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REPORT

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CO2 SAVINGS AND COST-EFFECTIVENESS IN TIMBER CONSTRUCTION

CO2 SAVINGS AND COST-EFFECTIVENESS IN TIMBER CONSTRUCTION
COMPARATIVE STUDY OF WOODEN BUILDINGS AND CONVENTIONAL BUILDINGS

Project name	**CO_2 savings and cost-effectiveness in timber construction**
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Approved by	**Andreas Qvist Secher**
Description	**Comparative study of conventional construction and timber construction, based on six case studies**
	Case 1: Single-family house
	Case 2: Multi-storey residential
	Case 3: Production facility
	Case 4: Office building
	Case 5: Row house complex
	Case 6: Daycare institution

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1. PREFACE

Globally, construction accounts for around 37% of the total climate impacts, of which 9% comes from the consumption of materials for new construction (UNEP, 2022). Furthermore, research published by the UN Climate Panel shows that it is necessary to significantly reduce any form of climate impact over the next ten years to prevent a global temperature increase of more than 1.5 degrees Celsius (IPCC, 2018). As a result of Denmark's climate target to reduce the emissions of greenhouse gases, including the beginning of a calculation of Denmark's consumption-based emissions, the Housing and Planning Authorities launched a National Strategy for Sustainable Construction in 2021 (Indenrigs- og Boligministeriet, 2021). The strategy includes the phase-in of calculations of the climate impact of buildings, as well as an upper limit value for the climate impact. Per January 1st 2023, the Building Regulations require that the climate impact of all new construction is documented through an LCA (BR18, 2024). In addition, buildings with a heated floor area larger than 1,000 m^2 must comply with a limit value of 12 kg CO_2e/m^2/year. From 2025, the limit value will be tightened and applies to all new construction, regardless of size.

The purpose of this report is to highlight the possible climate savings (based on reduced CO_2e) that can be achieved by increasing the use of wood and wood-based products in new construction in Denmark. The report is an update and significant expansion of the report Ramboll prepared for Træ i Byggeriet in 2020 (Sørensen, Schack, & Collin, 2020). This report includes three new buildings as well as shadow price calculations for each of the buildings. In addition, the existing cases have been updated so that the calculations comply with the current requirements for climate calculations in BR18. In addition to the static LCA, dynamic LCAs have been carried out for the six case buildings.

The purpose of the project is highlight which CO_2 savings can be achieved by converting conventional solutions to corresponding wood-based solutions, and what impact this has on the economy of the project.

The report has been prepared by Ramboll in 2024 for the associations Træ i Byggeriet, Danish Træforening and Træ- og Møbelindustrien, TMI. The analysis is aimed at decision-makers around construction, including builders, architects, engineers, contractors and craftsmen and stakeholders such as industry organisations, politicians and public authorities.

The report's main author is Sara Føns Steffen.

The analysis work is quality assured by Lise Horup Koch-Søfeldt who was the main author behind the 2020 report, while Andreas Qvist Secher has been project manager on the project.

The following specialists from Ramboll contributed to the report:
Sara Føns Steffen, Ramboll Buildings, has been responsible for data collection and LCA calculations
Morten Stistrup, Ramboll Buildings, has been responsible for converting the energy performance calculations and LCA calculations
Michael Gadegaard Espersen, Ramboll Management Consulting, has been responsible for the shadow price calculations
Frederik Hedetoft, Ramboll Buildings, has been responsible for the static calculations
Tim Møller, Ramboll Buildings, has, as a certified structural engineer, ensured the quality of the static calculations

Ramboll appreciate the opportunity to work on this important topic, and being able to contribute to the knowledge on climate impact of buildings.

2. SUMMARY

This report presents life cycle assessments of six specific building cases with four steps, increasing the use of wood. The six case buildings are a single-family house, a multi-storey residential building, a production facility, an office building, a row house complex, and a daycare institution. The life cycle assessments are conducted in accordance with the current requirements for LCA in the Danish Building Regulations §297-298. All the case buildings are, to varying degrees, wooden buildings and originate from member companies of *Træ i Byggeriet.* Ramboll has gradually converted each case to equivalent conventional buildings and performed life cycle assessments for all steps. The variations of the case buildings correspond in load-bearing capacity and thermal resistance to the actual buildings, allowing for comparison between the different steps.

The report consists of two main sections: LCA results and shadow pricing.

In the section on LCA results, it is examined through the six specific cases how large CO_2e savings can be achieved with different types of wooden buildings. The report highlights the potential CO_2e savings of converting to wood-based products in different building categories and components. The case studies are first analysed as conventional steel and concrete structures (Step 1) and are then gradually converted to wood-based structures and building parts. For five out of six cases, the conversion of the load-bearing structure shows the greatest potential CO_2e saving. The total savings from Step 1 to Step 2 vary between 7-31% for the six cases, corresponding to a saving of 0.28-1.92 kg CO_2e/m^2/year. The calculations are carried out as static LCAs according to BR18. Three of the six cases could, in the wood-based Step 4, comply with the draft limit value for 2029 of 7.5 kg CO_2e/m^2/year proposed by the Social and Housing Authorities.
Additionally, dynamic life cycle assessments for each of the six cases are included. The dynamic LCA is an alternative method to the static LCA, utilizing a dynamic projection of future emissions. Overall, the results show that more bio-based material leads to a greater reduction when switching from a static to a dynamic calculation, because the bio-based materials have the highest emissions at the end of life and are thus weighted lower in the dynamic calculation. The dynamic life cycle assessments for the six cases show results close to 0 kg CO_2e/m^2/year and even negative results for one case. The use of dynamic LCA in the report raises an important discussion about methodology but also highlights the time perspective of when emissions actually occur and assumptions about future emissions.

The section on shadow pricing presents an estimate of the costs per reduced ton of CO_2e compared to Step 1, and thus conventional buildings, as the baseline. Shadow pricing provides an indication of which CO_2e-reducing initiatives are most cost-effective for each of the six cases. The analyses for shadow pricing show that the sensitivity of the results is highly dependent on the price data used and therefore the results are considered largely indicative. The results indicate that transitioning to wood-based materials can lead to cost savings while achieving CO_2e reduction. The results suggest that it may be cost-effective to use wood-based materials, with several of the case buildings even having negative shadow pricing, and it should therefore always be assessed whether it is a possibility in each individual project to use wood-based products for the benefit of both climate and economy.

This report highlights the significant potential CO_2e savings through the use of wood-based materials, which in many instances are cost-effective.

Further background information for the results can be found in the Appendix of the supplementary report.

3. SCOPE

This report contains 24 LCAs distributed over six different case buildings with each four variations with increased use of wood-based materials. The six actual wooden buildings, which form the basis of the analysis, have been converted to equivalent typical Danish construction of concrete, steel and brick by Ramboll's engineers specialised in structural design and statics. As outlined in Figure 1, the case studies are first analysed starting from a typical Danish building consisting of e.g. steel, concrete and brick (Step 1) and are then gradually converted to wood-based structures and building parts. For each step, more building parts are replaced with wooden alternatives.

Step 1	**Step 2**	**Step 3**	**Step 4**
Typical Danish building, with materials such as steel, concrete and brick	Similar to Step 1, but primary and secondary structures in concrete and steel are changed to wood-based building materials	Similar to Step 2, but coverings such as façades, floors and ceilings are changed to wood-based building materials	Similar to Step 3, but mineral wool insulation is changed to wood fiber or cellulose insulation

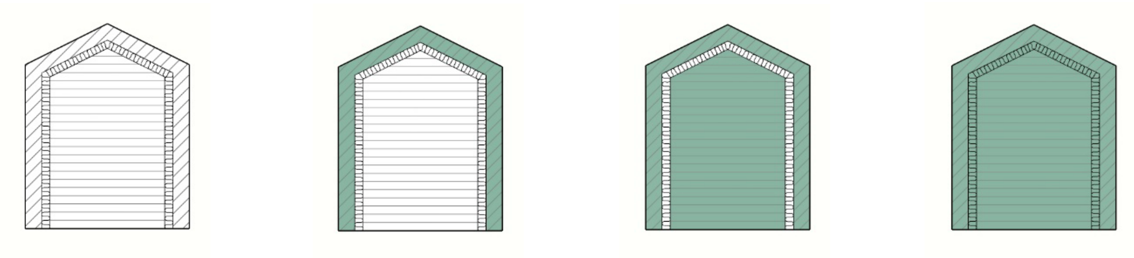


Figure 1– The case buildings are gradually converted from conventional to wood-based designs

The buildings are compared on their climate impacts through LCA, and on their economic costs through shadow price calculations.

The case studies are specific wooden buildings which meet the Building Regulations' requirements for fire safety and acoustic conditions, which has also been considered in the conversion to the four steps. Technical installations are included as standard values cf. *BR18 Bilag 2 Tabel 7* (BR18, 2022), and are thus the same across the four steps.

4. LCA METHOD

Life cycle assessment (LCA) is a method widely used to clarify the environmental impacts of products, processes or systems. LCA can be carried out according to a number of different international standards. An LCA for construction products is carried out according to the European standard EN15804 (DS/EN 15804:2021+A2:2019), which describes the method used to clarify the environmental impact of a construction product throughout its life cycle. LCA includes environmental impacts over the entire life cycle of the construction product, from extraction of raw materials, transport and production, over maintenance and replacements while the construction product is in use, until the construction product reaches its end of life and is disposed of either at demolition or replacement.

The calculations in this analysis are based on the method for climate calculations of buildings described in BR18 §297-298, which generally refers to (DS/EN 15978:2012), which describes the calculation method for assessing the environmental impact of buildings. The only environmental indicator included in §297-298 of BR18 is Global Warming Potential (GWP). Since this is the only environmental indicator included the calculations in this report are not full LCAs according to EN15804, as described above. When making decisions, the other environmental impact indicators should also be analysed and included.

The six cases are analysed independently of each other, but all follow the method described in this section.

4.1 System boundaries

An LCA can include both embodied impacts, which are the impacts related to the building's material consumption, as well as operational impacts, including heat, electricity and water consumption. The calculations in this report include the life cycle phases that are included in the description in BR18 §297-298, which are marked in blue in Figure 2. Note that B6 – Energy consumption for operations is included for the three new cases, but not for the existing cases that were also included in the 2020 report.

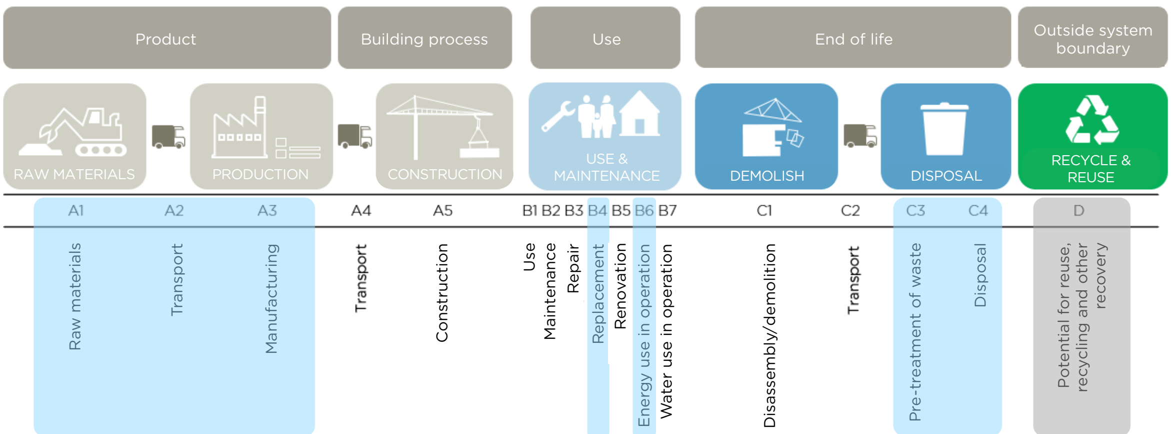


Figure 2– The building life cycle. Life cycle phases marked in blue are included in the calculation cf. BR18. Phase D is outside the system boundary and is not included in the overall results.

4.2 Functional unit

To ensure a correct basis for comparison, the functional unit is determined for each case. The functional unit describes and quantifies the properties of the building that must be present for the studied substitution to take place. It has been chosen to focus on the function of the building, the number of square metres, and the thermal resistance of the building envelope (U-values).

4.3 Bill of quantities

Bills of quantities are provided by the architects, suppliers and contractors of the case projects, as well as based on quantity extracts from 3D models. Quantities for the other steps have been calculated by Ramboll's structural engineers ensuring that they all meet load capacity requirements. Insulation thicknesses are also regulated to achieve the same thermal resistance in the examined steps, see Appendix 7-12. See also Appendix 1-6 LCI (Life Cycle Inventory) for inventory lists of materials and quantities.

4.4 Temporal consideration

The building's temporal consideration is set to 50 years, cf. BR18. The service life of the building materials are based on *BUILD Levetidstabel Version 2021* (Haugbølle, Mahdi, Morelli, & Wahedi, 2021), which is also embedded in the calculation tool LCAbyg. See Appendix 1-6 for LCI's where the service lives of the materials are indicated.

4.5 LCA tool and data

The analyses were made in LCAbyg 2023.2 (5.4.0.1), which is a tool for calculating LCA for buildings, developed by the Danish Building Research Institute, SBi. For the calculations, generic data from BR18 *Bilag 2, Tabel 7* is used (BR18, 2022), which contains Danish industry EPD's[1], as well as environmental data from the German database ökobaudat (ÖKOBAUDAT, 2023). See Appendix 1-6 for applied ökobaudat processes and industry EPD's.

4.6 Assessment and delineation of environmental impact potentials

This report focuses exclusively on the environmental indicator Global Warming Potential (GWP). GWP is measured in CO_2e, where "e" stands for equivalents, which means that the unit also contains the impact potential from other greenhouse gases. CO_2e thus includes e.g., CO_2, methane and nitrogen, all of which are greenhouse gases that contribute to global warming.

Table 1– Impact potentials

Environmental impact categories	
Global warming, GWP* [CO_2e]	When the amount of greenhouse gases in the atmosphere increases, the air layers near the ground are heated, resulting in climate change.

4.7 Biogenic carbon

Biobased materials can absorb, store and release carbon throughout their lifetime. This carbon is also referred to as biogenic carbon. With the current data in BR18 *Bilag 2, Tabel 7*, it is not possible to separate the biogenic carbon and the carbon that relates to fossil fuels in biobased material production. According to the updated product standard (EN 15804:2012+A2:2019) the stored

[1] A third-party verified LCA for a product according to the current EN standard is called an environmental product declaration or an EPD, which stands for 'Environmental Product Declaration'.

biogenic carbon should be reported separately, but since the data in BR18 *Bilag 2, Tabel 7,* follow the old standard, EN15804+A1:2013, this has not been possible in this report.

In the Danish construction sector, the -1/+1 rule is used when calculating biogenic carbon cf. (DS/EN 16485:2014). The -1/+1 rule prescribes that the CO_2 that is stored in biogenic materials during photosynthesis is credited with a negative climate impact, which is offset at the end of life, when biogenic building materials are assumed to be incinerated, whereby the stored CO_2 is released into the atmosphere.

4.8 Emissions associated with the operation of the buildings

For a more accurate picture of the buildings' climate impacts, and to follow BR18, the operating emissions for the three new cases have been added. Here, the starting point is the current and supplied energy performance calculations, where the heat capacity of the case buildings has been modified based on the constructions in the relevant steps. In general, this will result in higher heat capacity in Step 1, as traditional construction more often has thermally heavy materials as exposed interior surfaces. A large thermal mass results in greater heat capacity. Heat capacity affects the building's heat balance, where a higher heat capacity will result in more energy-efficient heating and cooling of the building. See Appendix 13-15 for operational emissions.

4.9 Static and dynamic LCA

LCA is based on assumptions, both regarding service lives and materials. With a static LCA, such as the one calculated for BR18, production methods and material selection are based on current practices, also for replacements and end-of-life, even if these occur 25-50 years into the future. The potential development that may occur during the building's lifetime is therefore not taken into account. In addition, the emissions are weighted equally regardless of when they occur during the buildings' life cycle. This means that future emissions, which are far more uncertain than emissions that occur today, are weighted equally with emissions that occur now and in the near future.

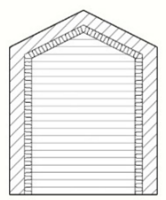
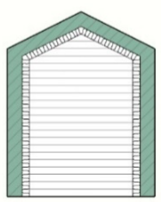
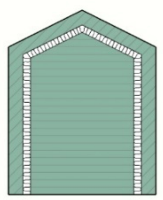
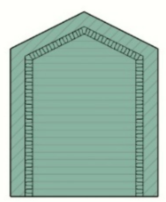
In order to account for the potential technological development that will take place over the next 50 years, as well as the time when the emissions will take place, a dynamic calculation is included in this report as an addition to the static LCA. The dynamic calculation is based on the scientific article *Estimating dynamic climate change effects of material use in buildings – Timing, uncertainty, and emissions sources* (Resch, Andresen, Cherubini, & Brattebø, 2020), which is part of the Danish DGNB pilot manual 2025, where the points given in the ENV 1 – Global Warming Criterion are based on the dynamic calculation (Rådet for Bæredygtigt Byggeri, 2024).

The dynamic calculation includes two projections that weigh the climate impact according to when during the building's life cycle it occurs: a technological projection and a time-specific projection. The technological projection assumes an annual improvement in the production and waste treatment of building materials of 1%. The temporal projection assumes that we only have to look at the effect of greenhouse gases for the next 100 years. This means that the later in the life of the building the emissions occur, the shorter the time the greenhouse gases will be present in the atmosphere, and will therefore have a lower accumulated climate impact. If a material is replaced in year 30, the material will only be calculated with a climate impact corresponding to the greenhouse gas having been in the atmosphere for 70 years. This assumption differs from static LCA's, as these take into account the impact potential for 100 years from the release and not from the year of construction.

5. LCA RESULTS

In this section, the results for Step 1-4 are presented for each of the six cases. Table Table **2**below shows the percentage savings for Step 2-4 compared to Step 1 for each of the six cases.

Table 2– Percentage savings in climate impact for each step for each of the six cases. Percentage savings shown in parentheses are the results from the report "CO2 reduction in timber construction" published in June 2020.

	Step 1 Typical Danish building, with materials such as steel, concrete and brick 	**Step 2** Similar to Step 1, but primary and secondary structures in concrete and steel are changed to wood-based building materials 	**Step 3** Similar to Step 2, but coverings such as façades, floors and ceilings are changed to wood-based building materials 	**Step 4** Similar to Step 3, but mineral wool insulation is changed to wood fiber or cellulose insulation 
Case 1: Single-family house	--	**10%** *(13%)*	**27%** *(27%)*	**34%** *(35%)*
Case 2: Multi-storey residential	--	**25%** *(28%)*	**35%** *(41%)*	**39%** *(45%)*
Case 3: Production facility	--	**31%** *(41%)*	**32%** *(42%)*	**32%** *(43%)*
Case 4: Row house complex	--	**19%**	**22%**	**22%**
Case 5: Office building	--	**16%**	**17%**	**18%**
Case 6: Daycare institution	--	**7%**	**11%**	**12%**

For all six cases, the greatest total savings are achieved in Step 4, where both structures, coverings and insulation are replaced with wood-based products where possible. Between the steps, the greatest savings can be seen from Steps 1 to 2 for Case 2-6. For Case 1, the biggest saving is from Step 2 to 3. The results for each individual case are further elaborated in the following sections.

