment accounts for the timing of emissions and considers their temporal climate effects.

Dynamic Life Cycle Assessment is particularly relevant for bio-based materials, as climate impact largely depends on the timing between CO_2 uptake during growth and CO_2 release at the material's end-of-life [4]. In this approach, carbon uptake and emissions are distributed over time, incorporating rotation periods and regrowth [4]. The temporal aspect is significant, as some greenhouse gases persist in the atmosphere for centuries, while others degrade relatively quickly [21]. By accounting for these temporal differences, dynamic Life Cycle Assessment provides a more accurate representation of climate impact than static Life Cycle Assessment [4].

Results are presented as both instantaneous and cumulative climate impacts over the assessment period, expressed as Global Warming Potential per m^2. This analysis forms the basis for the final evaluation of the potential of bio-based materials and provides insight into how material choices influence the climate footprint over time, from production to end-of-life.

3.5 Estimation of Future Housing Stock

To assess the national significance of the scenarios, the climate impact of the total housing stock is calculated and analyzed in a future projection. The future housing stock is estimated based on historical construction activity data from Statistics Denmark. It is further assumed that construction activity largely follows regular economic cycles [22], and the estimates are accordingly adjusted to reflect national economic trends, as described by The Danish National Bank [23].

3.6 Dynamic Calculations

3.6.1 Calculation of Instantaneous Global Warming Impact

The study's dynamic calculations of carbon uptake and emissions are based on data from the Environmental Product Declarations of the included materials. Emissions are distributed over time according to the service lives of the materials, allowing for a year-by-year analysis of how greenhouse gas concentrations and the resulting climate impact evolve. Early emissions have the greatest climate effect, while their contribution decreases over time as atmospheric concentrations change. Biogenic carbon uptake is included as negative CO_2 flows.

The temporal delay of carbon sequestration implies that later carbon uptake has a lower climate impact than earlier uptake, as CO_2 removed later has already spent more time in the atmosphere contributed to global warming

[24]. This is a direct consequence of the dynamic approach and reflects when and how CO_2 is actually removed from the atmosphere [25].

Levasseur et al. developed a dynamic calculation method that integrates time-dependent emissions into Life Cycle Assessment [24]. This method allows for the assessment of when and to what extent greenhouse gas emissions contribute to total climate impacts by explicitly accounting for the timing of emission release and their atmospheric decay. The approach is based on the calculation of Global Warming Impact and is described in Equation 1 - 4. Detailed calculations are provided in the accompanying Excel spreadsheet.

The instantaneous Global Warming Impact is calculated as a combination of two components:

- Dynamic Characterization Factor (DCF): Describes the decay of greenhouse gases over time
- Dynamic Inventory Result: Describes the timing of greenhouse gas emissions

The instantaneous characterization factor for year t can be calculated as follows [24]:

$$DCF(t)_{instantaneous} = \int_{t-1}^{t} a_i \, [C_i(t)] dt \qquad \textit{Equation 1}$$

Were $C_i(t)$ represents the atmospheric burden of the gas in year t after emission, and a_i is the instantaneous radiative forcing per unit increase in the atmosphere [26]. The calculation provides the expected year-by-year climate impact. This approach differs from the GWP_{100} which represents the aggregated climate impact over a fixed 100-year time horizon.

3.6.2 Decay of Greenhouse Gases

The decay of CO_2 is modelled using the Bern carbon cycle-climate model, which describes the proportion CO_2 that remains in the atmosphere following emissions [24]:

$$C(t) = a_0 + \sum_{i=1}^{3} a_i \; x \; e^{-t/\tau i} \qquad \textit{Equation 2}$$

Where:

a0 = 0,217; *a1*=0,259; *a2*=0,338, *a3*=0,186

τ1=172,9 år; *τ2*=18,51 år; *τ3*=1,186 år

For the remaining greenhouse gases, a first order decay equation is used [24]:

$$C(t) = \; e^{-t/\tau} \qquad \textit{Equation 3}$$

Where:

C(t): The atmospheric burden of the respective greenhouse gas

t = years after emission, τ-CH_4 = 12 år og τ-N_2O = 114 år [27].

The following values are used for the specific radiative forcing factors (α). These factors are used to estimate the contribution of each of the three gases (CO_2, CH_4, and N_2O) to overall global warming [28]:

α: CO_2= $1{,}76^{-15}$ W/m² per kg CO_2; *α: CH_4* = $1{,}28^{-13}$ per kg H_4; *α: N_2O*= $3{,}85^{-13}$ W/m² per kg N_2O

3.6.3 Calculation of Time-dependent Global Warming Impact

The instantaneous Global Warming Impact is calculated by combining the inventory results with annual characterization factors. The inventory is calculated based on material quantities multiplied with the respective GWP_{100} values from the Environmental Product Declarations. The life cycle is then divided into one-year intervals with emissions summed for each year in accordance with Levasseur et al [24]:

$$GWI(t) = \sum_i GWI_i(t) = \sum_i \sum_{j=0}^{t} [g_i]_j \; x \; [DCF_i]_{t-j} \qquad \textit{Equation 4}$$

Where:

GWI_i is the instantaneous Global Warming Impact at a given time, g_i is the dynamic inventory result, DCF is the instantaneous dynamic characterization factor, and *I* represent each greenhouse gas present in the inventory.

This approach accounts for both emission timing and atmospheric decay, providing a time-dependent representation of climate impacts.

3.6.4 Converting Global Warming Impact to Global Warming Potential

The time-dependent Global Warming Impact can subsequently be converted into a Global Warming Potential, as shown in Equation 5. This conversion is performed by integrating the instantaneous Global Warming Impact over the chosen time horizon t, and dividing it by the corresponding integral of CO_2's characterization factor [21]:

$$GWP\ (t) = \frac{\int_0^t GWI_{inst}\, dt}{\int_0^t DCF_{inst,\ CO2}\ dt} \qquad \textit{Equation 5}$$

This approach allows the climate impact to be expressed as a dynamic, time-dependent Global Warming Potential. It makes it possible to track how the Global Warming Potential evolves over time, while also enabling comparison with calculations based on the conventional, static GWP_{100} method.

3.6.5 Carbon Sequestration from Biogenic Regrowth

The use of bio-based materials enables temporary carbon storage. Two scenarios can be applied to assess the timing of carbon sequestration [4]:

1. Carbon sequestered prior to harvest is accounted for.
2. Only carbon sequestered doing regrowth after harvest is accounted for. An equivalent amount of biomass begins to grow immediately following the production process.

The calculations in this study are based on scenario 2. Carbon uptake from bio-based materials is included in the dynamic calculation as a temporary negative emission, taking into account both the timing of uptake and the rotation periods. Sustainable management and regrowth of harvested areas are assumed. Carbon sequestered is attributed to forest regrowth, meaning that the amount of carbon captured corresponds to the carbon stored in the harvested trees [10].

