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PAPER

Methodological aspects in assessing the whole-life global warming potential of wood-based building materials: comparing exterior wall structures insulated with wood shavings

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Abstract

Due to the heavy environmental impacts on the building industry, wood-based building materials are gaining interest. They may improve the indoor climate and have a low carbon footprint compared to steel and concrete structures. This study provides knowledge on the carbon footprint of wood shavings (WSs) and WSs improved with clay as insulation materials. The study defines the lifecycle emissions of five different wall structures, of which two are of conventional type in the Finnish context and three with WSs as insulation. The study follows the EN standards on buildings' life cycle assessment with a streamlined approach and discusses the applicability of the method in the normative context. The study analyzes multiple methodological aspects, including biogenic carbon, co-product allocation, and defining the functional unit in wall structure comparison. In the base case, the exterior wall using WS as insulation provided the lowest GHG emissions of the compared structures. The study finds global warming potential (GWP) of WSs moderately sensitive to allocation choices and energy sources used in the drying of WSs with clay, while the End-of-Life treatment option can radically change the results in biogenic GWP. From the perspective of applying the buildings' life cycle assessment in the normative context, there is a call for further research for controlling uncertainties in modeling End-of-Life options of biogenic materials.

Abbreviations

LCA	Life cycle assessment
EoL	End-of-Life
GHG	Greenhouse gas
GWP	Global warming potential
EPD	Environmental product declaration
WS	Wood shavings
WS+C	Wood shavings with clay
Inc	Incineration
LF	Land fill
Comp	Composting

1. Introduction

Wood shavings (WSs) was widely used in the Nordic countries as thermal insulation before the beginning of the era of industrial thermal insulations. Interest in it has grown again, as it might provide one solution to the heavy environmental impacts of the construction industry, such as high GHG emissions, non-renewable material consumption and waste output (Bajželj *et al* 2013, Salemdeeb *et al* 2016). Using wood, for example, in load-bearing structures reduces climate emissions in the construction industry (Duan *et al* 2022). WS, as a product stemming from recycled side streams of the wood planning industry, follows the principles of the circular economy (Joensuu *et al* 2020).

Another clear advantage of WS insulation is its high moisture capacity, equalizing moisture conditions and making conditions less favorable for microbe growth in the structures (Bunkholt *et al* 2021). Structures insulated with WSs can also be implemented in such a way that, instead of a plastic film, wood or wood-based materials are used as a vapor barrier on the inner surface of the structure (Bunkholt *et al* 2021). This helps to avoid non-biodegradable plastics, that have become an increasing problem when breaking up into small pieces and accumulating in organisms (Xu *et al* 2020). In general, the need for high water vapor resistance is reduced inside the structures as the moisture capacity of the thermal insulation increases (Bunkholt *et al* 2021). In that case, structures can also balance indoor air humidity by absorbing and re-emitting moisture (Wu *et al* 2013).

Clay can also be mixed with WS insulation, which improves its fire-technical performance (Tampere Universities n.d.). Clay acts as a natural fire retardant in insulation. Clay has also been found to prevent growth of harmful microbes in structures (Kibanova *et al* 2009, Ugochukwu and Fialips 2017, Selkäinaho *et al* 2018). In addition, clay increases the moisture capacity of thermal insulation, which improves its moisture performance even more. On the other hand, the thermal conductivity of WS insulation does not significantly increase due to the addition of clay which is important in terms of good thermal insulation of structures (Tuurala 2022).

The literature above indicates that WS and WS with clay (WS + C) are potentially new climate-friendly building materials that have benefits related to structural physics. However, research on the potential positive impact on global warming potential (GWP) of using WS as insulation is still inadequate. Some research articles are available that discuss the potential of wood chips as a filler in bricks or as an aggregate in concrete (Alabduljabbar *et al* 2021, Benchouaf *et al* 2023). Several papers discuss clay as a plaster or a material in earth blocks (Toguyeni *et al* 2012, Jannat *et al* 2020). When analyzing GWP of timber researchers study structures with mineral wool insulation or processed wood fiber (Duan *et al* 2022). One of the few studies on wood waste explores its physical properties (Cetiner and Shea 2018). Peer-reviewed research on novel types of wall structures using WS as insulation and clay as a mixture with WS does not exist. Since the claimed benefit of this type of structure is its global warming mitigation potential, it is necessary to verify these benefits through a thorough analysis of the whole-life GWP.

LCA has been widely used as a methodological basis for defining GWP for buildings, structures and building materials. Recently countries such as Finland, among other Nordic countries, have revealed plans to apply carbon footprint calculation and carbon budgeting in building regulations (Ministry of the Environment of Finland 2019, Kuittinen and Häkkinen 2020). However, previous studies have raised concerns about the consistency of the method and the comparability of the results (Schrijvers *et al* 2016, Hossain and Ng 2018). Applying buildings' LCA in legislation increases the importance of methodological exactness in achieving the intended steering effects and consistency, and not leaving any loopholes that would weaken the steering effects.

Researchers have especially debated allocation rules that are unavoidable in the case of recycling (Moretti *et al* 2020). WS structures, as an example of upstream recycling, offer an opportunity to discuss uncertainties related to the issue. A process that produces multiple products needs to define which part of the environmental burden of the process belongs to which output. In a normative context, allocation rules may change the order of preferable structures when builders are striving for a carbon budget laid out in the legislation (Ilic and Ödlund 2018). Analyzing the sensitivity of the results to allocation choices calls for testing LCA with different allocation rules.

As a wood-based material, WS also offers an opportunity for opening a discussion on modeling the biogenic carbon cycle from the perspective of LCA in the regulatory context. In addition to co-product allocation, one of the methodological issues of this study is how to model the biogenic GWP of wood as it sequesters carbon when growing. The method applied in Finnish building regulations advises reporting the carbon handprint separately as benefits outside the system boundaries, which is far from the standardized LCA (Kuittinen and Häkkinen 2020). In contrast, EN standards advise reporting biogenic GWP as its own impact category and in total GWP (EN 16485 2014, EN 15804 2019). In biogenic materials, the EoL scenario may radically change the life cycle GWP, as the material may end up in the atmosphere as methane or carbon dioxide and may also become solid carbon. As building materials have a long service life, the EoL treatment is hard to foresee, but only one scenario can apply in the regulatory context.

The objective of this study is to analyze the potential positive impact on GWP of WS structures. The study compares wall structures with WS and WS + C to the more conventional ones by calculating fossil GWP and total GWP (total includes GWP from fossil, biogenic and land use) over the cradle-to-grave system boundaries in each option. In addition to providing knowledge on the life cycle GWP of WS, the study discusses issues related to co-product allocation and modeling the biogenic carbon cycle when using side streams of the sawmill industry as building material. The study also examines the sensitivity of results to multiple variables, such as co-product allocation choices, type of drying energy in WS + C, and GHG emissions of EoL options. The research question of this paper is: can EN standards on the buildings' LCA reliably show the climate change mitigation potential of WS insulations?