If the results for 2020 are compared with 2024 as shown in Table 2, the percentages are generally slightly lower in 2024. This is, among other things, due to the fact that more elements have been included in the calculation in 2024, such as plaster, primers and paint on all internal surfaces and vapor and radon barriers. Since these are the same across all four steps, it results in an increased climate impact in all the calculations, and thus the percentage savings have decreased. Despite slightly lower percentages, the savings for both the single-family house and the multi-storey residential in 2024 are relatively close to the calculated savings from 2020. The biggest difference is seen for the production facility, where the savings in Step 2-4 have fallen by 10-11 percentage points. In 2024, the plinth and capping are included, which were not included in 2020. Both plinth and capping are the same across all four steps, and thus the percentage savings from step to step is also reduced here.

5.1 Case 1 - Single-family house

This LCA is based on a case study of a single-storey detached single-family house with a gross area of 116 m^2. The actual scenario is a wooden building with a roof structure and external walls made of wood and mineral wool insulation. This scenario corresponds to Step 3 (see 5.1.2 Scenario descriptions). Based on this scenario, structural engineers from Ramboll have calculated quantities and materials for similar structures with exterior walls consisting of an aerated concrete wall with a brick façade, as well as aerated concrete interior walls. The roof structure is the same in all four steps. To ensure a basis for comparison, the thermal capacity (U-values) has been calculated for exterior walls and roof structures (see Appendix 7: Case 1 – Single-family house – U-value calculations).

5.1.1 Functional unit

To ensure a correct basis for comparison for the four steps, the functional unit for the analysed systems is determined as

116 m^2 detached single-family house with a construction that meets the current loadbearing capacity requirements and exterior walls and roof with minimum U-values of 0.15 and 0.09 for 50 years.

5.1.2 Scenario descriptions

All scenarios have foundations made of concrete and reinforced ground slabs, a wooden roof structure with roof tiles and wood-aluminum windows and doors with triple glazing.

Step 1 consists of a wooden roof structure with mineral wool insulation and gypsum ceiling. The exterior walls consist of an aerated concrete wall with mineral wool insulation and a brick façade. The interior walls are of aerated concrete.

Step 2 consists of a wooden roof structure with mineral wool insulation and gypsum ceiling . The exterior walls are made of wood with mineral wool insulation and a brick façade. The interior walls consist of a wooden structure with mineral wool insulation and gypsum. The foundations are adapted in size to the exterior walls.

Step 3 consists of a wooden roof structure with mineral wool insulation and a wooden ceiling. The exterior walls are made of wood with mineral wool insulation and wooden façade cladding. The interior walls consist of a wooden structure with mineral wool insulation and gypsum.

Step 4 consists of a wooden roof structure with mineral wool insulation and a wooden ceiling. The exterior walls are made of wood with wood fiber insulation and wooden façade cladding. The interior walls consist of a wooden structure with wood fiber insulation and gypsum. The insulation in the roof is cellulose insulation.

Table 3– Scenario overview Case 1 – Single-family house

Building type		Step 1	Step 2	Step 3	Step 4
Detached single-family house Gross floor area Number of floors Floor height Static principle	 116 m^2 1 2.3 Load-bearing facades	Basis	Wood-based structure	Wood-based cladding	Wood fiber and cellulose insulation
Foundation	Concrete + leca blocks	x	x (adapted in size)	x (adapted in size)	x (adapted in size)
Ground slab	Concrete + EPS + floor tiles	x	x	Concrete + EPS + wooden floor	Concrete + EPS + wooden floor
Exterior walls	Aerated concrete + brick façade	x	Wooden frame + brick façade	Wooden frame + wooden cladding	Wooden frame + wooden cladding
Exterior walls insulation + interior surface	Mineral wool + gypsum	x	x	x	Wood fiber insulation + gypsum
Interior walls	Aerated concrete	x	Wooden frame + mineral wool + gypsum	Wooden frame + mineral wool + gypsum	Wooden frame + wood fiber insulation + gypsum
Roof structure	Pitched roof, lattice truss, gypsum ceiling	x	x	Pitched roof, lattice truss, wooden ceiling	Pitched roof, lattice truss, wooden ceiling
Roof insulation	Mineral wool	x	x	x	Cellulose
Roof covering	Roof tiles	x	x	x	x
Windows and doors	Wood-aluminium, triple glazing	x	x	x	x

5.1.3 Climate impact

In this section, results for the climate impact are shown for each of the four steps. All results are presented in kg CO_2e/m^2/year. The climate impact is thus distributed equally over the building's gross area over a temporal consideration of 50 years. The results presented below are based on Appendix 1: Case 1 – Single-family house – Life Cycle Inventory.

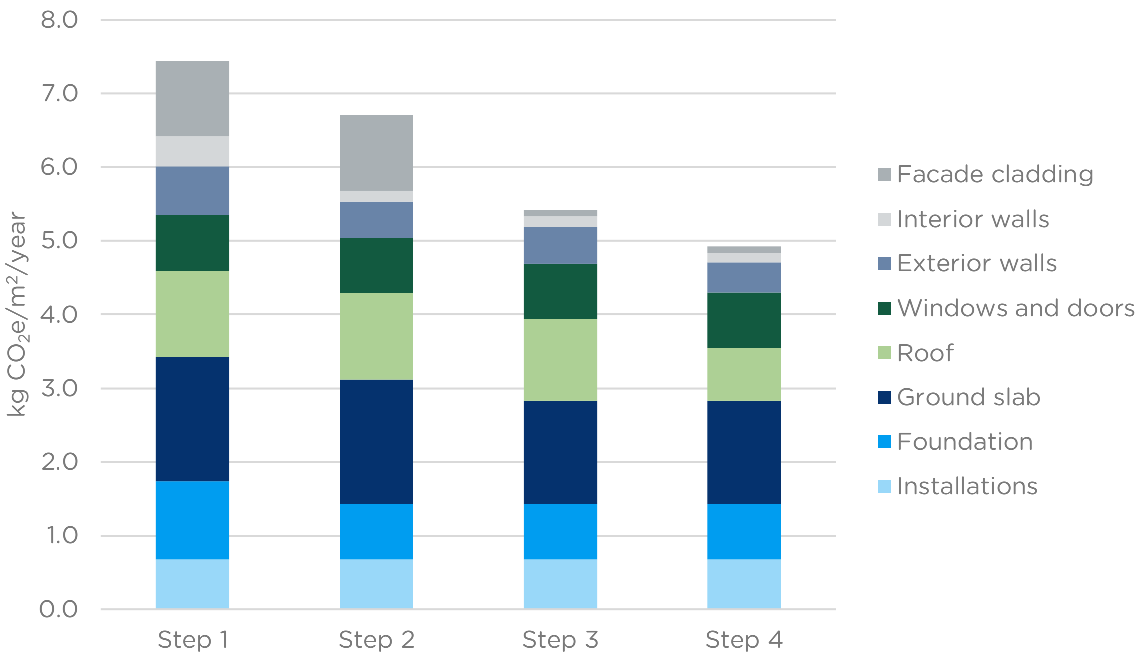


Figure 3 – Climate impact for Case 1 – Single-family house for each step divided by building elements

It can be seen from the results in Figure 3that the climate impact is highest for Step 1, where the total climate impact is 7.44 kg CO_2e/m^2/year. The climate impact decreases through all four steps and is lowest in Step 4, where it is 4.92 kg CO_2e/m^2/year. The greatest reduction is seen in the façade cladding, which in Step 1 and 2 is brick, replaced with wooden cladding in Step 3 and 4. The climate impact from the foundation decreases from Step 1 to 2, as it is adapted in size to the exterior walls.

In addition, a significant reduction is seen in the roof construction from Step 3 to Step 4, which is due to the replacement of mineral wool insulation with cellulose insulation.

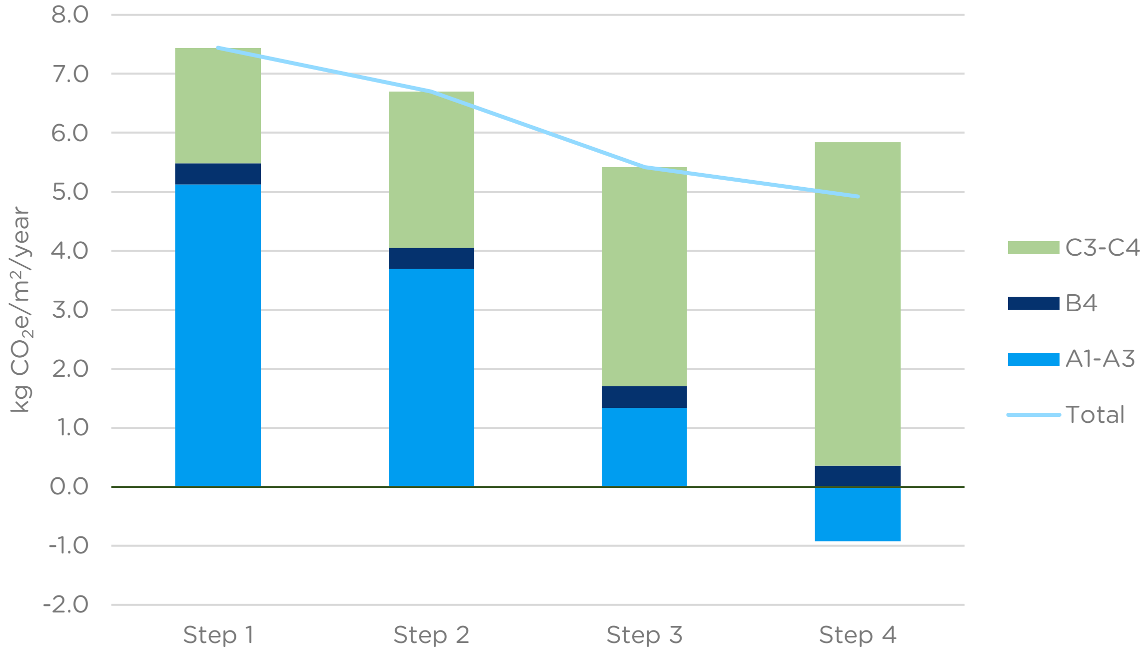


Figure 4 – Climate impact for Case 1 – Single-family house for each step divided into life cycle phases

Figure 4shows the climate impact distributed over the different life cycle phases. The majority of the climate impact in Step 1 occurs upfront in the production phase (A1-A3). As the amount of wood-based materials increase, the primary emission shifts from the production phase to End-of-Life (C3-C4). For Step 4, a negative climate impact is seen in the production phase, which is due to the large quantities of biogenic materials that store CO_2 in the production phase. The increased climate impact at the End-of-Life is also due to the biogenic materials that are assumed to be incinerated. The climate impact from replacements (B4) is similar across all four steps, as only windows and doors are replaced during the temporal consideration and these are the same for all four steps.

5.1.4 Dynamic calculation

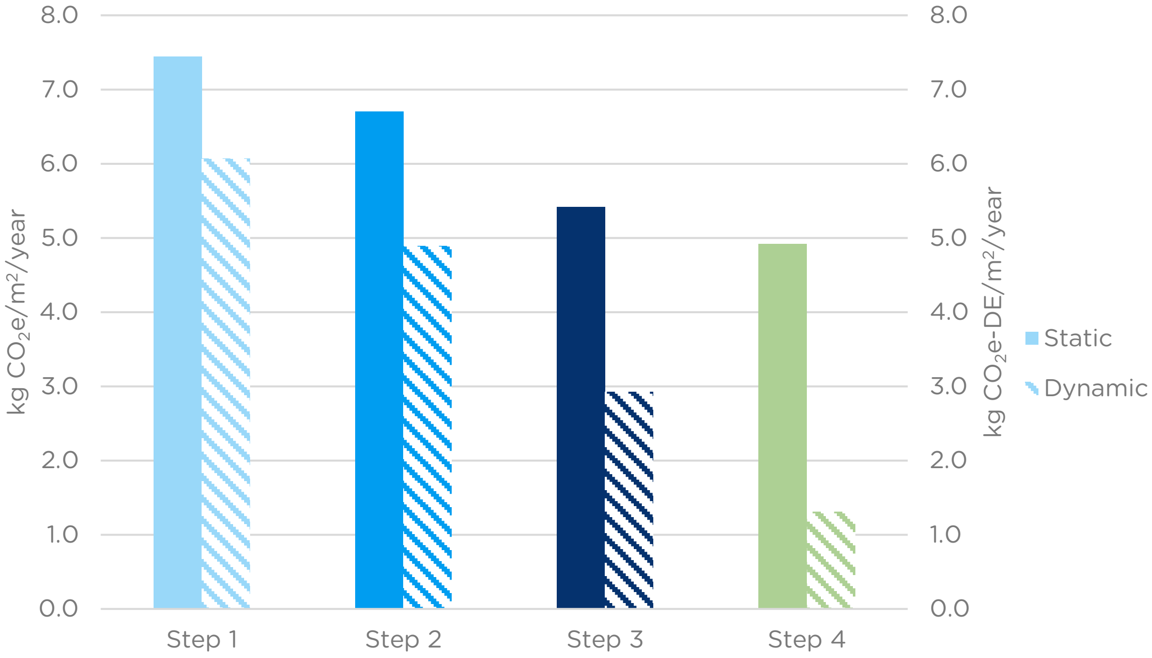


Figure 5 - Static and dynamic results for Case 1 - Single-family house for each step. The left y-axis indicates the static climate impact and the right the dynamic.

Figure Figure **5**shows the total climate impact for each step calculated as static and dynamic LCA, respectively. The dynamic results are generally lower than the corresponding static ones due to the projection factors. For Step 1, a reduction of 18% is seen from the static to the dynamic results. For the remaining steps, the reduction is 26%, 45% and 73% respectively. The increased reduction is due to the increased amount of biogenic materials in the building, which have a low emission during the production phase, but a relatively high emission at the end of their lifetime. As Figure 4shows, an increased amount of biogenic materials results in a larger proportion of the climate impact occurring at the end of life, and since the emissions at the end of life are weighted lower in the dynamic calculation, a greater reduction is seen in the dynamic results when the amount of biogenic materials is increased.

5.1.5 Sub-conclusion

The results for the single-family house show that the climate impact is reduced when several of the materials are replaced with wood-based alternatives. The lowest climate impact is seen in Step 4, which is 4.92 kg CO_2e/m^2/year, which corresponds to a saving of 34% compared to Step 1. The biggest reduction is seen from Step 2 to Step 3, where the façade cladding is changed from bricks to wooden cladding. For Step 1 and 2, the majority of the climate impact comes from the production phase, as conventional building materials such as brick and concrete, which are included in Step 1 and 2, have an energy-intensive production. For Step 3 and 4, the majority of emissions occur at End-of-Life, as wood-based products are assumed to be incinerated at End-of-Life, and thus the CO_2 stored in the wood is released.

The dynamic results show a reduction from Step 1 to Step 4 of 78%. Here, the reduction is significantly greater compared to the static results, as the shift of the climate impact from production to End-of-Life, which is seen with increased use of wood-based materials, provides a greater saving in the dynamic calculation.

5.2 Case 2 – Multi-storey residential

This analysis is an LCA study of a multi-storey residential building complex consisting of eight blocks with respectively three and four storeys. The building complex consists of 66 apartments and a common house with a total gross area of 6,235 m^2. The actual scenario is a wooden building with a roof structure and exterior walls made of wood and mineral wool insulation – this scenario corresponds to Step 3 (see 5.2.2 Scenario descriptions). Based on this scenario, structural engineers from Ramboll have calculated quantities and materials for similar structures with exterior walls consisting of respectively aerated concrete and concrete and a slate façade, interior walls of concrete and steel elements, respectively, and a roof and floor deck consisting of hollow-core slabs. In addition, the analysis contains scenarios where the wooden structures include wood fiber insulation instead of mineral wool insulation, where possible in relation to fire requirements. To ensure a basis for comparison, the thermal capacity (U-values) has been calculated for the exterior walls and roof structures (Appendix 8: Case 2 – Multi-storey residential – U-value calculations).

5.2.1 Functional unit

To ensure a correct basis for comparison for the 4 steps, the functional unit for the analysed systems is determined as

6,235 m^2 multi-storey residential building complex, which meets the current load-bearing capacity requirements and exterior walls and roof with minimum U-values of 0.12 and 0.09 for 50 years.

5.2.2 Scenario descriptions

All steps have concrete foundations and wood-aluminium windows and doors with triple glazing.

Step 1 is a roof structure consisting of hollow-core slabs, mineral wool insulation and roofing felt. There are two types of exterior walls: a reinforced concrete rear wall with mineral wool insulation and a ceramic slate façade, and one consisting of an aerated concrete rear wall, mineral wool insulation and a ceramic slate façade. There are also two types of interior walls: one heavy and one lightweight. The heavy interior walls consist of reinforced concrete. The lightweight interior walls are made of steel elements with mineral wool insulation and gypsum. The ground slab consists of reinforced concrete with a laminate floor. Slabs are hollow-core decks with laminate flooring.

Step 2 is a wooden roof structure with mineral wool insulation, roofing felt and gypsum ceilings. The exterior walls are made of wood with mineral wool insulation and a ceramic slate façade. The interior walls are a wooden structures with mineral wool insulation and gypsum. The ground slab is a wooden structure with laminate flooring. The slabs consist of a wooden structure with mineral wool insulation, gypsum ceilings and laminate flooring.

Step 3 is a wooden roof structure with mineral wool insulation, roofing felt and wooden ceiling. The exterior walls are made of wood with mineral wool insulation, gypsum and a façade with wooden cladding. The interior walls are a wooden structure with mineral wool insulation and gypsum. The ground slab is a wooden structure with wooden parquet flooring. The slabs consist of a wooden structure with mineral wool insulation, gypsum ceilings and wooden parquet flooring.

Step 4 is a wooden roof structure with mineral wool insulation, roofing felt and wooden ceiling. The exterior walls are made of wood with wood fiber insulation and gypsum and a façade with wooden cladding. The interior walls are a wooden structure with mineral wool insulation and gypsum. The ground slab is a wooden structure with wooden parquet flooring. The slabs consist of a wooden structure with mineral wool insulation, gypsum ceilings and wooden parquet flooring.

