Dual LCA for buildings

Minimize upfront CO_2-emissions without overspending materials!

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Note:

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FSC Netherlands and FSC Denmark are working on an ambitious initiative to increase the amount of wood from sustainably managed forests in social housing. HOME for the future is part of the EU LIFE programme. FSC collaborates with Centrum Hout, Lister Buildings, TBI Woonlab, TU Delft and VIA University College. The initiative is co-funded by the Precious Forests Foundation.

The project encompasses a variety of activities: improve the position of wood as a building material in legislation, increase the knowledge about building with wood in the construction sector, produce life cycle assessments (LCAs) and product cards (EPDs) that are added to the National Environmental Database. Furthermore, we develop tools to better map the costs and climate benefits of building with timber.

1. Abstract

The assessment of a buildings CO_2 emissions during its lifetime may be calculated by a life cycle assessment (LCA). In a time of a global climate crisis, it is important to limit CO_2-emissions immediately to minimize the contribution to global warming from buildings. In Europe the method for calculating the environmental impact is standardized by European standards EN15978 and EN15804 including underlying standards for product category rules (PCR). In this report a dual LCA-method that both promotes a minimized upfront carbon footprint as well a limit of material usage is presented.

According to LCA standards the biogenic carbon sequestered in wood and timber products may be included as a negative contribution (sequestration) to the LCA as one of few building materials. The dual LCA method is utilizing the lowering effect of biogenic carbon sequestration to estimate the effect of re-use of timber and wood-based building materials by postponing the release of the biogenic carbon after the first life cycle. The requirement for including this negative contribution up-front in a LCA is that the wood must be procured from a documented managed forestry scheme. The catch in this approach is that it will give better results when using larger quantities of biogenic materials (if designed for re-use). Thus, this must be countered by another method that does not allow for overspending materials. The approach of postponing the release of biogenic carbon is not in conformity with the underlying LCA standards but is proposed for design process purposes.

The dual LCA-method is tested on three case projects whereas just one of the case projects has been designed with the Dual LCA method approach. Two of the projects were completed at the time of calculation whilst the last project was at the detailed conceptual design level.

Results

For *LCA-method 1 – Re-use* the climate impact for all three case projects includes the climate impact from production, construction, building use and partially from waste treatment and disposal. Here the potential of delayed release of biogenic carbon for was proven to be higher than any other contribution to the LCA result for the global warming potential (CO_2e). The magnitude of the postponed emissions was calculated to be as much as 2,9-4,2 kg CO_2e/m^2/yr. corresponding to 50-87% of the total sequestered biogenic carbon. Just wood-based materials for structural elements, inner walls were considered as a potential for future re-use.

For *LCA-method 2 – BR18* the climate impact for all three case projects includes the climate impact from production, partial building use and waste treatment and disposal at end-of-life. Hence all sequestered biogenic carbon is released in the end. This method corresponds to benchmark LCA-method in Denmark and is mandatory for new buildings with a heated area above 1.000 m^2. In addition, this method is mandatory when a building owner communicates the environmental performance of a building. All three case projects demonstrate a low (or rather low) climate impact compared to similar more conventional Danish residential buildings constructed using brick and concrete.

To test the impact of sustainable forestry an addition to the Danish BR18 benchmark LCA was calculated to investigate what the results would be if the wood-based materials in the projects did not originate from a sustainably managed forestry scheme (i.e. not FSC-, PEFC-certified). In this case the biogenic carbon sequestered during growth of the trees may not be considered as a negative contribution in the product stage but should still be released at end-of-life. In the extreme case this leads to considerate increase of CO_2e-emissions at +4,5-5,7 kg CO_2e/m^2/yr. With this addition two of the case projects would go from a climate impact in the lower end of the scale to a level where they would not comply with the limit value for new buildings in Denmark at 12 kg CO_2e/m^2/yr.

The case project that has adopted the Dual LCA method during the design is likely to demonstrate the lowest climate impact of all case projects for both LCA methods, however the project is not completed, and comparison should therefore be postponed to all three projects are completed.

2. Introduction

The result of a building's environmental performance depends on what the question is asked. In Europe (and in Denmark) the environmental performance of a building is standardized by the European Standard EN15978:2012. The environmental performance must be declared as the result of a *life cycle assessment* (LCA) in a standardized manner. The life cycle is divided into four different life cycle stages: *Product stage, Construction stage, use stage* and *end-of-life stage* (please refer to figure 1). Each life cycle stage is further divided into modules, which in detail describes what's included in the LCA. In principle all stages and modules must be included and accounted for, but in practise most official LCA benchmark methods, fewer modules are included in the LCA. An example of an official LCA-benchmark method is the one adopted by the Danish Building Regulations BR18 §§297-298. This LCA-method must report a climate impact for a building during a reference study period at 50 years and include the climate impact from production (A1-A3 in figure 1) and disposal of materials (C3 and C4 in figure 1), replacements (B4 in figure 1), and operational energy consumption (B6 in figure 1) but not the construction phase (A4 and A5 in figure 1) and other modules for the use stage. The BR18 method used in Danish legislation assesses the climate impact for the building during its life cycle. It is not concerned by *when* the climate of materials occurs. This means that the BR18 method is not necessarily a good decision tool in terms of timing of when emissions occur which is of particular interest in a time of a global climate crisis where reduction and postponement of emissions are essential in terms of limiting the global warming of the planet (IPCC, 2023). In Denmark the BR18 LCA-method is the benchmark LCA-method for communication of compliance with legislative requirements for the climate impact of new buildings. Which means the focus in the development of the method was focused on how to compare projects with a national benchmark rather than how to promote climate-conscious decision-making. It is this relevant to apply alternative LCA methods for design and decision-making processes.

In a design process with focus on up-front carbon emissions and design for disassembly principles it is natural to ask the question:

> "*What is the climate impact of the building for 50 years if biogenic materials from managed forestry are re-cycled after the building is taken apart after 50 years, and that the release of biogenic CO_2 is postponed?"*

One cannot predict the future, but if a building is designed for disassembly, the possibility of re-use of building materials must be higher than if traditional methods are adopted especially considering that we are already seeing the first signs of resource scarcity in the building industry.

If timber and wood-based materials comes from managed forestry under an established certification scheme the biogenic carbon may be considered as a negative contribution to the climate impact corresponding to the sequestered carbon during the growth of the biogenic material. According to LCA standards the biogenic carbon must be in balance within a product or building life cycle which means that the negative contribution is levelled out by an equal, but positive, contribution in the disposal hereof. Even though an alternative method (*the re-use method*) will contradict the European LCA standards, it is interesting to assess the climate impact of a building, if the release of the biogenic carbon is kept sequestrated after the fictive lifetime of a building. This approach has a "blind angle" in terms of material consumption as it suddenly will be an advantage to use more biogenic materials than necessarily needed in terms of "lowering" the climate impact of the specific building. Therefore, another LCA-method must be used in combination with *the re-use method* where this benefit is not included. For this purpose, the Danish official LCA method for new buildings *the BR18 method* should be used as this requires the contribution from biogenic materials to be neutral. By combining the two methods the benefits of design for reuse and material optimisation are achieved within the same design process.

So, the second question is:

> "*What is the climate impact of the building according to BR18 §297?"*

In this report the dual LCA refers to the simultaneously use of the *re-use method* and The *BR18 method* and is demonstrated on three case projects. When the two methods are used simultaneously both material consumption and upfront climate impacts may be minimized. For each project the potential for recycling of the biogenic materials is identified and the resulting climate impact of the building within the alternative LCA-method is presented.

In addition to this it is also interesting to know the documented level of climate impact of a building if the biogenic materials do not originate from sustainably managed forestry:

> "*What is the climate impact of the building according to BR18 §297 if biogenic materials do not originate from sustainably managed forestry?*"

All LCA calculations are completed as attributional life cycle assessments (aLCA) and they do not consider various consequences up- or downstream outside of the case projects as in the case if a consequential life cycle assessment was made (cLCA).