The method used for attributing carbon uptake is conservative, as uptake is recorded only after regrowth. This implies that the effect of carbon storage occurs gradually over time and is not available at the time of harvest. In this way, the method accurately reflects when carbon from forests and bio-based materials is actually sequestered. This approach provides a more realistic description of carbon flows throughout the entire life cycle, as illustrated in Figure 2.

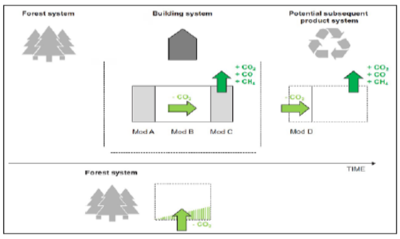


Figure 2 The dynamic approach, considering that trees regrow after harvesting (Hoxha).

For fast-growing bio-based materials such as hemp and straw, a short rotation period is assumed, with full growth achieved just one year after harvest. This results in an immediate reduction in climate impact due to rapid carbon uptake. In contrast, wood has a considerably longer regeneration period [21], meaning that carbon sequestration occurs gradually over many years.

3.6.6 Calculation of CO_2 Uptake over the Rotation Period of Trees

To describe the temporal distribution of CO_2 -uptake for trees over the entire rotation period, a derived formula based on Chapman-Richards growth function is used [10], which model typical vegetation growth over time. The annual growth function $f_{cr}(y)$, representing carbon uptake per year, is given by the following Equation 6 [10]:

$$fcr(y) = kpe^{-ky}(1 - e^{-ky})^{p-1} \qquad \textit{Equation 6}$$

Where: $k = 0{,}23$ og $p = 3$, are model parameters for tree growth rate and catabolism, and y is the year of uptake.

To calculate the annual CO_2 storage in the material, Equation7 is multiplied by the carbon content of the material and adjusted according to the rotation period [10]:

$$fbio, i(y) = Pco_2 \; x \; f_{cr}(y) / \; \sum_{y=0}^{TH} x \;\; f_{cr}(y) \qquad \textit{Equation 7}$$

Equation 7 distributes the CO_2 values over the rotation period to calculate the total amount of CO_2 stored in the product.

3.6.7 Calculation of CO_2 Mass in the Material

The total CO_2 mass stored in the material, P_{CO_2}, is calculated according to Equation 8, in accordance with DS/EN 16449 [19]:

$$Pco2 = \frac{44}{12}\ x\ cf\ x\ \frac{p\omega\ x\ V\omega}{1+\frac{\omega}{100}} \qquad \text{Equation 8}$$

$Pco2$ = CO2 emissions from product system into the atmosphere (at end of life)

$\frac{44}{12}$ = atomic weight of carbon (12) and carbon dioxide (44), cf =Carbon fraction of woody biomass

ω = Moisture content, $p\omega$ = Density of woody biomass of the product at that moisture content (kg/m^3)

$V\omega$ = Volume of solid wood product at that moisture content (m^3)

Equation 8 indicates the CO_2 content of the wood product at harvest, which is then distributed over the rotation period using $f_{bio,i}(y)$.

3.6.8 Application of Growth Rate for Spruce

To access the annual CO_2 uptake per tree, $f_{bio,i}(y)$ is compared with the growth rate in m^3 for spruce [29] over a 60-year rotation period [11]. The result indicates the annual carbon storage in newly planted trees after harvest, as illustrated in Figure 3. Detailed information on the calculation method, input data, and results can be found in the Excel spreadsheet and Appendix F.

Biogenic carbon uptake is further combined with the dynamic factors $C(t)$. This means that early sequestered carbon is given greater weight in the short term than in the long term [30]. This is illustrated in Figure 3 and 4:

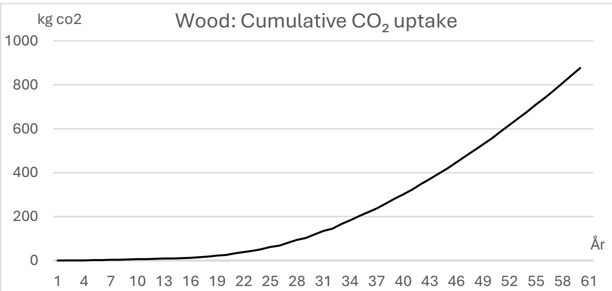


Figure 3 Cumulative CO_2 uptake from wood

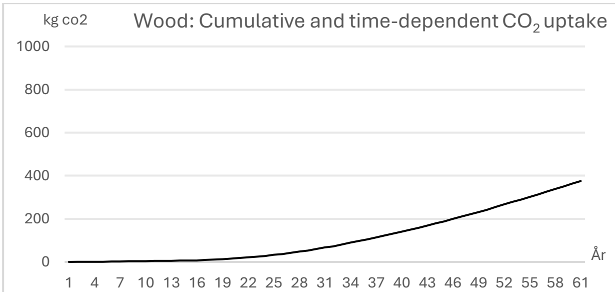


Figure 4 Cumulative CO_2 uptake weighted by dynamic factors

Figure 3 shows the actual biogenic carbon uptake over the rotation period, while Figure 4 shows how this uptake is weighted over time when combined with the dynamic factors. Using the regrowth approach, carbon benefits are distributed across the entire rotation period, meaning that the largest climate benefits are realized only once the forest has fully regrown. As a result, the majority of the uptake is assigned a lower weight [25].

The dynamic method calculates climate impacts over time by combining the decay of greenhouse gases with temporally distributed emissions. Negative emissions from biogenic uptake are subtracted from total emissions in the relevant years, providing a time-based representation of the climate impact throughout the product's life cycle.

3.7 Interpretation

This study examined four different construction scenarios for the purpose of a final comparison. The results of the Life Cycle Impact Assessment were analyzed for all scenarios, focusing on both static and dynamic Global Warming Potential. By comparing the outcomes of the static and the dynamic Life Cycle Assessment, it is possible to assess how the climate impact of the different constructions evolves over time, and when the emissions and carbon storage exert the greatest effect on the climate. This comparison also provides insight into how the choice of assessment method influences the final results. Dynamic Life Cycle Assessment, by providing values for time-dependent emissions and carbon flows, enables a more realistic and accurate estimation of cumulative annual emissions over time. These emissions can ultimately be aggregated, illustrating how each scenario affects the climate in both the short and long term.

The interpretation emphasizes the differences between scenarios and the potential for CO_2 reduction through the use of bio-based materials. Thus, the final results can support informed decision-making regarding material selection and construction design.

4.0 Results

4.1 Carbon Emissions from Materials

Figure 5 presents a comparison of all selected materials and their contribution to Global Warming Potential per m^2. Phase-specific emissions and the associated technical data are provided in Appendix E. Materials marked with (B) are classified as bio-based, (M) as mineral-based, and (S) as mineral-based materials that are, according to the manufacturer, additionally characterized as sustainable.

