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# Carbon Assessment of a Wooden Single-Family Building—Focusing on Re-Used Building Products

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**Abstract:** Previous research has shown a lack of studies with comparisons between primary (virgin) and secondary (re-used) building materials, and their embodied emissions. The creation of different scenarios comparing the environmental impact of virgin vs. re-used materials is also motivated by the scarcity of raw materials in the world and the emergency of mitigating greenhouse gas (GHG) emissions from buildings. The aim of this study was to investigate scenarios, including new vs. re-used building products, applying the LCA method for a wooden single-family building. The findings showed a 23% reduction potential for total released (positive) $CO_2$e when comparing the Reference scenario with Scenario I, using re-used wooden-based materials. Further, Scenario II, using all re-used building materials except for installations, showed a 59% $CO_2$e reduction potential compared to the Reference scenario. Finally, Scenario III, which assumes all re-used building products, showed a 92% decreased global warming potential (GWP) impact compared to the Reference scenario. However, when including biogenic carbon and benefits (A5 and D module), the Reference scenario, based on newly produced wooden building materials, has the largest negative GHG emissions. It can be concluded that the re-use of building products leads to significant carbon savings compared to using new building products.

**Keywords:** biogenic carbon; circularity; end-of-life (EOL); life cycle assessment (LCA); global warming potential (GWP); environmental impact; wood; single-family building

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## 1. Introduction

Buildings are responsible for climate impact, globally accounting for 39% of $CO_2$ emissions [1]. Operational energy accounts for 28%, while the remaining 11% are emissions created during the production of building materials [1]. In addition, construction projects are responsible for 1/3 of the total generated waste in the EU [2]. Thus, it has been identified that a significant number of environmental impacts are also created during the end-of-life (EOL) stages [2].

The EU has promoted different programs and initiatives [3] to encourage stakeholders to shift from a linear to a circular economy (CE), recognising the construction sector as the largest producer of waste and one of the main resource consumers [3]. The European Commission and the EU countries advocate circular strategies and their implementation by 2050 [4]. Moreover, due to the current trend of increased costs of construction materials according to Eurostat data from (2005–2022) [5], the building industry is being pushed to provide efficient resource materials, for instance through re-using and recycling processes [2,6,7]. Additionally, the adoption of circular strategies in the EU building industry would possibly save around €350 billion by 2030 through efficient resource usage and energy savings [2]. However, there is also a great need for authorities to introduce the

concept of re-use and enable different actors in the building industry to favour second-hand products over virgin materials to reduce the environmental footprint.

### 1.1. Greenhouse Gas Emissions from Building Materials

Life cycle assessment (LCA) is recognised as a method that assesses the environmental impacts of buildings, which is useful in evaluating different building designs. Recent LCA studies have shown that building materials have an important role in the buildings' life cycle. As a result, the EOL phase of buildings has a significant role in the building industry since only 20–30% of construction and demolition waste is re-used or recycled [8,9]. Further, in previous studies, a lack of environmental impact results for the EOL stage of buildings has been noted [9].

The LCA of building materials is a potential tool for this issue, which can be defined within different system boundaries [10]. First, 'Cradle to Gate' includes the impacts of the production process of building materials. Second, 'Cradle to Grave' includes the impacts from the production process, transportation of products, operational phase, and disposal stage). Finally, 'Cradle to Cradle' incorporates all impacts from the production process until the end-of-life, including the emissions beyond the system boundary presented in the D module.

In a study by Zimmermann et al. [1], including more than 650 analysed buildings [11], the materials were responsible for half of the buildings' $CO_2$ emissions, while in some cases this was even higher than 90% [1,11]. Further, in a case study of Danish buildings, materials accounted for around 75% of $CO_2$ emissions [1,12]. Therefore, there is a need to study the materials' environmental impact in more detail and especially to study how the materials' environmental impact can be reduced.

### 1.2. Circularity in Building Construction

One way of reducing the environmental impact of buildings is to work with circularity. Circularity in building construction is an area attracting more scientific interest. In the study by Eberhardt et al. [13], different building components were displayed, and their percentages of possible recycling and energy recovery were assumed. This way of presenting results can show the link between the production process and the EOL stage of materials to the building industry, develop suitable circular strategies, and provide valuable design decisions. In the study by Minunno et al. [14], the authors compared the environmental benefits of re-using and recycling building components and found that re-used components saved GHG emissions by up to 88% compared to the recycling process. Further, the recycling of steel, concrete, and plasterboard is based on long-term practices [14] and is regulated by policies in several countries [15]. However, the re-use practices have even higher benefits toward a CE. It is worth mentioning that the components that are designed for disassembly can be re-used; up to 95% of re-usable products can be restored [16] and put back on the market at the end of their previous service life [14]. The study by Eberhardt et al. [6] identified an office building with the purpose of re-use and investigates how a CE can be adopted in buildings. Their findings have shown that recycling and energy recovery are recognised as the most common circular practices, whereas they believe that the re-use process has much higher economic and environmental benefits. Further, they discovered that the re-use of concrete structures can avoid high embodied greenhouse gas (GHG) emissions and provide economic benefits. Moreover, they found decreased emissions when substituting concrete for alternative materials, such as wood, steel, and glass [6]. According to the Nordic study, the re-use of construction products can reduce resource consumption in the Nordic countries by 20% resulting in climate savings of around 900,000 tons $CO_2$e [17,18].

### 1.3. EOL Carbon Emissions, Waste Treatments, and D Module External Benefits

According to EN 15804 [10,19], the LCA of the EOL stage involves four sub-stages. The C1 life cycle module involves deconstruction and demolition of building products; the

C2 module involves transportation of discarded building products to the waste processing or to the final disposal; the C3 module includes waste processing (collection of materials intended for re-use, recycling, or energy recovery processes), and the C4 module includes waste disposal emissions.

In the study by Quéheille et al. [20], it was said that not every waste treatment is suitable for every type of waste and that this depends on the regulations of the target country. In the study [21], it was reported that re-used materials had lower environmental impacts than primary (virgin) materials; thus, there is potential for reduced embodied GHG emissions. Findings indicate that re-use is a profitable solution compared to linear production processes that provides significant reductions of embodied GHG emissions [21]. Due to the energy-intensive manufacturing process of concrete, the recycling process in the case of crushed concrete will provide positive climate benefits [22]. Minunno et al. [14] also claimed that recycling steel, concrete, and plasterboard is a beneficial method for mitigating environmental impacts.

However, the D life cycle module accounts for the next production process of a building product, including re-using and recycling processes. The second life of re-used/recycled products can be prolonged to many cycles, depending on the product quality. Beyond the system boundary, negative embodied carbon emissions (external benefits) are reported in the D module for re-usable and recyclable building products. Therefore, it is important to focus on the remaining materials' adaptability after demolishing the building for "new" use. Thus, the range of different building materials can be classified and inspected and can be considered under a decision-making process to determine the purpose of re-using/recycling them. However, using re-usable building materials instead of newly produced materials in the A1–A3 phase of LCA can lead to significant climate benefits that can be expressed as negative GHG emissions in the D module.

### *1.4. Building Materials End-of-Life Properties*

Concrete elements are hard to disaggregate for re-use without causing damage; instead, they are often crushed into small parts for road filling, while reinforced steel can be recycled into new steel products [13]. Due to its high mass potential, concrete has a large share of the total waste amount from a building and even though the recycling potential is 50%, there is still a huge contribution made to climate impact [9]. Windows can be treated in a similar way; they can be disassembled and collected for recycling, while window frames can be re-used in their original form with only the glass replaced [13]. Additionally, roof felt can be recycled and used as a second-hand material for other purposes, for example, as an additional component for asphalt roads [13]. The lifespan of timber can be prolonged by designing cross-laminated secondary timber that can be used for deconstruction and re-use [23]; hence, it could replace conventional cross-laminated timber (CLT) [24]. It has been identified that mass timber products have the dual benefits of decreasing embodied GHG impacts during their production and locking up carbon emissions during their use until the EOL [23]. Most strategies rely on cradle-to-gate or cradle-to-site approaches; it is, however, misleading to include only the embodied carbon of mass timber without considering the full life cycle emissions [23]. After the building is demolished, the EOL of its components can be recycled or landfilled [14]. For instance, steel, concrete, plasterboards, doors, and windows can be successfully recycled. The most beneficial practice is recycling steel, concrete, plasterboard elements, doors, and windows [14]. According to Honic et al. [9], the recycling potential of exterior walls is 52%, while the foundation accounts for around 20% of the recycling potential.