3. LCA method

A lifecycle assessment (LCA) is a standardized method to calculate the environmental impact and resource use for a service, product, or building. In this report only the global warming impact is considered in terms of emission of CO_2 equivalents (CO_2e).

An LCA for a building includes materials and energy use from the whole life cycle of the building for different life stages. The phases and modules of a full life cycle is described by the European Standard EN 15978:2012 and is shown in Figure 1. The life cycle includes the stages *Product*, *Construction*, *Use* and *End-of-life*. Each stage is divided into several modules such as extraction of raw materials, transportation, fabrication, operational use, maintenance, replacements, waste treatment and disposal. The duration of the life cycle is called the reference study period (RSP) and is typically 50 years. Most LCA-methods (BR18, DGNB, Level(s), etc.) includes only a selection of the modules and evaluate the environmental impact as the sum of the included stages/phases but does typically not look at *when* the environmental impact occurs.

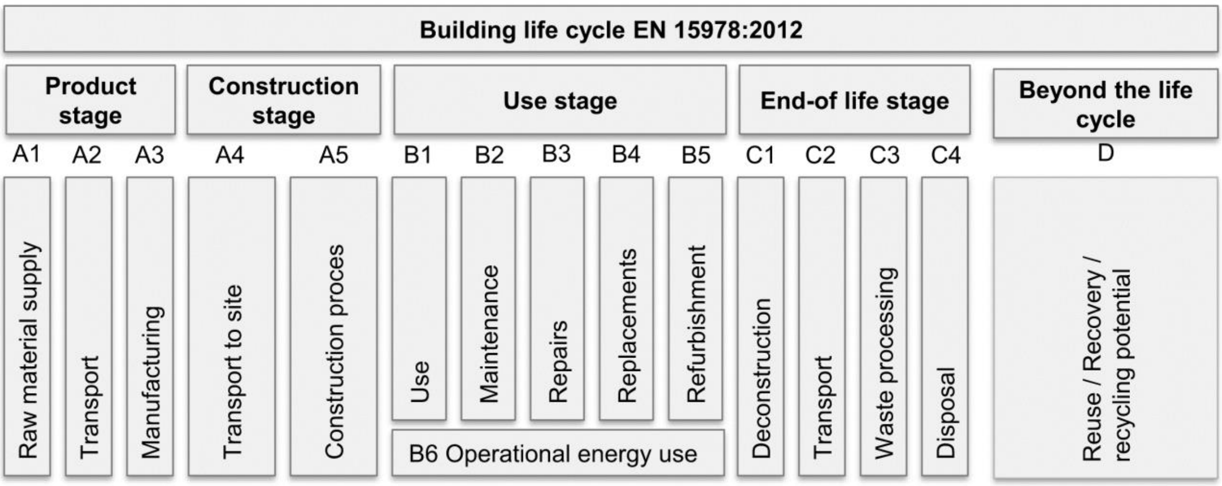

Figure 1 Life cycle of a building, EN 15978:2012

The environmental impact of a building starts with the extraction of raw materials for, transport of and production of building products (A1-A3). During the construction process building materials must be transported to site (A4) and a construction process includes fuel, energy, and waste during construction as well as temporary drying out etc. (A5). During the use of the building, the building is maintained (B2), refurbished (B3) and building parts with a life span less than the duration period must be replaced (B4). Emissions from production of consumed electricity and heating (B6) are included. At the end of the duration period the building is assumed to be decommissioned (C1) and materials transport from site (C2) and the environmental impact for waste processing (C3) and disposal (C4) are included. After de-commissioning the potential for reuse, recovery and recycling potential is estimated (D). Module D is a measure to what extent the building after decommissioning can reduce future emissions due to re-use/recycle of the building materials. The emissions in module D are negative and is typically not included in the result of the LCA.

The CO_2e-emissions from *building materials* (including replacements) are typically denoted as the *embodied* CO_2e-emissions while the CO_2e-emissions from the *energy consumption* (heating and electricity) is denoted as the *operational* CO_2e-emissions. The total emissions from the building during the reference study period is the sum of the two.

A typical LCA includes most building parts and -materials that may be in a building except for minor fixings, glues, panels etc. Emissions from the structural elements, the façade and roof comprise 60-80% of the total embodied CO_2e-emissions and the rest from technical systems, floors, ceilings etc.

3.1. When does emissions occur?

During an ongoing climate crisis, it is important not just to look at the total emissions of CO_2e, but also at *when* the emissions occur. In a time where all countries must and have pledged to reduce their CO_2e emissions, it would be beneficial to reduce climate emissions *now* and do everything in their power to reduce and delay emissions that will happen in the future.

Concrete, metals, mineral wool, and similar materials are characterized by having most of their climate emissions during the product stage and a smaller contribution in the end-of-life (waste processing and disposal). EPS insulation and plastic based products are characterised by having an almost equal share of emissions at production and at waste processing. Climate emissions from wood-based products are very different as CO_2e from the atmosphere is stored in the wood as biogenic carbon during the growth of wood. This carbon is sequestered and kept out of the atmosphere until the wood is incinerated or left for decay. The biogenic carbon is included as a negative contribution when the wood enters a product/building system and must be released as a positive contribution when the wood leaves the system again. This is usually called the -1/+1 flux of biogenic carbon. The -1/+1 rule is given by the European standard *EN 16485.* Biogenic carbon neutrality may only[1] be assumed for wood originating from forests which are operating under established schemes for sustainable forest management (FSC, PEFC, etc.). It is a key stone in the system that the contribution to a product or building climate impact (CO_2e-emission) is balanced over the life cycle of the product or building. This means that the net climate impact of wood products over their life cycle, is connected to activities that involve release of fossil carbon such as transportation, processing, glues, etc, but is net negative until the biogenic carbon is released at the end of the life cycle.

The timing of climate impact between production (A1-A3) and end-of-life (C3-C4) for different types of materials are shown in Figure 2. The figure is showing the relative climate impact but not the actual level of climate impact of the material types. The flux of biogenic carbon according to EN 16485 is shown in Figure 3. With these figures in mind, wood and other biogenic materials is the only material type that may be considered with a negative contribution at the start of a life cycle and will remain so until end-of-life. Wood-based materials can therefore be considered as a carbon sink (if timber products originate from managed and certified forestry) until the building or building material is disassembled and disposed of, and it is interesting to investigate at what time during its lifetime a building is net positive in terms of CO_2e emissions. The LCA methods used for analysis of three case projects are described in chapter 3.2.

[1] EN 16485:2014, 6.3.4.2

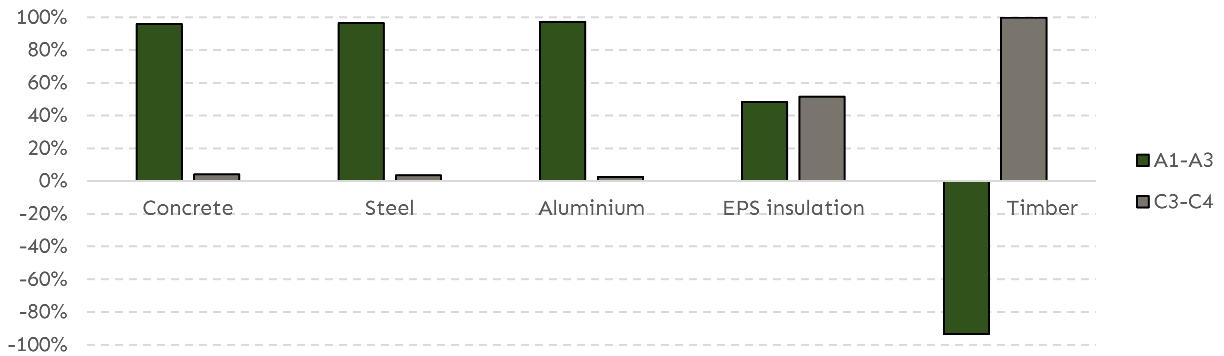

Figure 2 Distribution of climate impact in terms of production (A1-A3) and waste processing and disposal (C3-C4) for different material types.