The analysis indicates that bio-based materials do not necessarily exhibit a lower climate impact than mineral-based materials. This is partly due to the fact that the production of conventional materials has increasingly been climate-optimized in response to the stricter building regulation requirements. Industry-

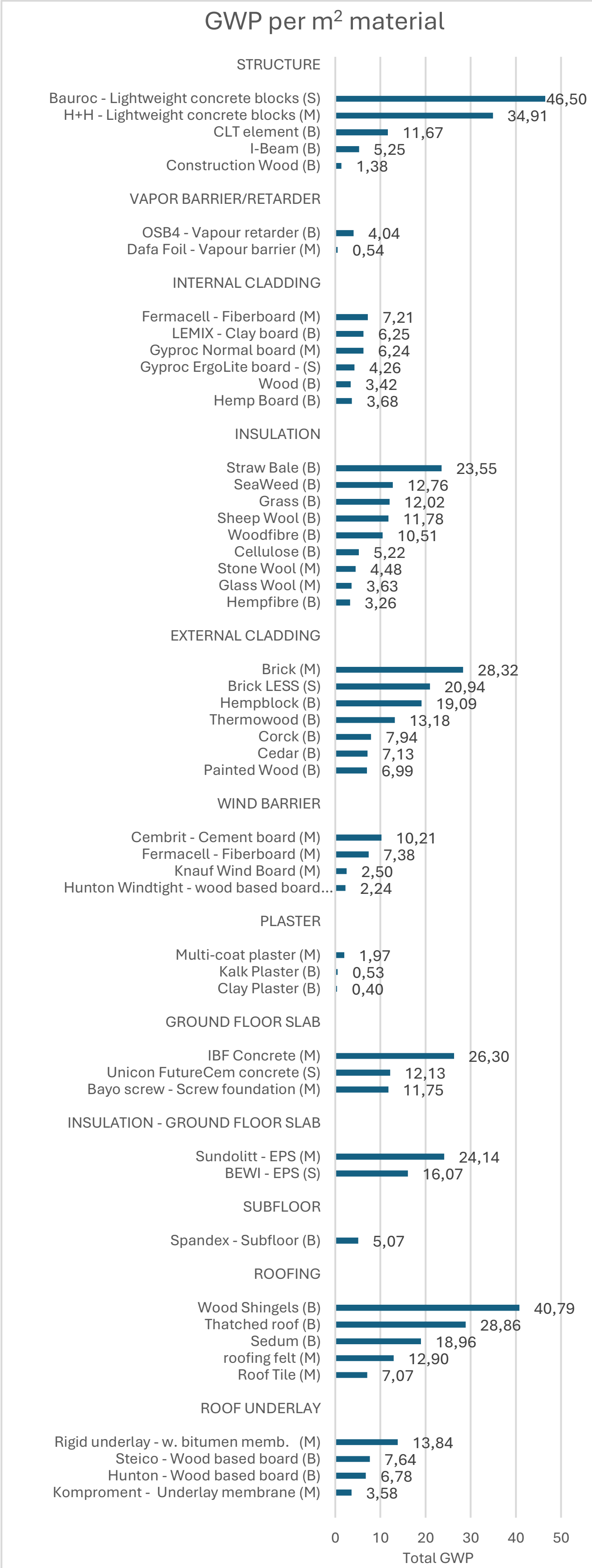


Figure 5 Global Warming Potential per m^2 of material

wide optimization efforts are primarily driven by the transition to biogas, increased use of renewable energy sources, process optimization, and waste reduction [31]. Specific examples related to the materials applied in this study are presented in Appendix G.

For mineral-based sustainable materials, in addition to the optimized processes described above, both material composition and material mass have been optimized to further reduce the Global Warming Potential. Relevant examples are provided in Appendix H.

Another significant factor influencing Global Warming Potential is the geographical location of production facilities. Many bio-based materials available on the market that have Environmental Product Declarations consistent with the principles applied in this study are not produced locally in Denmark. This results in long transport distances and, consequently, increased Global Warming Potential. Specific examples are presented in Appendix E.

Furthermore, the climate impact reported in Environmental Product Declarations increasingly reflects the purchase of green certificates for renewable energy generation [18].

4.2 Analysis of the Four Construction Scenarios

4.2.1 Static Life Cycle Assessment

Based on the material analysis and the construction scenarios, total emissions per scenario are calculated in kg CO2e/m^2/year, as illustrated in Figure 6. The calculations are performed as a static Life Cycle Assessment, showing the emissions per m^2 of heated floor area in accordance with BR18. However, the assessment period is extended from 50 to 100 years in order to ensure a consistent basis for comparison with the dynamic assessment.

The graph is based on emission data presented in Appendix I, together with the area and area factor calculations shown in Appendix C. Detailed calculations and results for other housing types are provided in Excel spreadsheet and Appendix J.