### *1.5. Aim of this Study and Research Questions*

Previous research on evaluating the embodied GHG emissions of the built environment indicates that circular solutions, using the life cycle assessment method, need to be studied more in detail. There is a great necessity to provide more knowledge within the field of carbon assessment of secondary (re-used) materials and other environmental impacts.

There is a lack of data from previous research on GHG emissions obtained from re-used building materials and their savings potential compared to emissions from new materials. Additionally, the circularity of buildings with the re-use of different materials is indeed a significant field that should be investigated. However, to decrease upfront embodied GHG emissions for new buildings, it is valuable for the building industry to consider re-used over new products in the future and also spontaneously shifting from linear to circular paths. Following this, the aim of this paper is to introduce and compare three different scenarios, including various degrees of re-used building materials and installations with the Reference scenario using only virgin materials, and to show the potential of climate impact reduction. According to the aim, two research questions have been developed:

- How does the use of re-usable products, as opposed to new ones, affect the released (positive) and negative embodied GHG emissions and other environmental impacts across various life cycle stages within different building components?
- How does the calculation of biogenic carbon and external benefits (A5 and D module) influence the negative embodied GHG impacts when analysing new vs. re-used building products?

## 2. Methodology and Case Study

### *2.1. System Boundaries and Data Sources*

The LCA method is used for carbon assessment through the global warming potential (GWP) indicator, which also includes other environmental impacts. The scope of this study involves the production phase (A1–A3), transportation phase (A4), EOL (C2–C4), A5 construction waste external benefits, and D module external benefits, using the software One Click LCA, version: 0.24.2 [25]. The inventory data can be seen in detail in our previous study [26]. The released (positive) embodied GHG emissions are presented within (A1–A3), A4 and EOL (C2–C4) life cycle modules, while the negative embodied GHG emissions are presented within A5 and D modules as environmental external benefits. Further, the biogenic carbon stored in the material is added in the calculation for new and re-used building materials as a negative value.

One Click LCA was used to calculate the released (positive) and negative GHG emissions. The production stage impacts (A1–A3) were given from the software data from the EPDs or, in some cases, from generic data emissions for building materials based on the Ecoinvent database. Further, the GHG emissions released from the (C2–C4) life cycle stage regarding building materials and installations were calculated for the EOL stage scenario. The external benefits beyond the system boundary were introduced in module D, where additional external benefits from the construction module (A5) were also reported. For the EOL stage, the default option from the software One Click LCA was chosen based on the market scenario method that considers the state of waste management regulations in the country, in this case, Sweden. The service life for building products is based on product-specific values from environmental product declarations (EPDs) that can vary by manufacturer. The results rely on the recent data on material manufacturing localisation targets, explaining that the emissions from electricity used in the production process are adjusted to present the power source electricity mix in the chosen location based on the energy grid. In this study, data were updated according to Boverket (the Swedish National Board of Housing, Building, and Planning) based on the Swedish electricity mix from the year 2021 [25]. The LCA system boundary presented in Table 1 includes the description of life cycle modules and classification of positive vs. negative GHG emissions using the GWP indicator.

**Table 1.** System boundary of this study.

| GWP Indicator | LCA | Description |
|---|---|---|
| Released (positive) GHG emissions | A | Material production stage (A1–A3). This stage covers impacts related to raw material extraction, transport, and manufacturing emissions. In the case of re-used materials, the emissions are calculated as zero.<br>Transportation to site (A4). This module covers impacts from the manufacturing processing location to the building site. |
| | C | End-of-life stage (C2–C4). This stage covers emissions from transportation for waste-to-waste processing (C2); emissions from different waste management practices (C3); and impacts of landfilling for waste streams (C4). * (C1) module was excluded. |
| Negative GHG emissions | A5 | External impact benefits from construction site based on material wastage that can be used for energy recovery |
| | D | External impact benefits from recycled/re-used materials with additional uses for energy recovery |

* (C1) module was excluded from the study as the program does not calculate impacts from the demolition of building products.

The EOL stage, especially waste treatment scenarios, was elaborated on in detail, while external benefits were added for further investigation of stored (negative) embodied GHG emissions within building products.

The calculation is based on emission factors specified for each specific waste treatment. Therefore, the materials' impacts considered for energy purposes (wooden-based products and plastics) are based on the emission factor from the Ecoinvent database for district heating in Borlänge (Dalarna region), near the location where the building is being constructed. Additionally, within the D module, the external benefits during the construction process are included in this study involving various construction wastes from the A5 module. In the A5 module, waste from the construction site can be used as energy for district heating, especially for wooden-based products. However, the method for calculating the GHG emissions from re-usable materials in this study is based on calculating it as having zero emissions during the production process.

Values of biogenic carbon emissions are provided in the EPDs within the database of One Click LCA software, and in cases where the values are not declared the software provides a close estimation. The calculation methods for the estimation of biogenic carbon is the one that is described by the software [25].

### *2.2. Case Study Building*

The case study building known as Dalarnas Villa, a wooden single-family house, was used in this paper for conducting a detailed analysis of GHG emissions of different building products from various EOL treatments, and of external benefits from the D and A5 modules.

The reference building shown in Figure 1 was used as a case study based on specific real data for building materials. The single-family building, including the house and garage, was built in Sweden in 2019 with a total gross floor area of 180 $m^2$. The main purpose of building a wooden-based house is to explore embodied GHG emissions from bio-based materials and show how different circular solutions will affect the results. The reference building consists of a wooden framework and wood panel facade with installed cellulose insulation in the roof and external walls, while wood fibre insulation was installed on the internal walls. Concrete was used only for the foundation. The roof was covered with steel, windows were triple glazed, and doors were a mixture of wood and glass for external use and only wooden-based doors were used indoors. Installations and energy systems used in the building include a solar PV system, ventilation system, and ground-source heat pump. The EPDs and generic data were found in the database within the One Click LCA software and used in further calculations of GHG emissions and other environmental impacts.

**Figure 1.** Reference building "Dalarnas Villa"—constructed in 2019.

### *2.3. Scenarios*

The carbon assessment was based on a Reference scenario, with the original inventory data, and then compared to different scenarios where the building products were partly and completely replaced by re-used materials. The description of the scenarios in the assessment is as follows:

- Reference scenario encompassed all newly produced building materials and installations used as original materials for the building. It consisted of new products (building materials and installations) where the main raw material was wood, while other parts of the building utilised metals, plastics, and concrete in the foundation only (Table A1);
- Scenario I encompassed re-used wooden-based materials (wooden framework, facade, wood fibre insulation, cellulose insulation, doors, and windows) instead of using new ones, while other building products, (roof, foundation, pipes, cables, installations, energy systems, etc.), remained unchanged (newly produced) (Table A2);
- Scenario II encompassed all re-used building materials except for installations and energy systems that remained unchanged (newly produced) (Table A3);
- Scenario III encompassed all re-used building materials and installations (Table A4).

## 3. Results

### *3.1. Released (Positive) and Negative Embodied GHG Impacts of Building Products*

Results for released (positive) embodied GHG carbon emissions showed that Scenario I, based on wooden-based materials as re-used solutions for the building, reduced climate impacts by 23% compared to the Reference scenario. Scenario II, which included all re-used building materials except for installations, reduced GHG impact by 59% compared to the Reference scenario. In the last case, Scenario III, which included all re-used materials and installations, emissions were decreased by 92% compared to the Reference scenario. However, when considering negative embodied GHG emissions, it can be observed that the Reference scenario was preferable compared to Scenarios I, II and III. This was mainly due to the biogenic carbon being considered only for Reference building scenario with the newly produced wooden products with the capacities to absorb carbon emissions, compared to other Scenarios I–III where wooden products were re-used and biogenic carbon was not allocated to this lifecycle. Moreover, it can be seen that all re-used building products for Scenario III resulted in total negative embodied GHG emissions, as the external benefits in D module surpassed the released (positive) embodied GHG emissions (Table 2). A clear picture of the total results for all building materials and installations across life cycle stages is shown in the Appendix A in Tables A1–A4.