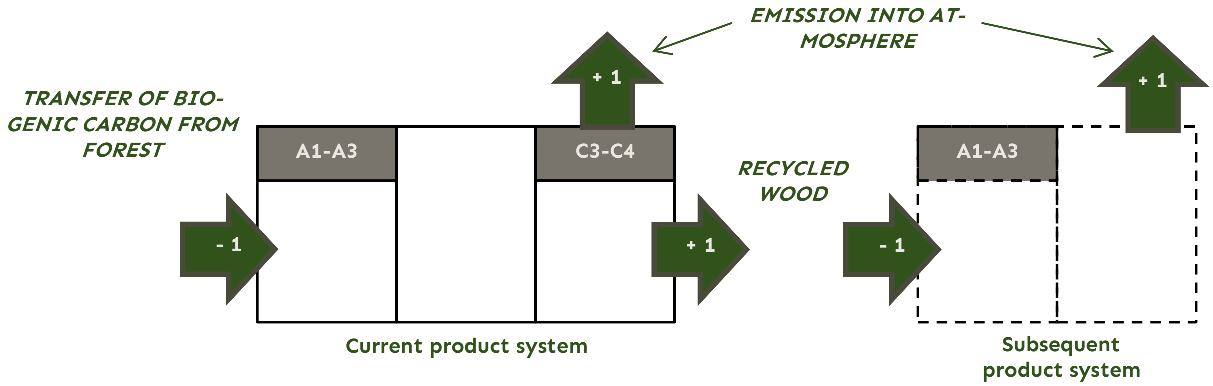

Figure 3 Biogenic carbon balance where carbon neutrality may be assumed (EN 16485, Figure 1)

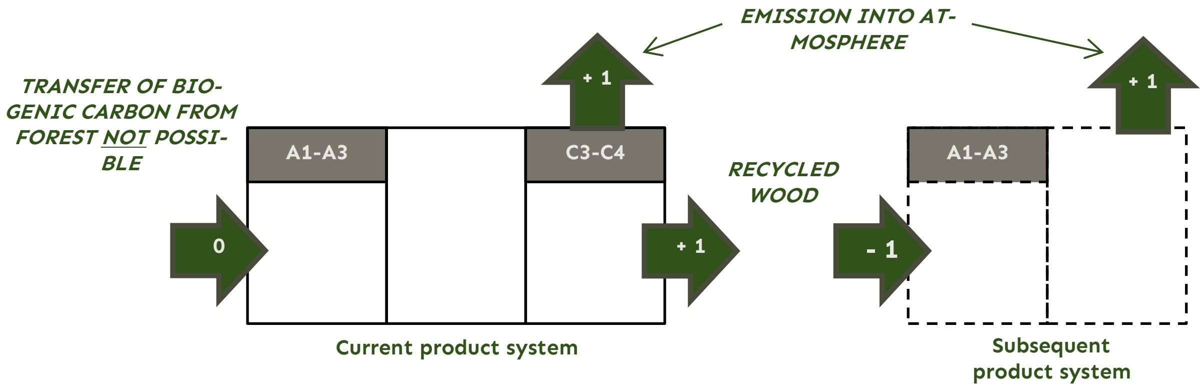

Figure 4 Biogenic carbon balance where carbon neutrality may not be assumed (EN 16485, Figure 2)

3.2. Dual LCA Method

Ideally a LCA method should be used with the purpose to *reduce material use*, *reduce up-front carbon emissions,* and *reduce carbon emissions for the whole life cycle* of a building. A method that includes the positive effect of postponing climate emissions from biogenic carbon will have an improved result when the quantity of biogenic materials is increased. To reduce the risk of using an excessive number of materials, a second method must be used to control material consumption as well. In this report two LCA methods are used and combined as the *Dual LCA method.* The two methods are called:

- Method 1 – Re-use

- Method 2 – BR18

In the following sections the two methods are briefly described. The methods have the following things in common:

- The reference study period for the LCA is 50 years.
- Results of the LCA are presented in kg CO_2e/m²/year where the reference area is calculated as the gross areas according to BR18 §297, stk. 3.
- The LCA includes building parts and materials according to BR18, bilag 2, table 6.
- Materials and areas for external areas are not included in the LCA.
- Both generic and specific data is used for material emissions.
    - Generic data: BR18, bilag 2, table 7
    - Specific data: Environmental product declarations (EPD) if valid and representative
- Replacement of materials and service life for materials according to BR18 §297, stk. 7.
- Emissions from heating and electricity according to BR18 §297, stk. 8.

The included lifecycle modules in the two LCA methods are shown in Figure 5. The Re-use factor (RF) used for end-of-life emissions from wood-based materials in Method 1, is explained in section 3.2.1.

The LCA calculations are done using an inhouse developed LCA software (SJ LCA Tool, vers. 1.1)

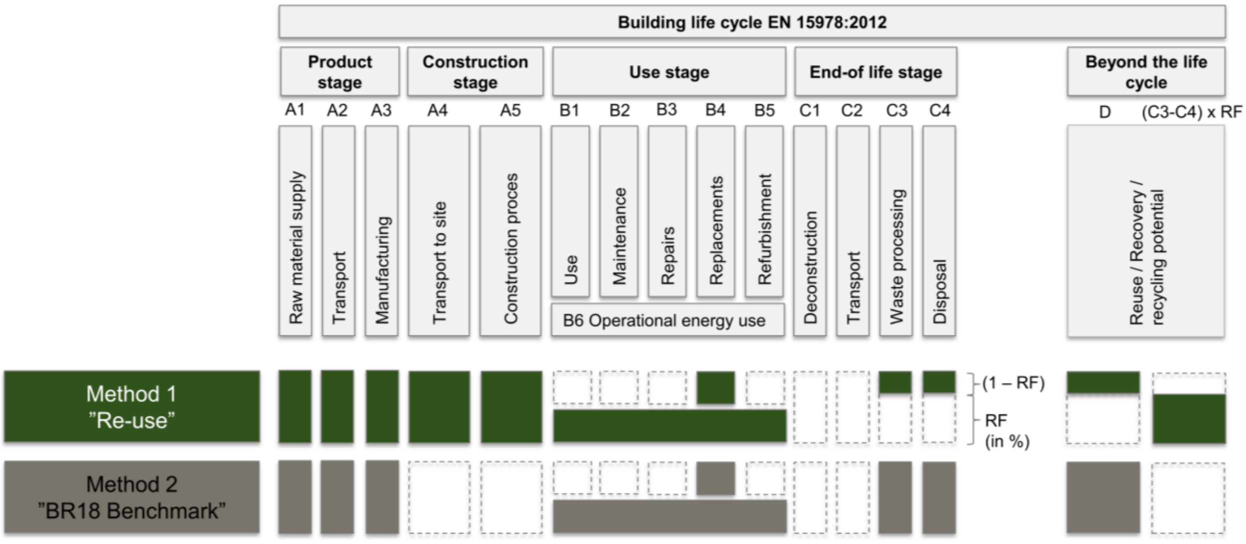

Figure 5 System boundaries for LCA methods 1 and 2

3.2.1. Method 1 – Re-use

The LCA method *Method 1 – Re-use* is used to estimate the climate impact including the construction stage and the potential reductions in climate impact connected to the re-reuse of timber-based building materials beyond the lifecycle reference period. This method does not comply with the standardized requirement of biogenic carbon balance for a product system according to EN 15978 and EN 16485. Despite of this, the analysis is still valid in terms of estimating when and if a building has building net-positive climate impact connected to re-use of wood-based materials.