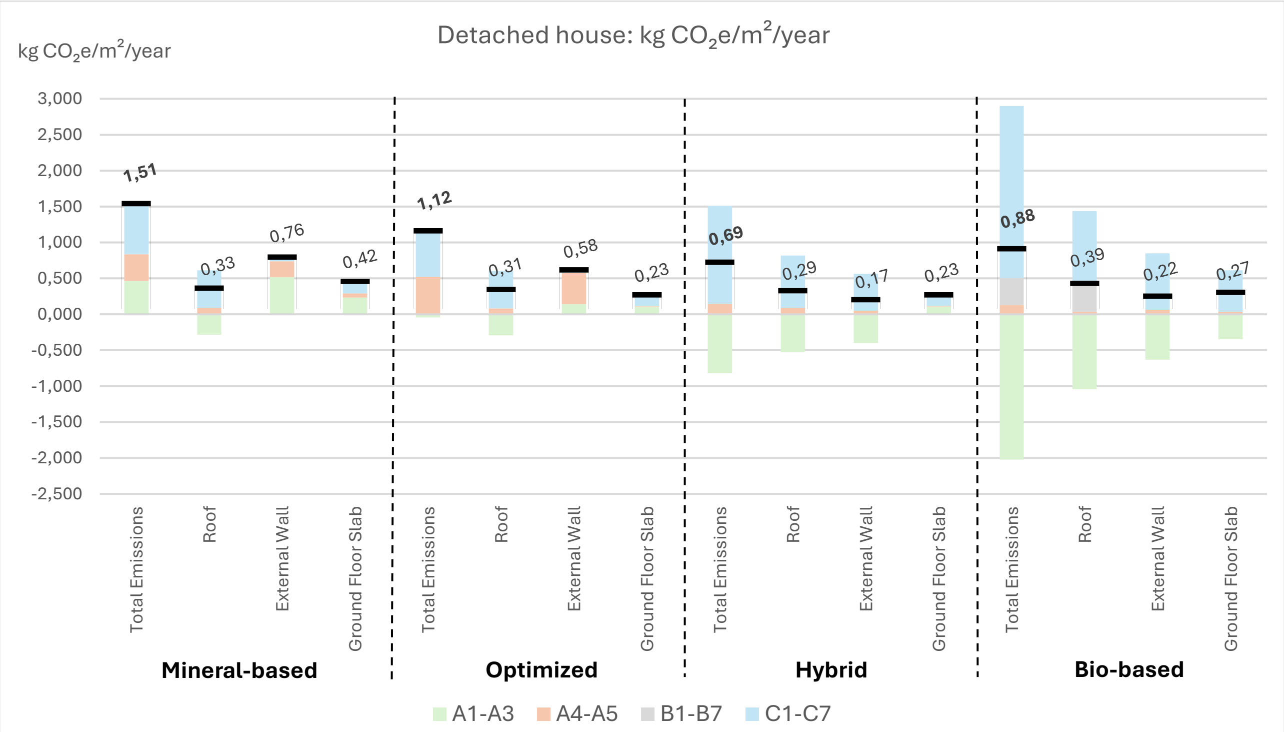
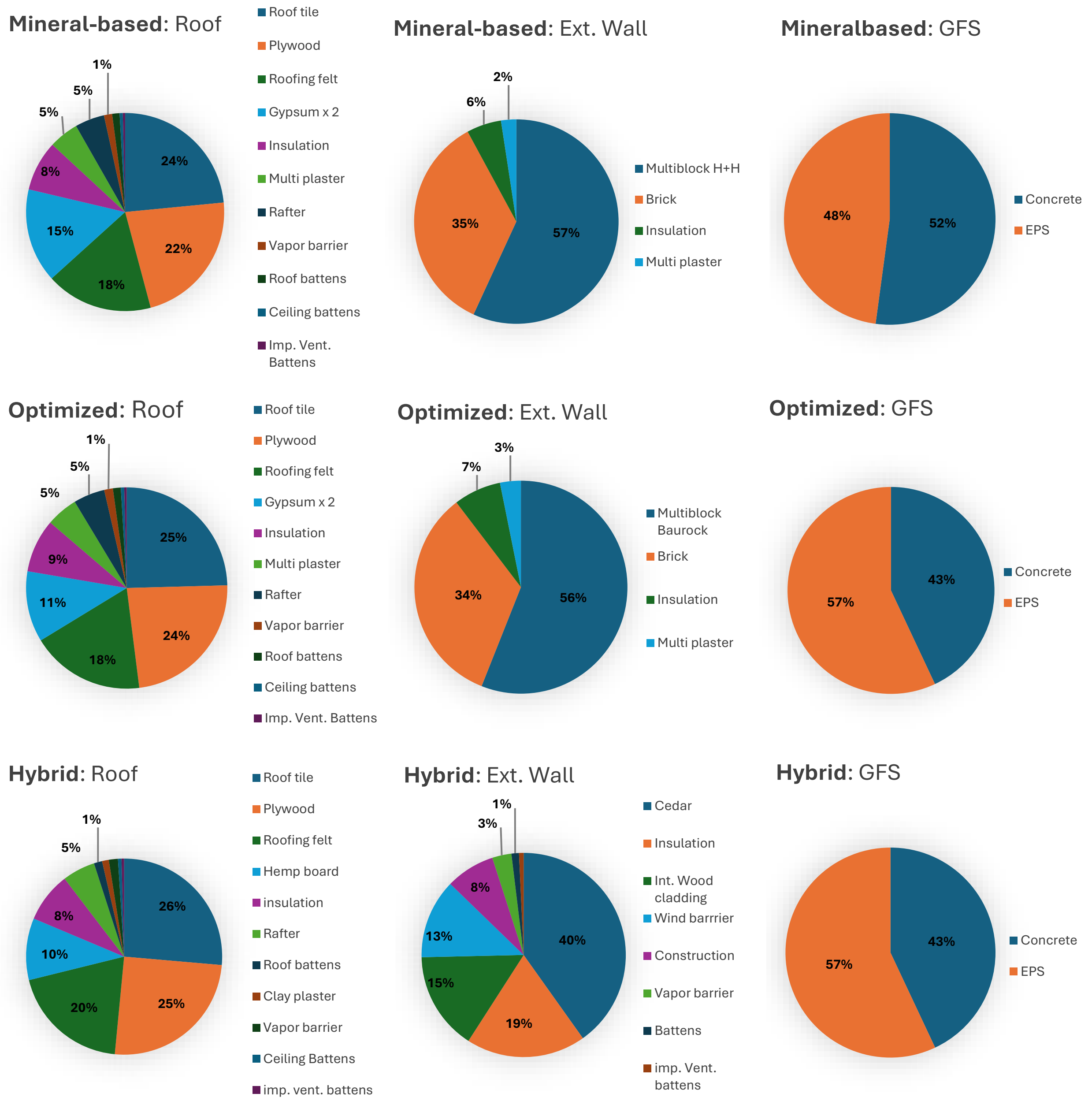


Figure 6 Total emissions expressed as kg CO_2e/m^2/year for constructions and associated building components. Assessment period of 100 years.

Figure 6 presents the total contribution of the scenarios to Global Warming Potential, as well as the contribution per building component. The figure indicates that the mineral-based scenarios exhibit the highest emissions, which can be attributed to energy- and process-intensive manufacturing methods, as well as the transport with high-density materials.

It is further evident that the hybrid scenario results in lower CO_2 emissions than the bio-based scenario. As discussed earlier, this can partly be explained by the fact that the production of bio-based materials primarily takes place outside Denmark, leading to increased transport-related emissions.



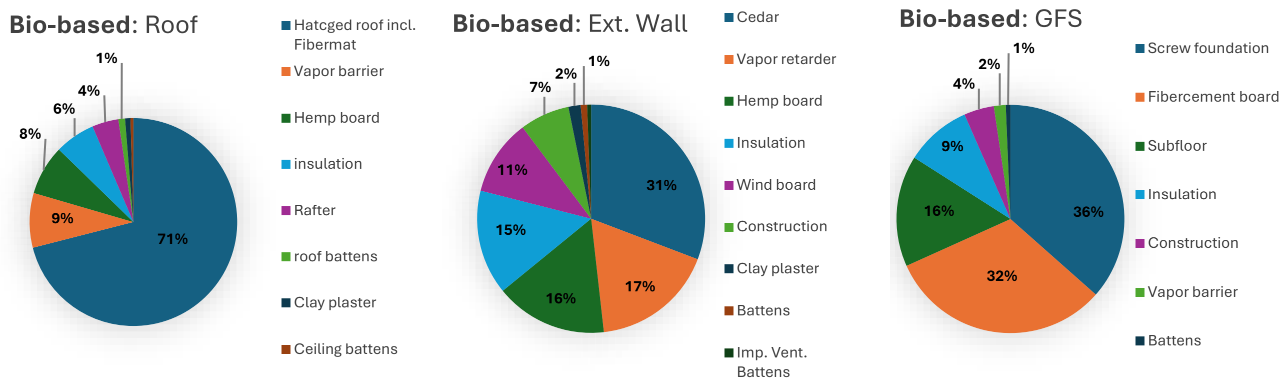


Figure 7 Emissions at material level

Figure 7 additionally provides a detailed breakdown of impacts at a material level. The figure shows that the thatched roof constitutes the primary source of emissions within the bio-based scenario. This is partly due to the inclusion of a fiberglass mat, which provides fire and water protection for the roof. In addition, thatched roofs require large quantities of roofing straw per m^2, thereby increasing emissions associated with both production and transportation.