Table 4– Scenario overview Case 2 – Apartment buildings

Building type		Step 1	Step 2	Step 3	Step 4
Multi-storey residential Gross floor area Number of floors Floor height Static principle	 6,235 m^2 3-4 2.53 m Frame construction	Basis	Wood-based structure	Wood-based cladding	Wood fiber and cellulose insulation
Foundation	Strip foundation	x	x	x	x
Ground slab and floor construction	Reinforced concrete with pressure-resistant insulation + laminate floor	X	Wooden structure + laminate floor	Wooden structure + parquet floor	Wooden structure + parquet floor
Exterior walls	Reinforced concrete + mineral wool + ceramic slate and Aerated concrete + mineral wool + ceramic slate	X	Wooden structure + gypsum + mineral wool + ceramic slate	Wooden structure + gypsum + mineral wool + wooden cladding	Wooden structure + gypsum + wood fiber insulation + wooden cladding
Heavy interior walls	Reinforced concrete	x	Wooden structure + gypsum	Wooden structure + gypsum	Wooden structure + gypsum
Lightweight interior walls	Steel + gypsum	x	Wooden structure + gypsum	Wooden structure + gypsum	Wooden structure + gypsum
Interior wall insulation	Mineral wool	x	x	x	x
Slabs	Hollow-core slab + laminate floor + gypsum ceiling	x	Wooden structure + laminate floor	Wooden structure + parquet floor + wooden ceiling	Wooden structure + parquet floor + wooden ceiling
Edge beams in slabs	Steel	x	Included in the wooden construction in slabs	Included in the wooden construction in slabs	Included in the wooden construction in slabs
Roof	Hollow-core slabs, mineral wool, roofing felt	x	Wooden structure + gypsum ceiling + mineral wool + roofing felt	Wooden structure + wooden ceiling + mineral wool + roofing felt	Wooden structure + wooden ceiling + mineral wool + roofing felt
Windows and doors	Wood-aluminium, triple glazing	x	x	x	x

5.2.3 Climate impact

In this section, the climate impact (GWP) is analysed for each of the four steps. All results are presented in kg CO_2e/m^2/year. The climate impact is thus distributed over the building's gross area over a temporal consideration period of 50 years. Results presented in the following sections can be seen in Appendix 2: Case 2 – Multi-storey residential – Life Cycle Inventory.

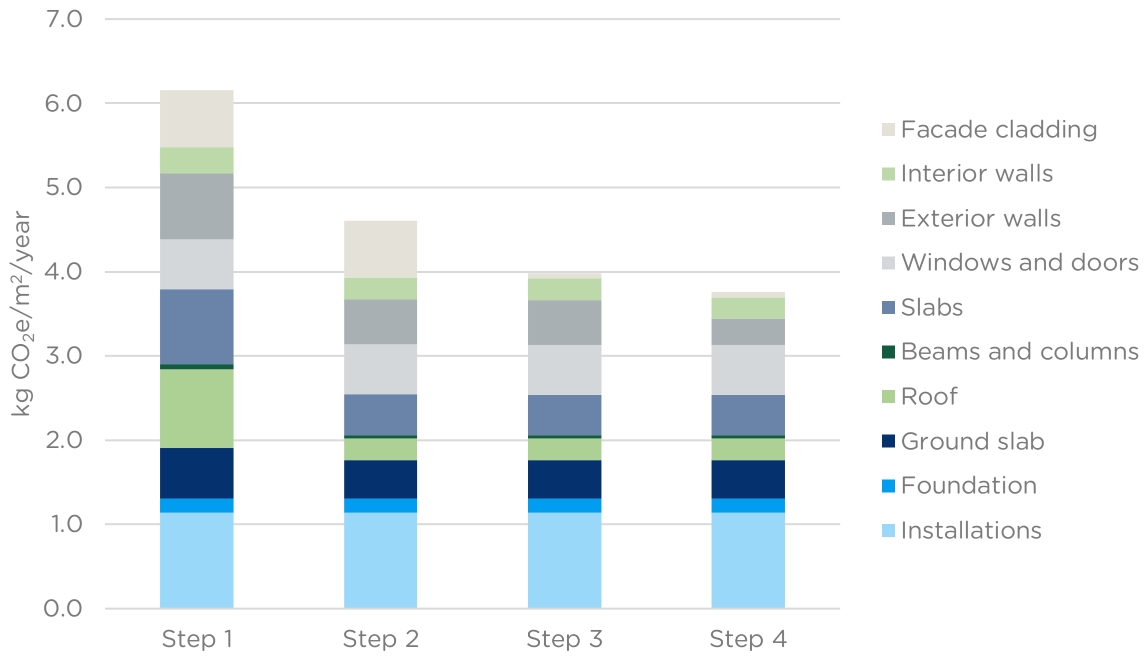


Figure 6 - Climate impact for Case 2 – Multi-storey residential for each step divided by building elements

Figure 6shows the climate impact distributed over the different building parts for each of the four steps. The highest climate impact is seen in Step 1, and from Step 1 to 2 the greatest reduction is seen. The reduction is primarily due to the change in the roof structure and slabs, which in Step 1 are both hollow-core slabs, where in Step 2 they are replaced by a wooden structure. In addition, there is a reduction from Step 2 to Step 3, where the façade cladding is changed from ceramic slate to a wooden cladding. The reduction from Step 3 to 4 is primarily due to the replacement of the insulation material in the exterior walls, where the mineral wool insulation is replaced by wood fibre.

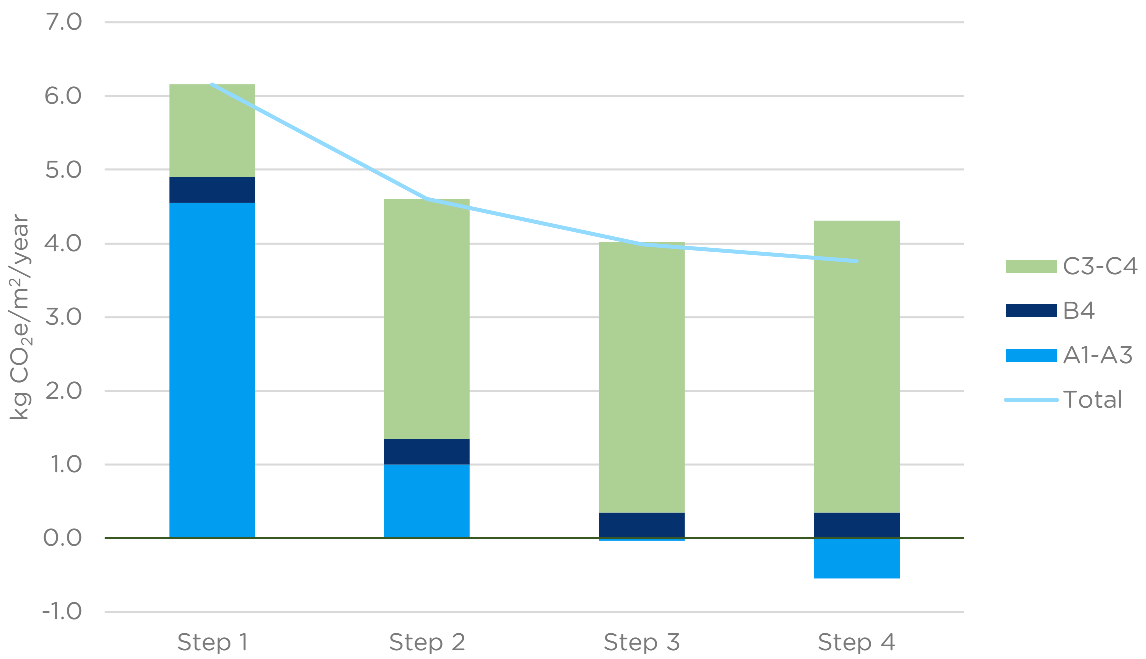


Figure 7 – Climate impact for Case 2 – Multi-storey residential for each step divided into life cycle phases

Figure 7 shows the climate impact distributed over the different life cycle phases. The upfront emissions (A1-A3) make up most of the total emissions for Step 1, which is due to the high amount of mineral construction materials included in this Step. As these are replaced with wood-based construction materials, the distribution changes so the majority of emissions occur at End-of-Life (C3-C4), which is the case in both Step 2, 3 and 4. In Step 4, the share of wood-based materials is so large that a negative impact is seen in the production phase, due to the large amount of biogenic carbon that is stored in the wood-based materials during the production phase.

5.2.4 Dynamic calculation

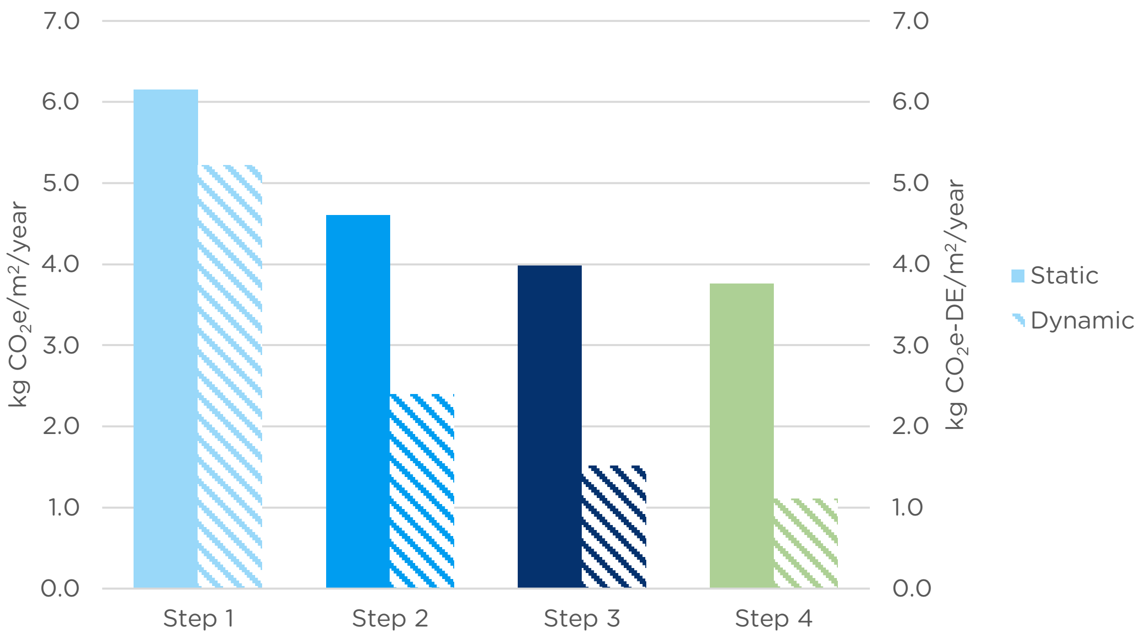


Figure 8 - Static and dynamic results for Case 2 – Multi-storey residential for each step. The left y-axis indicates the static climate impact and the right the dynamic.

The static and dynamic results for each step are presented in Figure 8. For Step 1, a reduction of 15% is seen from the static to the dynamic calculation. The reduction for Step 2, 3 and 4 is 48%, 62% and 71%, respectively. Again, the increased reduction from Step 1 to Step 4 is due to the fact that the amount of wood-based materials in the construction is increased, and that the climate impact at the End-of-Life is thus increased, which results in a lower climate impact with the dynamic calculation projections.

5.2.5 Sub-conclusion

For the multi-storey residential building, the biggest reduction is seen from Step 1 to Step 2, where the roof and floor decks are changed from hollow-core slabs to a wooden structure. The lowest total climate impact is seen in Step 4, which is 3.76 kg CO_2e/m^2/year, which corresponds to a reduction of 39% compared to Step 1. For Step 1, the emissions occur primarily in the production phase, whereas the majority of the emissions for Step 2-4 occur at End-of-Life, due to the increased amount of wood-based material. For both Step 3 and 4, a negative climate impact is seen in the production phase, due to the CO_2 stored in the biogenic materials during production, which is released at End-of-Life, when it is assumed that the materials are incinerated.

The increased amount of wood-based materials is also reflected in the dynamic calculations, where a significantly greater difference is seen between the static and dynamic results for each step.

5.3 Case 3 - Production facility

This analysis is an LCA study of a production facility with a gross area of 4,954 m^2 . The actual scenario is a wood building, with a roof structure and external walls made of wood and mineral wool insulation and fiber cement façade panels – this scenario corresponds to Step 2 (see 5.3.2 Scenario descriptions). Based on this scenario, structural engineers from Ramboll have calculated quantities and materials for a similar structure with a roof and exterior walls made of steel and fiber cement façade panels. In addition, the analysis contains scenarios where the wooden structure uses wood fiber insulation in the façade and cellulose insulation in the roof structure instead of mineral wool insulation (Step 4). To ensure a basis for comparison, the thermal capacity (U-values) has been calculated for exterior walls and roof structures (see Appendix 9: Case 3 – Production facility – U-value calculations).

5.3.1 Functional unit

In order to ensure a correct basis for comparison for the four steps, the functional unit for the analysed systems is determined as

4,954 m^2 production facility with a construction that meets the current load-bearing capacity requirements and outer walls and roof with minimum U-values of 0.24/0.35 and 0.25 for 50 years.

5.3.2 Scenario descriptions

All the scenarios have reinforced foundations and ground slabs and wood-aluminum windows with triple glazing.

Step 1 is a steel frame structure with a trapezoidal roof panel and mineral wool insulation. The exterior walls are made up of steel frames with mineral wool insulation and fiber cement façade panels.

Step 2 is a wooden frame structure with a roof of wood-based cassettes and mineral wool insulation. The exterior walls are made of wood with mineral wool insulation and fiber cement façade panels.

Step 3 2 is a wooden frame structure with a roof of wood-based cassettes and mineral wool insulation. The exterior walls are made of wood with mineral wool insulation and wooden façade cladding.

Step 2 is a wooden frame structure with a roof of wood-based cassettes and cellulose insulation. The exterior walls are made of wood with wood fiber insulation and wooden façade cladding.

Table 5- Scenario overview Case 3 – Production facility

Building type		Step 1	Step 2	Step 3	Step 4
Hall construction		Basis	Wood-based structure	Wood-based cladding	Wood fiber and cellulose insulation
Gross floor area	4,954 m^2				
Number of floors	1				
Floor height	8 m				
Static principle	Frame construction				
Load-bearing structure	Steel structure	x	Glulam structure	Glulam structure	Glulam structure
Foundation	Reinforced concrete	x	x	x	x
Ground slab	Reinforced concrete + EPS insulation	x	x	x	x
Exterior walls	Steel frame + mineral wool insulation + fiber cement façade panels	X	x	Wood structure + mineral wool insulation + wooden cladding	Wood structure + wood fiber insulation + wood cladding
Roof	Trapezoidal roof panel + mineral wool insulation	x	Wooden cassettes + mineral wool insulation	Wooden cassettes + mineral wool insulation	Wooden cassettes + cellulose insulation
Windows and doors	Wood-aluminium, triple glazing	x	x	x	x

5.3.3 Climate impact

In this section, the climate impact (GWP) is analysed for each of the four steps. All results are presented in kg $CO_2e/m^2/year$. The climate impact is thus distributed over the building's gross area over a consideration period of 50 years. Results presented in the following sections can be seen in Appendix 3: Case 3 – Production facility – Life Cycle Inventory.

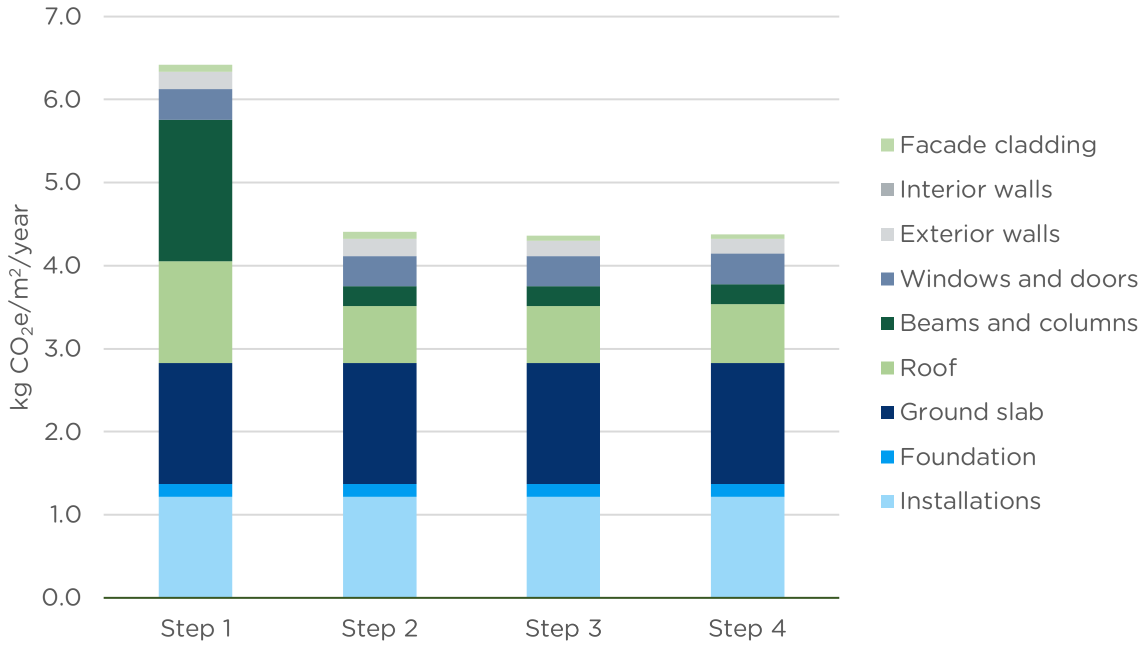


Figure 9 – Climate impact for Case 3 – Production facility for each step divided by building elements

Figure 9shows the climate impact for each step of the production facility. The total climate impact in Step 1 is 6.40 kg $CO_2e/m^2/year$. The most significant reduction in climate impact is seen from Step 1 to 2, where the change from a steel structure to a glulam construction in particular contributes to the reduction. In addition, a significant reduction is seen due to the replacement from trapezoidal panels to wooden cassettes in the roof structure. From Step 2 to 4, the difference in climate impact is infinitesimal. There is a reduction of 0.05 kg $CO_2e/m^2/year$ from Step 2 to 3 due to the change from fiber cement façade panels to wooden cladding and an increase of 0.02 kg CO_2e/m^2/year from Step 3 to Step 4 due to the cellulose insulation in the roof in Step 4.