The climate impact of the building during its life cycle includes the *product* stage (A1-A3), the *construction* stage (A4 & A5), *replacements* (B4), *operational use* (B6), and a *modified end-of-life stage* including *waste processing (C3) and disposal (C4).* The *modified end-of life* modules (C3 and C4) include the positive effect of postponing the release of the biogenic carbon in the future for re-used timber materials. The term *Re-use* in this report is used for materials that are used again for the same purpose as for the original use. The calculated potential will either be considered as a *best-case-scenario* with the potential of complete re-use (Re-use factor = RF = 100%) for some building parts and worst-case-scenario (RF = 0%) for other building parts. The realistic degree of the potential will be somewhere between the two limits. For the considered materials the climate emissions for re-used materials with a re-use factor (RF) will include the following modules:

- **Production stage**
  - 100 % of *A1-A3 Product stage*.
    (Biogenic carbon as a negative contribution)

- **End-of-life stage**
  - (100 % - RF) of *C3 Waste processing*
    (100 % - RF) of *C4 Disposal*
    (~ postponed release of biogenic carbon)

In the analyses, the stored biogenic carbon is only partially released (100% - RF) and the biogenic carbon of the re-used parts is postponed and disregarded in the calculation of the building's climate impact during the lifecycle. In this method the contribution from wood-based materials to the climate emissions is typically net-negative for a Re-use factor above 20%. The biogenic carbon "balance" used for Method 1 is shown graphically in Figure 6.

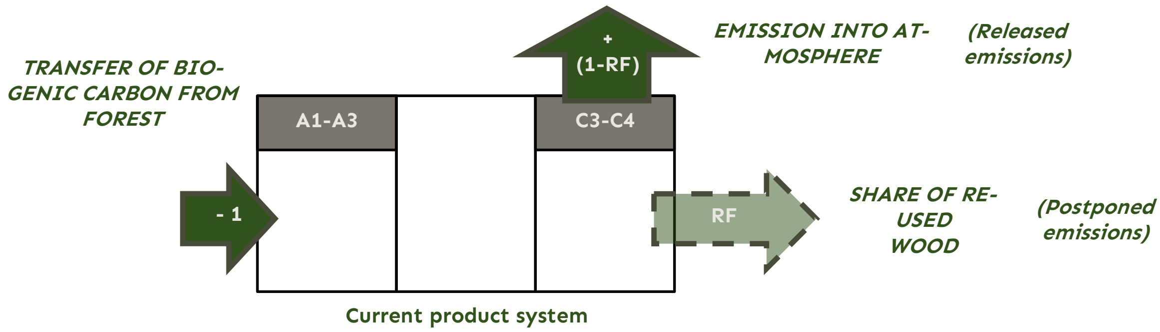

Figure 6 Adopted biogenic carbon "balance" for case projects in Method 1

There are several prerequisites that must be fulfilled if timber materials in a building may be considered for re-use in the future. At least three four prerequisites must be in place:

- The building parts are constructed in a way that they can be disassembled from other building parts again after end-of-life. This means that both connection methods and surface treatment must be carefully considered in the design of the buildings for *maximizing the possibility* of re-use in the future.
- The building parts are maintained during the lifetime of the building.
- Timber building parts must be designed and built in such that water and moisture is not reducing the lifetime of timber-based building parts.
- Special attention to surface and durability treatment (chemicals) that will not allow parts to be re-used.

For the three case projects the following re-use factors are applied on wood-based building materials:

- **RF = 100 % (i.e. re-used completely)**
  - Load bearing structural elements.
  - Timber framing in non-load bearing partitions.
  - Biogenic insulation in non-load bearing partitions
  - Wood flooring including framing.

- **RF = 0 % (i.e. incinerated)**
  - Wood based building parts with service life < 50 years, e.g. wood-based cladding material.
  - Biogenic insulation in outer walls and roof.

The climate impact from the *construction stage* (A4 and A5) is not documented for the three case projects. This contribution will be included as a statistical value for a typical construction process as presented in the report *BUILD 2023:14 Ressourceforbrug på byggepladsen - Klimapåvirkning af bygningers udførelsesfase*. From this reference the contribution from the construction process is approximately 1,4 kg CO_2e/m²/yr in total for a 50-year reference period. The distribution between the two modules is:

- **A4 Transport to site**
  - Based upon calculation for 9 projects.
  - GWP ≈ 0,4 kg CO_2e/m²/yr
- **A5 Construction process**
  - Based upon data from 52 projects.
  - Covers electricity, heating, fuel, building waste and transport on and from site.
  - GWP ≈ 1,0 kg CO_2e/m²/yr (median)

The system boundary for Method 1 is defined by the included lifecycle modules as shown in Figure 5.

3.2.2. Method 2 – BR18 Benchmark

The LCA method *Method 2 – BR18 Benchmark* is used to document the climate impact according to the LCA method in the Danish building regulations (BR18 §297). This method complies with the standardized requirement of biogenic carbon balance for a product system according to EN 15978 and EN 16485. Thus, the contribution from biogenic carbon is zero during the life cycle for this method.

The climate impact of the building during its life cycle includes the *product* stage (A1-A3), *replacements* (B4), *operational use* (B6)*,* and the *end-of-life stage* including *waste processing (C3) and disposal (C4).* The *end-of life* modules (C3 and C4) include the negative effect of releasing of the biogenic carbon regardless of the wood-based materials are re-used, recycled, or incinerated at the end of the lifecycle. This method may therefore be used to minimize material use if used with Method 1.

The system boundary for Method 2 is defined by the included lifecycle modules as shown in Figure 5. In addition, the climate impact is calculated for Method 2 – BR18 if the biogenic materials do not originate from managed forestry[2].

4. Case projects

In this report three different case projects from Denmark are included in the analysis using LCA methods 1 and 2. All case projects are residential type buildings, including a Danish single-family house and two multistorey buildings. The projects are from this point identified by the acronyms *SFH*, *MSRB1* and *MSRB2*. All three projects are characterized by an extensive use of wood-based materials for both the structural system, the façade cladding, and partitions, compared to a traditional and typical distribution of materials in similar Danish buildings. All case projects are anonymised after wish of the building owners. The three case projects are briefly described in this chapter with an overview of size and material use for building parts in Figure 8. Two of the case projects are built already (*SFH*, *MSRB2*) while the third one is currently being designed for construction (*MSRB1*). A summary of the case projects including the material distribution is shown in Figure 8 and a more thorough description of building parts is given in Table 1. The table is found in section 7.

[2] Which means that the biogenic carbon in the building is added to the result.