Plywood and OSB boards also make a substantial contribution to overall emissions due to energy-intensive processing steps such as drying, gluing, and pressing at high temperatures, as documented in the relevant Environmental Product Declarations.

The analysis indicates that the hybrid scenario represents the option with the lowest climate impact when assessed using a static Life Cycle Assessment. This is primarily because the material selection in this scenario is based exclusively on materials with the lowest Global Warming Potential values. The optimized scenario achieves a substantial reduction in emissions compared to the mineral-based scenario; however, its emissions remain considerably higher than those of the other scenarios.

4.2.2 Dynamic Life Cycle Assessment

Figure 8 below presents the time-dependent impact of greenhouse gas emissions, calculated as both instantaneous and cumulative Global Warming Potential. The graphs represent values for the building components converted to one m^2 of heated floor area. Detailed calculations and graphs for individual building components are provided in the accompanying Excel spreadsheet and Appendix K.

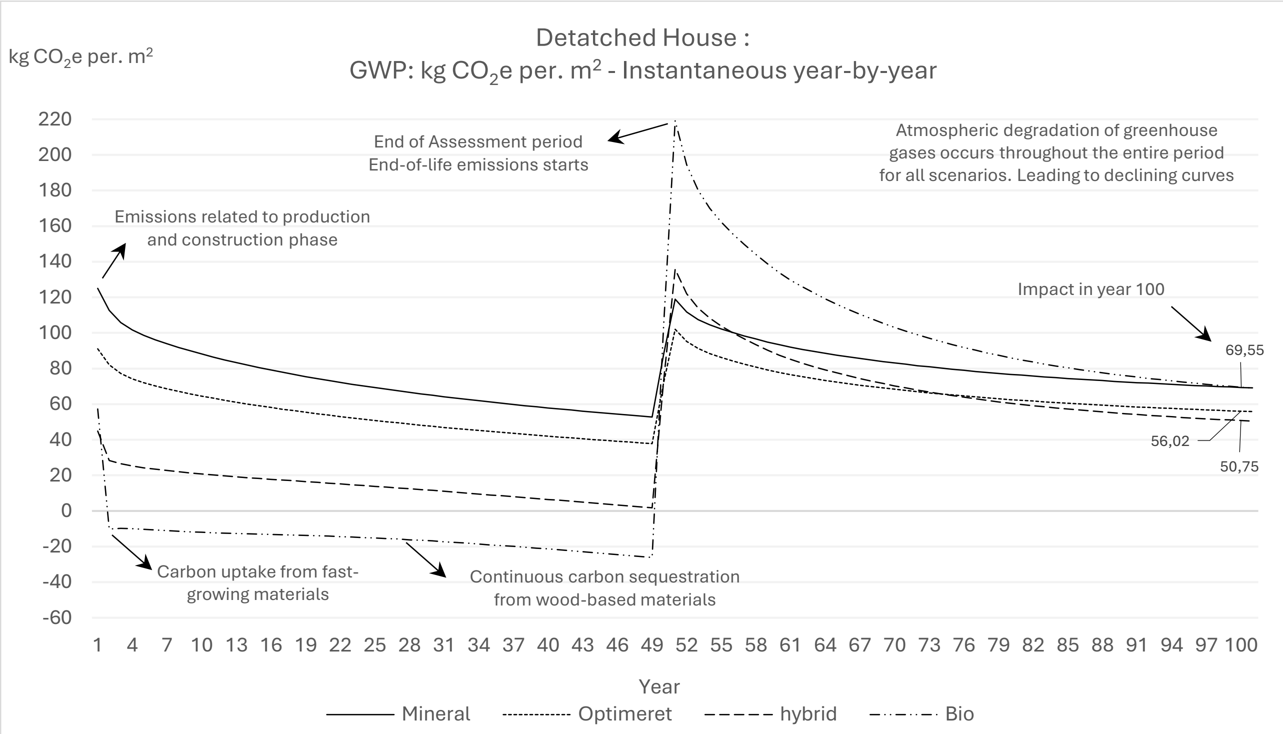


Figure 8 Annual CO_2 uptake and emissions per m^2 construction scenario. Example of a detached single-family house

Figure 8 presents the instantaneous Global Warming Potential of the scenarios over a 100-year reference period, expressed per m^2 of heated floor area. Years 0-1 correspond to the construction phase (A1-A5), while the full 0–100-year period encompasses the use, replacement, and end-of-life phases of the materials.

The figure demonstrates, in accordance with the static assessment, that the hybrid scenario exhibits the lowest climate impact at the end of the 100-year period. It is also evident that the bio-based and mineral-based scenarios display the highest and nearly identical climate impacts at the end of the period. This in part occurs because, unlike in the static Life Cycle Assessment, biogenic carbon uptake is assigned a lower weight over longer time horizons.

The bio-based scenario experiences a notable reduction in CO_2 emissions during year 1 due to the regeneration of fast-growing materials. Following this initial sharp decrease, emissions continue to decline gradually until year 50 as a result of new tree growth and the atmospheric decay of emissions. At year 50, the construction is assumed to be deconstructed and disposed of, leading to a sharp increase in emissions, visible as a peak in the graph. Thereafter, the bio-based scenario maintains higher emissions than the other scenarios for an extended period. However, the climate impact subsequently declines relatively rapidly compared to the mineral-based scenarios, as CO_2 uptake from trees continues throughout the entire rotation period. In addition, a higher proportion of methane is assumed in the biogenic emissions, resulting in higher Global Warming Potential values upon release but also faster atmospheric decay [27]. Further details are provided in Appendix L.

The hybrid scenario follows a similar trend but with smaller fluctuations due to its lower content of bio-based materials. The mineral-based scenarios exhibit the smallest fluctuations, as CO_2 emissions are primarily associated with the production and end-of-life phases and therefore more evenly distributed over time.