2. Materials and methods

To explore the potential climate change mitigation potential of WS and WS + C, this study calculates life cycle GHG emissions of five different wall structures in the Finnish context. A wall structure is a whole where particular insulation material choices influence choices in associated materials and, eventually, the carbon footprint of the whole wall. For example, WS is a blow-in insulation and a flame-spreading material, needing plywood or plasterboard on both sides of the structures. Also, thermal conductivity varies between different insulations, impacting the thickness and dimensions of load-bearing structures. Since comparing the life cycle GWP of a single material does not provide meaningful information, the assessment should recognize the context of use.

2.1. Studied structures

This paper examines five different exterior wall structures listed in table 1. Three structures (WS1–WS3) have been under development in the ECOSAFE project. (Tampere Universities n.d.). The project has studied the acoustics, fire resistance, building physical and microbiological performance of the wall structures. Wall structures WS2 and WS3 are designed to perform under Finnish fire protection regulations as non-load-bearing exterior wall structures in apartment buildings with a non-combustible frame, making them comparable with BAU1 and BAU2 (FINLEX 2017a). Wall structure WS1 does not have fire resistance, making it comparable only to BAU1. The structures are not precisely identical in the sense of fire and acoustic features but are still comparable, as they are applicable for the same purposes according to current Finnish regulations (FINLEX 2017b). More in detail, the structures function as follows:

- WS1, an exterior wall with a timber frame and façade, and WS insulation. Total thickness 402 mm. Under Finnish fire protection regulations, this structure is applicable in buildings with no apartments on top of each other. This structure has the highest possible fraction of bio-based material. The idea is to pack the WS tightly between plywood and porous fiberboard to enable using the structure as an element. The inner side of the structure has additional battens under the plasterboard for hidden electric installations. If the exterior wall has no electric sockets, battens and plasterboard are unnecessary.
- WS2, an exterior wall with a timber frame and façade, and WS + C. Total thickness 380 mm. Under Finnish regulations, this wall structure is applicable in buildings with two apartments on top of each other and multi-floor apartment buildings with inflammable load-bearing structures. The structure is otherwise similar to WS1 but uses a stone wool-based windproof board on the outer surface and WS + C as insulation to improve fire resistance.
- WS3, an exterior wall with cross laminated timber, wood façade and WS + C. Total thickness 430 mm. This wall structure is applicable in multi-floor apartment buildings. Most of the material in the wall is cross-laminated timber, a thick timber panel made by gluing and pressing. The structure has a stone wool-based windproof board on the outer surface and WS + C as insulation to improve fire resistance.
- BAU1, an exterior wall with a timber frame and façade, and rock wool insulation. Total thickness 303 mm. This is a standard wall structure for Finnish single-family houses, but the structure is also applicable in multi-floor apartment buildings. The structure is applicable in prefab panels as well as in situ construction and is standardized in RT 82-11006 (2010).
- BAU2, a non-load-bearing pre-cast concrete wall with rock wool insulation. Total thickness 380 mm. This is a standard wall structure for Finnish multi-floor apartment buildings. It has a so-called sandwich structure with rock wool insulation between two layers of concrete tied with steel rebars. The structure is also standardized in RT 82-11006 (2010).

2.2. The method

The study follows the procedures of EN 15804 and EN 15978, which also form the basis for the whole-life carbon assessment of buildings that Finland aims to include in its building regulations by the mid-2020s (EN 15978 2011, EN 15804 2019, Ministry of the Environment of Finland 2019). The idea of EN standards is to combine the data for the whole building LCA from several environmental product declarations (EPDs)

Table 1. Dimensions of material layers in studied structures.

		WS1			**BAU1**
		Waterborne exterior paint			Waterborne exterior paint
>23	mm	Timber cladding	>23	mm	Timber cladding
32	mm	Air gap + battens 32 × 100 k600	32	mm	Air gap + battens 32 × 100 k600
25	mm	Porous fiberboard with bitumen,	30	mm	Rock wool wind protection slab,
		lambda d = 0.049			lambda_d = 0.033
250	mm	Load-bearing structure and insulation	9	mm	Gypsum plasterboard for exterior
		Wood shaving	148	mm	Load-bearing structure and insulation
		* Load-bearing structure 48 × 250 k600			* Stone wool insulation 48 mm,
0	mm	Vapor barrier paper			lambda_d = 0.036
15	mm	Plywood			* Load-bearing structure 48 × 148 k600
44	mm	Battens 2 × 22 × 100 k600	0	mm	Plastic vapor barrier
13	mm	Plasterboard for interior	48	mm	Insulation and battens
					* Stone wool insulation 48 mm,
		WS2			lambda_d = 0.036
		Waterborne exterior paint			* Battens 48 × 48 k600
>23	mm	Timber cladding	13	mm	Plasterboard for interior
32	mm	Air gap + battens 32 × 100 k600			
30	mm	Rock wool wind protection slab,			**BAU2**
		lambda_d = 0.033	70	mm	Reinforced concrete layer
223	mm	Load-bearing structure and insulation			*Concrete
		* Wood shavings + clay			*Steel rebars 30 kg m^{-3}
		* Load-bearing structure 48 × 223 k600	220	mm	Rock wool insulation
0	mm	Vapor barrier paper	80	mm	Reinforced concrete layer
15	mm	Plywood			*Concrete
44	mm	Battens 2 × 22 × 100 k600			*Steel rebars 30 kg m^{-3}
13	mm	Plasterboard for interior			
		WS3			
		Waterborne exterior paint			
>23	mm	Timber cladding			
32	mm	Air gap + battens 32 × 100 k600			
30	mm	Rock wool wind protection slab,			
		lambda_d = 0.033			
148	mm	Load-bearing structure and insulation			
		* Wood shavings + clay			
		* Load-bearing structure 48 × 148 k600			
140	mm	Cross-laminated timber			
44	mm	Battens 2 × 22 × 100 k600			
13	mm	Plasterboard for interior			

produced by the industry and approved by an independent verifier. However, in some cases, such as WS insulations, EPDs are missing where the data needs homogenization through process-based analysis and combining multiple sources.

The study defines the system boundaries as cradle-to-grave, including all the life cycle stages. Figure 1 shows the system boundaries and life cycle stages classified into modules A–D according to advice in EN standards on buildings' LCA. The reference study period is defined as 50 years, which has a minor impact on module B as façades require regular repair or painting. This paper calls the method streamlined LCA, as the calculation focuses on the category of GWP only (Crawford 2011). In addition to the fossil GWP, the study reports total GWP, which also includes biogenic carbon cycle.

According to Schrijvers *et al* (2016), EN 15804 represents a fully attributional approach, that relies on the EPD system and supports its bookkeeping perspective. Schrijvers *et al* (2016) claim that the attributional framework of EN 15804 does not fit together and is not comparable with the consequential approach, as they ask different questions: the attributional states the status quo, while the consequential indicates the change and impact to the market. Therefore, this study leaves the consequential approach outside consideration.

EN 15804 allows reporting the benefits outside the system boundaries, such as climate change mitigation potential from avoided production in the other product system, in a separate Module D. EN standards on buildings' LCA advise reporting the benefits outside the system boundaries in a separate module D that should never impact the product system under study (EN 15978 2011).