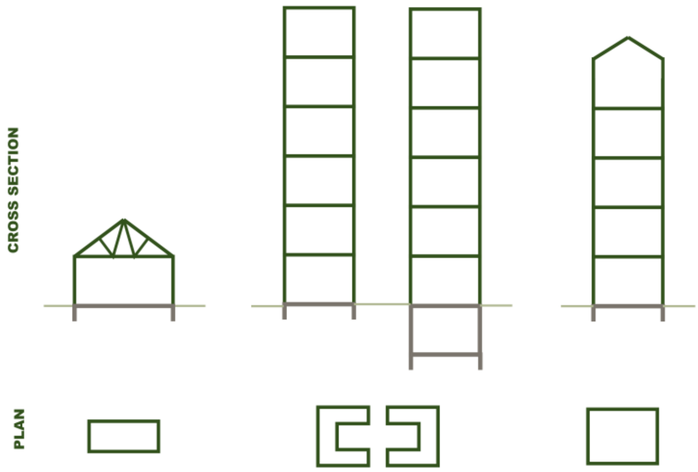

Figure 7 Principal section and plan for case projects, SFH – MSRB1 – MSRB2

	Case 1 - SFH	Case 2 - MSRB1	Case 3 - MSRB2
Building type	Single family housing	Multi-storey residential	Multi-storey residential
Gross area	135 m²	13.900 m²	580 m²
Stories above ground	1	6	5
Basement levels	0	1 (partial)	0
LCA Status	As built	As designed	As built
Year of completion	2019	exp. 2026	2023

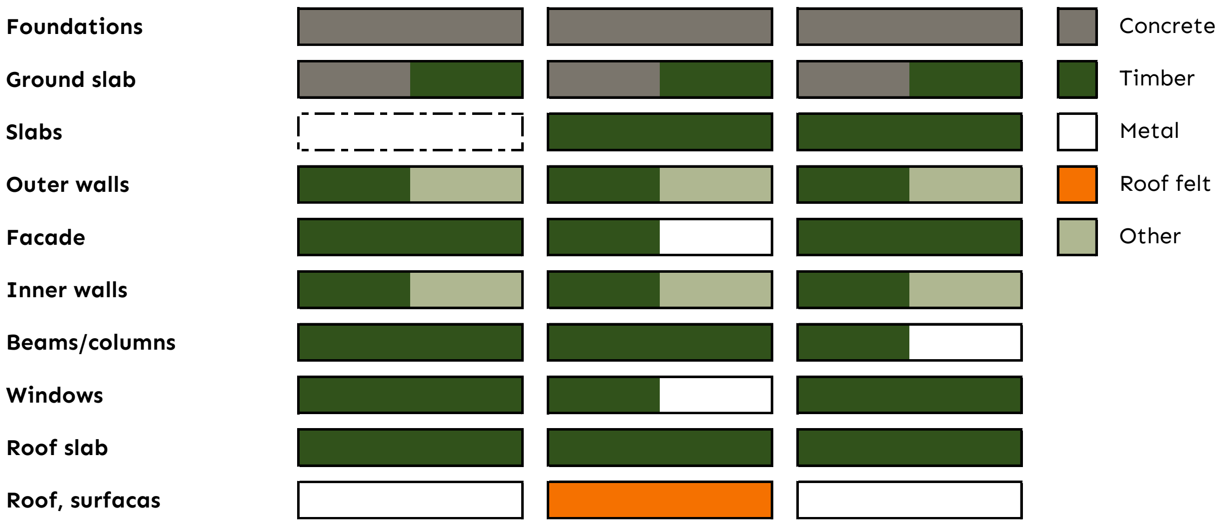

Figure 8 Size and material use for the included case projects.

5. Results

In the next sections the results of the life cycle assessment for the three case projects will be presented. The results for each case are presented in two graphs. One presenting the climate impact distribution on life cycle modules, Method 1 and Method 2 and a second one presenting the embodied climate impact distribution on building parts. With reference to Figure 5 climate impact for Method 1 and Method 2 is calculated as:

M1 Re-use = A1-A3 + A4 + A5 + B4 + B6 + C3-C4 x (1 – RF)

M2 BR18 = A1-A3 + B4 + B6 + C3-C4 x (1 – RF) + C3-C4 x RF[3]

The potential climate impact savings for re-used wood-based building parts are calculated as the *modified end-of-life* module *C3-C4 x RF*, where RF equals the degree of re-use in percentage. The re-use factor for specific building part materials either equals 0% or 100% as described in section 3.2.1.

5.1. Single family house (SFH)

The LCA results for case SFH are shown in Figure 9. The climate impact according to Method 2 (BR18) is 8,2 kg CO_2e/m²/yr which is comparable to similar buildings of this type. This relative high climate impact per m² and per year is often seen for single story buildings, as the climate impact from the foundations, ground slab and roof can only be distributed to a single story.

Due to a high degree of wood-based materials the climate impact is net negative for production of materials (A1-A3) and just above zero when including the construction stage (A4+A5). Due to replacement of the windowpanes and the steel roof the climate impact in module B4 is rather high compared to a standard project with this level of climate impact. The re-use of timber framing, roof girders and biogenic insulation in partitions is calculated to be as much as 2,9 kg CO_2e/m²/yr out of 5,7 kg CO_2e/m²/yr of total biogenic carbon. If the origin of the biogenic materials does not originate from managed forestry the climate impact according to BR18 is 8,2 + 5,7 = 13,9 kg CO_2e/m²/yr; well above the limit value at 12 kg CO_2e/m²/yr, that applies for new buildings in Denmark with a heated area above 1.000 m².

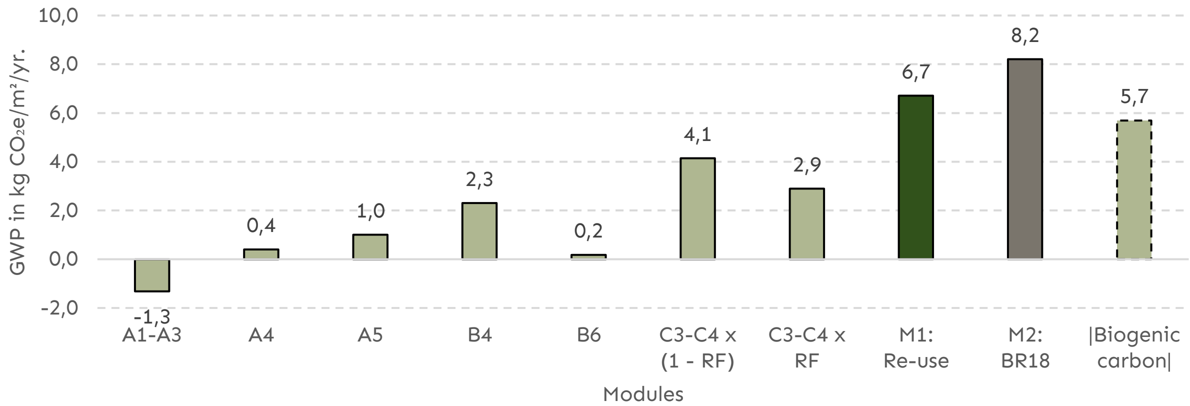

Figure 9 SFH - LCA results for lifecycle modules and LCA methods 1 and 2 for a 50-year period.

The distribution of embodied[4] climate impact from building parts is shown in and Figure 10. In the graph Slab is part of the ground slab. From the result it is seen that the main potential lies in the roof comprising roof girders and roof diaphragm (OSB). Timber framing in outer and inner walls also have a potential for future CO_2e-emissions.

[3] Which equals the required system boundary defined by BR18 §297, stk. 2. (A1-A3 + B4 + B6 + C3-C4)
[4] Embodied climate impact is the climate impact from building materials.