**Table 2.** Comparable analysis: released and stored embodied GHG impacts of the Reference vs. Scenarios I, II, and III expressed in kg $CO_2e/m^2$ for GWP indicator.

| Life Cycle Modules | GWP (kg $CO_2e/m^2$) | | | |
|---|---|---|---|---|
| | **Reference** | **Scenario I** | **Scenario II** | **Scenario III** |
| A1–A3—production phase | 175.3 | 131.6 | 63.7 | 0.0 |
| A4—transportation to site | 3.3 | 3.3 | 3.3 | 3.3 |
| C2—waste transport | 3.3 | 3.3 | 3.3 | 3.3 |
| C3—waste process | 8.2 | 8.2 | 8.2 | 8.2 |
| C4—disposal | 0.1 | 0.1 | 0.1 | 0.1 |
| Total released (positive) GHG emissions | 190.3 | 146.6 | 78.7 | 15.0 |
| A5—construction external benefits | −1.9 | −1.0 | −0.1 | 0.0 |
| D—secondary material external benefits | −32.9 | −32.9 | −32.9 | −32.9 |
| * Biogenic carbon (A1–A3) | −100.7 | 0.0 | 0.0 | 0.0 |
| Total negative GHG emissions | −135.5 | −33.9 | −33.0 | −32.9 |
| Total positive + negative GHG emissions | 54.8 | 112.7 | 45.7 | −17.9 |

* Inserted biogenic carbon for (A1–A3)—uptake.

The largest released embodied GHG emissions during the production stage were within the Reference scenario as all products were produced from new (virgin) resources in contrast to other scenarios that incorporated re-used options, which resulted in lower impacts (Table 2). It can be highlighted that the transportation emissions (A4) overcame the production emissions (A1–A3) for the re-used products in Scenario III. The EOL stage remained the same for all scenarios as in this stage it was assumed that the new/re-used products will not be re-used again after their service lives. Therefore, they will have the same transport emissions, waste processing emissions, and disposal emissions. It can be noted that the major reduction potentials comparing the Reference scenario with all the Scenarios I–III was within the production process of re-usable products where the emissions were set at zero. Furthermore, it can be seen that there were lower external benefits presented as negative GHG during the construction stage A5 for Scenarios I, II, and III.

### *3.2. GHG Emissions across Different Building Parts*

Figures 2–5 present a classification breakdown for the Reference building and Scenarios I–III focusing on the released (positive) embodied GHG emissions across A1–A4 and C2–C4 life cycle modules. The Reference building showed the largest upfront embodied GHG emissions during the production process of building products, pointing out energy systems (solar PV panels) as the largest contributors to total outcome. Further, Scenario I presented similar findings to the Reference building, highlighting building energy systems and installations embodied GHG emissions as contributing the largest share among the building parts. Scenario II presented the largest embodied GHG emissions for the production process of energy systems, while the other building components had negligible emitted impacts during the transportation and the EOL process. Finally, the last Scenario III presented the largest emissions for the foundation structures of a building during the waste processing treatment compared to other building components, while the production process emissions were zero. In this study, variations were found in phase A when re-usable building products in contrast to newly produced products had zero emissions, while the transportation emissions, EOL emissions, and D module external benefits remained the same regardless of the change in the production process.

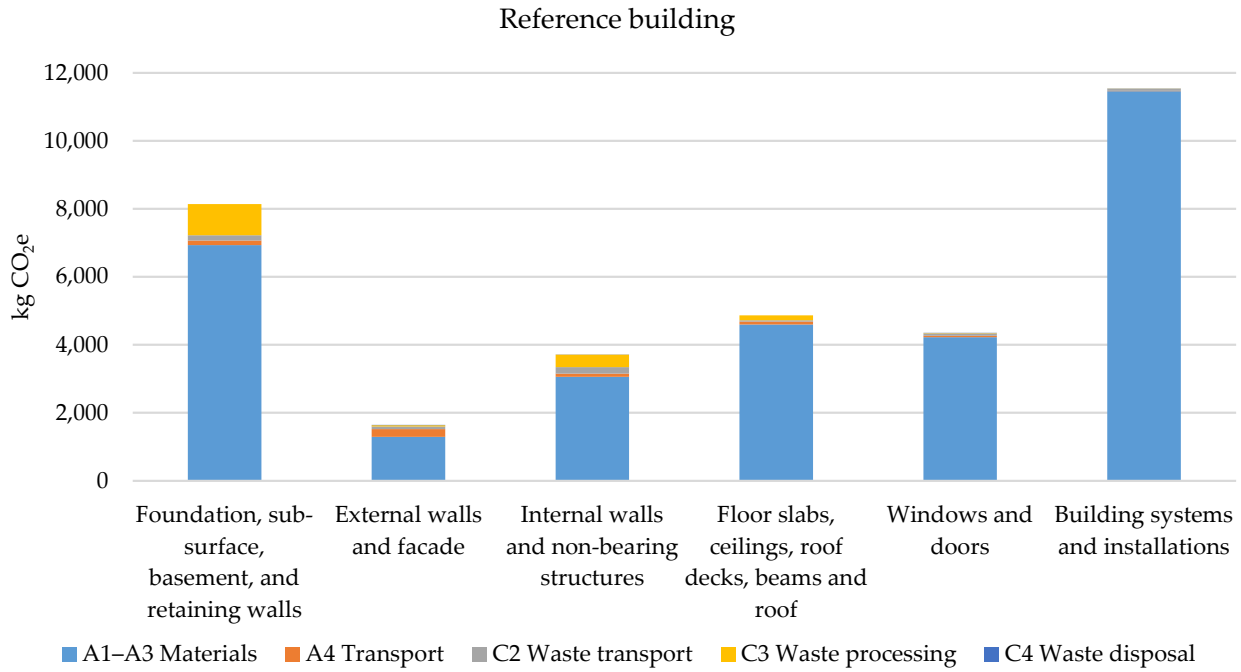


**Figure 2.** Classification breakdown for Reference building, including embodied released (positive) GHG emissions covering LCA scope (A1–A4 and C2–C4) for different building parts.

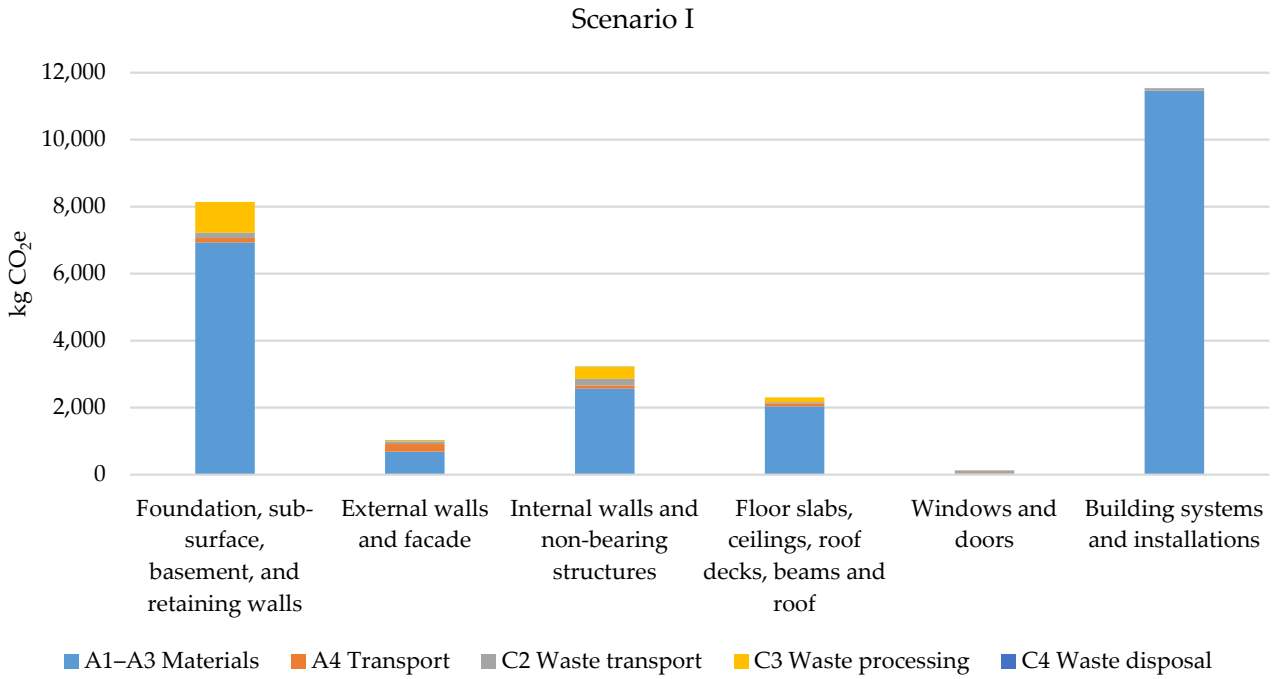


**Figure 3.** Classification breakdown for Scenario I, including embodied released (positive) GHG emissions covering LCA scope (A1–A4; and C2–C4) for different building parts.