Module D, as well as impact category of GWP total and GWP biogenic, may provide negative values for different reasons. Figure 2 explains the logic of carbon storage and benefits outside system boundaries in EN

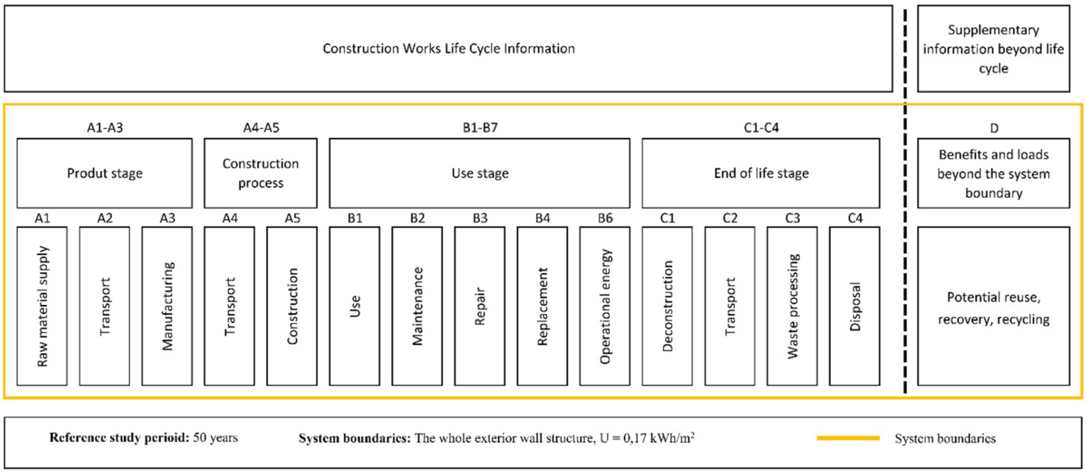


Figure 1. System boundaries of the study and life cycle phases in the building's LCA according to EN 15804.

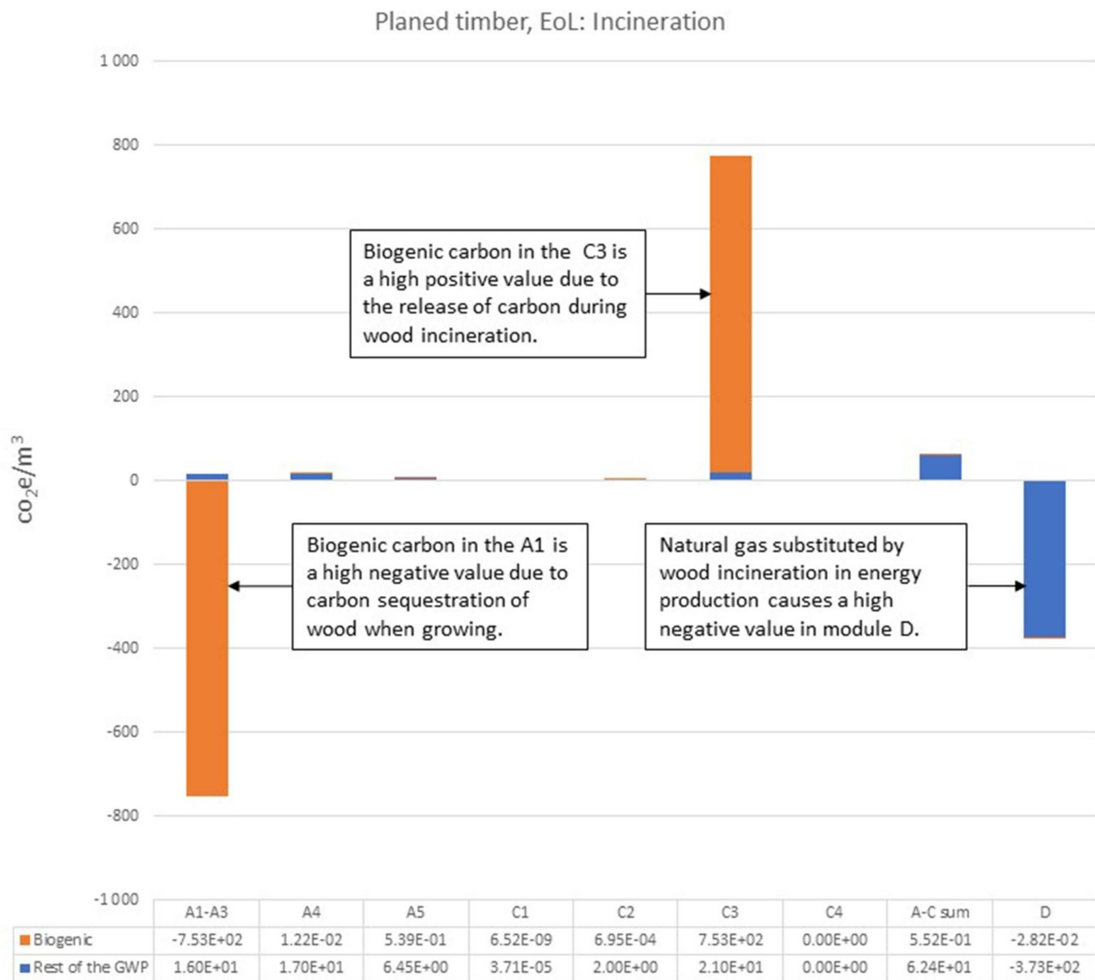


Figure 2. The logic of biogenic carbon and module D in EN 15804 is explained by illustrating data from EPD of planed timber by Stora Enso with incineration as an EoL scenario (EPD International 2020a). The negative value in A1–A3 illustrates the carbon sequestration of wood when growing, and the high positive value in C3 illustrates the release of carbon storage when incinerating the wood in the EoL phase. A–C sum sums up the impact of the product system under study.

15804 by illustrating the data from EPD of planed timber (EN 16485 2014, EN 15804 2019, EPD International 2020a).

2.3. The functional unit

The objective of making the results in different options comparable from the whole building's carbon footprint perspective guides the definition of the functional unit in the study. Insulation materials have different thermal transmittance properties that have an impact on the life cycle GWP of the whole building. It means that reliable comparison needs a functional unit that is based on thermal transmittance (Nasir *et al* 2017). Use of the U-value that considers the impact of conduction, convection, and radiation on thermal transmittance is recommendable if the data is available (Nasir *et al* 2017). The definition of identical thermal transmittance in all the structural options enables the comparison, as it allows leaving the energy use of the whole building, including speculations on the emission intensity of energy and heating system of the building, outside system boundaries. Therefore, this study uses the functional unit in all the compared structures as 1 m^2 of the wall structure with thermal transmittance $U = 0.17$ W ($m^{-2}K^{-1}$) calculated according to EN ISO 6946 (EN ISO 6946 2017). The U-value chosen is a benchmark value for exterior walls in Finnish regulations (FINLEX 2017c). Due to fixed thermal transmittance, the thickness of structures varies. The study considers the 50 mm additional thickness of WS3 compared to BAU2 as not decisive in real-life situations.

2.4. The data

The material quantities, including volumes and GHG emissions per functional unit, are presented in Supplementary Data File 1, which reports the data under the same abbreviations and topics as in this article. In addition to fossil GWP, the study reports total GWP, which includes fossil GWP, biogenic GWP and land use GWP. However, the land use GWP has systematically a non-significant role, which is why this study discusses biogenic GWP based on total GWP.