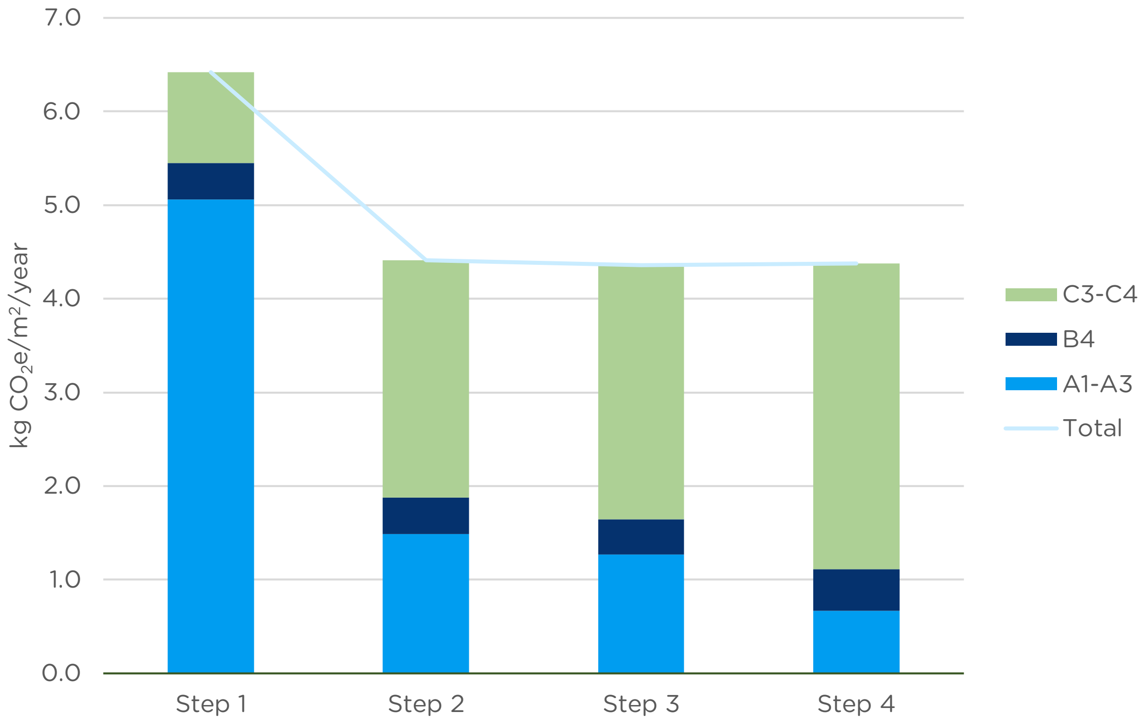


Figure 10 – Climate impact for Case 3 – Production facility for each step divided into life cycle phases

Figure 10shows the climate impact divided by life cycle phases. Here it can be seen that the majority of emissions for Step 1 occur in the production phase (A1-A3). Although Step 2 to 4 have largely the same overall climate impact, there is a difference in when the climate impact occurs. In Step 2, the emission from the production phase is 1.49 kg CO_2e/m^2/year, which drops to 1.27 kg CO_2e/m^2/year and 0.67 kg CO_2e/m^2/year for Step 3 and Step 4, respectively. In Step 4, the climate impact from replacements (B4) is slightly higher, as the cellulose insulation in the roof has a lifespan of 40 years, and thus must be replaced during the life of the building, whereas the mineral wool insulation in the roof in Step 1- 3 has a lifespan of 50 years, and is not replaced during the temporal consideration. The amount of bio-based materials gradually increase from Step 1-4, but not to an extent that results in a negative climate impact in the production phase, as seen for the two previous cases.

5.3.4 Dynamic calculation

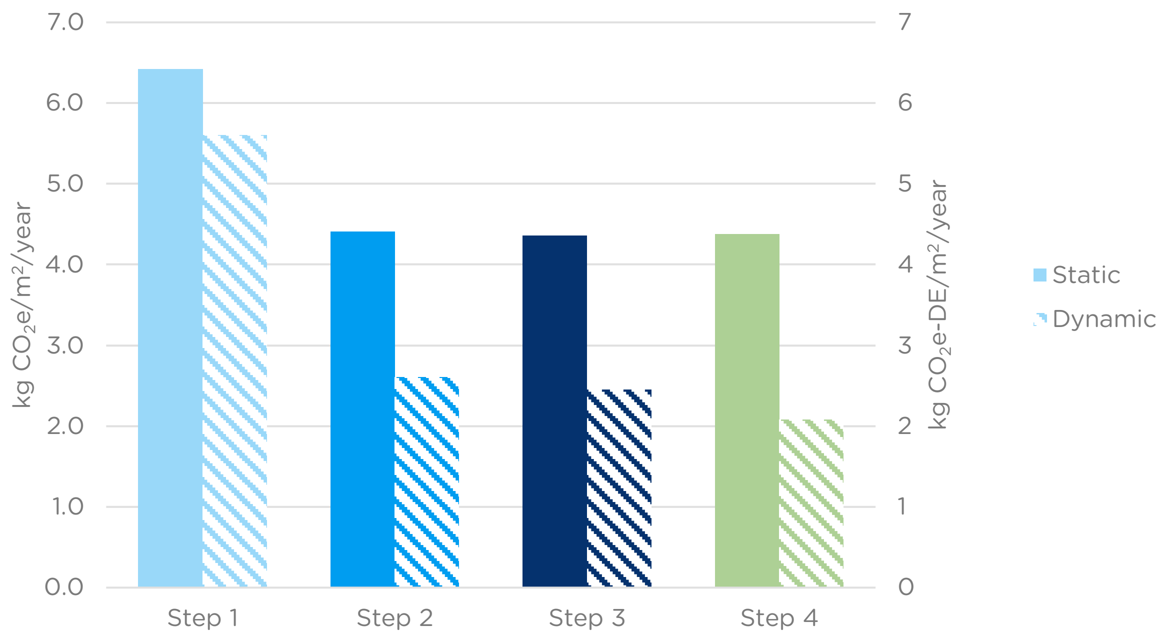


Figure 11 - Static and dynamic results for Case 3 – Production hall for each step. The left y-axis indicates the static climate impact and the right the dynamic.

In the dynamic calculation shown in Figure 11the difference between Step 2-4 is also expressed. The total climate impact in the static calculation is close to the same for all three Steps, but is reduced by respectively 41%, 44% and 53% in the dynamic calculation, due to the increased amount of bio-based materials in Step 3 and 4. For Step 1 the reduction from the static to the dynamic calculation is 13%.

5.3.5 Sub-conclusion

For the production facility, the reduction in climate impact is most significant from Step 1 to 2, where the steel structure is replaced with a glulam structure, and the trapezoidal panels in the roof are replaced with wooden cassettes. From Step 2 to 4, the overall climate impact is largely the same. There is a slight increase from Step 3 to Step 4, which is due to the change to cellulose insulation in the roof structure. Despite the small difference in the overall climate impact, there is however a difference in when the emissions occur during the life cycle. For Step 2, 33% of the emissions come from the production phase, for Step 3 it is 29% and for Step 4 only 13% of the emissions come from the production phase.

For the dynamic results, the greatest reduction is also seen from Step 1 to Step 2. However, a reduction is still seen from Step 2 to Step 4, and despite the static results showing a higher impact in Step 4 than Step 3, it is the other way around for the dynamic results due to the increased amount of biogenic materials in Step 4, which impacts at End-of-Life is weighted lower than the impact in the production phase.

5.4 Case 4 – Office building

This analysis is an LCA study of a two-storey office building with a basement and a gross area of 2,145 m^2. The actual scenario is a wooden building with a frame in glulam, slabs consisting of wooden cassettes with mineral wool, roof cassettes and exterior walls made of wood and mineral wool insulation and façade cladding made of aluminum and wood. The slab above the basement and basement walls consist of concrete and ground slab of concrete insulated with polystyrene, corresponding to Step 3 (see 5.4.2 Scenario descriptions). Based on this scenario, Ramboll's structural engineers have calculated the quantities and materials for a similar structure consisting of a steel frame, concrete slabs and exterior walls, and roof elements in steel insulated with mineral wool. In addition, the analysis contains a scenario where the mineral wool insulation in the exterior walls is replaced with wood fiber insulation (Step 4). To ensure a basis for comparison, the thermal capacity (U-value) has been calculated for exterior walls and roof structures (Appendix 10: Case 4 – Office building – U-value calculations).

In this case, operational energy is also included. Here, the change of slabs is the only building element that has an influence on the heat capacity and thus the operational energy (see Appendix 13: Case 4 – Office building – Operating emissions).

5.4.1 Functional unit

To ensure a correct basis for comparison for the four steps, the functional unit for the analysed systems is determined as

2,145 m^2 office building with a structure that meets current load-bearing capacity requirements and exterior walls and roof with minimum U-values of 0.16 and 0.09 for 50 years.

5.4.2 Scenario descriptions

All steps have reinforced foundations and ground slabs as well as wood-aluminum windows with triple glazing.

Step 1 is a steel frame structure with concrete slabs with mineral wool insulation, gypsum ceilings and vinyl and tile flooring. The roof elements consist of trapezoidal panels and mineral wool. The exterior walls consist of façade elements in steel with mineral wool insulation. The façade cladding is aluminum sheets.

Step 2 is a frame construction in glulam with slabs consisting of wooden cassettes with mineral wool insulation, gypsum ceilings and vinyl and tile flooring. Roof cassettes and exterior walls are wooden structures with mineral wool insulation. The façade cladding is aluminum sheets.

Step 3 is a frame construction in glulam with slabs consisting of wooden cassettes with mineral wool insulation, gypsum ceilings and laminate and tile flooring. Roof cassettes and outer walls consist of wooden constructions with mineral wool insulation. Roof cassettes and exterior walls are wooden structures with mineral wool insulation. The façade is covered partly with wood and partly with aluminum sheets.

Step 4 is a frame construction in glulam with slabs consisting of wooden cassettes with mineral wool insulation, gypsum ceilings and laminate and tile flooring. Roof cassettes consist of wood and mineral wool insulation. The exterior walls consist of wooden structures with wood fiber insulation and façade cladding of partly wood and partly aluminum sheets.

Table 6- Scenario overview Case 4 – Office building

Building type		Step 1	Step 2	Step 3	Step 4
Office		Basis	Wood-based structure	Wood-based cladding	Wood fiber and cellulose insulation
Gross floor area	2,145 m^2				
Number of floors	3 incl. cellar				
Floor height	2.5-3.3 m				
Static principle	Frame construction				
Load-bearing structure	Steel structure	x	Glulam structure	Glulam structure	Glulam structure
Foundation	Reinforced concrete	x	x (adapted in size)	x (adapted in size)	x (adapted in size)
Ground slab	Reinforced concrete + EPS	x	x	x	x
Exterior walls	Steel structure + mineral wool insulation + aluminium cladding	x	Wooden cassettes + mineral wool + aluminium	Wooden cassettes + mineral wool + aluminium/wood cladding	Wooden cassettes + wood fiber insulation + aluminium/wood cladding
Basement walls	Reinforced concrete + EPS	x	x	x	x
Heavy interior walls	Aerated concrete and wood cassettes + mineral wool	x	x	x	x
Lightweight interior walls	Wooden construction + mineral wool + gypsum	x	x	x	x
Slabs	Concrete slabs + mineral wool + vinyl floor + gypsum ceiling	x	Wooden cassettes + mineral wool + vinyl floor + gypsum ceiling	Wooden cassettes + mineral wool + laminate floor + gypsum ceiling	Wooden cassettes + mineral wool + laminate floor + gypsum ceiling
Roof	Trapezoidal roof panel + mineral wool + roofing felt + gypsum ceiling	x	Wooden structure + mineral wool + roofing felt + gypsum ceiling	Wooden structure + mineral wool + roofing felt + gypsum ceiling	Wooden structure + mineral wool + roofing felt + gypsum ceiling
Windows and doors	Wood-alu, triple glazing	x	x	x	x

5.4.3 Climate impact

In this section, the climate impact (GWP) is analysed for each of the four steps. All results are presented in kg $CO_2e/m^2/year$. The climate impact is thus distributed over the building's gross area over a temporal consideration period of 50 years. Results presented in the following sections can be seen in Appendix 4: Case 4 – Office building – Life Cycle Inventory.

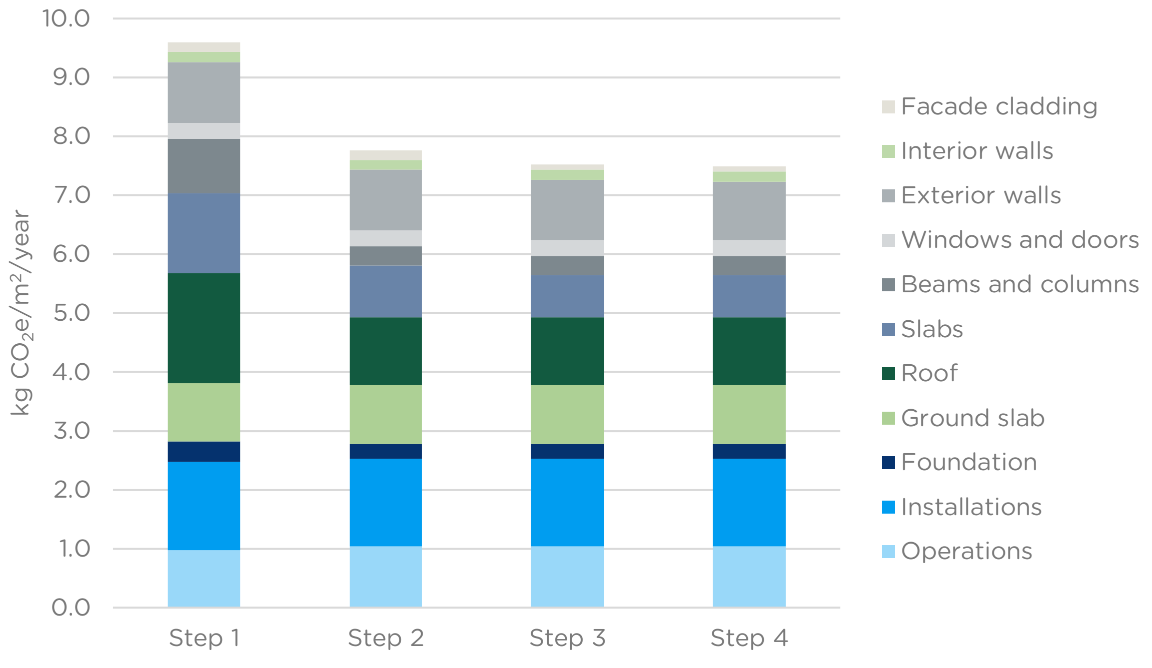


Figure 12 – Climate impact for Case 4 – Office building for each step divided by building elements

Figure Figure **12**shows the climate impact for each of the four steps divided by building elements. Unlike the three previous cases, operational emissions are included in this case. The operational emissions are converted based on the thermal mass of the building in each step. However, it can be seen for this specific case that the change in thermal mass does not have a big impact on the climate impact from operations. Looking at the total climate impact, the largest reduction occurs from Step 1 to Step 2, which is primarily due to three parameters: the roof construction is changed from trapezoidal panels to a wooden structure, the slabs are changed from concrete slabs to wooden cassettes, and the steel columns and beams are replaced with a glulam structure. From Step 2 to Step 3, the climate impact drops from 7.76 kg CO_2e/m^2/year to 7.53 kg CO_2e/m^2/year, which is due to the change of the flooring from vinyl to laminate, as well as the façade cladding changing from a pure aluminum façade to partially wood and partially aluminum, corresponding to the actual built scenario. Due to fire requirements, only the insulation in the exterior walls has been changed to wood fiber in Step 4, which results in a reduction of 0.03 kg CO_2e/m^2/year from Step 3 to 4.

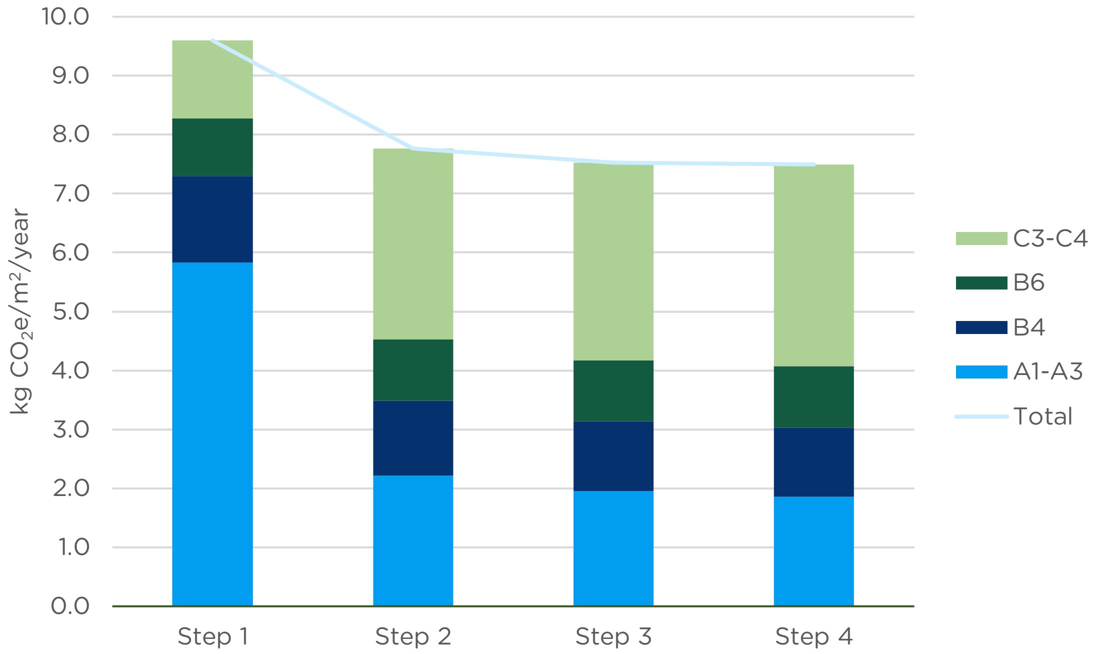


Figure 13 – Climate impact for Case 4 – Office building for each step divided into life cycle phases

Figure 13shows the climate impact divided by life cycle phases. Unlike the previous cases, the operating emissions (B6) are also included. The biggest difference is again seen from Step 1 to Step 2, where the majority of the emissions go from being in the production phase (A1-A3) to being at End-of-Life (C3-C4). For Step 2-4, the distribution between the emissions in the different life cycle phases is largely the same. The change in thermal mass from Step 1 to Step 2 results in a small increase of 0.06 kg CO_2e/m^2/year from operational emissions.

5.4.4 Dynamic calculation

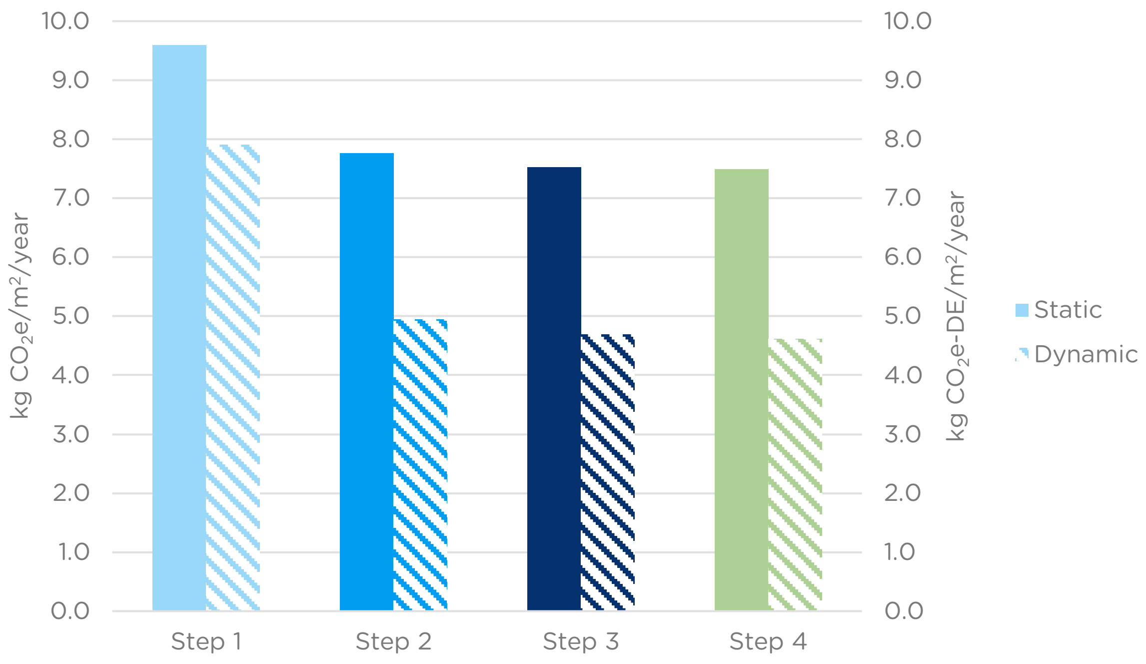


Figure 14 – Static and dynamic results for Case 4 – Office building for each step. The left y-axis indicates the static climate impact and the right the dynamic.