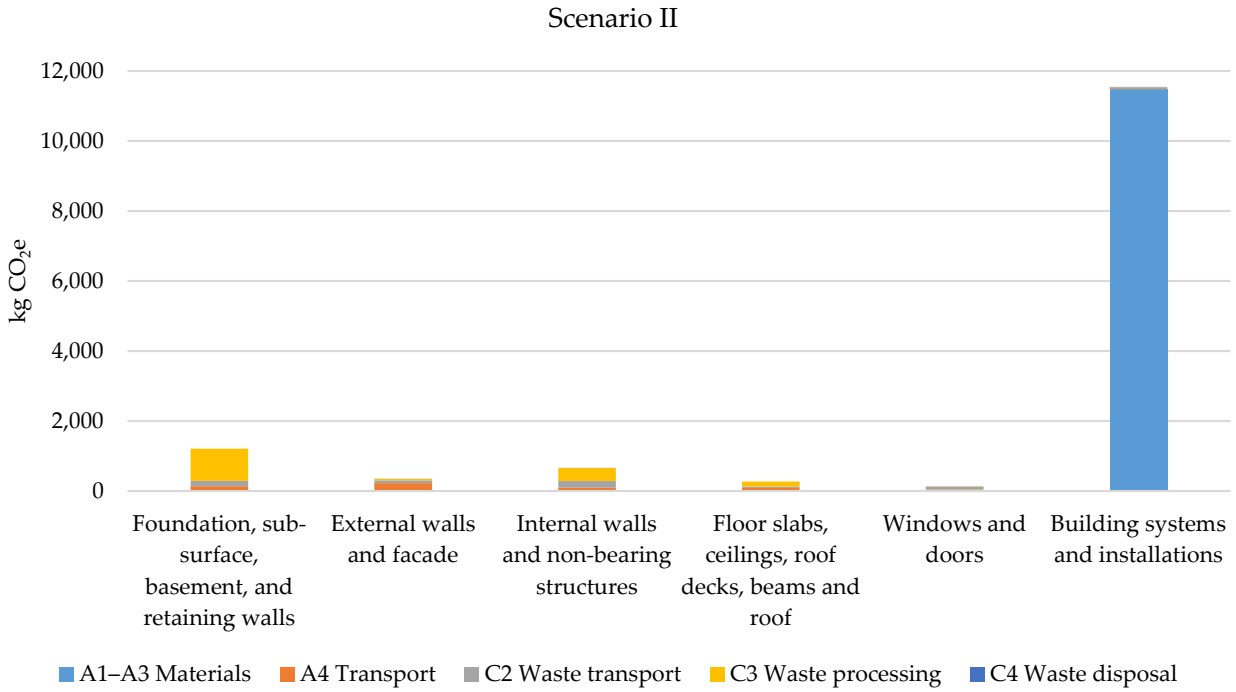


**Figure 4.** Classification breakdown for Scenario II, including embodied released (positive) GHG emissions covering LCA scope (A1–A4 and C2–C4) for different building parts.

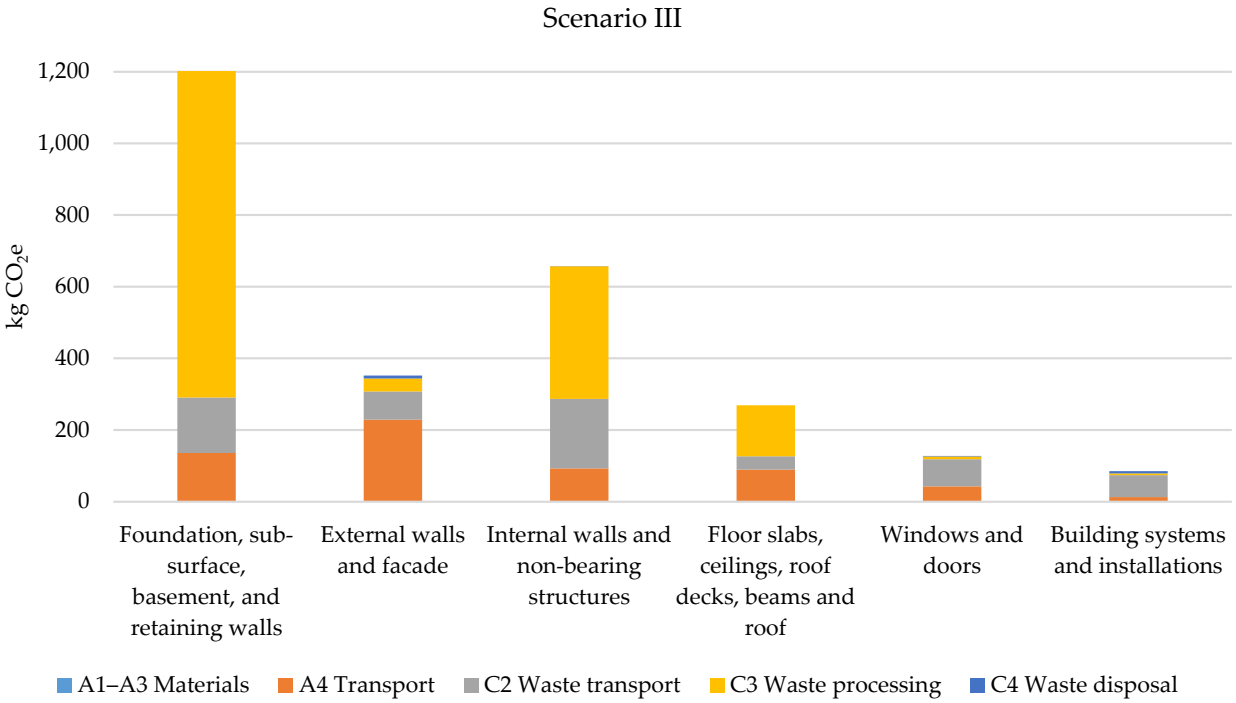


**Figure 5.** Classification breakdown for Scenario III, including embodied released (positive) GHG emissions covering LCA scope (A1–A4 and C2–C4) for different building parts.

### *3.3. Analysis of Other Impact Categories*

When analysing the emissions from the other impact categories presented in Figures 6 and 7, the same tendency as the GWP indicator was found when comparing between different scenarios and the Reference scenario for each category. However, the differences in the relative reduction of emissions between the Reference building and Scenario II were much larger for the formation of lower-atmosphere ozone than for GWP. Eutrophication, on the

other hand, had a lower relative reduction in the Reference building than in Scenario II. For this environmental impact category, the reduced negative emissions for the A5 construction external benefits were much larger than the negative emissions for the other environmental impact categories, where A5 had a minor impact. The environmental impact for the Reference building and Scenarios I, II, and III decreased in a linear way for acidification and primary energy, while for eutrophication the difference between Scenario II and III was much larger than the difference between Scenarios I and II. For ozone layer formation, it was between Scenarios I and II that the difference was the largest. In this impact category, almost all of the emissions came from phases A1–A3. The impacts from the other LCA phases that were included were minimal.