As the basis of the calculations, the data used in most of the materials is gathered from the EPDs. As multiple EPDs are typically available for the same products, this study used EPDs and data best suitable for the Nordic conditions. To find best suitable EPD, the study uses the baseline data provided by Finnish Environment Institute as a selection criterion (Rakentamisen päästötietokanta 2022). The database by Finnish Environment Institute provides average values of multiple EPDs with publicly available background reports for 200 typical construction materials. However, separate EPDs are needed in this study because the Finnish Environment Institute only provides data for modules A1–A3. The list of used EPDs is provided in supplementary data file 2.

2.5. Homogenizing data in the cases of WS and WS + C

From the data perspective, WS and WS + C differ from the other materials in the structures because their EPDs do not exist. The study homogenizes the data by analyzing GWP in these two materials more closely through process-based analysis and by combining data from EPDs and other applicable sources. This section provides a wrap inventory of the life cycle impacts of WS and WS + C. Table 2 summarises the GWP data of WS1 and WS2 at different life cycle stages in the base case scenario.

2.5.1. Production (modules A1–A3)

Sawing mills produce WS in the very last phase of the process of scaling sawn timber to exact measurements. The study assumes that there is no additional processing of WS after the co-product comes from sawmill and the product is ready for installation as such. As WS is a side stream of the sawmill industry, LCA must consider how to share the impact of the process among sawmill products and WS. The study recognizes two different approaches (cut-off and allocation) that EN 15804 allows using in the case of WS (EN 15804 2019). Different allocation methods change incentives the use of the co-product (Ilic and Ödlund 2018). This study uses a cut-off approach when calculating the impact of WS but also performs a sensitivity analysis in section 3.1. to show the impact of the allocation method.

The cut-off approach uses the 'polluter pays' principle when defining the impact of material supply as zero, puts all the impact on the main product, and credits main product only of the avoided waste processing in its EoL phase (EN 15804 2019). According to EN 15804, biogenic carbon makes a difference as it is an inherent material property that always reflects the physical flows. Biogenic carbon appears in total GWP as a high negative value in module A1 and as a high positive value in module C3.

This paper also examines WS improved with clay (WS + C). The production process for producing WS + C starts by mixing WS with clay powder, and after that, by adding water to enable clay to stick into WS. The percentages of components were WS (storage dry) 50%, clay 25% and water 25% of weight. The

Table 2. GWP fossil and GWP total of WS and WS + C in base case scenarios. 'Cut-off' refers to the case where the study applies the cut-off approach when calculating the product phase impact of WS. 'Inc' refers to incineration used as an EoL scenario. 'Grid mix' refers to the energy factor of average Finnish electricity in 2019 used in drying WS + C.

WS, Cut-off, Inc

	Life cycle phase								
Indicator	A1–A3	A4	A5	B	C1	C2	C3	C4	D
GWP Fossil	—	6.3×10^{-01}	1.0×10^{-02}	—	1.9×10^{-02}	6.3×10^{-01}	—	—	$-8.1 \times 10^{+01}$
GWP Total	$-1.6 \times 10^{+02}$	6.3×10^{-01}	1.0×10^{-02}	—	1.9×10^{-02}	6.3×10^{-01}	$1.6 \times 10^{+02}$	—	-8.1×10^{-01}

WS + C, Cut-off, Grid mix, Inc

	Life cycle phase								
Indicator	A1–A3	A4	A5	B	C1	C2	C3	C4	D
GWP Fossil	$1.0 \times 10^{+01}$	9.5×10^{-01}	1.0×10^{-02}	—	1.9×10^{-02}	9.5×10^{-01}	—	—	$-8.1 \times 10^{+01}$
GWP Total	$-1.5 \times 10^{+02}$	9.5×10^{-01}	1.0×10^{-02}	—	1.9×10^{-02}	9.5×10^{-01}	$1.6 \times 10^{+02}$	—	$-8.1 \times 10^{+01}$

data on emissions of clay powder is available in the EPD of clay plasters (EPD International 2020b). However, the water added must be removed from the mix by drying, which this study assumes will cause an 81.9 kWh m^{-3} energy consumption. The water content requiring removal is 50 kg m^{-3} to get water content from 70–80 kg m^{-3} at the start to 20–30 kg m^{-3} at the end. According to data on grain drying provided by Viita (2013), this study estimates the drying energy of WS + C to be 1.64 kWh kg^{-1}. In the baseline scenario, the study assumes that the drying energy has an emission intensity of 87 g CO_2eq/kWh, the energy factor of average Finnish electricity in 2019 (Tilastokeskus 2023). As the drying energy source may vary and have a significant impact on production phase emissions of WS + C, the study analyses the sensitivity of the issue in section 3.2.

2.5.2. Construction (modules A4–A5)

It was assumed that the product ready for installation was transported to the site with a fully loaded 40 ton truck. The assumed transportation distance is 50 km and back. According to the Finnish Environment Institute database, the emission intensity is 63 g CO_2e/ton km (Rakentamisen päästötietokanta 2022).

The insulation will be installed with a specific blowing machine that has a 3.55 kW output. The assumed installation speed is 30 m^3 h^{-1}. The assumed emission intensity of electricity is 87 g CO_2e/kWh.

2.5.3. Use (module B)

The study recognized no impact during the use of insulation materials.

2.5.4. EOL (Modules C1-C3)

In the phase C1, the material will be uninstalled with a wood chip vacuum that has a 2.2 kW output. The assumed working speed is 10 m^3 h^{-1} and the assumed emission intensity of electricity is 87 g CO_2e/kWh.

It was assumed that the uninstalled product will be transported to waste processing with a fully loaded 40-ton truck. The assumed transportation distance is 50 km and back without load. According to the Finnish Environment Institute database, the emission intensity is 63 g CO_2e/ton km (Rakentamisen päästötietokanta 2022).

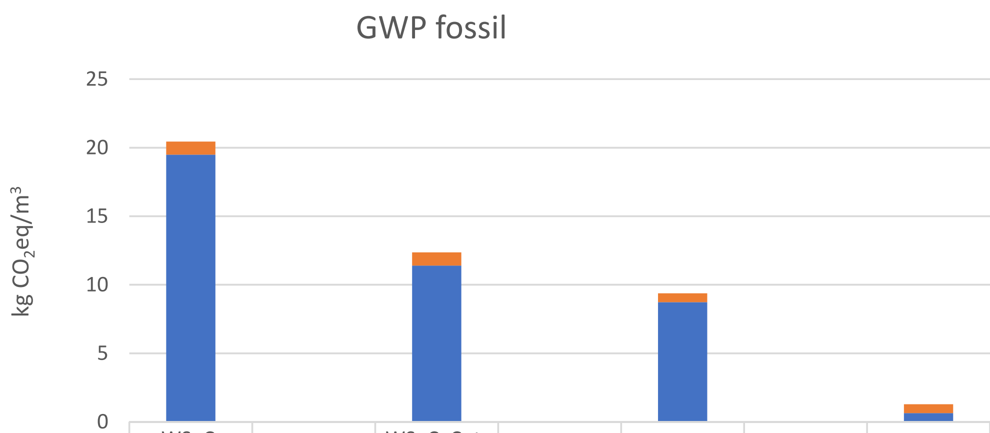
This study uses an incineration baseline scenario in the EoL treatment in phase C3. The study assumes that WS needs no additional processing when prepared for incineration. However, the incineration releases carbon storage of 163.70 kg CO_2e/m^3, which is visible as a high positive value in module C3 in the GWP total. Biogenic materials have multiple EoL treatment options with significantly varying impacts, which is why this study analyses the issue in section 3.3.