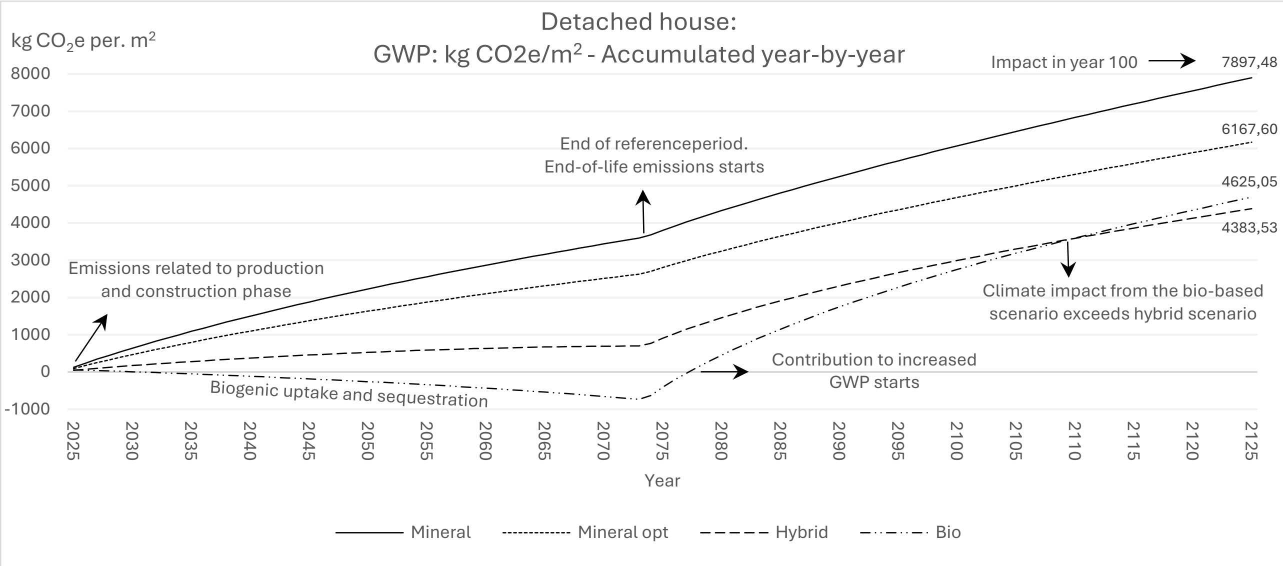


Figure 9 Annual accumulated CO_2 uptake and emissions per m^2 construction scenario. Example of a detached single-family house

Figure 9 shows the cumulative CO^2 emissions over the assessment period. The graph illustrates that, in the short and medium term, the bio-based scenario exhibits a significantly lover climate impact than the other scenarios. This is due to the contentious CO_2 uptake from biomass growth, resulting in a period of overall negative cumulative Global Warming Potential and the formation of a temporary carbon buffer. In the long term, this buffer is neutralized as carbon is released at the end of the life cycle, leading to an increasing trend from year 50 onwards. Over the extended time horizon, the climate impact of the bio-based scenario surpasses that of the hybrid scenario. The mineral-based scenarios are substantially more climate-impacting, with the traditional scenario exhibiting the highest emissions.

The analysis demonstrates how calculating annual, instantaneous emissions enable the tracking of climate impacts for each scenario throughout the entire life cycle. This time dependent approach reveals that temporary carbon storage in bio-based materials merely delays emissions, which are subsequently released. At the same time, cumulative emissions provide a clear overview of how climate impacts accumulate over time and how the timing of emissions influences the overall outcome. The results show that the bio-based scenario exhibits the lowest climate impact in the short and medium term. However, over the long term, these differences are neutralized, and the bio-based scenario becomes more climate-impacting than the hybrid scenario, assuming that the building is ultimately deconstructed and the carbon stored in the wood is released. The mineral-based scenarios remain the most climate-impacting over the assessment period.

4.3 Forecast of CO_2 Emissions

The projected building mass of single-family houses is used to assess the total CO_2 emissions associated with the analyzed construction scenarios. By combining trends in newly constructed single-family houses with dynamic emission profiles, the cumulative climate impact over a 100-year period can be estimated. Calculations are provided in Excel spreadsheet. Scaling the results from the building level to the sector level provides a comprehensive assessment of the overall climate impact.

The estimated development of single-family housing is illustrated in Figure 10. The figure shows how the number of detached, terraced, chain, and semi-detached houses is assumed to evolve in response to economic cycles.

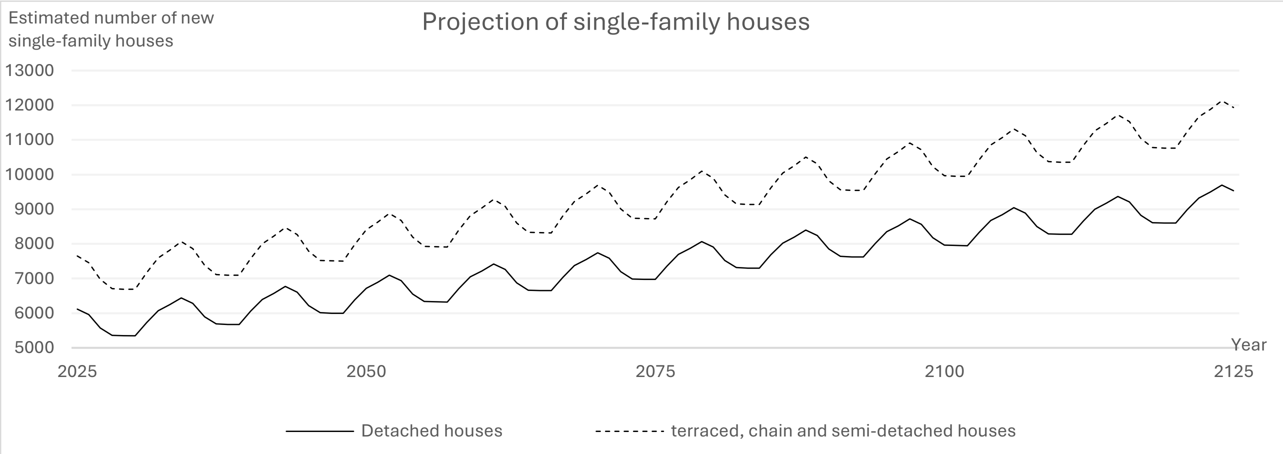


Figure 10 Projection of single-family houses over 100 years horizon

Figure 10, together with the time-dependent CO_2 emissions per housing unit, forms the basis for Figure 11. Figure 11 presents the total cumulative emissions from all newly constructed single-family houses on a year-by-year basis over the assessed period.