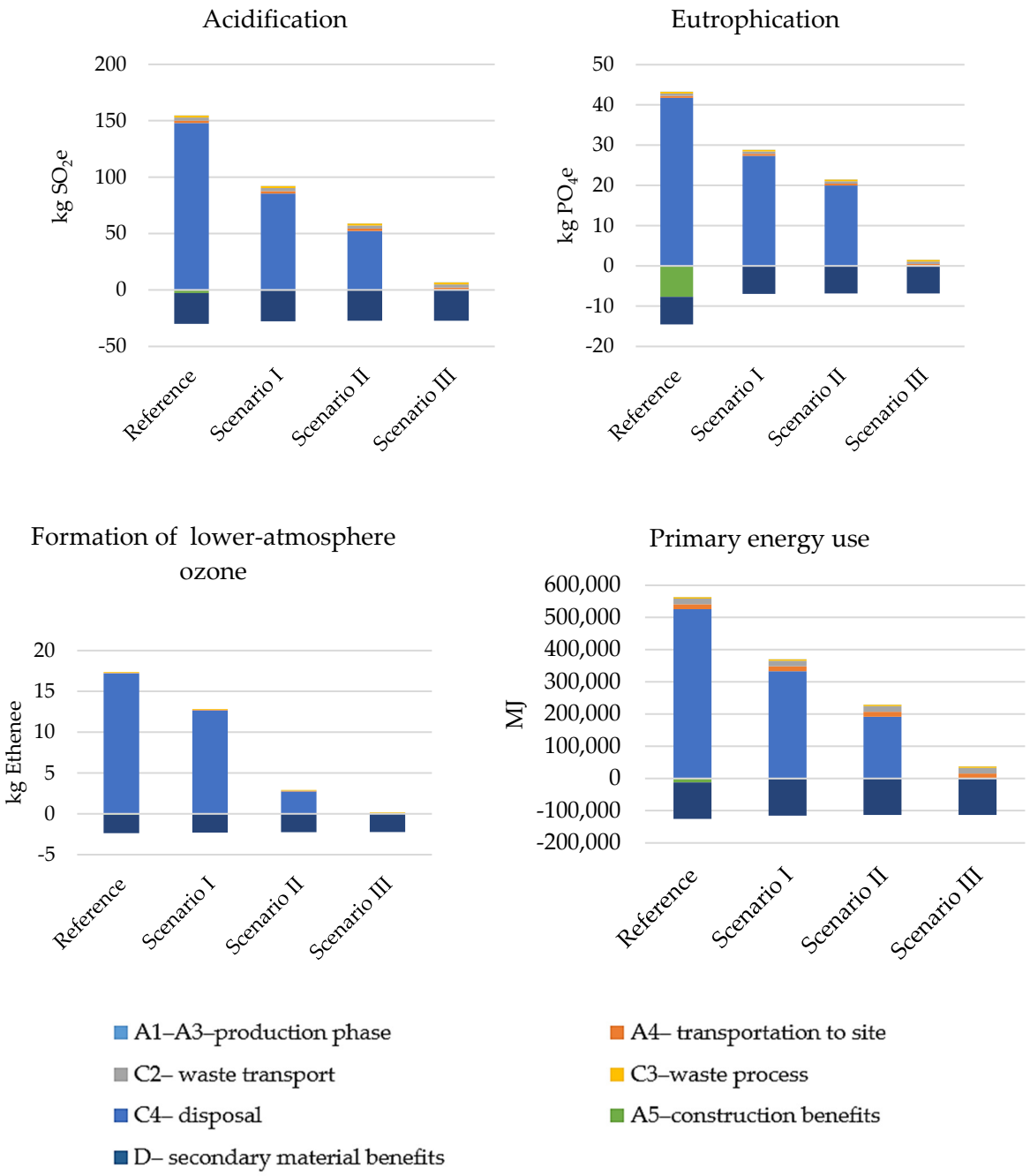


**Figure 6.** The results include different environmental indicators when comparing Scenarios I, II, and III with the Reference building.

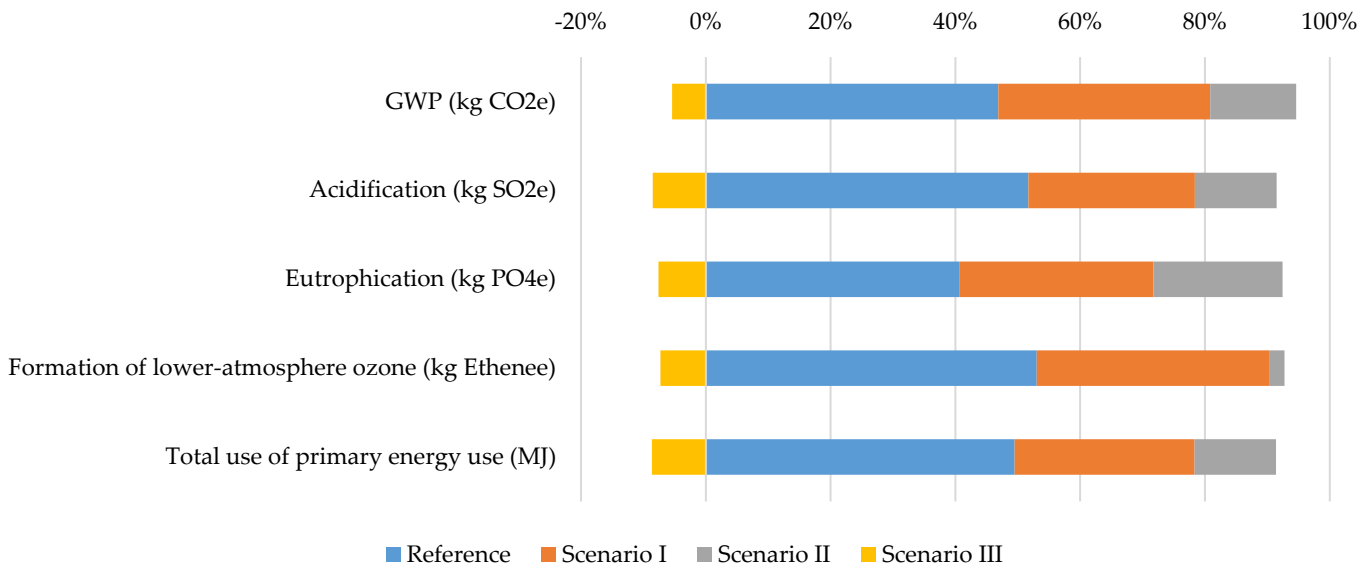


**Figure 7.** Total share of different impact categories.

The findings show that the largest share for the Reference scenario followed by Scenario I was due to the great use of newly produced materials for all environmental indicators. However, the last two scenarios, Scenarios II and III, presented low emissions across all environmental indicators due to the high number of re-used materials utilised instead of new ones.

## 4. Discussion

### *4.1. The Results in Relation to Previous Findings*

In line with our results, there are some previous studies that also revealed the environmental benefits of re-used products. There is a practical example of a study from the Nordic perspective regarding re-usable solutions that was conducted for an office building during its renovation [27]. In their case study, nearly 80% of re-used/recycled products were used in the building project. The achieved carbon reduction was 70% compared to their baseline new construction, while in our Scenario II where all materials except installations were re-used, the score was similar to their findings, at around 71%. Another case study was based on the business model of a Scandinavian company that provides circular solutions for windows, wood cladding, and concrete are made from re-used materials [21]. Their findings showed a large carbon saving potential for re-used windows, with around 77% lower emissions compared to the primary materials, while in our case the achieved carbon reduction was calculated as 100% because a whole product was assumed to be re-used as a secondary building material. Secondary-based concrete showed 4% lower carbon emissions compared to the reference product, while for our study the carbon reduction was 100%, assuming that the service life of concrete is prolonged and that it will be re-used if the building is renovated [21]. Material re-use does not always indicate significant emissions reductions of a product. It is important to investigate the way re-used materials are processed. For example, secondary-used concrete does not reduce embodied GHG emissions significantly compared to the primary product, mainly due to its heavy cement production that emits 91% of carbon emissions that cannot be decreased by using secondary aggregates [21]. If the concrete is re-used as it is and it is not used as secondary aggregates, the reduction of embodied GHG emissions will be larger; thus, there are various ways to re-use concrete, and this can influence the climate significantly. In the future, both steel and concrete, being the largest contributors to $CO_2$ emissions in the building industry, will have to become more environmentally positive. For example, cement as the main element in the production of concrete can be partly replaced by fly ash [26], while steel can become a

less energy-intense material due to a fossil-free production process run on electricity made from renewable energy sources.

The same outcome is observed when comparing the results in this study with the study from Quéheille et al. [20] that includes stages C (C1–C4) and D (external benefits), including the waste management practices in France; the waste processing emissions from C3 are the highest within the EOL stage, while the external benefits from the D module are large for half of the building products. In the previous findings, the embodied GHG emission impact greatly depends on which LCA stage is included in the assessment, resulting in an urgent need for covering all life-cycle-stage impacts. Linking between different life cycle stages can develop circular strategies referred to by Eberhardt et al. [13]. Further, the study performed by Ruocco et al. [28] highlights the significant benefits of re-used building components considering C and D modules and achieving an overall negative $CO_2$e rate.