2.5.5. Benefits and loads beyond the system boundaries (module D)

The study assumes that incinerated WS substitutes natural gas in heat production.

3. The results

This section discusses two kinds of results. First, the section discusses how sensitive the whole life GWP of WS insulation is to the various allocation approaches used and EoL scenarios applied. Second, the section calculates the GWPs of the compared structures. When showing the result of structures, the study also



	WS+C, Mass	WS+C, Cut-off	WS, Mass	WS, Cut-off
Sum of modules C1-C4	1.0	1.0	0.6	0.6
Sum of modules A1-A5	19.5	11.4	8.7	0.6

Figure 3. Impact of the allocation approach to the fossil GWP of insulation made of WS and WS with clay. The drying energy of the WS with clay is the grid mix. The EoL scenario in all the options is incineration. 'Cut-off' refers to the case where the study applies the cut-off approach when calculating the product phase impact of WS, and 'Mass' refers to the case in which the study allocates the burden between WS and timber according to masses.

demonstrates the impact of modeling choices made in WS and WS + C to reveal if they have a significant role in the context.

3.1. The impact of allocation approach

As discussed in section 2.5, the EN standards enable two different ways to allocate the impact of sawmill product between the main product and co-product. Figure 3 illustrates the effect of the allocation approach on the results.

The first compared method is the cut-off approach, which this study employs in the base case. EN 15804 does not present the cut-off approach as an allocation method but as an option to streamline the calculation by leaving marginal data out of consideration. However, in the case of EoL recycling, researchers call cut-off a 100/0 allocation approach (Eberhardt *et al* 2019). The cut-off method simply allocates the whole impact of the product phase to the main product and none to WS. The only benefit allocated to the main product is the avoided waste processing from the utilization of WS.

EN 15804 allows using a cut-off approach when the process covers 1% of the total mass input of the main product. According to the Finnish sawmill industry, WS covers 1.8% of the material input, but the construction industry only uses a marginal share of the material as insulation (Sahateollisuus Ry 2020). Currently, clearly less than 1% of the material input of sawmill industry is used as WS insulation but it is possible that the sales of WS insulation will grow and the share of the utilized side stream will cross the 1% limit. In such case, the study would need to use an allocation method.

The second option for calculating the impact of the side stream is the allocation according to the allocation factors originating from an allocation rule. As the production of WS depends on the demand for timber products, the specific definition of the side stream is joint co-product (Weidema 2000). In this case, EN 15804 guides allocating the impact primarily using physical properties (e.g. mass, volume) as an allocation factor, then, secondarily, using economic values, and thirdly, using other inherent properties (EN 15804 2019). This study uses the allocation following underlying physical relationships, basically by using the ratio of masses as an allocation factor. In this case, the allocation based on other relations, such as economic value, seems an inappropriate approach due to the underdeveloped markets of WS insulation.

Due to its nature as a side stream of the sawmill industry, the product phase GWP is de facto a share of the sawmill industry's impact. Therefore, gathering data from applicable EPD would be a reliable and appropriate way of modeling the product phase GWP of WS when using the ratio of masses as an allocation factor. This study applied data from EPD of planed timber by Stora Enso when calculating product phase GHG emissions of WS (EPD International 2020a). According to data provided by the Finnish sawmill industry, the output of WS is 4.2% of the whole output of the industry (Sahateollisuus Ry 2020). Therefore, every cubic meter of planed timber with a density of 460 kg m^{-3} would provide 19.3 kg of WS with a density

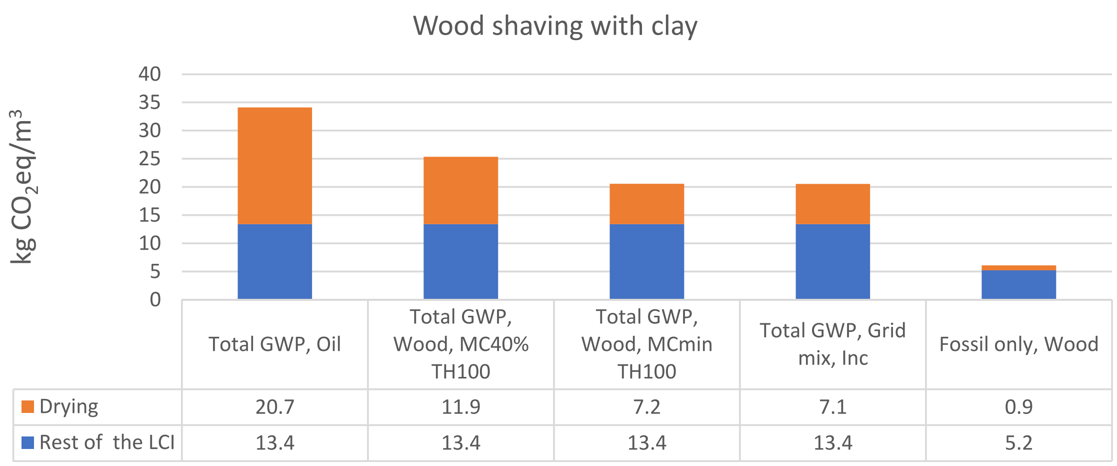


Figure 4. Impact of drying energy options to GWP of WS with clay. EoL scenario in all the cases is incineration. MC refers to the moisture content of wood chips in storage. TH100 refers to the TH used in assessing the biogenic carbon cycle in wood chip incineration. 'Rest of the LCI' refers to the life cycle GWP excluding the impact of drying energy.

of 100 kg m^{-3}. The study allocates 4% of the GWP of the process to WS. Based on the data above, this study defines fossil GWP in modules A1–A3 at 8.1 kg CO_2eq/m^3.

3.2. The role of drying energy in GWP of WS insulation with clay

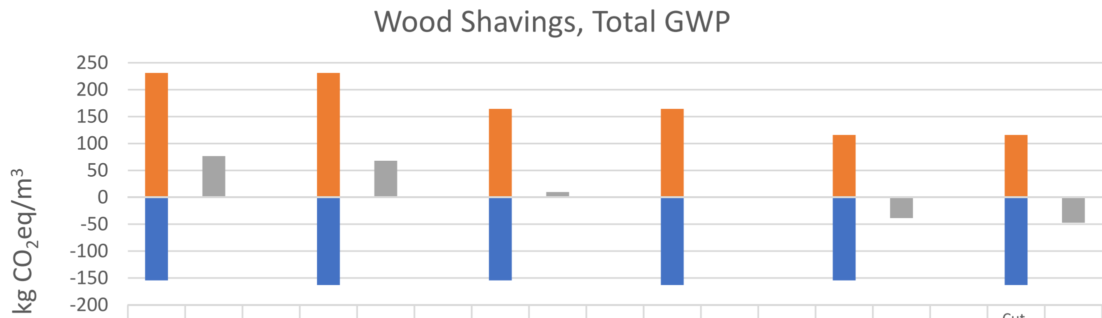
As discussed in section 2.5, changing the energy source used in the drying may cause a significant variance in the GWP of WS + C. The study compares five different energy sources to analyze the sensitivity. The first two compared energy factors are the average Finnish electricity in 2019, with 87 g CO_2eq/kWh emission intensity, and heating oil, with 252 g CO_2eq/kWh emission intensity (Tilastokeskus 2022, 2023). The rest of the energy factors are from wood chips when calculating fossil GWP only (11 g CO_2eq/kWh), total GWP of wood chips stored in 40% moisture content (146 g CO_2eq/kWh) and total GWP of wood chips stored in minimal moisture content (88 g CO_2eq/kWh). Figure 4 shows the impact of drying energy to the GWP of structure applying WS with clay. The study shows that the energy source used in the drying may cause a 19.8 kg CO_2eq/m^3 gap in the fossil GWP and a 13.6 kg CO_2eq/m^3 gap in the biogenic GWP of WS + C. In the structural comparison in section 3.4, this study uses the average Finnish electricity as an energy factor in the baseline scenario and the energy factor of oil in the worst-case scenario.