The comparison between the static and dynamic results is presented in Figure 14. The reduction for Step 1 is 18%, after which it increases significantly to 36%, 38% and 38% respectively for Step 2-4, which is consistent with the results presented in Figure 13, where we saw the largest shift in the occurrence of emissions from Step 1 to 2. The dynamic results for Step 2-4 are relatively close, which was to be expected since the emissions for the three steps are distributed fairly evenly across life cycle phases.

5.4.5 Sub-conclusion

For the office building there is an overall reduction in the total climate impact from Step 1 to Step 4. The biggest reduction occurs from Step 1 to Step 2, where the roof construction is changed from trapezoidal panels to a wooden structure, the slabs go from concrete slabs to wooden cassettes, and the steel columns and beams are replaced with a glulam structure. From Step 1 to 2, a small increase is seen from operational emissions, which is due to the change in the thermal mass of the building. For Step 1, the majority of emissions are related to the production phase, which from Step 2 and onwards changes to End-of-Life emissions making up the largest share.

This is also reflected in the dynamic results, where the difference between static and dynamic results goes from 18% in Step 1 to 36-38% for Step 2-4, due to the increased amount of emissions that occur at End-of-Life.

5.5 Case 5 – Row house complex

This analysis is an LCA study of a row house complex consisting of one- and two-storey terraced houses with a total gross area of 6,701 m^2. The actual scenario has roofs and exterior walls of wooden cassettes with mineral wool insulation, wooden façades and wooden slabs with wood floors. Vertical residential partitions are also made as wooden cassettes with mineral wool. Foundations and ground slabs are made of reinforced concrete with EPS, corresponding to Step 3 (see 5.5.2 Scenario descriptions). Based on this scenario, Ramboll's structural engineers have calculated quantities and materials for a similar structure consisting of lightweight concrete exterior walls with mineral wool insulation and brick façades, hollow-core slabs, wooden roof cassettes with mineral wool insulation and vertical residential partitions in lightweight concrete and mineral wool insulation. In addition, the analysis contains scenarios where the wooden structure uses wood fiber insulation in the exterior and interior walls instead of mineral wool, where the fire requirements allow it (Step 4). To ensure a basis for comparison, the thermal capacity (U-value) has been calculated for exterior walls (see Appendix 11: Case 5 – Row house complex – U-value calculations).

In this case, operational energy is also included, where changes in slabs, ground slabs and exterior walls have an influence on the heat capacity and thus the operational energy. The operational emissions for the row house complex are determined based on an area-weighted summation of energy performance calculation results for a representative house of each housing type (see Appendix 14: Case 5 – Row house complex – Operating emissions).

5.5.1 Functional unit

In order to ensure the basis of comparison for the four steps, the functional unit for the analysed systems is determined as

6,701 m^2 row house complex development with a structure that meets current load-bearing capacity requirements and exterior walls with a minimum U-value of 0.15 for 50 years.

5.5.2 Scenario descriptions

All steps have reinforced foundations and ground slabs and wood-alu windows with triple glazing.

Step 1 consists of exterior wall elements in lightweight concrete and mineral wool insulation with brick façades and hollow-core slabs. The floor is covered with laminate and tiles, and ceilings are made of wood concrete. The roof consists of wooden cassettes with mineral wool insulation, and vertical residential partitions are made as lightweight concrete walls with mineral wool insulation.

Step 2 consists of wooden exterior wall elements with mineral wool insulation, brick façades and wooden slabs with mineral wool insulation. Flooring is laminate and tiles, and ceilings are made of wood concrete. The roof consists of wooden cassettes with mineral wool insulation, and vertical residential partitions are made of wooden cassettes with mineral wool insulation.

Step 3 consists of wooden exterior wall elements with mineral wool insulation, wooden cladding and wooden slabs with mineral wool insulation. The floor is partly wood and partly tiles, and ceilings are made of wood concrete. The roof consists of wooden cassettes with mineral wool insulation, and vertical residential partitions are wooden cassettes with mineral wool insulation.

Step 4 consists of wooden exterior wall elements with wood fiber insulation, wooden cladding and wooden slabs with mineral wool insulation. The floor is partly wood and partly tiles, and ceilings are made of wood concrete. The roof consists of wooden cassettes with mineral wool insulation, and vertical residential partitions are wooden cassettes with mineral wool insulation.

Table 7- Scenario overview Case 5 – Row house complex

Building type		Step 1	Step 2	Step 3	Step 4
Row housing Gross floor area Number of floors Floor height Static principle	 6,701 m^2 1-2 2.5-3.5 m Element construction	Basis	Wood-based structure	Wood-based cladding	Wood fiber and cellulose inslation
Foundation	Reinforced concrete	x	x (adapted in size)	x (adapted in size)	x (adapted in size)
Ground slab	Reinforced concrete + EPS	x	x	x	x
Exterior walls	Lightweight concrete + mineral wool + brick façade	x	Wooden cassettes + mineral wool + brick façade	Wooden cassettes + mineral wool + wood cladding	Wood cassettes + wood fiber insulation + wood cladding
Residential partition	Lightweight concrete + mineral wool	x	Wooden cassettes + mineral wool	Wooden cassettes + mineral wool	Wooden cassettes + mineral wool
Lightweight interior walls	Wooden structure + mineral wool + gypsum	x	x	x	Wooden structure + wood fiber insulation + gypsum
Slabs	Hollow-core slab + wood concrete ceiling + laminate floor/tiles	x	Wooden cassettes + wood concrete ceiling + laminate floor/tiles	Wooden cassettes + wood concrete ceiling + wooden floor/tiles	Wooden cassettes + wood concrete ceiling + wooden floor/tiles
Roof	Wooden cassettes + mineral wool insulation	x	x	x	x
Windows and doors	Wood-aluminum, triple glazing	x	x	x	x

5.5.3 Climate impact

In this section, the climate impact (GWP) is analysed for each of the four steps. All results are presented in kg $CO_2e/m^2/year$. The climate impact is thus distributed over the building's gross area over a temporal consideration of 50 years. Results presented in the following sections can be seen in Appendix 5: Case 5 – Row house complex – Life Cycle Inventory.

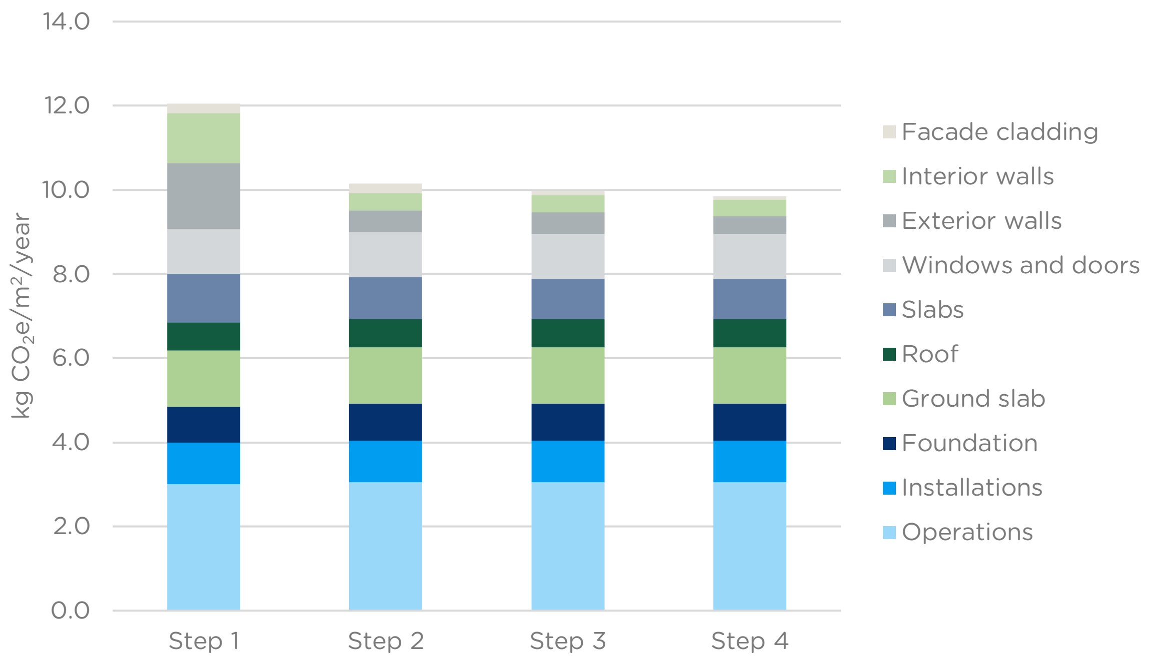


Figure 15 – Climate impact for Case 5 – Row house complex for each step divided by building elements

The results in Figure 15show the total climate impact for each step, distributed among the different building elements and operational emissions. For Step 1, the total climate impact is 12.05 kg CO_2e/m^2/year, which is above the limit value from BR18, which per January 1st 2023 is set to 12 kg CO_2e/m^2/year. The climate impact drops to 10.15 kg CO_2e/m^2/year in Step 2, which is primarily due to the change from lightweight concrete to wooden cassettes in both exterior walls and vertical residential partitions. From Step 2 to Step 3, a reduction of 0.18 kg CO_2e/m^2/year is seen, which is primarily due to the replacement from brick to wooden cladding. From Step 3 to Step 4, a further reduction of 0.12 kg CO_2e/m^2/year is seen as a result of the change for wood fiber insulation in exterior and light interior walls.

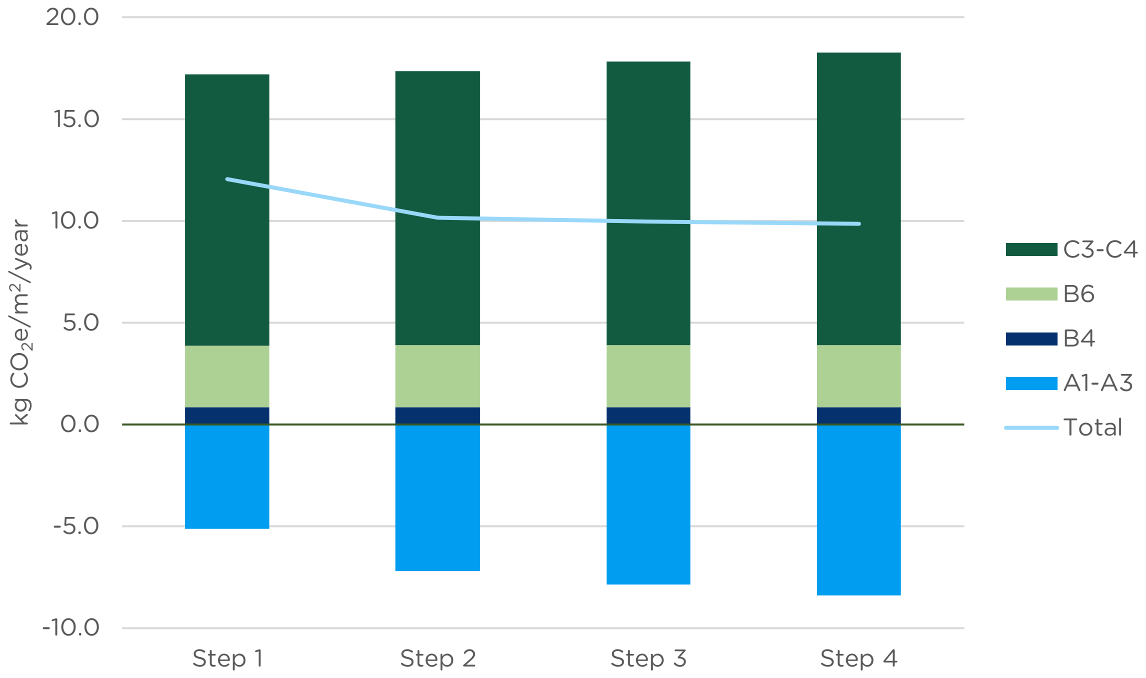


Figure 16 - Climate impact for Case 5 - Row house complex for each step divided into life cycle phases

Figure Figure 16This is due to the relatively large amount of wood-based materials that are included across all steps, such as the roof cassettes. The quantity of wood-based materials increases gradually from Step 1-4, and thus the negative climate impact in the production phase also becomes greater from Step 1 to Step 4. Correspondingly, the climate impact at the end of life (C3-C4) increases from Step 1 to Step 4, as the wood-based materials are assumed to be incinerated at End-of-Life, thus emitting the CO_2 that has been stored during the production phase.

5.5.4 Dynamic calculation

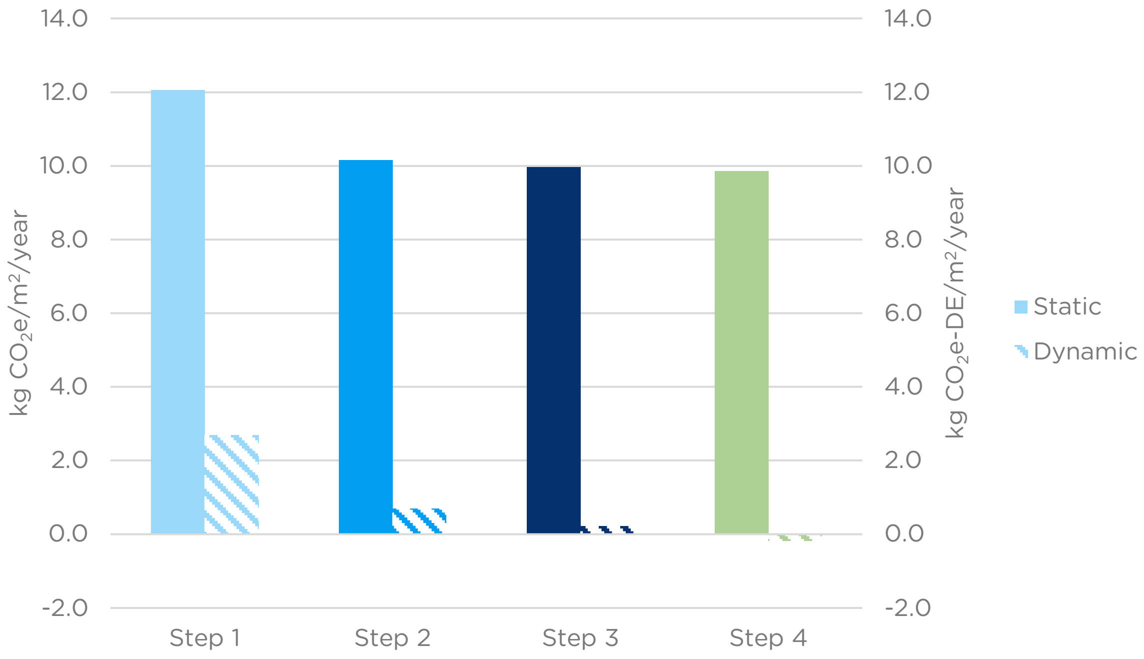


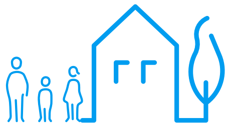
Figure 17 - Static and dynamic results for Case 5 – Row house complex for each step. The left y-axis indicates the static climate impact and the right the dynamic.

Figure 17shows the static and dynamic calculations for each Step. Due to the large amount of wood-based materials, a large reduction from the static to the dynamic calculation is already seen from Step 1, where the reduction is 78%. For Step 2 and Step 3 the reduction is 93% and 98% respectively, where for Step 4 a reduction of 102% is seen. The fact that the reduction is over 100% is because the dynamic calculation ends up giving a negative result. The negative emission in the production phase is, due to the projection factors in the dynamic calculation, high enough to offset the impact that occurs from operations, replacements and at End-of-Life, and thus the dynamic calculation for Step 4 ends at -0.17 kg CO_2e/m^2/year.

5.5.5 Sub-conclusion

For the row house complex, the largest reduction is seen from Step 1 to Step 2, where exterior walls and residential partitions are changed from lightweight concrete to wooden cassettes, which results in a reduction of 16%. Smaller reductions are seen from both Step 2 to 3 and Step 3 to 4. Already at Step 1, a negative climate impact is seen in the production phase, which is due to the large amount of wood-based materials. This increases through all four steps. The large amount of wood-based materials is also reflected in the dynamic results, where the largest differences between static and dynamic results are seen across all six cases. Here, a reduction of 78-102% is seen from static to dynamic calculations. For Step 4, a negative result is obtained in the dynamic calculation, which is due to the fact that the amount of biogenic materials that store CO_2 in the production phase, together with the projection factors, is large enough to offset the emission that comes under the assumption of burning the materials at End-of-Life.

5.6 Case 6 – Daycare institution



This analysis is an LCA study of a single-storey daycare institution with a gross area of 2,472 m^2. The building consists of a glulam and steel frame structure and a glulam rafter roof insulated with mineral wool. The exterior walls are partly wooden cassettes with mineral wool insulation and partly concrete element walls with mineral wool insulation and wooden cladding. The stabilizing interior walls are made of concrete. The foundation and ground slab consist of reinforced concrete and EPS insulation with rubber and vinyl flooring. Since the structure contains both conventional and wood-based solutions, the actual building is not represented 1:1 in any of the four steps. Instead, based on this scenario, Ramboll's structural engineers have calculated quantities and materials for similar constructions, where all the exterior walls consist of concrete and mineral wool insulation covered with brick cladding. In Step 2, all exterior walls and stabilizing interior walls are converted to wooden cassettes with mineral wool insulation (see 5.6.2 Scenario descriptions). The foundation has not been reduced as a result of the change to the exterior wall construction. There is a potential additional saving of an expected 3% for Step 2-4 in the reduction of the size of the foundation, which is not included in the results below. In addition, the analysis contains scenarios where wood fiber insulation is used in exterior and interior walls, where fire requirements allow it (Step 4). To ensure a basis for comparison, the thermal capacity (U-value) has been calculated for exterior walls (see Appendix 12: Case 6 – Daycare institution – U-value calculations).

In this case, operational energy is also included. Here, however, there are no changed constructions that have an influence on the heat accumulation and thus no differences in the operational energy across the four steps (see Appendix 15: Case 6 – Daycare institution – Operating emissions).

5.6.1 Functional unit

In order to ensure a basis for comparison for the four steps, the functional unit for the analysed systems is determined as

2,472 m^2 daycare institution with a structure that meets current load-bearing capacity requirements and exterior walls with a minimum U-value of 0.13 for 50 years.

5.6.2 Scenario descriptions

All scenarios have reinforced foundations and ground slabs and wood-aluminum windows with triple glazing

Step 1 is a glulam and steel frame structure with a roof of glulam rafters. The exterior walls consist of concrete elements insulated with mineral wool and brick façades. The load-bearing interior walls consist of concrete elements.