### *4.2. Benefits of Re-Using Building Components*

Significant benefits of second-hand building products in this study can be seen from another perspective; for instance, leftovers within the EOL stage of the reference building can be further re-used/recycled for other purposes in the construction field, i.e., open-loop recycling. Concrete, which is only used for the foundation of the building, is crushed into small pieces that can be used for road construction, bridges, fillings, etc. Glass from windows is recycled and used for other types of glass products in the second cycle. Also, steel is used as the base material for solar panels, roof, and ventilation, and heat pumps are recycled and can be re-used as reinforcement steel for other purposes. The building materials that will be incinerated during the EOL are wooden materials and plastics, while insulation materials and pipes are subject to landfill disposal according to One Click LCA default data. However, incinerated wood is used as energy in the district heating system for Borlänge, thus presenting carbon benefits. Further, if wooden products are in good condition, after their EOL they can be maintained and re-used for another building in closed or open-loop recycling. The EOL waste processing in this study is based on default data from the One Click LCA adjusted for Sweden, and it is different for various products (Appendix A section for details).

### *4.3. Limitations, Barriers, Policy Measures and Future Development*

In this study, there are some limitations that can be further developed in future research. Replacement phase emissions (B4) for building materials and installations remain uncalculated, as the replacement rate is influenced by occupant preferences and the characteristics of building products. Furthermore, the program includes the same transport emissions for re-used and new building materials. Therefore, consequently, the transport GHG impacts overcome the production GHG impacts of re-used building materials. Further, the calculation of biogenic carbon emissions for re-used building materials might be further developed, due to the finding that new wooden building materials have stored GHG emissions compared to re-used materials reporting zero stored impacts. However, when re-used building materials are used for new buildings, there is a potential of released GHG emissions during their adoption process, whereas the emission factor is currently zero. Following the new updated EU standard EN15804:2012+A2:2019, the new EPDs need to declare $GWP_{fossil}$ A1–A3, C1–C4 and D modules. Further, some new EPDs have already declared the $GWP_{biogenic}$ content following these modules. As the EPDs are still in the development phase, the biogenic carbon is reported separately, while some life cycle modules remain uncalculated. When considering the C-life cycle stage in this study, the EOL treatment used was not studied in detail as the waste processing was based on the default scenario data from the program One Click LCA for both new and re-used building products. Therefore, detailed calculation and evaluation of external benefits declared in the D module, such as recycling potential, can be explored in future research. Hence, the shares and availability of re-used and recycled building materials and installations can be further evaluated.

Nowadays, most of the existing buildings have not been constructed for future effective deconstruction. Therefore, it is hard to estimate the re-use potential of existing components, the availability of re-usable products, and the quality of second-hand products for new buildings. Cutting down trees can, in some locations, lead to increased release of GHG emissions due to changes in the ground. How biogenic carbon should be accounted for could be further studied. Further, it is important to include the biogenic accounting for calculating the impacts of wooden products and to present "complete carbon flows", including carbon uptake and carbon release [29]. It can be noted that a number of different methods are discussed and applied in case studies [30] such as the cut-off method, end-of-life method, European Commission Environmental Footprint (EC EF), distributed allocation method, degressive method, and SIA 2032 norms. However, the main findings in their case study do not present the full perspective of the re-use practice, as their boundaries are significantly limited.

According to a recent qualitative study by Knoth et al. [18], lack of knowledge is the main barrier investigated by main building actors such as architects, consultants, and public institutions. At present, the re-use of building materials is not an established concept in the building industry; therefore, there are pilot projects that provide more experience and knowledge to the building stakeholders [18]. Moreover, the focus is on introducing more innovative projects based on re-used solutions and sharing best-practice case studies [18]. Therefore, the case study single-family house "Dalarnas Villa" is a frontrunner project that involves/tests innovative alternatives to achieve more knowledge in the building industry.

Today, the most important barriers to re-use are policy measures and regulations, lack of data related to the emissions factors of re-used components, compatibility of re-used products for new projects, and a lack of knowledge of material loops. Important barriers that cause a high uncertainty level are economic factors for the successful implementation of re-use in the building industry, logistics, and storage [18,31]. Further, the climate impact of using re-used and recycled building materials instead of using the incineration process can also be elucidated in future assessments.

Regarding indicators other than GWP, it could be beneficial to investigate whether impact categories are relevant for buildings. Further, it could be useful to include the cradle-to-cradle approach for building materials and to introduce a circularity certification system in Nordic countries. In that way, many actors in the building industry will be encouraged to include a significant percentage of re-usable products in their list of building products for new buildings or renovation alternatives. "Material passports" could be a valuable document that describes all impacts of a product. Further, it is important to include a complete life cycle assessment of buildings and involve both released and stored $CO_2$e emissions to have a "full carbon picture" of a building [13,29,32]. In the context of single-family buildings that are mostly made of wood in the Nordic European region, it is crucial to highlight that wood construction has significant benefits in saving emissions to the atmosphere by storing them during the whole service life. To make sure that the use of wood does not deplete forests and biodiversity, it is important that the wood comes from responsible and sustainable forestry.

Giorgi et al. [3] highlight in their study that the life cycle tools for assessing the environmental impacts of circular strategies such as pre-demolition audits, materials passport, end-of-waste criteria, and traceability guidelines are widely used in the literature but rarely adapted in practice. Further, they noted a great need for international policy, practices, and tools. In practice, the re-use of building products is still rarely applied, mainly due to several barriers such as lack of certification for quality performance, technical characteristics of the re-used materials, and no regulation for testing the re-used products [3]. Moreover, they advocate the improvement of a re-use strategy locally, encourage stakeholder networks to manage the flow of building materials, and development of supporting tools, for instance, the introduction of material passports. [3]. Likewise, according to Rahla et al. [33], the environmental impacts of building materials and components should be low. Thus, to reduce climate impacts, it is recommended to select building products at a local level

and stimulate the local economy. In addition, the focus should be on the durability and resilience of building products to endure numerous use cycles during their lifetimes [33].

Introducing the concept of CE can be an approach to decreasing the climate impact of building materials [1]. By switching from a linear concept to circular flows, reduced potential environmental impact can be achieved with the extension of a material's service life through reducing, re-using, recycling, repairing, and refurbishing processes [33]. The purpose of adopting CE thinking is that building materials could have a second life when a building is demolished [33]. Thus, the main aim of CE is to encourage designers to rethink the way of designing buildings and consider their EOL phase, thereby considering designing for disassembly and the use of recycled and re-used materials [33]. Knoth et al. [18] state in their study that the re-use of building materials has great potential to decrease the environmental impacts of a building, despite different barriers. Further, alongside the environmental assessment of re-used building products, there is a need for their economic evaluation in future studies. Therefore, the total costs for secondary-used products need to be investigated and compared with primary-based building products.

### *4.4. Recommendations for Circular Logistics*

According to Knoth et al. [18], various challenges exist when the re-use method is used for building products. For example, demolition of buildings or disassembly of components from a donor building might not be at a suitable time for a new building, hence timing is an important issue [18]. Difficulties related to the length of deconstruction, lack of storage place for building materials, and costs due to transport and storage are also highlighted by architects, re-use consultants, and contractors. However, the quality rate of secondary products can vary depending on the previous service life and the nature of the materials. Therefore, in the future, it will be beneficial to include waste auditors [20] on a building site to have full control of products considered for the re-using process. Assessments of the re-use of different building materials and installations are necessary measures for a thorough decision-making process in the early stage of a new building design.

Also, the mapping and evaluation process for re-use is crucial for further use. Designing flexible buildings that are designed for disassembly without causing any damage can lead to less waste in the building industry and thus can also reduce climate impact. Further, it is important to put emphasis on EPDs when selecting new products and to use high-quality data to ensure accuracy. According to Knoth et al. [18], the focus should be on data collection and distribution of knowledge through practices and on making re-use standard in the construction sector. Further, authorities need to adapt the concept of re-use, and the introduction of legislation adjusted in favour of re-use is needed; financial support for manufacturers willing to adapt re-use as a business strategy and generous research funding for pilot projects could also be impactful measures.