The data on wood chip energy is provided by Jäppinen *et al* (2014), who found the moisture content in storage the most significant uncertainty in GHG emissions from the energy use of forest biomass. It is because higher moisture content causes stronger methanation of stored wood chips. As there is no specific standard on the calculation of biogenic GWP of forest bioenergy, Jäppinen *et al* (2014) use a 100 year TH in calculating emission intensity of wood ships incineration. With the concept of TH, the assessment can compare the instant release of biogenic GWP in energy use to the natural decay of wood in the forest. The approach differs from EN 16485 on round and sawn timber EPDs that suggest assuming incinerating sawmill industry side streams climate neutral without considering the TH if the wood comes from countries applying Article 3.4 of the Kyoto protocol (Achenbach *et al* 2018).

3.3. End of life scenarios of WS insulations

As discussed in section 2.5, WS as a bio-based material could have a number of potential waste treatment scenarios with significant impacts, especially on its biogenic GWP and total GWP. For example, landfilling may lead to uncontrolled biodegradation of the material that causes methane emissions. Methane is a heavy GHG, having 29-fold GWP compared to carbon dioxide (Edwards *et al* 2016). On the other hand, some treatment methods may turn a part of the wood into permanent soil carbon storage. This study analyzes the sensitivity in GWP of WS to the three most potential EoL scenarios. The EoL scenarios under study are incineration, landfill, and composting. Figure 5 demonstrates the impact of EoL treatment options in the life cycle GWP of WS.

The scenarios are different mainly in phases C3–C4 which include the preparation and supply of the material to the final process. In the scenarios of incineration and landfill, the study applies the same EPD of the sawmill industry that the product phase of WS insulation applies (EPD International 2020a). According to Andersen *et al* (2012), the study assumes that composting in optimal conditions will cut the GWP in the



	Mass, Lf	Sum	Cut-off, Lf	Sum	Mass, Inc	Sum	Cut-off, Inc	Sum	Mass, Com	Sum	Cut-off, Com	Sum
Sum		76.5		68.0		9.8		1.3		- 38.7		- 47.2
Modules C1-C4	231.1		231.1		164.3		164.3		115.9		115.9	
Modules A1-A5	- 154.		- 163.		- 154.		- 163.		- 154.		- 163.	

Figure 5. Impact of EoL scenario and allocation approaches to total GWP. EoL scenarios: landfill (LF), incineration (Inc), composting (Com). Allocation approaches: cut-off allocates all the product phase impact to planed timber, and mass allocates the impact between WS and planed timber according to the ratio of output mass. In the table, A refers to product phase impacts, and C refers to EoL phase impacts. 'Sum' refers to the whole life cycle GWP of the material under study.

waste processing phase in half compared to landfilling. The analysis shows that the right EoL treatment option can turn a part of EoL wood into a permanent carbon stock, showing a negative life cycle carbon footprint.

3.4. Life cycle GWP of compared wall structures

The results of LCA are illustrated in figures 6 and 7 that illustrate the life cycle GWP of compared wall structures. Figure 6 compares fossil GWP and figure 7 total GWP. The numerical values on the contribution of different materials and life cycle phases to compared wall structures are available in supplementary data file 1.

The results show that exterior wall structures with WS insulation can provide a solution to the building industry with competitive GWP. All the compared options with wood frames provided radically lower GHG emissions compared to pre-cast concrete wall elements. In the base case, structures using WS without clay (WS1) provided the lowest GHG emissions as its fossil GWP is approximately 28% lower and total GWP 25% compared to BAU1 with wood frame and rock wool insulation. Due to its fire protection features, WS1 is applicable in the same building typology and commensurate with BAU1 only. In the base case, the fossil GWP of the structure with WS + C (WS2) is approximately 20% lower and total GWP 17% lower compared to BAU1. The structure WS3 with cross-laminated timber and WS + C provided clearly higher GHG emissions compared to BAU1, but still radically lower GHG emissions compared to BAU2.

Options in allocation approach, EoL scenario and drying energy provide significant fluctuation in the results. Allocation according to masses in WS can increase the fossil GWP and total GWP approximately by 13% in WS1, 10% in WS2 and 4% in WS3. The results in the total GWP are highly sensitive to EoL options as it would increase landfill scenario 93% in WS1, 72% in WS2 and 30% in WS3 compared to incineration. The gap between scenarios with WS composted or with WS landfilled is nearly two-fold compared to the impact of the rest of the materials in the structure. Despite the variation, all the options with wood structures have a clearly lower GWP compared to BAU2 where a great share of the impact originates from concrete. When the assessment uses composting as an EoL scenario, the results show WS1 having 75% lower and WS2 having 54% lower total GWP than BAU1.

A closer look at the background data (supplementary data file 1) shows that the role of the insulation is limited in any of the studied structures. The main bulk of insulation represents 33% of the GWP of BAU1. For example, the total GHG emissions of WS1 could be notably lower when using some other windproof sheet than porous fiberboard with bitumen that has a relatively high GWP in the EoL phase. Although WS insulation provides no game-changing climate benefits, the material might contain other advantages that argue for its use.