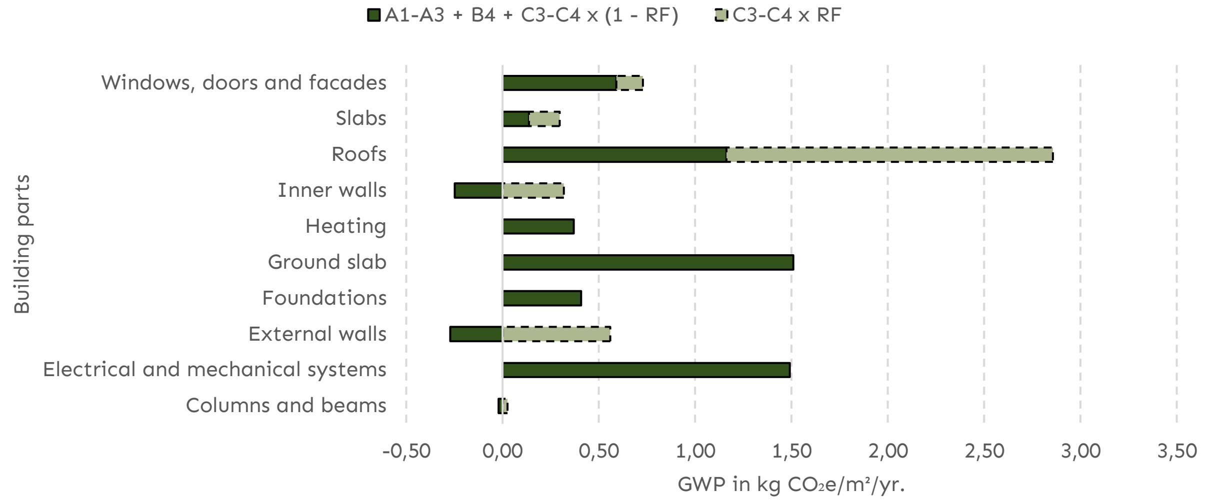

Figure 10 SFH - Embodied climate impact for building parts with potential postponed emissions (C3-C4 x RF) for a 50-year period.

5.2. Multi-storey residential building 1 (MSRB1)

The LCA results for case MSRB1 are shown in Figure 11. The climate impact according to Method 2 (BR18) is 5,0 kg $CO_2e/m^2/yr$ which quite low compared to other multistorey residential buildings. This result is based upon design only as the building is not built yet. The low GWP is the result of the project using LCA as part of the design tool for decision making from the very beginning of the project.

Due to a high degree of wood-based materials the climate impact is net negative for production of materials (A1-A3) and just above zero when including the construction stage (A4+A5). The potential CO_2e-savings from re-use of the glue laminated structural frame, engineered slabs, glulam roof slabs and biogenic insulation in partitions is calculated to be as much as 3,9 kg $CO_2e/m^2/yr$ out of 4,5 kg $CO_2e/m^2/yr$ of total biogenic carbon. With these potential reductions the climate impact for MSRB1 is rather low at 2,5 kg $CO_2e/m^2/yr$. for Method 1. If the biogenic insulation in the outer walls and roof also could be re-used, an additional 0,1 kg $CO_2e/m^2/yr$. could be reduced from the climate impact for Method 1. Compared to case SFH the potential CO_2e-savings are greater, as the structural elements are solid wood compared to traditional framing and roof girders. If the origin of the biogenic materials is not from managed forestry the climate impact according to BR18 is 5,0 + 4,5 = 9,5 kg $CO_2e/m^2/yr$; still below the general limit value at 12 kg $CO_2e/m^2/yr$.

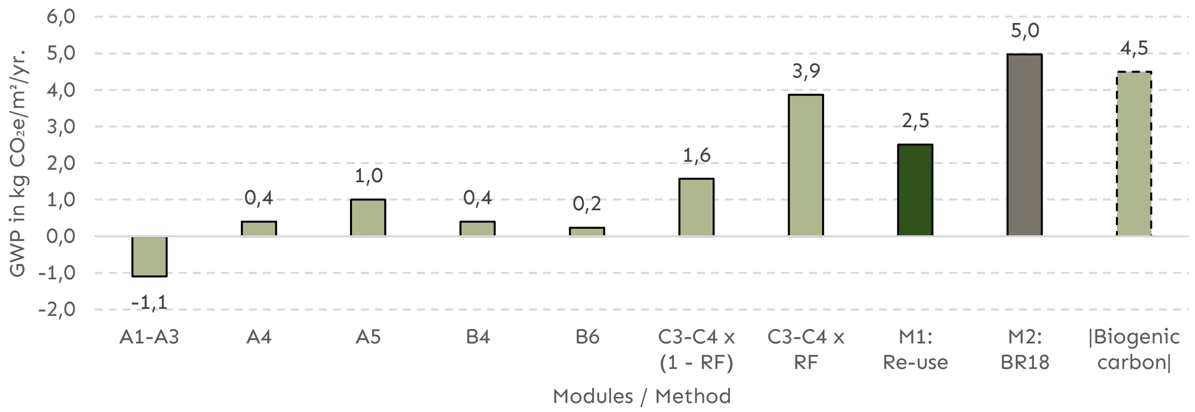

Figure 11 MSRB1 - LCA results for lifecycle modules and LCA methods 1 and 2 for a 50-year period.

The distribution of embodied climate impact from building parts is shown in Figure 12. From the result it is seen that the main potential lies in the slabs comprising glue laminated timber and 2 two-layered plywood diaphragms. The Glue laminated columns and beams also have a considerate potential for future CO_2e-emissions. Timber framing, internal biogenic insulation and roof slab all have minor potential for future CO_2e-emissions.

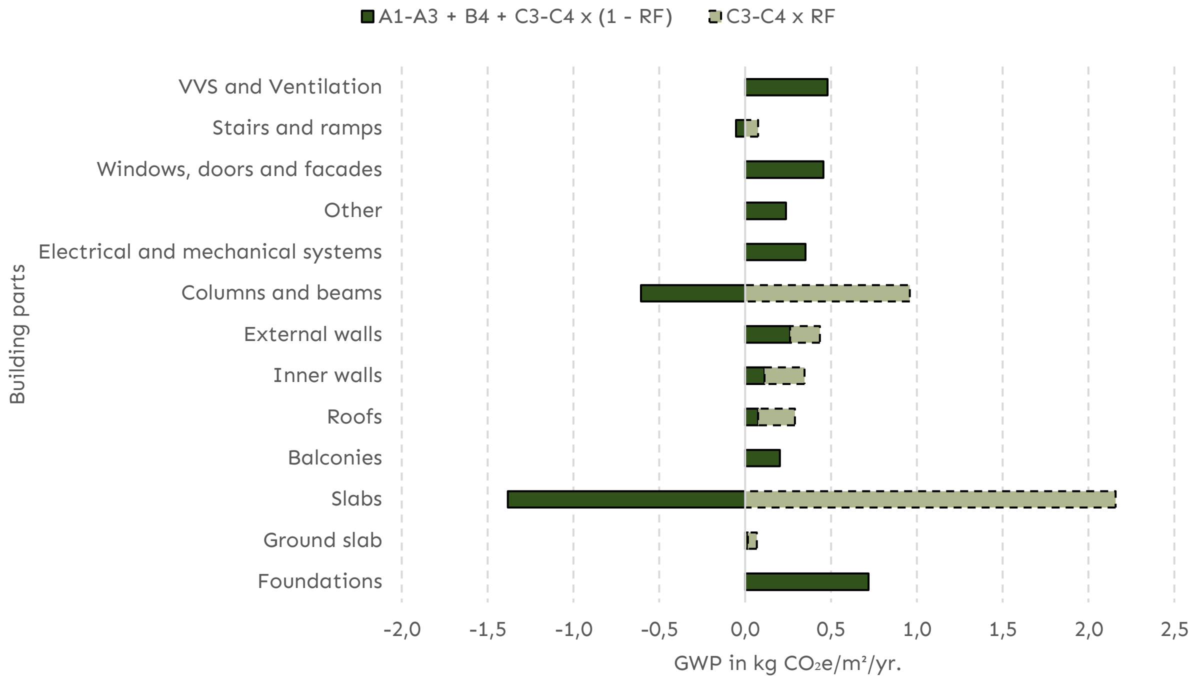

Figure 12 MSRB1 - Embodied climate impact for building parts for LCA method 1 and potential postponed emissions (C3-C4 x RF) for a 50-year period.