Step 2 is a glulam and steel frame structure with a roof of glulam rafters. The exterior walls consist of wooden cassettes insulated with mineral wool and brick façades. The load-bearing interior walls are a wooden structure with mineral wool insulation and fire gypsum.

Step 3 is a glulam and steel frame structure with a roof of glulam rafters. The exterior walls consist of wooden cassettes insulated with mineral wool and with wooden façade cladding. The load-bearing interior walls are a wooden structure with mineral wool insulation and fire gypsum.

Step 4 is a glulam and steel frame structure with a roof of glulam rafters. The exterior walls consist of wooden cassettes insulated with wood fiber insulation and with wooden façade cladding. The load-bearing interior walls are a wooden structure with mineral wool insulation and fire gypsum.

Table 8– Scenario overview Case 6 – Daycare institution

Building type		Step 1	Step 2	Step 3	Step 4
Daycare institution Gross floor area Number of floors Floor height Static principle	 2,472 m^2 1 2.6 m Frame construction	Basis	Wood-based structure	Wood-based cladding	Wood fiber and cellulose insulation
Load-bearing structure	Steel and glulam structure	x	x	x	x
Foundation	Strip foundation reinforced concrete	x	x	x	x
Ground slab	Reinforced concrete + EPS	x	x	x	x
Exterior walls	Precast concrete wall + mineral wool	x	Wooden cassettes + mineral wool	Wooden cassettes + mineral wool	Wooden cassettes + wood fiber insulation
Exterior wall cladding	Bricks	x	x	Wood cladding	Wood cladding
Heavy interior walls	Concrete	x	Wooden cassettes + mineral wool	Wooden cassettes + mineral wool	Wooden cassettes + mineral wool
Lightweight interior walls	Wood/steel frame + mineral wool + gypsum	x	x	x	Wood/steel frame + wood fiber insulation + gypsum
Roof	Rafter roof + roofing felt + wood concrete	x	x	x	x
Windows and doors	Wood-aluminum, triple glazing	x	x	x	x

5.6.3 Climate impact

In this section, the climate impact (GWP) is analysed for each of the four steps. All results are presented in kg $CO_2e/m^2/year$. The climate impact is thus distributed over the building's gross area over a temporal consideration period of 50 years. Results presented in the following sections can be seen in Appendix 6: Case 6 – Daycare institution – Life Cycle Inventory.

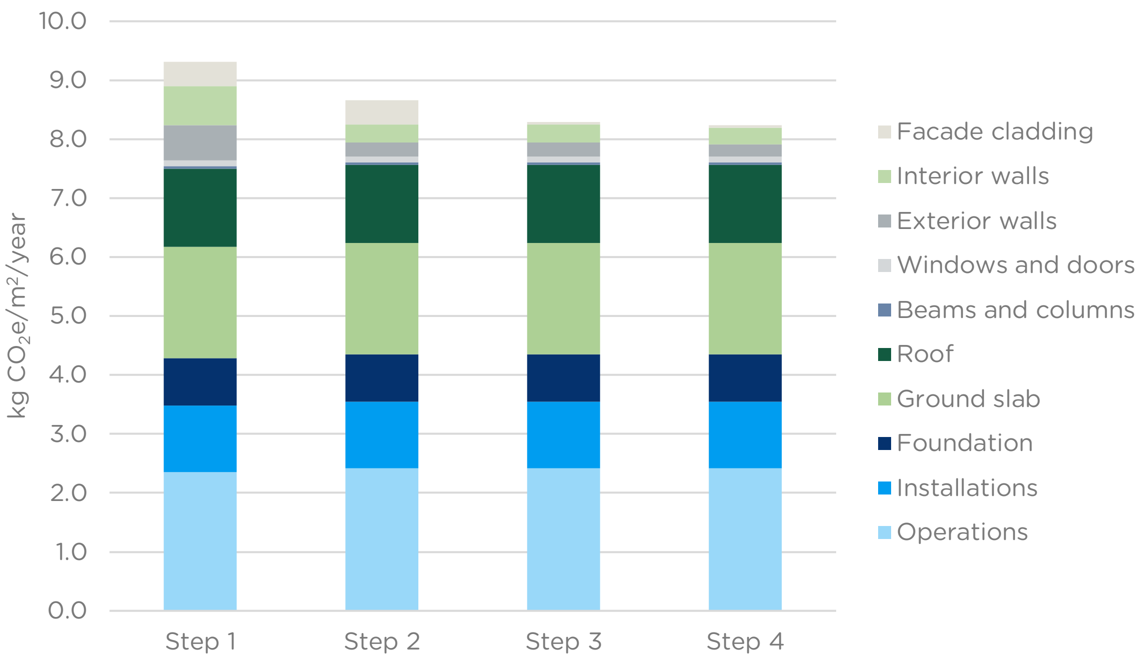


Figure 18 – Climate impact for Case 6 – Daycare institution for each step divided by building elements

Figure 18shows the total climate impact for each step divided by building component categories and operational emissions. The reduction between the four steps is smaller than seen in the previous cases. This is due to several of the building parts with the largest climate impact – including ground slab, roofs and installations – being identical in all four steps. The roof structure is the same for all four steps, as the wooden construction on the existing building is considered to be the most likely solution for this type of construction. The biggest reduction is seen from Step 1 to Step 2, where the climate impact goes from 9.32 kg CO_2e/m^2/year to 8.66 kg CO_2e/m^2/year, which is due to both exterior and interior walls being changed from concrete structures to wooden cassettes. From Step 2 to Step 3, a reduction of 0.37 kg CO_2e/m^2/year is seen, which is due to the change of the façade material from bricks to wooden cladding. From Step 3 to Step 4, there is a small reduction due to the exchange of mineral wool with wood fiber insulation in the exterior and interior walls.

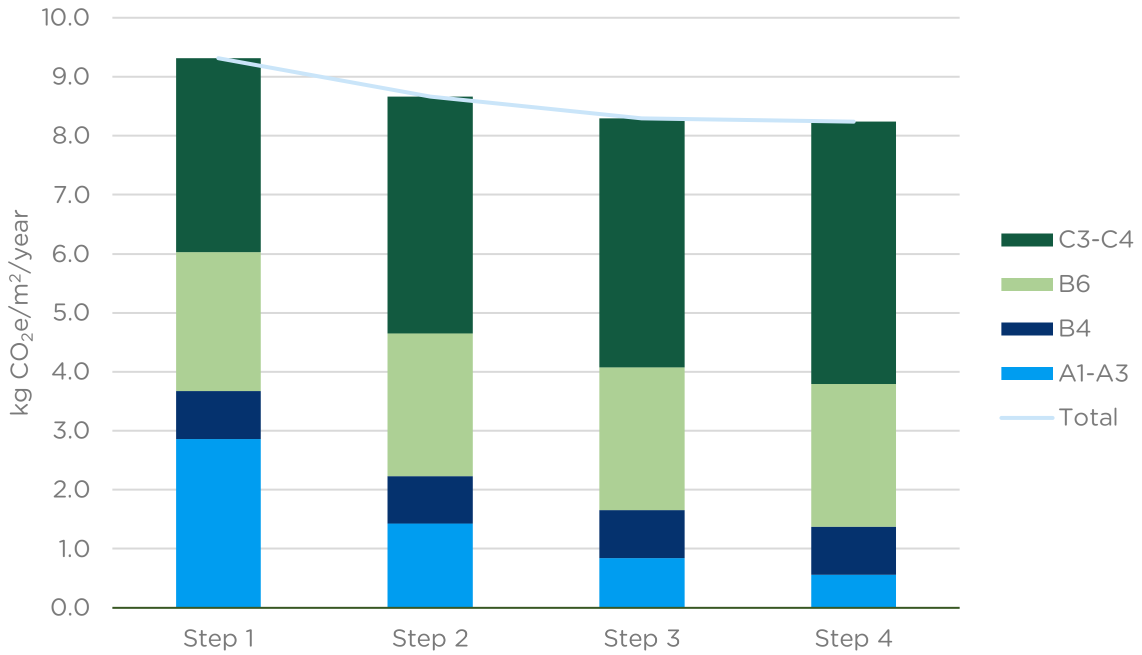


Figure 19 – Climate impact for Case 6 – Institution for each step divided into life cycle phases

Looking at the climate impact divided by life cycle phases as shown in Figure 19, the majority of emissions occur at End-of-Life (C3-C4) for all four steps. For Step 1, End-of-Life emissions make up 35% of the total emissions, increasing to 46%, 51% and 52% for Step 2, 3 and 4, respectively, due to the increased amount of wood-based materials. Despite the fact that the largest part of the emission occurs at End-of-Life, all four steps still contain a certain amount of materials with an energy-intensive production, and thus no negative impact is seen in the production phase (A1-A3). For Step 1, the emissions from operations (B6) are 2.36 kg CO_2e/m^2/year, corresponding to 25% of the total emission. When changing from concrete to wood-based exterior walls, the operational emissions increase slightly, thus operational emissions in Step 2-4 are 2.42 kg CO_2e/m^2/year, which corresponds to 28-29% of the total climate impact.

5.6.4 Dynamic calculation

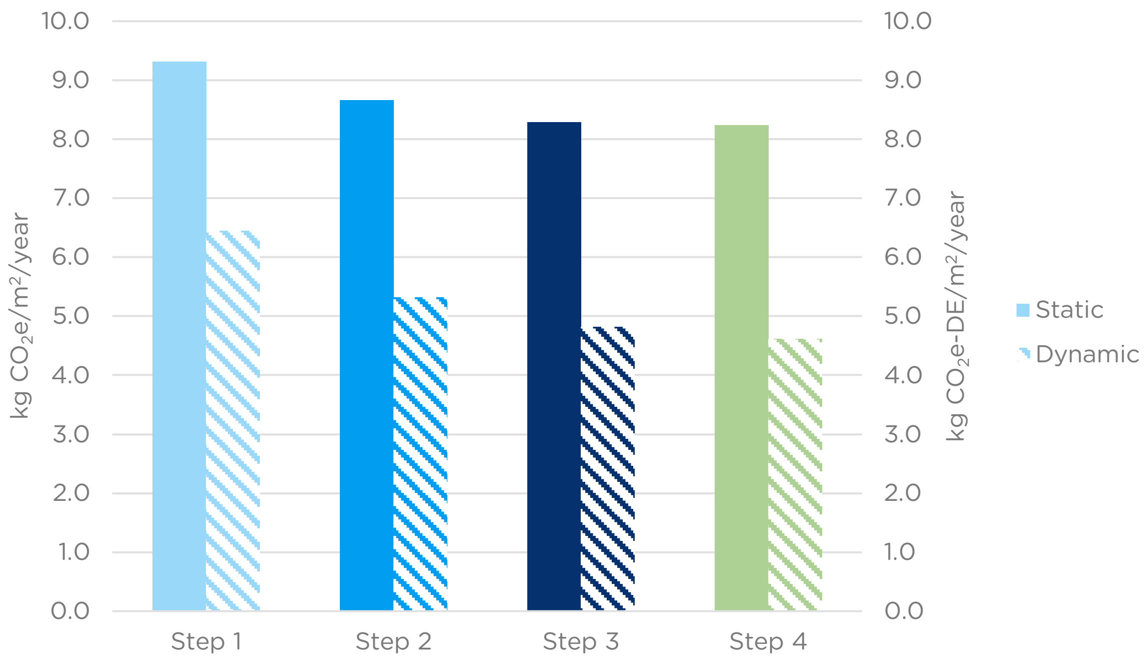


Figure 20 - Static and dynamic results for Case 6 – Daycare institution for each step. The left y-axis indicates the static climate impact and the right the dynamic.

Figure Figure **20**compares the static and dynamic results for Case 6. The difference between the static and dynamic calculation is 31%, 39%, 42% and 44% for Step 1-4 respectively. The increased reduction between the results is due to the increased amount of wood-based materials, which leads to a lower result for the dynamic calculation, due to the projections that benefits emissions further into the future compared to the upfront emissions. As Step 4 has the largest share of emissions at End-of-Life, this is where the lowest results are obtained in the dynamic calculation.

5.6.5 Sub-conclusion

For the daycare institution, a gradual reduction of the climate impact is seen from Step 1 to Step 4. Compared to the other cases, the reduction is smaller, due to several of the building parts with the largest climate impact being identical throughout all four steps. The most significant reduction is from Step 1 to 2, where concrete exterior and interior walls are replaced with wooden cassettes. Looking at when in the life cycle phase the emissions occur, it applies to all four steps that the majority of the emissions occur at End-of-Life. However, it increases gradually, thus for Step 1 it is 35% of the emissions that occur at End-of-Life, and for Step 4 it is 52%.

This is also reflected in the results for the dynamic calculation, where the increased amount of End-of-Life emissions results in the largest difference between the static and dynamic calculations for Step 4, at 44%.

5.7 Discussion and perspective

In the previous sections, each of the six typologies' LCA's are presented by their static and dynamic results. With regard to operational energy, the following section examines the impact the change from conventional to wood-based materials has on the operational energy in the six case buildings. In addition, the results for all 24 calculations are compared, where the advantages and disadvantages of the two calculation methods are discussed. A closer look is taken at how the LCA's by dynamic calculations can lead to negative results.
Finally, perspective is given both to industry results and to the building regulations' climate requirements and how the six cases perform in that context.

It is noted that across all six cases the climate impact of operations, installations, foundations, and ground slabs constitutes a significant part of the total climate impact. For the embodied emissions from installations, foundations and ground slabs, there are potentially large savings to be made for all buildings if development is made to optimize these, e.g., through the use of screw foundations. Looking solely at the building elements above the foundation, there will be a potential saving by using wood-based building elements of up to 50%.

5.7.1 Static and dynamic results

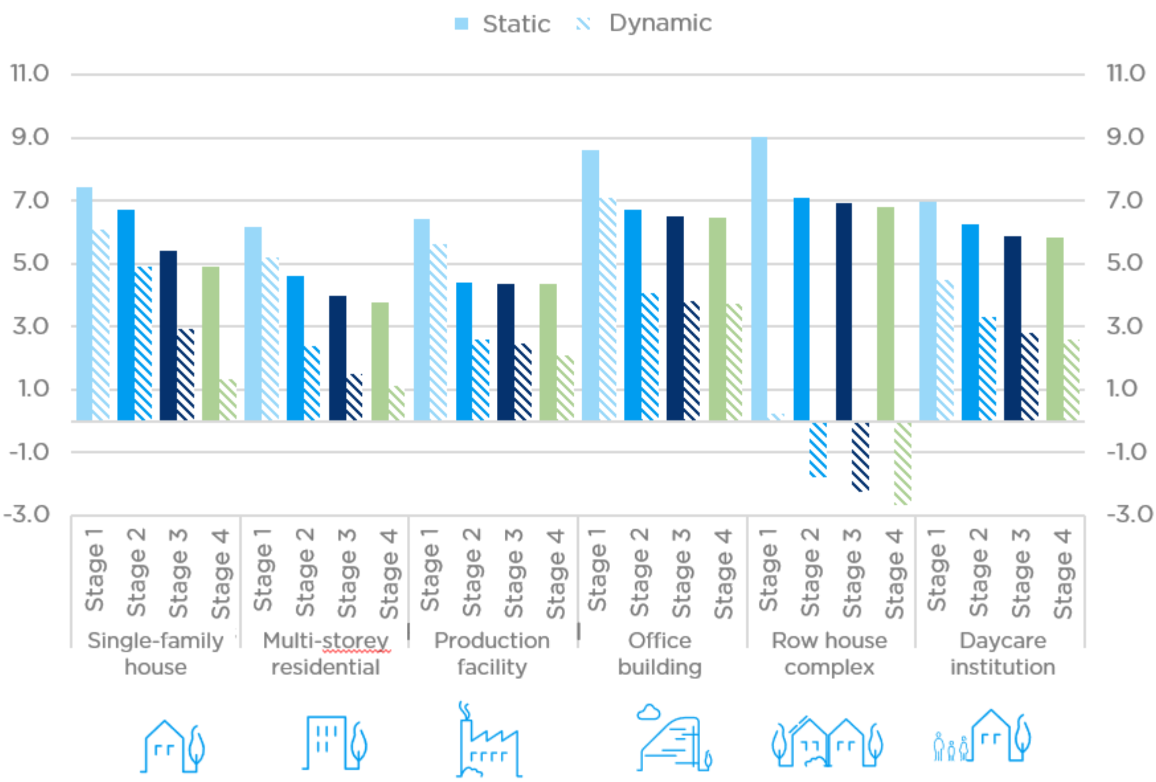


Figure 21 – Static and dynamic results for Step 1-4 for each typology for the embodied CO_2e in materials. The left y-axis indicates the static climate impact and the right the dynamic. It should be noted that the results are calculated without B6 operating emissions.

In Figure 21the static and dynamic results are presented for all six typologies. It is noted that the results for Case 4-6 here are shown without the operational emissions. For all cases, the construction has a lower accumulated impact in the dynamic LCA stated in kg CO_2e-DE/m^2/year than the corresponding static calculation stated in kg/CO_2e/m^2/year.

Overall, the results show that more bio-based materials lead to a greater reduction by switching from a static to a dynamic calculation, due to the fact that the bio-based materials have the largest share of emissions at End-of-Life and are thus weighted lower in the dynamic calculation.

The reason why the dynamic calculation accommodates biogenic materials is, as previously mentioned, that in the Danish construction sector the -1/+1 rule is used for calculating biogenic carbon, which means that the CO_2 that is stored in biogenic materials during photosynthesis is credited with a negative climate impact in the production stage. The negative impact is offset at the end of the material's lifetime, as biogenic building materials are assumed to be incinerated at End-of-Life, whereby the stored CO_2 is released into the atmosphere. The method is based on an assumption that the wood comes from sustainable forestry, where the amount of CO_2 stored in the forest remains the same, so that it can be perceived as being CO_2 neutral (Andersen, Hoxha, Rasmussen, Sørensen, & Birgisdottir, 2024).

In the case of Case 5 – Row house complex, Step 2-4, a negative impact is seen for the dynamic calculation due to the large amount of bio-based material. That result thus indicates that a building can have a negative embodied climate impact over its lifetime, if technological development and the delay in emissions are taken into account. It can be debated whether it makes sense to attribute a negative impact to buildings being constructed today, as it implies that by building with perhaps an unnecessary amount of wood, we can help reduce our overall climate impact. Furthermore, in sustainable construction, other environmental impact indicators that affect the planetary boundaries should also be taken into consideration, including biophysical impacts.

Furthermore, all emissions are not included in the LCA calculation currently mandatory by law, cf. BR18. First of all, not all life cycle modules are included in the system boundaries in the Danish Building Regulations. For example, module A4 – Transport to construction site and A5 – Construction, both of which contribute to emissions during the construction of the building, are omitted. For A4 – Transport, the weight of the materials will play a large role, where lighter building materials will have a lower climate impact related to transport. In addition, there are several building parts that are not included, including smaller electrical installations and utilized roof surfaces and outdoor areas. It is always important to keep in mind that a building's LCA has methodological and actual limitations and thus does not include all emissions related to the construction. This is even more important when we obtain results with negative emissions, as is the case here with the dynamic calculation for the row house complex, so that we *do not* come to the conclusion that by building more, we can reduce our overall climate impact.