### *4.5. Re-Use as a Key Driver towards Carbon Reduction*

The most efficient way towards a decarbonized built environment and achieving a net zero strategy relies on the use of re-used products instead of new ones. The marketplace for re-usable building materials and installations is at the early stage and collaboration between different actors is needed. Most of the challenges are related to the lack of data for building products, their preparation for the next loop of use, and the estimation of logistic costs and emissions [18,31]. According to this study and the reviewed articles discovered in this study [31], significantly reduced environmental footprints can be achieved through the re-use of building materials. In fact, manufacturers can play key roles and be more involved in the re-use processes. As an important step in the building industry, all actors should be included in making legislation that will be adjusted in favour of re-use [18].

## 5. Conclusions

This study provides a valuable contribution to the research on circular strategies in buildings. Due to the EU's goals to implement a CE, this paper presents the evaluation of the production phase, transportation distance, EOL processes, and external benefits of building materials and installations. When summarizing our study, it can be pointed out that re-use solutions considering biogenic carbon content from wooden products can lead to significant carbon reduction. For instance, recycled materials that still need a re-production process and have released emissions are in an inferior position compared to re-used solutions that have zero emissions as a starting point. In conclusion, considering more re-used materials in the assessment of the total outcome identifies increased negative embodied GHG emissions. Thus, it is noted that directly implementing re-used building products leads to significantly larger carbon savings compared to using newly inserted building products. The benefits of using re-used building products over virgin products depend on the large potentials for negative embodied emissions in the D module.

Finally, there is still a need to develop more methods and tools for circularity evaluation. Hence, there is a lack of standards, regulations, and emission factors for re-usable materials. It is necessary to adapt circular measures in practices and include them in the climate policy. To achieve the goal of 50% $CO_2$ reduction by 2030 in the building industry, the most realistic approach is a circular scenario where a large share of new materials will be substituted with re-used or/and recycled materials for new buildings or/and renovation. Therefore, environmental advisors need to encourage actors in the building industry to shift towards secondary choices for their buildings. This is the fast-moving way toward a decarbonized and resilient built environment.

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## Abbreviations

| | |
|---|---|
| $CO_2e$ | Carbon-dioxide equivalents |
| CE | Circular economy |
| CLT | Cross-laminated timber |
| EOL | End-of-life |
| EPD | Environmental product declaration |
| GHG | Greenhouse gas |
| GWP | Global warming potential |
| LCA | Life cycle assessment |

## Appendix A

**Table A1.** Material assessment: production emissions (A1–A3), transport emissions (A4), EOL emissions (C2–C4), external benefits (A5, D), and biogenic carbon of Reference scenario based on default values from One Click LCA for EOL treatment, performed using the methodology explained in Section 2.1.

| | | | Reference Scenario | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Process** | **Building Products** | **EOL Treatment** | **A1–A3** | **A4** | **C2** | **C3** | **C4** | **A5** | **D** | **Biogenic Carbon** |
| New | Concrete foundation | Crushed to aggregate | 5841 | 129.2 | 153.1 | 18.1 | 0.0 | −66.4 | −1660.7 | 0 |
| New | Wood framework | Incineration | 48 | 15.9 | 1.5 | 4.9 | 0.0 | −10.2 | −57.2 | −602 |
| New | Wood panel | Incineration | 39 | 13.0 | 1.2 | 4.0 | 0.0 | −8.4 | −46.9 | −494 |
| New | CLT | Incineration | 211 | 96.1 | 8.9 | 29.9 | 0.0 | −57.8 | −346.2 | −3877 |
| New | Thermo-wood | Incineration | 2026 | 63.3 | 5.9 | 19.7 | 0.0 | −38.3 | −213.7 | −2669 |
| New | Parquet | Incineration | 531 | 16.3 | 7.6 | 25.4 | 0.0 | −52.7 | −294.2 | −3611 |
| New | Cellulose insulation | Landfilling | 357 | 26.0 | 9.4 | 0.0 | 8.3 | 0.0 | 0.0 | −4407 |
| New | Wood fibre insulation | Landfilling | 438 | 2.6 | 0.9 | 0.0 | 0.8 | 0.0 | 0.0 | −445 |
| New | EPS insulation | Incineration | 1090 | 6.3 | 1.7 | 900.5 | 0.0 | −5.8 | −144.2 | 0 |
| New | Gypsum | Recycling | 2859 | 166.8 | 250.3 | 8.1 | 0.0 | −3.2 | −25.9 | 0 |
| New | Windows | Recycling | 2886 | 25.8 | 64.5 | 0.4 | 0.9 | 0.0 | −17.6 | −777 |
| New | Doors | Incineration | 1335 | 17.0 | 10.8 | 7.6 | 0.5 | 0.0 | −2.2 | −1248 |
| New | Roof−steel | Recycling | 1736 | 9.6 | 23.3 | 1.3 | 0.0 | −78.5 | −1046.2 | 0 |
| New | Plastics | Incineration | 701 | 1.7 | 0.9 | 455.0 | 0.0 | −7.9 | −79.2 | 0 |
| New | Solar PV system | Recycling metal | 5766 | 1.1 | 14.7 | 1.3 | 0.1 | 0.0 | 86.7 | 0 |
| New | Heat pump | Recycling metal | 604 | 6.0 | 4.9 | 0.4 | 0.0 | −2.6 | −256.0 | 0 |
| New | Ventilation system | Recycling metal | 622 | 1.1 | 22.0 | 2.0 | 0.2 | −11.4 | −1141.1 | 0 |
| New | Water supply piping system | Landfilling | 2784 | 3.6 | 5.6 | 0.0 | 5.0 | 0.0 | 0.0 | 0 |
| New | Underfloor heating pipes | Landfilling | 1211 | 0.5 | 0.8 | 0.0 | 0.7 | 0.0 | 0.0 | 0 |
| New | Electricity cables | Recycling metal | 471 | 0.6 | 13.0 | 1.2 | 0.1 | −6.7 | −672.6 | 0 |
| | Total: | | 31,556 | 602.3 | 600.9 | 1479.8 | 16.6 | −349.9 | −5917.1 | −18,130 |

**Table A2.** Material assessment: production emissions (A1–A3), transport emissions (A4), EOL emissions (C2–C4), external benefits (A5, D), and biogenic carbon of Scenario I based on default values from One Click LCA for EOL treatment, performed using the methodology explained in Section 2.1.

| | | | Scenario I | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Process** | **Building Products** | **EOL Treatment** | **A1–A3** | **A4** | **C2** | **C3** | **C4** | **A5** | **D** | **Biogenic Carbon** |
| New | Concrete foundation | Crushed to aggregate | 5841 | 129.2 | 153.1 | 18.1 | 0.0 | −66.4 | −1660.7 | 0 |
| Re-used | Wood framework | Incineration | 0 | 15.9 | 1.5 | 4.9 | 0.0 | 0.0 | −57.2 | 0 |
| Re-used | Wood panel | Incineration | 0 | 13.0 | 1.2 | 4.0 | 0.0 | 0.0 | −46.9 | 0 |
| Re-used | CLT | Incineration | 0 | 96.1 | 8.9 | 29.9 | 0.0 | 0.0 | −346.2 | 0 |
| Re-used | Thermo−wood | Incineration | 0 | 63.3 | 5.9 | 19.7 | 0.0 | 0.0 | −213.7 | 0 |
| Re-used | Parquet | Incineration | 0 | 16.3 | 7.6 | 25.4 | 0.0 | 0.0 | −294.2 | 0 |
| Re-used | Cellulose insulation | Landfilling | 0 | 26.0 | 9.4 | 0.0 | 8.3 | 0.0 | 0.0 | 0 |
| Re-used | Wood fibre insulation | Landfilling | 0 | 2.6 | 0.9 | 0.0 | 0.8 | 0.0 | 0.0 | 0 |
| New | EPS insulation | Incineration | 1090 | 6.3 | 1.7 | 900.5 | 0.0 | −5.8 | −144.2 | 0 |
| New | Gypsum | Recycling | 2859 | 166.8 | 250.3 | 8.1 | 0.0 | −3.2 | −25.9 | 0 |
| Re-used | Windows | Recycling | 0 | 25.8 | 64.5 | 0.4 | 0.9 | 0.0 | −17.6 | 0 |
| Re-used | Doors | Incineration | 0 | 17.0 | 10.8 | 7.6 | 0.5 | 0.0 | −2.2 | 0 |
| New | Roof−steel | Recycling | 1736 | 9.6 | 23.3 | 1.3 | 0.0 | −78.5 | −1046.2 | 0 |
| New | Plastics | Incineration | 701 | 1.7 | 0.9 | 455.0 | 0.0 | −7.9 | −79.2 | 0 |
| New | Solar PV system | Recycling metal | 5766 | 1.1 | 14.7 | 1.3 | 0.1 | 0.0 | 86.7 | 0 |
| New | Heat pump | Recycling metal | 604 | 6.0 | 4.9 | 0.4 | 0.0 | −2.6 | −256.0 | 0 |
| New | Ventilation system | Recycling metal | 622 | 1.1 | 22.0 | 2.0 | 0.2 | −11.4 | −1141.1 | 0 |
| New | Water supply piping system | Landfilling | 2784 | 3.6 | 5.6 | 0.0 | 5.0 | 0.0 | 0.0 | 0 |
| New | Underfloor heating system | Landfilling | 1211 | 0.5 | 0.8 | 0.0 | 0.7 | 0.0 | 0.0 | 0 |
| New | Electricity cables | Recycling metal | 471 | 0.6 | 13.0 | 1.2 | 0.1 | −6.7 | −672.6 | 0 |
| | Total: | | 23,685 | 602.3 | 600.9 | 1479.8 | 16.6 | −182.5 | −5917.1 | 0 |