5.3. Multi-storey residential building 2 (MSRB2)

The LCA results for case MSRB2 are shown in Figure 13. The climate impact according to Method 2 (BR18 benchmark) is 7,7 kg $CO_2e/m^2/yr$ which lower than most multistorey residential buildings. This is the result of the project using LCA as part of the design tool for decision making from the very beginning of the project. Due to a high degree of wood-based materials the climate impact is net negative for production of materials (A1-A3) and just above zero when including the construction stage (A4+A5). The potential CO_2e-savings from re-use of the CLT slabs, CLT walls and biogenic insulation in partitions is calculated to be as much as 4,2 kg $CO_2e/m^2/yr$ out of 4,8 kg $CO_2e/m^2/yr$ of total biogenic carbon. With these potential reductions the climate impact for MSRB2 is at 4,9 kg $CO_2e/m^2/yr$. for Method 1. If the biogenic insulation in the outer walls and roof also could be re-used, an additional 0,2 kg $CO_2e/m^2/yr$. could be reduced from the climate impact for Method 1. Compared to case SFH the potential CO_2e-savings are greater, as the structural elements are solid wood compared to traditional framing and roof girders. Compared to MSRB1 the potential CO_2e-savings are comparable.

If the origin of the biogenic materials does not originate from managed forestry the climate impact according to BR18 is 7,7 + 4,8 = 12,5 kg $CO_2e/m^2/yr$; which is above the general limit value at 12 kg $CO_2e/m^2/yr$.

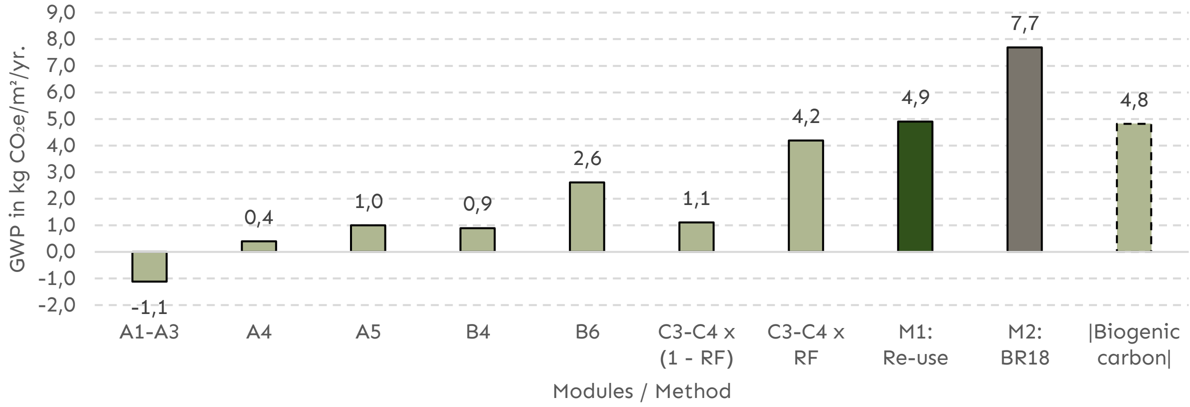

Figure 13 MSRB2 - LCA results for lifecycle modules and LCA methods 1 and 2 for a 50-year period.

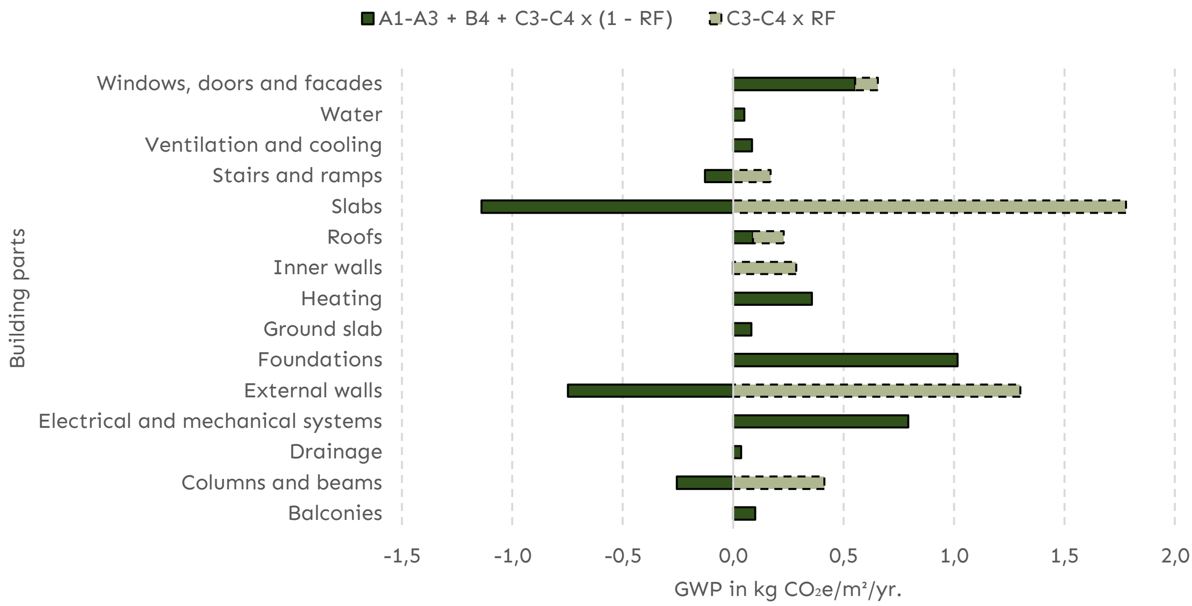

Figure 14 MSRB2 - Embodied climate impact for building parts for LCA method 1 and potential postponed emissions (C3-C4 x RF) for a 50-year period.

The distribution of embodied climate impact from building parts is shown in Figure 12. From the result it is seen that the main potential lies in the slabs comprising glue laminated timber and 2 two-layered plywood diaphragms. The Glue laminated columns and beams also have a considerate potential for future CO_2e-emissions. Timber framing, internal biogenic insulation and roof slab all have minor potential for future CO_2e-emissions.

5.4. Summary of results

In the previous sections the Dual LCA method was presented and demonstrated on three case projects. The summary of results is presented in Figure 15. All three projects demonstrate a climate impact in the lower end compared to similar buildings, when the BR18 LCA method is used (Method 2). All three projects have a climate impact below the current BR limit value at 12 kg CO_2e/m²/yr and are near or below the BR18 voluntary CO_2 class at 8 kg CO_2e/m²/yr.

The potential savings in climate impact from future re-use of wood-based materials was estimated at 2,9-4,2 kg CO_2e/m²/yr corresponding to 50-87% of the total sequestered biogenic CO_2e.

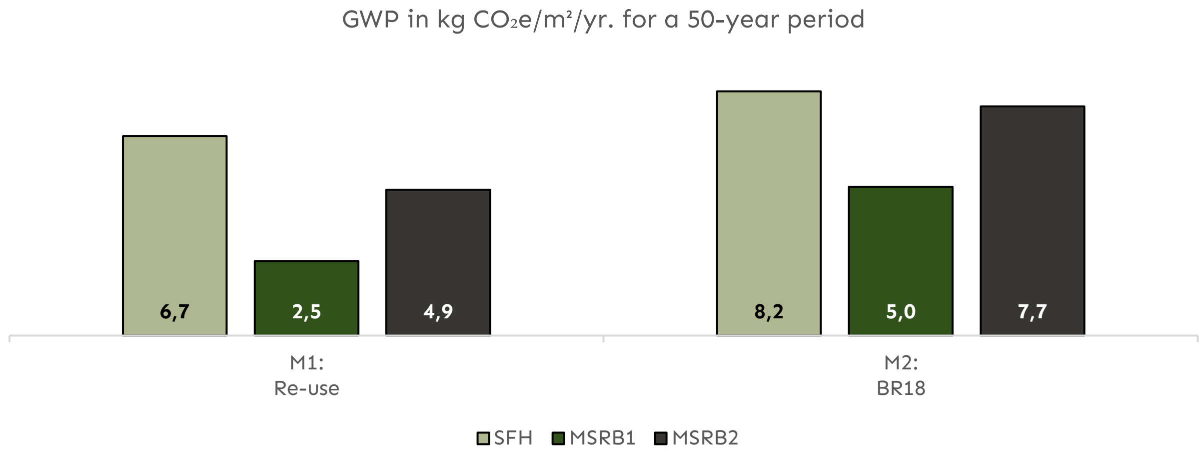

Figure 15 Summary of results for case projects and methods.

