

Article

The Effect of Circular Strategies on Reducing the Embodied Carbon When Renovating Residential Dwellings in Flanders

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Abstract

As buildings are responsible for an important share of the energy use and related greenhouse gas (GHG) emissions in Europe, renovation of the building stock is a key priority in the coming decades. As these large-scale renovations will require a vast amount of materials, sustainable solutions for material use in renovations must be searched for. To date, the use of circular materials is put forward to reduce the embodied impact of building renovations. To get a better insight into the carbon footprint of building renovation using circular materials, the life cycle carbon footprint for these renovation solutions is studied in this paper. To avoid burden shifting, multiple impact categories have been assessed. For each element of the building envelope, a life cycle assessment (LCA) has been conducted of a renovation with conventional materials and four circular renovation measures, i.e., avoiding materials, using reclaimed materials, using recycled materials, and using bio-based materials. The results provide insight into the environmental benefits and burdens of these circular renovation approaches for single family houses in Flanders. This paper is expected to contribute to the debate on using circular strategies for renovation by highlighting their benefits and burdens.

Keywords: burden shifting; decarbonisation; energy renovation; life cycle assessment; sustainable material use

1. Introduction

To limit global average temperature increase to well below 2 °C and pursue efforts to limit it to 1.5 °C above preindustrial levels, a legally binding international treaty on climate change was adopted at the UN Climate Change Conference (COP21) in Paris in 2015 [1]. These ambitions are translated by the European Commission into a reduction in EU greenhouse gas (GHG) emissions of at least 55% compared to 1990 levels by 2030 [2]. Buildings play an important role in this challenge as these are responsible for 40% of the energy use [3] and 35% of the energy-related GHG emissions in Europe [4]. As the majority of existing buildings were constructed without energy performance requirements and as it is estimated that today's buildings will account for at least 75% of the EU building stock by 2050 [5], energetic building renovation is a key priority in the coming decades [5,6]. These large-scale renovations will, however, require a vast amount of materials and, consequently, have an effect on the environmental impact of the building sector [7,8]. Moreover, as the construction sector is currently responsible for about 50% of all extracted materials [9] and more than 35% of EU's total waste generation [9], sustainable solutions for material use in renovations must be searched for [10]. Typically, environmental assessment of building



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renovation shows a high impact related to the material use at the moment of renovation, the so-called carbon spike [11]. To date, circular economy (CE) strategies are put forward to reduce the peak in embodied impact [11–15].

This paper investigates whether the EU emission reduction goals could be achieved when renovating a building through implementing circular economy strategies and what would be the most effective strategy for the renovation of single family houses. Various definitions or classes of circular material use in the building sector are found in the literature. Nußholz et al. [13], for example, summarise the CE strategies in four categories: (1) narrowing resource loops (i.e., using fewer resources), (2) slowing resource loops (i.e., keeping products in use as long as possible), (3) closing resource loops (i.e., recycling materials) and (4) regenerating resource loops (i.e., using renewable resources). Sáez-de-Guinoa et al. [12] mention 19 circular strategies and López Ruiz et al. [16] mention 14 circular strategies. This paper follows the work of Nußholz et al. [13]. Consequently, in this paper four circular renovation approaches are studied: (1) avoiding material use, (2) applying reclaimed materials, (3) applying recycled materials and (4) applying bio-based materials.

The comparison of the four circular renovation approaches presented in this paper provides insight into the benefits and burdens of each approach. The paper aspires to answer the following research questions: (1) what is the short- and long-term reduction potential of various circular renovation approaches, and (2) which renovation approach results in the aspired emission reduction?

2. Materials and Methods

2.1. Environmental Impact Assessment Method

To compare the impact of the materials used for renovating existing dwellings, an identical U-value for each of the renovation measures is assumed. To this end, the thresholds defined in the Energy Performance and Buildings Directive, further referred to as the EPBD regulation, were used. The U-value, i.e., the thermal transmittance, of all opaque building envelope elements obtained after renovation equals $0.24 \text{ W/m}^2\text{K}$ which is in line with EPBD regulation in Flanders in 2025 [17]. The U-values are calculated according to the Flemish assessment method for primary energy use in residential buildings [18]. According to EPBD regulation in Flanders [17], a default lambda value [19], i.e., the thermal conductivity, shall be used when the thermal characteristics of an (insulation) material cannot be proven. Therefore, the higher default lambda values included in the standards are assumed for reused materials, whereas lambda values declared on the manufacturers' technical data sheets are used for the new materials. It is important to note that these default lambda values are rather high values, i.e., conservative approach, to reflect the uncertainty of the characteristics of old materials and reflect the potential performance degradation over time. The circular approaches for the renovation of the windows result in different U-values, as explained in Section 2.3. To compare the effect of the renovation, the whole life cycle carbon footprint, i.e., operational and embodied impacts, of the renovated elements is compared to the existing element. The energy use for heating is calculated for a period of 5 years, i.e., until 2030, and for a period of 60 years, i.e., the assumed service life of the building, using the Equivalent Heating Degree Day Method, in line with the Belgian LCA tool TOTEM [20]. To estimate the impact of the energy used for heating the building, the carbon footprint related to burning natural gas in a condensing gas boiler with a system efficiency of 94%, i.e., $0.28 \text{ kg CO}_{2\text{eq}}/\text{kWh}$, is assumed.