**Table A3.** Material assessment: Production emissions (A1–A3), transport emissions (A4), EOL emissions (C2–C4), external benefits (A5, D), and biogenic carbon of Scenario II based on default values from One Click LCA for EOL treatment, performed using the methodology explained in Section 2.1.

| Scenario II | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Process** | **Building Products** | **EOL Treatment** | **A1–A3** | **A4** | **C2** | **C3** | **C4** | **A5** | **D** | **Biogenic Carbon** |
| Re-used | Concrete foundation | Crushed to aggregate | 0 | 129.2 | 153.1 | 18.1 | 0.0 | 0 | −1660.7 | 0 |
| Re-used | Wood framework | Incineration | 0 | 15.9 | 1.5 | 4.9 | 0.0 | 0 | −57.2 | 0 |
| Re-used | Wood panel | Incineration | 0 | 13.0 | 1.2 | 4.0 | 0.0 | 0 | −46.9 | 0 |
| Re-used | CLT | Incineration | 0 | 96.1 | 8.9 | 29.9 | 0.0 | 0 | −346.2 | 0 |
| Re-used | Thermo-wood | Incineration | 0 | 63.3 | 5.9 | 19.7 | 0.0 | 0 | −213.7 | 0 |
| Re-used | Parquet | Incineration | 0 | 16.3 | 7.6 | 25.4 | 0.0 | 0 | −294.2 | 0 |
| Re-used | Cellulose insulation | Landfilling | 0 | 26.0 | 9.4 | 0.0 | 8.3 | 0 | 0.0 | 0 |
| Re-used | Wood fibre insulation | Landfilling | 0 | 2.6 | 0.9 | 0.0 | 0.8 | 0 | 0.0 | 0 |
| Re-used | EPS insulation | Incineration | 0 | 6.3 | 1.7 | 900.5 | 0.0 | 0 | −144.2 | 0 |
| Re-used | Gypsum | Recycling | 0 | 166.8 | 250.3 | 8.1 | 0.0 | 0 | −25.9 | 0 |
| Re-used | Windows | Recycling | 0 | 25.8 | 64.5 | 0.4 | 0.9 | 0 | −17.6 | 0 |
| Re-used | Doors | Incineration | 0 | 17.0 | 10.8 | 7.6 | 0.5 | 0 | −2.2 | 0 |
| Re-used | Roof−steel | Recycling | 0 | 9.6 | 23.3 | 1.3 | 0.0 | 0 | −1046.2 | 0 |
| Re-used | Plastics | Incineration | 0 | 1.7 | 0.9 | 455.0 | 0.0 | 0 | −79.2 | 0 |
| New | Solar PV system | Recycling metal | 5766 | 1.1 | 14.7 | 1.3 | 0.1 | 0.0 | 86.7 | 0 |
| New | Heat pump | Recycling metal | 604 | 6.0 | 4.9 | 0.4 | 0.0 | −2.6 | −256.0 | 0 |
| New | Ventilation system | Recycling metal | 622 | 1.1 | 22.0 | 2.0 | 0.2 | −11.4 | −1141.1 | 0 |
| New | Water supply piping system | Landfilling | 2784 | 3.6 | 5.6 | 0.0 | 5.0 | 0.0 | 0.0 | 0 |
| New | Underfloor heating system | Landfilling | 1211 | 0.5 | 0.8 | 0.0 | 0.7 | 0.0 | 0.0 | 0 |
| New | Electricity cables | Recycling metal | 471 | 0.6 | 13.0 | 1.2 | 0.1 | −6.7 | −672.6 | 0 |
| | Total: | | 11,458 | 602.3 | 600.9 | 1479.8 | 16.6 | −20.7 | −5917.1 | 0 |

**Table A4.** Material assessment: production emissions (A1–A3), transport emissions (A4), EOL emissions (C2–C4), external benefits (A5, D), and biogenic carbon of Scenario III based on default values from One Click LCA for EOL treatment, performed using the methodology explained in Section 2.1.

| Scenario III | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Process** | **Building Products** | **EOL Treatment** | **A1–A3** | **A4** | **C2** | **C3** | **C4** | **A5** | **D** | **Biogenic Carbon** |
| Re-used | Concrete foundation | Crushed to aggregate | 0 | 129.2 | 153.1 | 18.1 | 0.0 | 0 | −1660.7 | 0 |
| Re-used | Wood framework | Incineration | 0 | 15.9 | 1.5 | 4.9 | 0.0 | 0 | −57.2 | 0 |
| Re-used | Wood panel | Incineration | 0 | 13.0 | 1.2 | 4.0 | 0.0 | 0 | −46.9 | 0 |
| Re-used | CLT | Incineration | 0 | 96.1 | 8.9 | 29.9 | 0.0 | 0 | −346.2 | 0 |
| Re-used | Thermo−wood | Incineration | 0 | 63.3 | 5.9 | 19.7 | 0.0 | 0 | −213.7 | 0 |
| Re-used | Parquet | Incineration | 0 | 16.3 | 7.6 | 25.4 | 0.0 | 0 | −294.2 | 0 |
| Re-used | Cellulose insulation | Landfilling | 0 | 26.0 | 9.4 | 0.0 | 8.3 | 0 | 0.0 | 0 |
| Re-used | Wood fibre insulation | Landfilling | 0 | 2.6 | 0.9 | 0.0 | 0.8 | 0 | 0.0 | 0 |
| Re-used | EPS insulation | Incineration | 0 | 6.3 | 1.7 | 900.5 | 0.0 | 0 | −144.2 | 0 |
| Re-used | Gypsum | Recycling | 0 | 166.8 | 250.3 | 8.1 | 0.0 | 0 | −25.9 | 0 |
| Re-used | Windows | Recycling | 0 | 25.8 | 64.5 | 0.4 | 0.9 | 0 | −17.6 | 0 |
| Re-used | Doors | Incineration | 0 | 17.0 | 10.8 | 7.6 | 0.5 | 0 | −2.2 | 0 |
| Re-used | Roof−steel | Recycling | 0 | 9.6 | 23.3 | 1.3 | 0.0 | 0 | −1046.2 | 0 |
| Re-used | Plastics | Incineration | 0 | 1.7 | 0.9 | 455.0 | 0.0 | 0 | −79.2 | 0 |
| Re-used | Solar PV system | Recycling metal | 0 | 1.1 | 14.7 | 1.3 | 0.1 | 0 | 86.7 | 0 |
| Re-used | Heat pump | Recycling metal | 0 | 6.0 | 4.9 | 0.4 | 0.0 | 0 | −256.0 | 0 |
| Re-used | Ventilation system | Recycling metal | 0 | 1.1 | 22.0 | 2.0 | 0.2 | 0 | −1141.1 | 0 |
| Re-used | Water supply piping system | Landfilling | 0 | 3.6 | 5.6 | 0.0 | 5.0 | 0 | 0.0 | 0 |
| Re-used | Underfloor heating system | Landfilling | 0 | 0.5 | 0.8 | 0.0 | 0.7 | 0 | 0.0 | 0 |
| Re-used | Electricity cables | Recycling metal | 0 | 0.6 | 13.0 | 1.2 | 0.1 | 0 | −672.6 | 0 |
| | Total: | | 0 | 602.3 | 600.9 | 1479.8 | 16.6 | 0 | −5917.1 | 0 |

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