The dynamic calculation is included in this report to illustrate how technological development in the production of our building materials and the timing of emissions may affect the result. The dynamic method used in this report can be criticized for oversimplifying the projections, for example for assuming that there is the same technological development across all materials and thus production methods, but the static LCA can also be criticized for *not* taking into account any technological development over the next 50 years, as well as neglecting the aspect of when the emissions take place.

5.7.2 Operational emissions

Life cycle phase B6 – Operational energy is included in the calculation of Case 4-6. By including B6, the comparison between Step 1 and Step 2-4 and the validity of the results is stronger, as the results for each step include the influence of thermal mass on energy consumption. As can be seen from the results in Case 4-6, the difference in the operational emissions among the four steps is quite small. The savings in Step 1 are 0.03-0.06 kg CO_2e/m^2/year compared to Step 2-4 for the three cases where operational emissions are included.

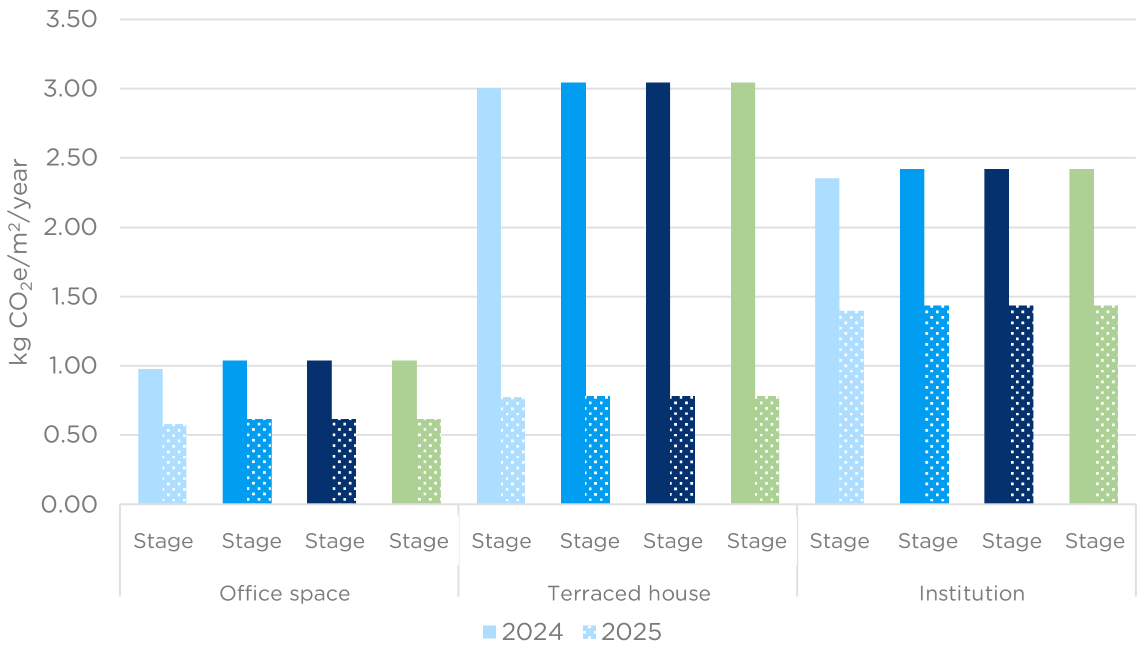
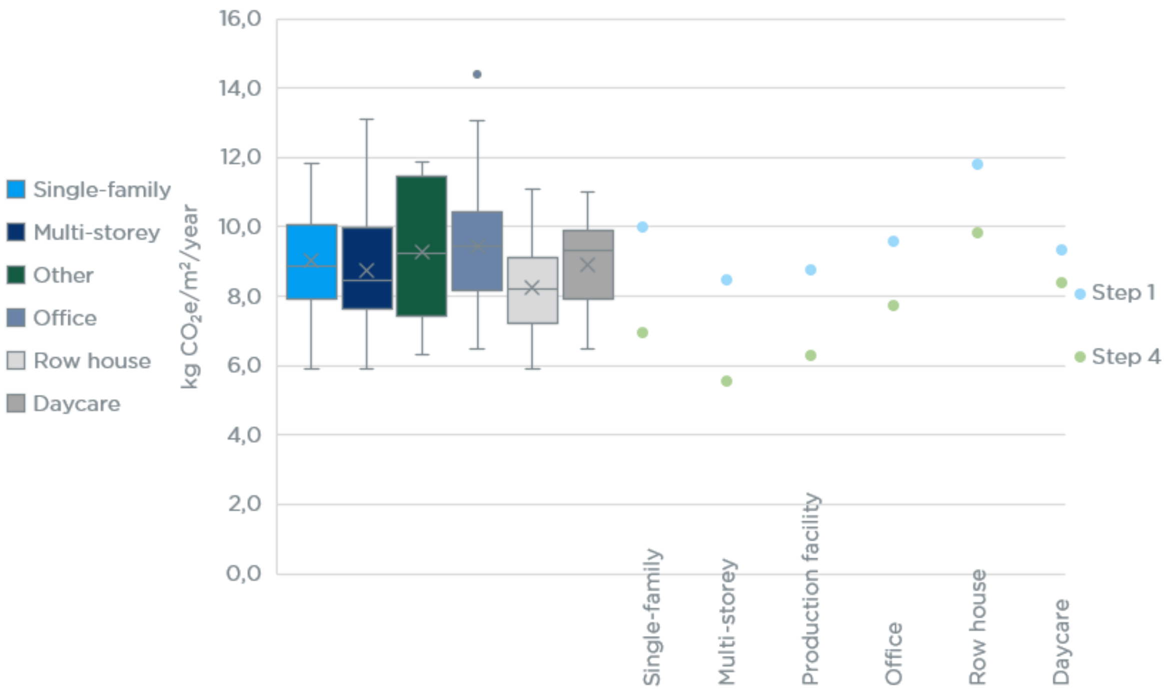


Figure 22 – Operational emissions for each step for Cases 4-6 calculated with emission factors for 2024 and 2025, respectively.

The operational emissions are calculated with the, in 2024, current emission factors for electricity, district heating and piped gas. From 2025, the emission factors used to calculate the operational emissions will be updated (Nilsson, Høibye, & Maagaard, 2023). With the new emission factors from 2025, the climate impact calculated in kg CO_2e/kWh is reduced for both electricity, district heating and piped gas compared to the current emission factors. This means that the calculated climate impact from operations is reduced, and thus constitutes a smaller part of the total climate impact for the individual building. Figure Figure **22**shows the operational emissions for Case 4-6 calculated with 2024 and 2025 emission factors, respectively. The difference between the result in 2024 and 2025 is greatest for Case 5 – Row house complex, which is due to the fact that the building is heated with district heating, and for district heating there is a greater difference between the current and updated emission factors than there is for electricity. Both Case 4 – Office building and Case 6 – Daycare institution are heated with heat pumps, and thus the reduction is smaller for both of these cases. However, the results show, as expected, that the climate impact is significantly lower for all three cases when the 2025 emission factors are used. Thus, operational emissions play an even smaller role in the comparison between conventional and wood-based buildings, taking the updated emission factors into account, meaning the choice of materials weigh even more.

5.7.3 Comparison with reference values

The results for the six cases are compared with the results from the report *Greenhouse gas emissions of new buildings* (Tozan, et al., 2023) (hereinafter referred to as the BUILD report), where the climate impact for 163 case buildings divided into eight typologies is calculated. The production facility is compared with buildings listed as 'other' in the BUILD report. The BUILD report includes results for 35 single-family houses, 42 multi-storey residential buildings, 22 row house complexes, 35 office buildings, seven institutional buildings and eight buildings that fall under the category 'other' . The distribution of the climate impact for these typologies is shown in the boxplots on the left in Figure 23. The results in the BUILD report are calculated including operational energy, which



is only the case for Case 4-6 in this report. In order to be able to compare Cases 1-3 with the results from the BUILD report, an average value for the operational energy has been added. According to the BUILD report, operations account for an average of 26% of the total climate impact of a building, when using the emission factors from 2024. The results, including operational emissions, for Step 1 and 4 for each of the six cases are presented on the right in Figure 23.

Figure 23 – Comparison of climate impact. Left: Results from the BUILD report for the six typologies: single-family house, multi-storey residential, other, office, row house complex and daycare insitution. Right: Results for Step 1 and 4 for each of the six cases in this report. The results are presented including operational emissions.

For Step 1, four of the buildings – multi-storey residential, production facility, office building and the daycare institution – lie between the upper and lower quartiles for the corresponding typology in the BUILD report. Looking at Step 4, five out of six cases – with the exception of the row house complex – are lower than the lower quartile for the corresponding typology. In general, the wooden buildings in Step 4 have a lower climate impact than buildings within the same typology, when compared with the results in the BUILD report, with the exception of the row house complex, which for both Step 1 and 4 is higher than the upper quartile. For the production facility, it should be taken into account that the comparison is made with buildings in the category 'other', which covers a wider range of building typologies that do not fit into the remaining categories included in the BUILD report.

In the National Strategy for Sustainable Construction, (Indenrigs- og Boligministeriet, 2021) it is described that the limit value for buildings' climate impact must be reduced every two years. As previously mentioned, the limit value per January 1st 2023 is set to 12 kg CO_2e/m^2/year. As part of the National Strategy, examples are included of what the revised limit values could potentially be set to in 2025, 2027 and 2029. These examples are set at 10.5 kg CO_2e/m^2/year, 9 kg CO_2e/m^2/year and 7.5 kg CO_2e/m^2/year in the years 2025, 2027 and 2029, respectively. It is important to emphasize that these are *proposals* for limit values in the coming years. The final limit values for 2025, 2027 and 2029 have not been determined at the time of publication of this report.

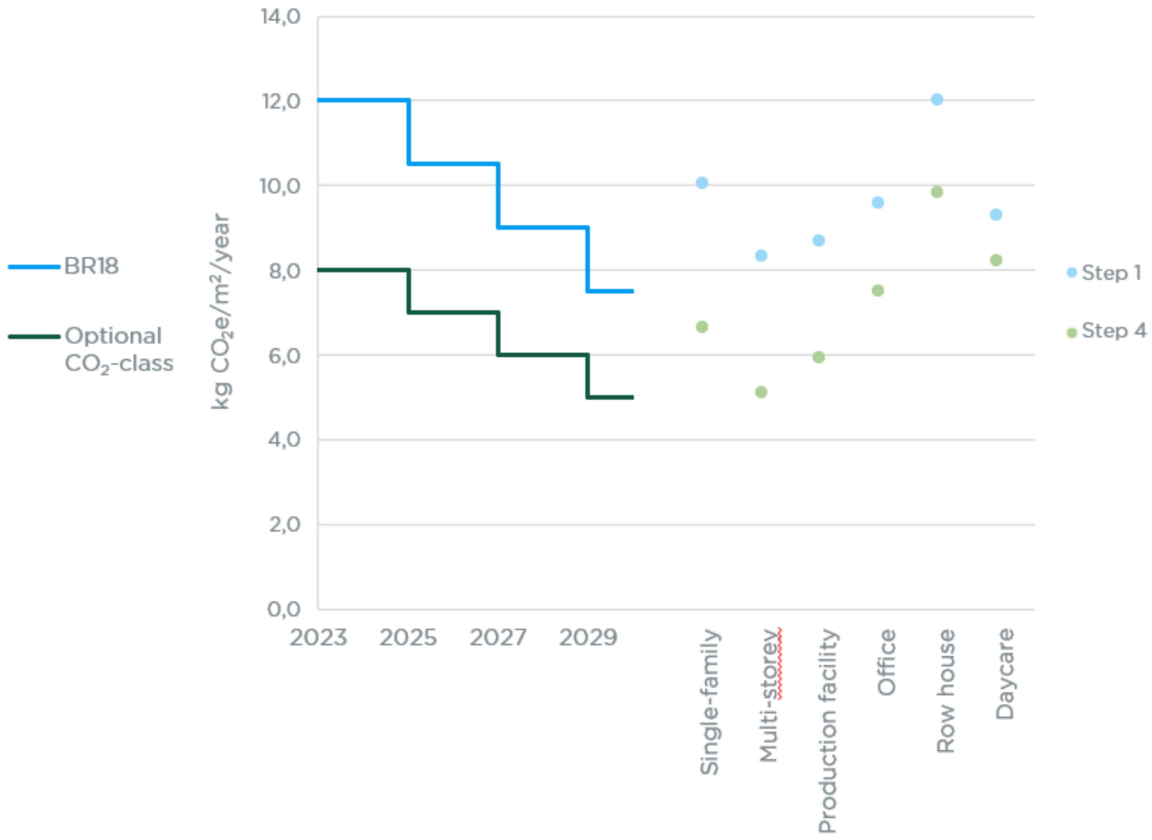


Figure 24 – Comparison of climate impact. Left: Proposal for gradual reduction of the climate impact regulation in BR18 as described in the National Strategy for Sustainable Construction. Right: Results for Step 1 and 4 for each of the six cases in this report. The results are presented including operational emissions.

In Figure 24the proposals for the revised limit value from the National Strategy for Sustainable Construction are shown on the left, and the results for Step 1 and 4 for each of the six cases are shown on the right. With the current limit value of 12 kg CO_2e/m^2/year, only Case 5 – Row house complex, Step 1, cannot comply with the requirement. For Step 1, five of the buildings can comply with the proposed limit value for 2025, two of the buildings can comply with the proposed limit value for 2027, while none of the buildings in Step 1 can comply with the proposed limit value for 2029. Looking at Step 4, all six buildings can comply with the proposed limit value in 2025, five of them can comply with the value in 2027, and three of them – single-family house, multi-storey residential and the production facility – can comply with the proposed limit value in 2029 at Step 4.

In the above section, the results for potential savings in climate impact when converting to more wood-based constructions are presented. In order to give an insight into the potential additional costs or savings that come with the reduction in climate impact, shadow price calculations have been carried out in the following section for each of the six cases for Step 1-4, which can give an indication of which measures are cost effective.

6. SHADOW PRICE CALCULATIONS

6.1 Method

6.1.1 Shadow price calculations

Shadow prices present an estimate of the cost per reduced ton of CO_2e compared to a baseline. This means that a low shadow price is advantageous, as you 'pay' less per ton of CO_2e saved. Shadow prices give an indication of which CO_2e-reducing initiatives are the most profitable; that is, which CO_2e-reducing measures are most cost-effective compared to the baseline.

The shadow price is shown as the ratio between the CO_2e saving and the additional cost that the saving entails. The lower the shadow price, the lower the additional cost per reduced ton of CO_2e. Thus, scenarios with low shadow prices are the most cost-effective[2]. As a frame of reference for the positive shadow prices, the Ministry of Finance's Key Figures Catalogue (Finansministeriet, 2023) refers to the Climate Council's path for CO_2e-prices, which in 2030 is recommended to be set at DKK 1,730/ton in 2023 prices (factor prices).

Shadow prices are typically used to uncover the most economically profitable way to achieve a climate objective. By comparing the shadow price for different reduction measures, it is possible to find the path to the goal that is most cost-effective. A catalogue of potential means of actions is typically prepared in which the CO_2e-shadow price for various means of actions is calculated based on the Ministry of Finance's guidance on socio-economic analyses (cf. the Government's latest Climate Program from 2023). On this basis, society can prioritize the measures associated with the lowest shadow prices. This means that the socially optimal solution is the one where 'cheap' efforts are prioritized over the 'expensive' ones. If a shadow price is negative, climate reductions can be achieved without additional costs.

6.1.2 Negative shadow prices

If a CO_2e-reducing initiative is also associated with a price saving compared to the baseline, the shadow price becomes negative. Thereby, you can achieve a CO_2e and a cost saving at the same time, which is clearly positive. However, shadow price calculations are not designed to clarify which measures amongst several with negative shadow prices is more advantageous, and it is therefore not meaningful to compare different measures with negative shadow prices. The negative shadow prices will therefore simply appear as 'negative', and do not reflect a concrete negative value. Instead, the cost savings and the CO_2e reductions are presented, so that Step 1-4 can be compared on the basis of these parameters.

Figure 25is an example of why negative shadow prices *cannot* reveal which alternative is most advantageous. In the example, the results for the shadow price calculation for Case 3 – Production facility are shown. Step 4 has both the largest CO_2e reduction and the largest savings compared to the baseline and is therefore strictly the best alternative. Looking at the shadow price, Step 4 has the lowest value. Similarly, Step 2 has the smallest CO_2e reduction and the smallest savings, but the shadow price is placed between Step 3 and Step 4. Since the shadow price only takes into account the ratio, but not the volume of the CO_2e reduction and the cost savings, the negative shadow price

[2] In some cases, the CO_2e saving can also be linked to a cost saving, which will result in a negative shadow price. All other things being equal, this will be preferable compared to positive shadow prices. For a discussion of the applicability of shadow prices for prioritization in this case, see section 6.1.2.

therefore does not represent which of the three solutions is most efficient, measured in terms of both CO_2e and cost savings.

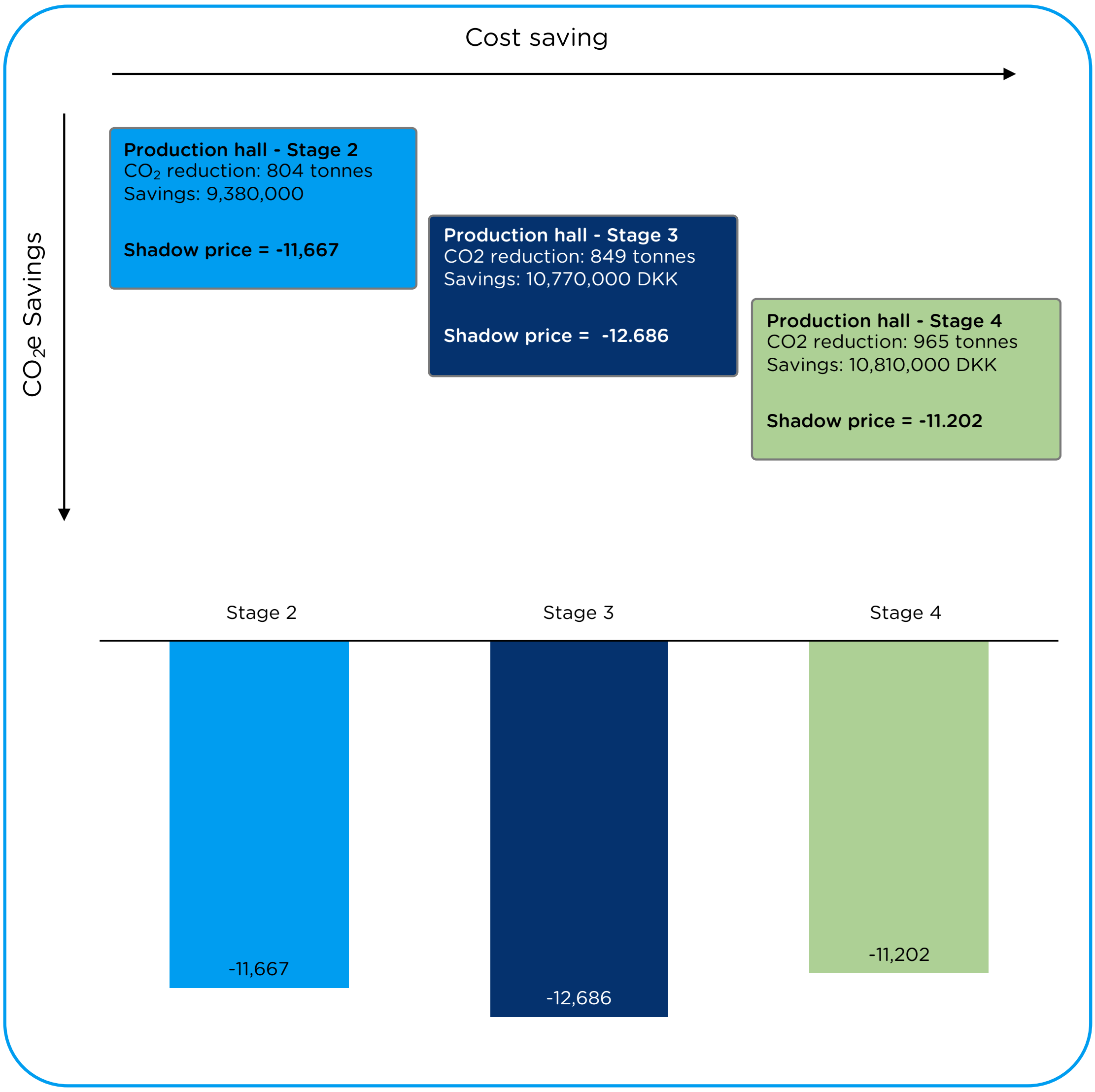


Figure 25 - Example of negative shadow prices and why these CANNOT be compared in the same way as positive prices

6.1.3 Establishing the baseline

In order to calculate shadow prices, a baseline must be established against which the CO_2e-reducing initiatives can be compared. In this report, Step 1 (the conventional buildings) forms the baseline against which the other steps are measured. This means that the shadow price at Step 2, Step 3 and Step 4 shows the additional cost per reduced ton of CO_2e compared to Step 1. For example the shadow price for Step 2 shows the additional cost per reduced ton CO_2e if you decide to build with a wood-based structure instead of conventionally as in Step 1. If the shadow price is, for example, DKK 1,000/per ton CO_2e, this means that the reduction in CO_2e emissions in Step 2 costs DKK 1,000 per tonnes saved CO_2e.