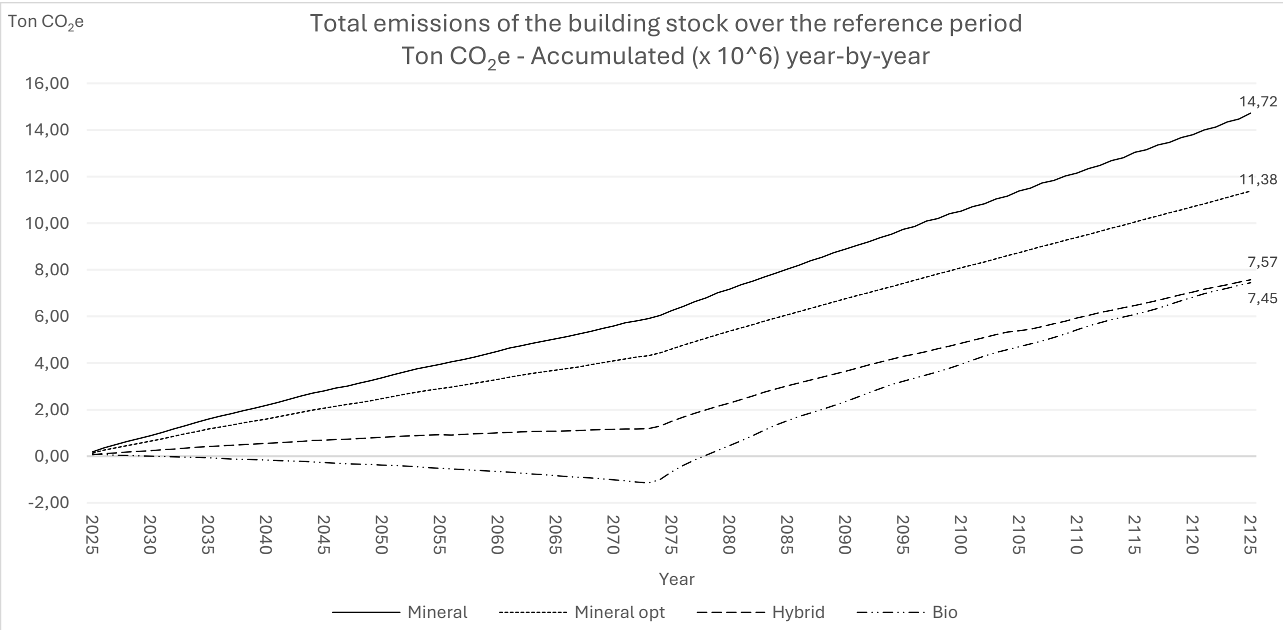


Figure 11 Future cumulative CO_2 emissions per year, calculated with dynamic Life Cycle Assessment

The results presented in Figure 11 follow the overall trend observed in Figure 9. However, the differences between the scenarios are markedly amplified when assessed at a larger scale. The greater the proportion of bio-based constructions, the larger the resulting carbon buffer and the longer the associated emissions are delayed. Consequently, the disparity between the bio-based and hybrid scenarios increases with scale. These findings indicate that both material selection and scale are key determinants of the long-term climate impacts of the scenarios. The consequences of these results for future temperature changes are illustrated in Appendix M.

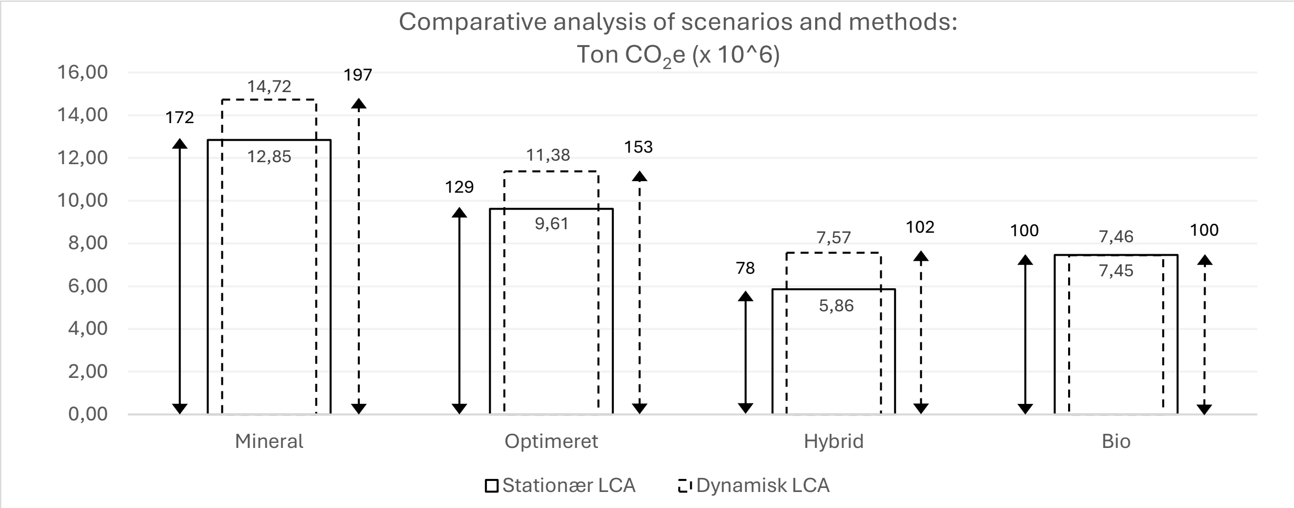


Figure 12 Comparison between scenarios and methods. Accumulated values over the 100-years horizon. Biogenic emission is set to an index of 100 for both methods to demonstrate method-dependent differences.

Figure 12 presents the cumulative climate impact over the 100-year period for the four scenarios, calculated using both static and dynamic Life Cycle Assessment.

For the mineral-based scenarios, the static Life Cycle Assessment consistently results in lower cumulative values than the dynamic approach. This is because the substantial early emissions associated with material production are weighed equally over time in the static method, whereas in dynamic Life Cycle Assessment they contribute more strongly to the total climate impact. The differences between the two methods are greatest for the purely mineral-based scenario and are reduced in the optimized scenario, where overall emissions are lower.

For the hybrid scenario, a higher cumulative climate impact is also observed when applying dynamic Life Cycle Assessment compared to the static method, although the sensitivity to the choice of method is smaller than for the mineral-based scenarios. This reflects the limited biogenic CO_2 uptake, which only partially offsets the early emissions.

By contrast, in the bio-based scenario, the difference between static and dynamic Life Cycle Assessment is minimal. In this case, early biogenic CO_2 uptake and later emissions are largely balanced over the 100-year period, resulting in nearly identical cumulative climate impacts.

Overall, these results demonstrate that the choice of Life Cycle Assessment method has a significant influence on the assessment outcome and may alter conclusions regarding which solution provides the greatest climate benefits.

5.0 Discussion

The aim of this study was to investigate and quantify the potential contribution of bio-based building materials to carbon reduction. The analysis considered four construction scenarios, ranging from traditional mineral-based constructions to constructions entirely composed of bio-based materials.