4. Discussion

This study and the methodological framework of LCA contain uncertainties in the GWP of WS and WS + C. Minor uncertainties are related to material quantities in wall structures and associated structures. One of these is the varying thickness of the wall structure caused by the functional unit and influencing the main

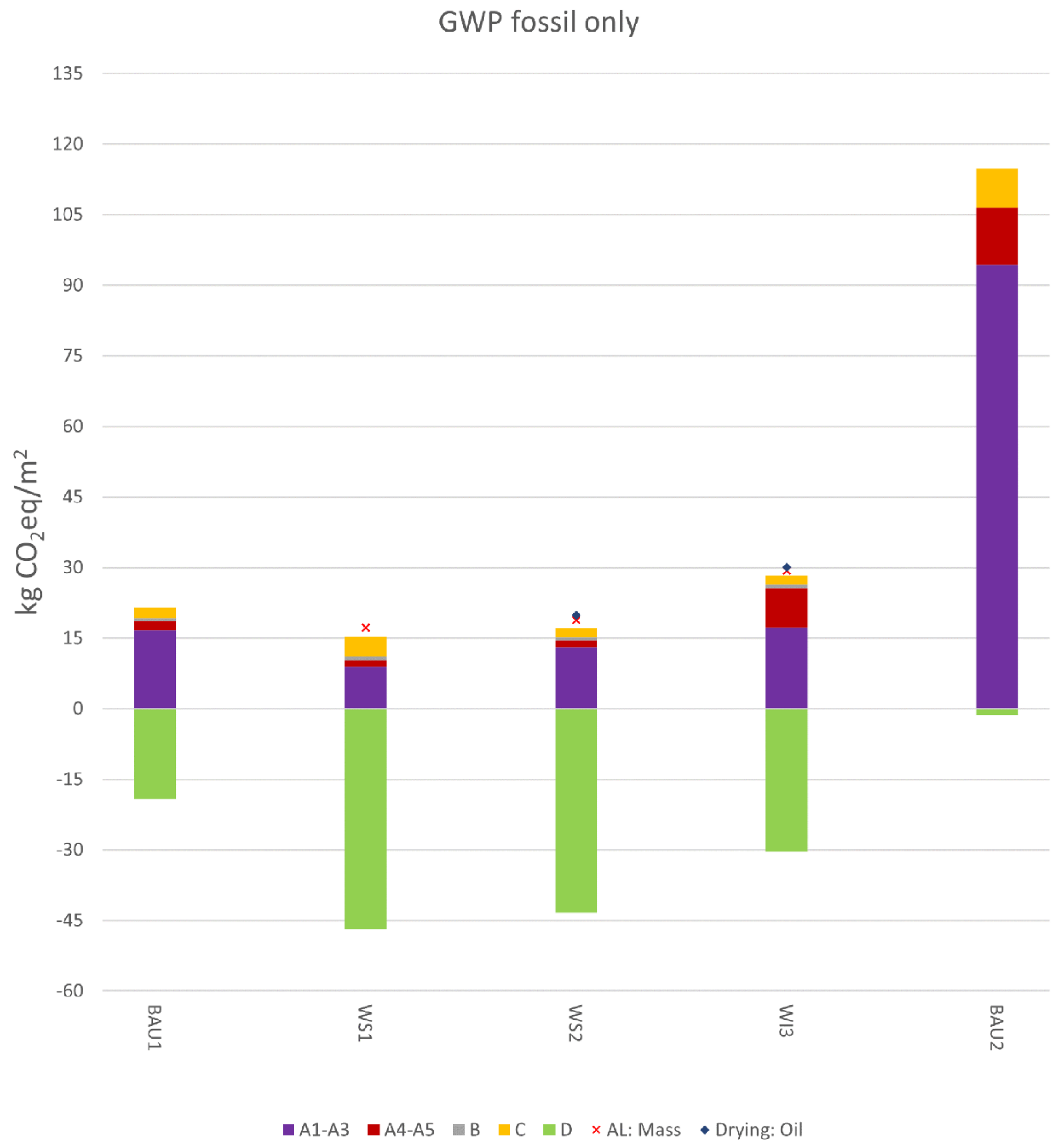


Figure 6. Fossil GWP of studied wall structures. In the base case, the allocation method in WS is cut-off, and the drying energy source in WS + C is wood chips. Thick marks show the sum of GWP when using the alternative allocation method in WS (AL: mass = impact allocated between main product and WS according to masses) and the sum of GWP when using the worst scenario in drying energy of WS + C (Drying: oil = heating oil as an energy source in drying).

dimensions of the foundations. Another marginal uncertainty is the quantity of bottom and top studs per functional unit, depending on structure height. While the issues on material quantities have a marginal role, the uncertainties of methodological issues are significant.

The most extensive methodological uncertainty may be tracked down to the biogenic GWP of EoL options, which causes the GWP to vary WS between −39.1 kg CO_2eq/m^3 of the composting scenario and 76.1 kg CO_2eq/m^3 of the landfill scenario (see figure 5). The result on EoL options aligns with the study by Petersen and Solberg (2002) that shows higher GHG emissions in the wood structures with landfill scenario compared to steel structures. The results indicate that, when using bio-based materials, it is highly recommendable to ensure the availability of correct EoL treatment options. One concrete measure to take in the product phase is to follow the cradle-to-cradle approach, which guides analyzing the EoL phase so that the product design does not harm sustainable treatment, for example, by mixing materials (Braungart and McDonough 2002). Mixing clay and WS might disable the incineration of the material, thus causing it to end up in landfills.

In the regulatory context of LCA, selecting the EoL scenario cannot be left to the user, as results are sensitive to the selected EoL option, and the realization as planned is highly uncertain. The realization as planned is uncertain because, after a 50 year service life, the builder and the material producer will most