The shadow price at Step 3 shows, like the shadow price for Step 2, the additional costs per reduced tons of CO_2e compared to if you alternatively built conventionally as in Step 1. Since Step 3 contains the wood replacements from Step 2, by comparing Step 2 and Step 3 you can see whether the additional material replacements in Step 3 are more or less advantageous than the initial replacements in Step 2. If the shadow price is higher at Step 3 than Step 2, this means that the additional materials that are replaced in Step 3 have a higher shadow price than the first materials that are also replaced in Step 2. On the other hand, a lower shadow price means that the additional material replacements have a lower shadow price than the first material replacements, which are also replaced in Step 2.

6.1.4 Calculation and data

The calculations of shadow prices in this report consist of dividing the lifetime costs by the lifetime emissions over 50 years calculated in present values – meaning the value is discounted using the discount rates from the Ministry of Finance’s Key Figures Catalogue (Finansministeriet, 2023). The total climate impact over the entire life cycle, which is included in the shadow price calculation, is based on the LCA calculations, and is also discounted with the discount rates from the Ministry of Finance’s Key Catalogue.

In the calculations, any differences in the buildings' subsequent value is assumed to be the same across the steps. The calculations do not take into account standard values for installations, as there are no prices for the standard values – and in addition, these are assumed to be the same for all four steps, and thus the price for these will not influence the price difference between the four solutions.

Lifetime costs consist of material prices, material hire and wages for construction, replacements and ongoing maintenance of the buildings. The prices are calculated on the basis of price data from Molio Priskalk (Molio, u.d.), and are then adjusted for inflation and calculated as present values. Molio Priskalk is a tool that is used to carry out estimate calculations within the construction industry.

No price for wood fiber insulation appears from Molio Priskalk, and the market price for this has therefore been obtained from manufacturers. In order to correct the price for any differences between market prices and prices in Molio Priskalk, a conversion factor is determined based on the difference between the price of cellulose insulation on the market and the price in Molio Priskalk. This conversion factor is used to convert wood fiber insulation from market price to 'Molio' price. See Appendix 22-27 for Inventories, where the used data sets from Molio Priskalk are specified.

6.2 Results

Below in Table 9– Table 14the results for the shadow price calculations for all six typologies are presented. The lower the shadow prices are, the fewer additional costs associated with a CO_2e reduction. Therefore, scenarios with low shadow prices are the most cost-effective. The steps and building typologies that are associated with negative shadow prices have both lower discounted CO_2e emissions throughout the life cycle and lower discounted lifetime costs, which is why one should consider the concrete cost and CO_2e savings between the steps.

Table 9– Shadow price calculation for Case 1 – single-family house with Step 1 as baseline. The additional costs and the CO_2e savings are rounded off. The shadow prices are calculated on the basis of non-rounded numbers.

	Step 2	Step 3	Step 4
Additional cost (discounted) in lifetime costs compared to Step 1 [DKK]	310,000	250,000	240,000
Discounted CO_2e savings compared to Step 1 [t CO_2e]	7	20	30
Shadow price with Step 1 as baseline [DKK/t reduced CO_2e]	44,210	12,320	7,750

Table Table **9**shows the results of the shadow price calculation for Case 1 – Single-family house. There is a small CO_2e saving compared to the additional cost. Step 2 in particular has a high shadow price, but Step 3 and 4 also have relatively high shadow prices. Based on this calculation, there is therefore no economic advantage, since with every ton of CO_2e saved, a large additional cost for the construction follows.

Table 10– Shadow price calculation for Case 2 – multi-storey residential with Step 1 as baseline. The additional costs and the CO_2e savings are rounded off. The shadow prices are calculated on the basis of non-rounded numbers.

	Step 2	Step 3	Step 4
Additional cost (discounted) in lifetime costs compared to Step 1 [DKK]	7,970,000	2,600,000	2,920,000
Discounted CO_2e savings compared to Step 1 [t CO_2e]	980	1,275	1,415
Shadow price with Step 1 as baseline [DKK/t reduced CO_2e]	8,150	2,040	2,070

The results in Table 10show the results for Case 2 – Multi-storey residential. Here, a large additional cost is seen in relation to Step 2, which results in a high shadow price. Both Step 3 and 4 are around DKK 2,000/t of reduced CO_2e, which is why it is recommended that a concrete assessment is made at project level of whether the shadow price is assessed as satisfactory for Step 3 and 4.

Table 11– Shadow price calculation for Case 3 – Production facility with Step 1 as baseline. The additional costs and the CO_2e savings are rounded off. The shadow prices are calculated on the basis of non-rounded numbers.

	Step 2	Step 3	Step 4
Additional cost (discounted) in lifetime costs compared to Step 1 [DKK]	-9,380,000	-10,770,000	-10,810,000
Discounted CO_2e savings compared to Step 1 [t CO_2e]	804	849	965
Shadow price with Step 1 as baseline [DKK/t reduced CO_2e]	Negative	Negative	Negative

For Case 3 – Production facility, the results are presented in Table 11. For all steps, a saving in lifetime costs and CO_2e emissions are seen in comparison with Step 1, and thus the shadow price is negative. As previously described, negative shadow prices cannot be illustrated, which is why one should instead look at the savings in lifetime costs and CO_2e, to decide which solution is more viable.

Table 12– Shadow price calculation for Case 4 – Office building with Step 1 as baseline. The additional costs and the CO_2e savings are rounded off. The shadow prices are calculated on the basis of non-rounded numbers.

	Step 2	Step 3	Step 4
Additional cost (discounted) in lifetime costs compared to Step 1 [DKK]	-3,280,000	-2,400,000	-1,380,000
Discounted CO_2e savings compared to Step 1 [t CO_2e]	350	375	385
Shadow price with Step 1 as baseline [DKK/t reduced CO_2e]	Negative	Negative	Negative

Table 12shows the results for Case 4 – Office building, which also all have a negative shadow price. Which scenario is assessed as the most advantageous is a balance of the savings in lifetime costs and CO_2e. The biggest CO_2e saving is seen in Step 4, whereas the biggest saving in lifetime costs is seen in Step 2.

Table 13– Shadow price calculation for Case 5 – Row house complex with Step 1 as baseline. The additional costs and the CO_2e savings are rounded off. The shadow prices are calculated on the basis of non-rounded numbers.

	Step 2	Step 3	Step 4
Additional cost (discounted) in lifetime costs compared to Step 1 [DKK]	-6,760,000	-3,630,000	-2,340,000
Discounted CO_2e savings compared to Step 1 [t CO_2e]	560	743	898
Shadow price with Step 1 as baseline [DKK/t reduced CO_2e]	Negative	Negative	Negative

For Case 5 – Row house complex, the results are shown in Table 13. Negative shadow prices are also achieved here for all three steps. The greatest saving in lifetime costs is seen for Step 2, whereas the greatest saving in CO_2e is achieved at Step 4.

Table 14– Shadow price calculation for Case 6 – Daycare institution with Step 1 as baseline. The additional costs and the CO_2e savings are rounded off. The shadow prices are calculated on the basis of non-rounded numbers.

	Step 2	Step 3	Step 4
Additional cost (discounted) in lifetime costs compared to Step 1 [DKK]	-720,000	-520,000	-220,000
Discounted CO_2e savings compared to Step 1 [t CO_2e]	112	159	180
Shadow price with Step 1 as baseline [DKK/t reduced CO_2e]	Negative	Negative	Negative

Table 14shows the results for Case 6 – Daycare institution. The calculation results in negative shadow prices for all three steps. Step 2 results in the biggest savings in lifetime costs and Step 4 in the biggest CO_2e savings.

6.3 Discussion and perspective

The results for each of the six cases vary greatly. For four out of six cases, the shadow price is negative, and thus indicates that in these cases there is a financial saving associated with the CO_2e saving. For the first two cases – single-family house and multi-storey residential – the shadow prices are between DKK 2,070 and 44,210/t reduced CO_2e. In the section below, we delve into the results for the single-family house to take a closer look at which parameters influence the results.

If you look at the data input for the exterior walls of the single-family house, there is a difference in the annual maintenance. The annual maintenance is set for each building part in Molio Priskalk and is 1% for the exterior wall in Step 1, 3 and 4, whereas maintenance for the exterior wall in Step 2 is 2%. It is not elaborated how the maintenance percentage is determined in Molio Priskalk. If the maintenance percentage in Step 2 is changed to 1%, the shadow price drops to DKK 21,310/t reduced CO_2e. Thus, the maintenance percentage has a large influence on the result, and it can be debated whether there is more maintenance associated with just one type of wall than there is for the other steps.

Table Table **15**shows the additional cost for Steps 2-4 in percentage, both for shown for construction of the building solely and the total costs including maintenance and replacements. For construction alone, the cost of Step 2 is approximately 13% higher than Step 1. Step 3 is approximately 23% more expensive and Step 4 approximately 16% more expensive, but whether the additional costs for Step 2-4 match the actual additional costs is not known. Looking at the total costs – including maintenance and recovery – Step 2 is 16% more expensive and Step 3 and 4 13% more expensive than Step 1. Once again, the increased costs for maintenance associated with the exterior wall in Step 2 can be seen, which increases the total additional cost of Step 2 compared to Step 1.

Table 15– Additional cost in percentages for construction and total expenses for the Single Family House, Step 2-4

	Step 2	Step 3	Step 4
Additional cost for construction in percentage	13%	23%	16%

Additional total costs in percentage	16%	13%	13%

Based on the cost data from Molio Priskalk and the LCA results, the shadow prices for Step 2-4 are calculated with Step 1 as the baseline for each typology. The shadow price calculations are thus not based on real price data, which can have an influence on the results.
For several of the typologies, negative shadow prices are obtained, which means that both CO_2e emissions and lifetime costs for the given step are lower than for Step 1. This applies to all steps for Case 3-6. The results thus indicate that by switching to wood-based materials, you can achieve a cost saving and at the same time achieve a CO_2e reduction, for these specific cases.
For Cases 4, 5 and 6, it is the replacement of the load-bearing structure from Step 1 to Step 2 that results in the biggest cost savings, whereas the biggest CO_2e savings for the same three cases are seen at Step 4.
The shadow prices are highest for the single-family house, where Step 2 in particular is associated with a high shadow price, while Step 3 and 4 also have relatively high shadow prices.
For Case 2 – Multi-storey residential, Step 3 and 4 have the lowest and relatively similar shadow prices of around DKK 2,050 per reduced ton CO_2e. The same applies to Step 4 for Case 6 – Daycare institution.

The analysis of the results for the shadow prices and subsequent dialogue with timber construction suppliers highlighted a clear perceived difference between the generic price data and the actual prices. The results in this report have therefore led to greater insight into a potential improvement of the generic price data as well as the potential for better correlation between the built and the theoretical economic calculations in early construction planning and design.

7. CONCLUSION

In order to reduce the climate impacts from construction, climate requirements have been introduced in the Danish Building Regulations from January 1st 2023. This includes that all new construction must have a documented climate impact through life cycle assessments. In 2021, 60 case studies formed the basis for the first limit value of 12 kg CO_2e/m^2/year, which was introduced on January 1st 2023. Since 2021, many more life cycle assessments have been carried out on construction projects in the industry. In 2023, BUILD followed up with a number of representative case studies, 163 in total, in their report *Greenhouse gas emissions of new buildings* (Tozan, et al., 2023). The case studies showed great variation in climate impact for all building typologies, where, for example, climate impact from the building components vary from 4.85 to 13.15 kg CO_2e/m^2/year. The climate impact from the building components has the greatest impact. The climate impact from building components contribute on average with 74%, while emissions associated with energy consumption for operations contribute with an average of 26%. If you take into account the future emission factors for electricity, district heating and piped gas, the picture changes further, as an average of 91% of the climate impact will be linked to the materials in the construction. There is and will therefore continue to be a great deal of attention on how to reduce CO_2e impacts in constructions through the choice of building materials.

This report clearly shows potential CO_2e savings by using wood-based materials rather than conventional materials in various selected Danish building typologies. The analyses from the six case studies of a single-family house, multi-storey residential, production facility, office building, row house complex and daycare institution show a total potential saving varying between 12% and 39%, corresponding to 1.08-2.52 kg CO_2e/m^2/year. For five out of the six case studies, the biggest potential CO_2e savings turned out to come from changing the load-bearing structures to wood-based alternatives.

The largest overall reduction is seen for Case 2 – Multi-storey residnetial, which has a total saving of 39% from Step 1 to Step 4. The primary reason for this reduction can already be seen in Step 2, where the slabs and the roof structure are changed from hollow-core slabs to wooden structures. Next, the replacement of the façade cladding from ceramic slate to wood and the replacement of insulation in the exterior walls from mineral wool to wood fiber also contribute to the reduction. It can also be inferred that if you simply consider the building parts above ground and leave out installations, the potential savings could reach over 50%**.**

With the current limit value of 12 kg CO_2e/m^2/year in the Danish Building Regulations, all Step 4 cases are able to comply. The fully wood-based Step 4 cases can also in all six cases comply with the proposed limit value in 2025 of 10.5 kg CO_2e/m^2/year, five of them can comply with the suggested limit value in 2027 of 9 kg CO_2e/m^2/year , and three of them – the single-family house, the multi-storey residential and the production facility – can comply with the proposed limit value in 2029 of 7.5 kg CO_2e/m^2/year in Step 4. It is also noted that one of the projects will be able to comply with the requirements of the Reduction Roadmap[3], set to 5.8 kg CO_2e/m^2/year even with current emission factors, while three of the cases will be able to comply with the requirements with the emission factors applicable from 2025.

For three of the case projects the operational energy was included by adapting the energy performance calculations from the existing buildings to the four steps with the aim of seeing how important the thermal mass of conventional constructions is compared to wooden constructions. The difference between emissions associated with the operational energy between conventional and wooden constructions is 0.03-0.06 kg CO_2e/m^2/year if you compare Step 1 with Step 2-4. If the future emission factors for electricity, district heating and piped gas are taken into account, the savings will be even smaller. It can therefore be concluded that the structural differences between conventional and wooden construction have no significant impact on the CO_2e impact associated with the operational energy of the case buildings.

[3] https://reductionroadmap.dk/

To put the results into perspective, an alternative method and thus results for the life cycle assessments were included. Although all steps, including the conventional buildings, have lower climate impacts with dynamic LCA than with static LCA, the biggest difference is associated with the amount of biobased materials that are introduced and therefore with Step 4. Overall, the results show that more bio-based material leads to a greater reduction by switching from a static to a dynamic calculation, due to the bio-based materials having the largest share of emissions occurring at End-of-Life and are thus weighted lower in the dynamic calculation. The results also made it clear that by using the dynamic LCA method, it is possible to achieve results close to 0 kg CO_2e/m^2/year and, in some cases, even negative results. The use of dynamic LCA in the report raises an important discussion about methodology, but also highlights the time perspective of when emissions actually occur. At least one thing is certain – we can be more precise about the upfront emissions (A1-A3) emitted in relation to the production of materials for the buildings and less about future emissions associated with replacements, maintenance and End-of-Life.

This report has included shadow price calculations, which is a classic calculation method used to show the costs associated with potential CO_2e reductions. For several of the typologies, a negative shadow price is achieved, which means that both CO_2e emissions and lifetime costs for the wood-based steps are lower than the conventional building represented in Step 1.
The results thus indicate that by switching to wood-based materials, you can achieve a cost saving at the same time as achieving a CO_2e reduction for these specific cases. For four out of the six cases, the shadow price when converting to wood-based materials is negative, which means that it is beneficial both climate-wise and economically to change to wood-based materials. The cost-effectiveness is very context-dependent and there are too few cases to be able to say anything in general about whether replacing conventional materials with wood-based alternatives will generally be cost-effective or even have negative shadow prices. However, the results indicate that in many cases it will be cost-effective to use wood-based materials and it should therefore always be assessed whether this is an option in the individual construction project.
The analyses for shadow prices also showed that the sensitivity of the results is very dependent on the price data used (from Molio), including especially the maintenance percentages. Based on the sensitivities of the analysis and comments on the data, these should be examined in more detail.

Although the cases are based on new construction, the report can also be used as inspiration for renovation projects, especially for those renovation projects that have building parts that are replaced in the same way as in the six case buildings.

The construction industry, both concerning renovations and new built, is continuously in search of good solutions to reduce climate impacts in the building sectors value chain. This report highlights the large potential CO_2e savings that can be obtained by using wood-based materials, which in many cases are cost-effective. It can therefore be advantageous for the climate and economy to investigate the possibilities of using wood-based building materials in the specific construction project.

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9. APPENDIX

The following appendices appear in the separate appendix report:

Appendix 1: Case 1 – Single-family house – Life Cycle Inventory
Appendix 2: Case 2 – Multi-storey residential – Life Cycle Inventory
Appendix 3: Case 3 – Production facility – Life Cycle Inventory
Appendix 4: Case 4 – Office building – Life Cycle Inventory
Appendix 5: Case 5 – Row house complex – Life Cycle Inventory
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Appendix 7: Case 1 – Single-family house – U-value calculations
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