The results indicate, consistent with previous research [32, 21], a significant climate mitigation potential associated with the use of bio-based materials, particularly in comparison with conventional mineral-based materials. Furthermore, the analysis shows that fast-growing materials substantially reduce climate impact relative to materials with longer rotation periods. These findings emphasize the importance of strategic material selection; fast-growing materials should be applied wherever their properties allow, while wood should be primarily reserved for load-bearing and structurally demanding applications. Furthermore, the carbon footprint could be reduced if bio-based materials were produced locally in Denmark. Replacing energy-intensive and polluting materials with environmentally preferable alternatives would also be beneficial.

However, when compared to the hybrid construction scenario over the assessment period, the observed differences are limited and fall within the margin of uncertainty. This raises the question of whether the analysis should be extended to capture potentially larger differences, or whether the apparent climatic equivalence of the two strategies itself should be considered a key finding.

A more nuanced assessment could be achieved by applying actual reference lifetimes, alternative end-of-life scenarios, or more detailed assumptions regarding reuse and recycling. In this study, an assessment period of 50 years was applied in accordance with building regulations. However, using a uniform assessment period may lead to a misleading representation of emission dynamics. Mineral-based materials are often associated with longer service lives and are generally less sensitive to biological degradation than bio-based materials [16, 33]. Applying a uniform reference lifetime may therefore result in an overestimation of the relative environmental benefits of bio-based materials. Conversely, the same assumption may lead to an underestimation of climate advantages if the actual service lives exceed the assessment period [34].

Furthermore, the treatment of biogenic carbon stored in branches and roots after harvesting constitutes a significant source of uncertainty. The decomposition of this residual biomass releases CO_2, typically resulting in a temporary carbon dept, as carbon sequestration is gradually rebuilt through regrowth. Consequently, the biogenic carbon credits associated with the building are not realized immediately but accumulate progressively over time [25]. This introduces substantial uncertainty, as up to approximately 30% of carbon uptake may be stored in the root system. In this study, root biomass was excluded due to methodological complexity and limited data availability. Furthermore, it was not possible to determine whether this carbon fraction is already accounted for in the respective Environmental Product Declarations.

The hybrid scenario combines low production emissions from optimized mineral-based materials with a limited but stable biogenic carbon uptake, rendering the solution robust over time. In contrast, the bio-based scenario demonstrates a clear climate advantage in the short to medium term but is more sensitive to assumptions regarding service life, carbon dynamics, and end-of-life scenarios. Bio-based materials therefore address the need for rapid near-term emission reductions, whereas hybrid solutions represent a more conservative, risk-mitigated long-term strategy.

A central ethical and climate-related dilemma concerns whether it is legitimate to postpone CO_2 emissions through the use of bio-based materials, as emissions are effectively shifted in time and partially deferred to future generations. The dynamic analysis demonstrates that bio-based materials do not eliminate emissions but rather delay them. The results of this study therefore indicate that the timing of emissions is critical to the overall climate impact. This is particularly relevant given that short-term emission reductions are essential to limit temperature increases and avoid irreversible tipping points [35].

The postponement of emissions may nevertheless have a significant positive effect if applied strategically to alleviate acute climate pressure in the coming decades. This presupposes that the intervening period is actively used to implement permanent emission reductions and to develop technologies for long-term carbon storage. From this perspective, bio-based materials can be viewed as a means of creating a temporary window of opportunity for climate action.

As the life cycle of buildings is decisive for their climate footprint, renovation of existing buildings and a reduction in new constructions emerge as the most effective strategies for lowering CO_2 emissions. Optimization and reuse of the existing building stock can extend service lives and reduce both short- and long-term emissions [36]. Renovation can moreover be carried out using bio-based materials where this is structurally and functionally feasible, thereby further enhancing the climate benefits.

Overall, this study demonstrates that bio-based building materials can play a significant role in reducing the construction sector's footprint. However, the climate benefits are highly dependent on the time horizon, methodological choices, and ethical considerations. Rather than pointing to a single definitive solution, the results of this study highlight the need for a nuanced, combined material strategy in which hybrid and bio-based solutions are applied deliberately and contextually. Such a strategy should simultaneously support short-term climate targets, promote biodiversity through sustainable forestry, and ensure long-term responsibility for inevitable emissions.

6.0 Strengths and Limitations

The strength of this study lies in its contribution to understanding the climate performance of bio-based materials compared to traditional mineral-based materials. It also highlights how the choice of methodology can influence the results and, consequently, the assessment of the material's climate impact.

The combined use of static and dynamic Life Cycle Assessment, together with scenario analysis, provided insights into the differences in CO_2 emissions between bio-based and mineral-based materials. These methods also enabled an evaluation of the significance of material choice for the overall climate impact of the building envelope under different construction scenarios and temporal emission patterns.

However, several limitations should be noted. The study's calculations depend on the selected Life Cycle Assessment method and assumptions regarding carbon uptake. The static method analyzes environmental impacts over the entire product life cycle without accounting for when the emissions or resource consumption occur, meaning that all emissions are assumed to occur as a single aggregate. The dynamic method provides a more nuanced picture, but results can still vary significantly depending on assumptions regarding the timing of carbon sequestration credits.

This analysis is based solely on Environmental Product Declarations, which introduces additional uncertainty. Methodological differences, variations in reporting practices, and missing data in Environmental Product Declarations can result in variations in reported environmental scores, even for identical products [18, 37].

Overall, the results of this study support the potential of bio-based materials to provide both short-term and long-term climate benefits. However, they should be interpreted with caution, taking into account the limitations associated with methodological choices, data quality, assumptions regarding carbon storage, and the building's end-of-life.

7.0 Conclusion

This study demonstrates that bio-based materials can contribute to a substantial reduction in the climate impact of constructions compared to traditional mineral-based materials. The reduction is primarily achieved through temporary storage of biogenic carbon, resulting in a temporal shift of emissions. The results highlight the need for a differentiated material strategy, in which fast-growing bio-based materials are prioritized, while long-rotation timber should be prioritized for structural or functional applications, as the climate impact of these materials depends on their growth and rotation times.

Bio-based materials exhibit significant climate benefits in the short and medium term, but are sensitive to assumptions regarding service life, carbon dynamics, and end-of-life scenarios. The analysis therefore indicates that hybrid constructions, combining both mineral- and bio-based materials, may serve as a conservative, risk-minimizing strategy. Such an approach reduces immediate emissions while enabling partial carbon storage, making constructions less sensitive to uncertainties related to service life, carbon dynamics, and end-of-life scenarios.

The results of this study cannot be directly transferred to other building types, such as multi-story residential or commercial and industrial constructions, which are often subject to more complex and stringent structural requirements. Nevertheless, the analysis indicates a general trend regarding how the use of bio-based materials can contribute to reducing the climate footprint, depending on the composition of the construction.

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