In addition to the BR18 LCA calculations (Method 2) the climate impact of the case projects was calculated in the case that the wood-based materials did not originate from sustainably managed forestry. In this case the climate impact increases for the three case projects with up to 4,5-5,7 kg $CO_2e/m^2/yr$ (please refer to figure 16). This corresponds to the level of biogenic carbon that can no longer be regarded as a negative contribution at the product stage. With this assumption just one of the case projects (MSRB1) is below the limit value of new buildings above 1.000 m² in Denmark[5] - this is the project which has used the Dual-LCA approach in the design process and thus optimised on both CO_2 emissions and material usage.

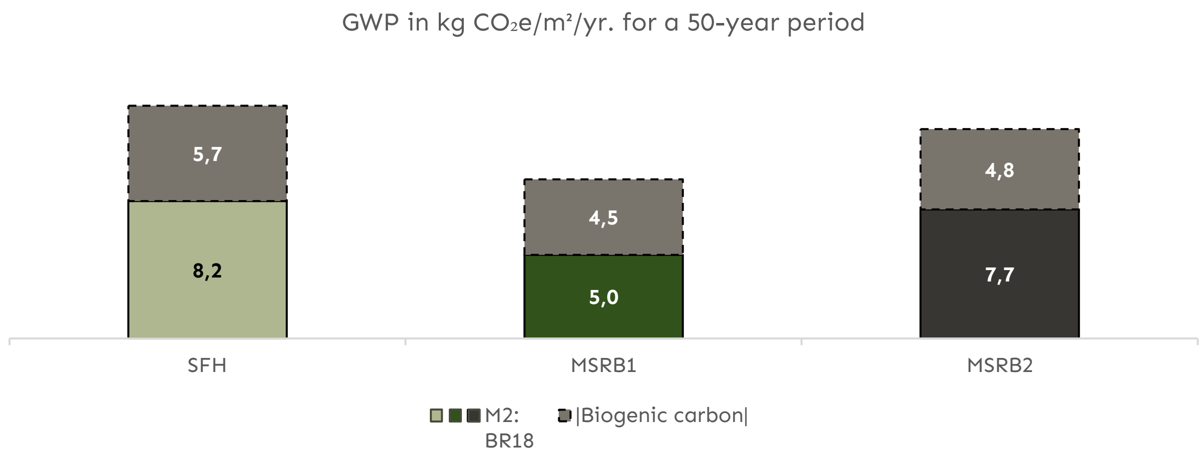

Figure 16 Climate impact of case project according to BR18 if wood-based materials are not certified.

[5] Danish building regulations BR18 §§297-298.

6. Conclusions

In the previous sections the climate impact of the three case projects was calculated by two different LCA methods. The dual LCA method combines the two LCA-methods and is a proposed design approach that will promote both a minimized upfront carbon footprint as well a reduction of material usage that allows for lowering both the up-front and total climate impact.

For *LCA-method 1 – Re-use* the climate impact for all three buildings was calculated including the climate impact from *production*, *construction*, *building use* and partially from *waste treatment and disposal*. The potential of postponed release of biogenic carbon was shown to be higher than any other contribution to the LCA result. The potential was identified to be as much as 2,9-4,2 kg $CO_2e/m^2/yr$. corresponding to 50-87% of the total sequestered biogenic carbon. The potential was limited to wood-based materials for structural elements, inner walls if designed for re-use.

Due to a high degree of timber in all case projects the climate impact according to *LCA-Method 2 – BR18* was shown to be low (5,0-8,2 kg $CO_2e/m^2/yr$.) compared to residential buildings in Denmark constructed in conventional materials such as concrete and brick. Therefore, all three case projects have a climate impact that is well below the current national limit value at 12 kg $CO_2e/m^2/yr$.

An additional LCA according to BR18 was made for the case projects, under the assumption that (all) the wood-based materials are not produced from a sustainably managed forestry scheme (i.e. not FSC-certified). In this case, the biogenic carbon sequestered during growth of the trees, may not be considered as a negative contribution in the product stage (*A1 Raw materials*) but should still be released at end-of-life (*C3 Waste treatment)*. In the extreme case this would lead to an increase of climate impact in the order of 4,5-5,7 kg $CO_2e/m^2/yr$. With this contribution two of the case projects would go from a climate in the lower end to a level where they would not meet the limit value at 12 kg $CO_2e/m^2/yr$. for new buildings in Denmark.

The case project (MSRB1) that had adopted the Dual LCA method during the design is also demonstrating the lowest climate impact of all case projects for both LCA methods. If this is a coincidence or a result of the Dual LCA method is not certain.

7. Tables

Table 1 Description of building parts in case projects, SFH – MSRB1 – MSRB2

Building part	**SFH**	**MSRB1**	**MSRB2**
Foundations	Concrete strip foundations	Piles and concrete foundation beams	Piles and concrete foundation beams
Ground slab	Concrete ground slab on EPS insulation and drainage layer	Self-supporting prefabricated timber elements with	Concrete ground slab on EPS and drainage layer
Basement	-	Watertight basement with concrete base plate, walls and basement slab with XPS insulation	-
Slabs	-	Glulam rib decks with clay	CLT slabs
Outer walls	Timber stud walls with biogenic insulation and OSB and gypsum boards	Timber stud walls with glass wool insulation and gypsum and gypsum fibre boards. CLT walls with gypsum fibre boards.	Timber stud walls with glass wool insulation and gypsum and gypsum fibre boards. CLT walls with gypsum fibre boards.
Façade	Timber boards	Timber boards and steel sheets	Timber boards
Inner walls	Timber stud walls with biogenic insulation, gypsum fibre boards and clay plaster	Timber stud walls with biogenic insulation, gypsum fibre boards and clay plaster	Timber stud walls with biogenic insulation and gypsum fibre boards. CLT walls with gypsum fibre boards.
Beams / columns	Glulam beams	Glulam beams	Glulam and steel beams Glulam columns
Doors	Wooden doors internally and aluminium frame doors externally	Wooden doors internally and aluminium frame doors externally	Wooden doors internally and aluminium frame doors externally
Bathrooms	Ceramic tiles on screed layer	Prefabricated bathroom elements with concrete base and ceramic tiles	Ceramic tiles on concrete base
Balconies	-	Steel frame with wooden boards and steel railing.	Steel frame with wooden boards and steel railing.
Windows	Wooden frame with 3-layered windowpanes	Wood/Alu frame with 3-layered windowpanes	Wooden frame with 3-layered windowpanes Roof lights in aluminium frame with 3-layered windowpanes.
Roof	Timber girder with biogenic insulation and biogenic wind barrier	Timber rib deck with mineral wool insulation	Prefabricated timber elements with biogenic insulation
Ceilings	Wood-cement boards	Gypsum and fibre gypsum boards	Gypsum and fibre gypsum boards
Roof, surfaces	Steel sheets	Two-layered roof felt	Steel sheets
Heating	Heat pump	Heat pumps	District heating
Solar cells	Yes (on ground)	Yes (on roof)	Yes (on roof)

8. References

EN 15978

DS/EN 15978:2012 – " Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method"

EN 15804

DS/EN 15804 + A2:2019 - "Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products"

EN 16485

DS/EN 16485:2014 – "Round and sawn timber – Environmental Product Declarations – Product category rules for wood and wood-based products for use in construction

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