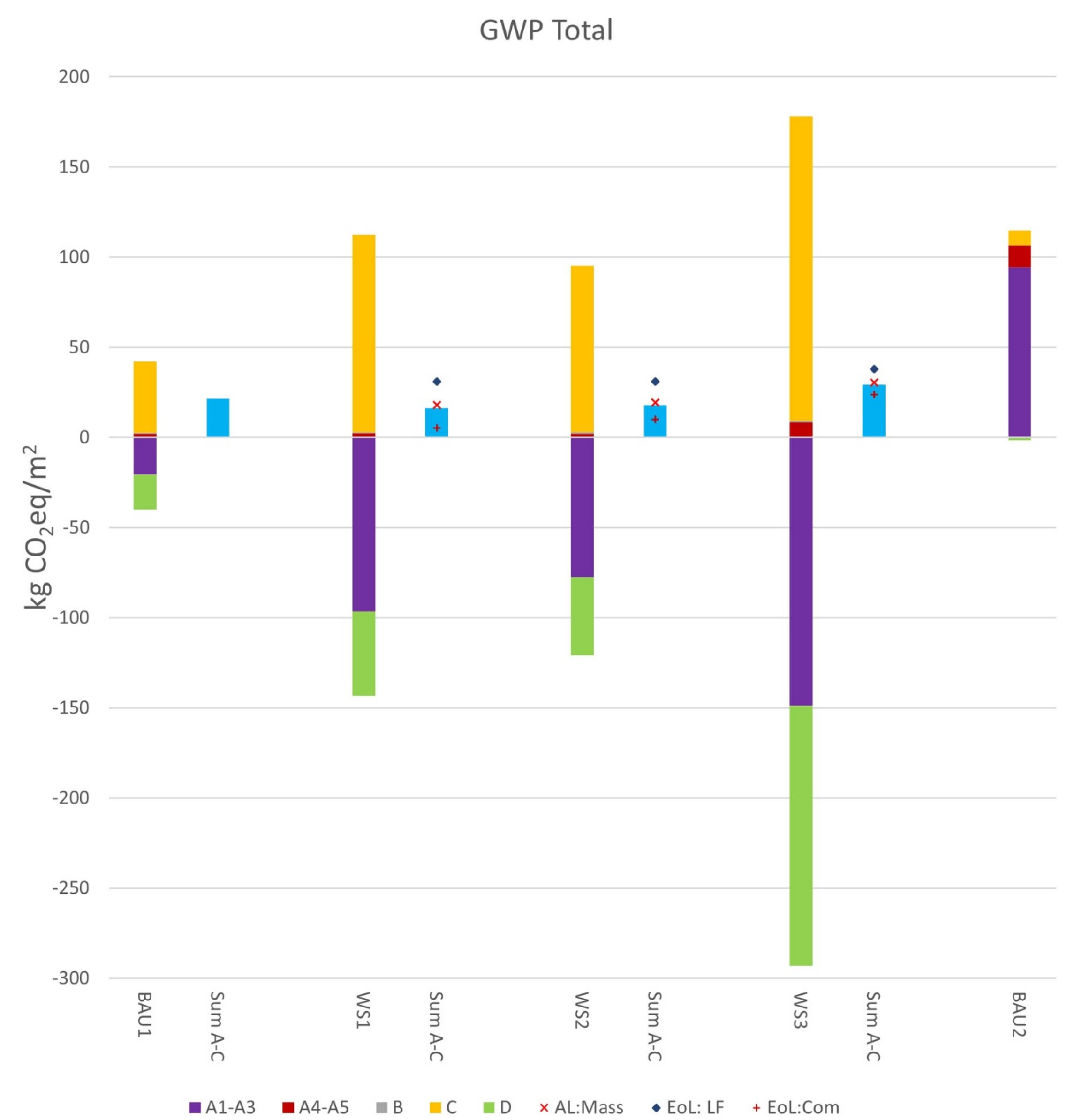


Figure 7. Total GWP of studied wall structures. In the base case, the allocation method in WS is cut-off, and the drying energy source in WS + C is grid mix. Thick marks show the sum of GWP when using the alternative allocation method in WS (AL: mass = impact allocated according to masses) and the sum of GWP when using the alternative EoL scenarios in WS (EoL: LF = landfilling as an EoL scenario, EoL: Com = composting).

likely not be present to guarantee an EoL treatment option. A consistent way to assess EoL options would be calculating the national average mix, which is a typical practice in whole building LCA when calculating operational energy. The average EoL mix could create collective pressure on the waste treatment sector and promote the most sustainable treatment options in the long term.

The EoL treatment is not the only uncertainty in assessing the GWP of wooden products (Häkkinen and Haapio 2013). One major issue is the carbon dynamics of biogenic carbon in forest use. According to (Jäppinen *et al* 2014), forest biomass would be a source of GHG emissions after 100 years of single-event combustion. With the same logic, a wood structure that gets demolished and incinerated after a 50 year service life would be a source of GHG emissions over the next 50 years. Therefore, it is debatable whether EN 16485 follows the 'polluter pays' principle in the production phase, as it advises reporting wood material input as negative value, without considering TH and comparison to natural decay if Article 3.4 of the Kyoto protocol applies to the origin (EN 16485 2014). The negative value in the material input offsets the emissions not only from EoL incinerations but also from the incineration of the sawmill side streams (Achenbach *et al* 2018). Thus, despite timber products being the root cause of waste generation, the standard does not consider emissions from sawmill waste as its burden. As 40% of the material gets wasted and incinerated in the sawmill and harvesting process, EN 16485 might give a significant unjustified advantage to sawmill products. The results indicate that the current methods that ignore the whole dynamics of biogenic carbon could be far from physical reality, which leads to underestimating the GWP of wood-based materials. Also, the method by the Ministry of the Environment only calculates the positive effects of biogenic material use in a separate category of carbon handprint (Ministry of the Environment of Finland 2019). The approach ignores the biogenic emissions from the product system under study, thus failing to steer sustainable waste management in bio-based construction materials. However, including biogenic GWP in the LCA applied in the normative context would require that there is a solution to manage the uncertainties.

The allocation method is an issue that has been debated in the field of LCA for nearly three decades, mainly between consequential and attributional schools (Moretti *et al* 2020). The consequential approach interprets co-product as a material that would otherwise go to waste but substitutes some other products when utilized. It credits the product system for the avoided burden that utilization of the side stream enables. The methodological challenges in the consequential approach is the difficulty to sometimes define which product to substitute (Heijungs and Guinée 2007). Another methodological issue is the risk of violating mass balance by mixing attributional and consequential approaches (Weidema 2013). Still, Plevin *et al* (2014) claim that the consequential approach is needed because the attributional would mislead policymakers. The debate might have had an impact on the originally attributional EN 15804, as it allows reporting the benefits outside the system boundaries, in the separate module D. The data reported in module D is not commensurable and has no impact to the product system under study which seems to provide methodologically feasible consensus in the case of upstream recycling. Still, it is questionable whether module D can provide the intended steering effects and whether it is applicable in the building regulations.

This study shows that the critique on the attributional method for its weakness in showing benefits in side stream utilization despite being logically beneficial is justified. Compared to the cut-off method, the results of this study show 12% higher fossil GWP in WS1 when applying allocation according to masses. As discussed in section 3.1, EN 15804 allows using the cut-off method when a certain co-product utilizes less than 1% of the side stream. The cut-off method might provide another compromise in achieving steering effects of upstream recycling: the method would give favorable results, especially in the product launch phase when the markets are underdeveloped. The assessment would apply the allocation factor to define the product phase impact of WS insulations later when its share increases.

5. Conclusion

The study on the whole-life GWP of WS insulations provided two types of findings. First, the study compares structures using the material to typical wall structures used by the construction industry in Finland. Second, the study provides knowledge on the impact and sensitivity of modeling choices made when assessing the GWP of the material. The study discusses methodological issues from the perspective of applicability of the buildings' LCA in the normative context, where avoiding loopholes needs the highest possible consistency.

The study shows that compared to a wall structure with a wood frame and rock wool insulation (BAU1), an exterior wall with wood structures and WS insulation (WS1) can have 28% lower GWP total if the base case scenario with cut-off as a co-product allocation option and incineration as an EoL scenario applies. The structure with cross-laminated timber and WS-clay mix insulation (WS3) have higher GWP compared to BAU1, but significantly lower GWP compared to prefabricated concrete wall elements (BAU2). The study shows that the insulation material may not play a decisive role in the GWP of a wall, while timber frame wall offers clear climate change mitigation potential compared to a concrete structure. Therefore, the study can recommend using wood-structure exterior walls instead of concrete-structure exterior walls, regardless of the insulation materials used.

The study finds results on WS sensitive to allocation choices, energy source used in drying of WSs with clay and EoL treatment options. While the uncertainties related to allocation choices and energy source play a minor role on the structure level, EoL treatment option can radically change the results in total GWP. It is because there is a 115 kg CO_2eq/m^3 gap between landfill, inflicting uncontrolled methanation, and composting that produces soil carbon storage. As the results depend on modeling choices, the study cannot give a strict positive answer to the research question of whether the buildings' LCA can reliably show the climate change mitigation potential of WS insulations.

The study shows a call for future research to develop buildings' LCA in a twofold way. Firstly, future research should further explore improvements in the allocation rules to support the circular economy perspective by systematically promoting the utilization of side streams that would otherwise end up in incineration. More importantly, there is a call for developing the buildings' LCA for the normative context to better reflect the biogenic carbon cycle without adding uncertainty caused by users' choices. Focusing only on fossil GWP values, as the method used in Finnish legislation does, cannot capture all the risks and opportunities of wood-based building materials.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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