The carbon footprint is calculated according to the current European standards EN15804:2012+A2:2019 [21], EN 15978 [22], EN 15643 [23], ISO 14040 [24], and ISO 14044 [25]. The assessment includes all life cycle stages from the production stage (A1–A3) to the end of life (EoL) stage (C4). Additionally, the results for Module D, benefits and burdens outside

the system boundary, are assessed. In line with current standards, these are separately reported as additional information. To avoid burden shifting, all impact categories of the EN15804:2012+A2:2019 standard [21] have been assessed. Data on the environmental impact of the materials are based on the ecoinvent database version 3.8 allocation method cutoff by classification, while SimaPro software version 9.6 is used for the LCA calculations.

2.2. Description of the Renovation Modelling Approach

For each renovated element of the building envelope, a renovation measure with conventional materials (further referred to as common practice renovation) and four circular renovation measures have been assessed. Figure 1 describes how these various measures have been modelled in terms of life cycle stages included. The functional unit is defined as a residential building with a service life of five years or 60 years from the moment of renovation, depending on the timeframe studied: five years to assess the 2030 policy goals and 60 years to assess the long term effects of the renovation. Traditionally, an LCA of a building starts at the moment of construction, while here a shift in the reference study period is proposed to a later stage in the service life of the building, more specifically at the moment of renovation. At this moment it is decided which building components are kept, improved or dismantled, and hence a more in-depth assessment of the renovation options and better identification of the hotspots of the renovation measures is possible. The production stage (A1–A3), hence, considers the materials needed for the renovation. For the renovation approach with reclaimed materials, no impact for the production stage of the reclaimed materials is included, assuming that no additional treatment of the materials is needed. In this scenario, dismantled materials (from a different building) are assumed to be reused, while materials that cannot be dismantled are assumed virgin. The impact of dismantling and transporting the reclaimed materials to a storage warehouse is allocated to the previous building (and hence are outside the system boundaries). For all renovation approaches, the transport to the building site (life cycle stage A4), the installation of materials into the building and the dismantling of materials during the renovation process (life cycle stage A5) are included. For materials that are preserved during renovation, no impact is accounted for. All renovation approaches include the necessary activities for maintenance (life cycle stage B2) during the building service life of 60 years. For the assessment considering the full service life of the building, life cycle stage B4 (replacement) is included. For the timeframe until 2030, the latter is excluded from the assessment. Life cycle stage B6 considers the energy use for heating during the service life of the building, i.e., five years or 60 years. For the end of life (EoL) stage (C1–C4), the dismantling of materials and transport to waste treatment is included in all renovation approaches. In this approach it is assumed that the transport to a storage warehouse is identical to the transport to EoL treatment. Module B1, referring to the impact of the release of substances to the indoor environment, is not included in this research, in line with the Belgian LCA method for buildings, i.e., the MMG method [20,26]. Similarly, accidental damage or failure (B3) is not included in the assessment. As renovation has no impact on the cleaning process, the latter is not included in the assessment.

Scenarios for material lifespans, transport to the building site, maintenance, replacement, transport to EoL treatment and EoL treatment are in line with the scenarios of the MMG method [20,26] as these are representative for the Belgian context. For Module D, the scenarios for recycling and reuse are based on the literature, information from the manufacturers and expert judgement. The scenarios included in the assessment are described per installed material for all elements and all renovation approaches in the Supplementary Materials.

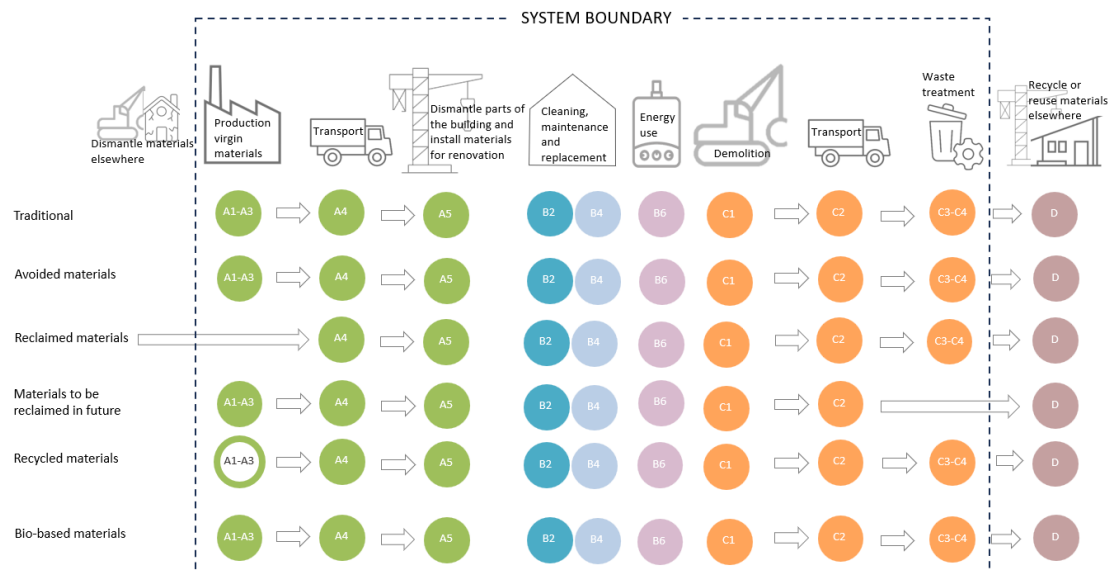


Figure 1. Overview of system boundary and life cycle stages assessed per renovation approach.

2.3. Description of the Renovated Element Buildups

The existing buildups are based on a real case study, a terraced single family house constructed in 1954, located in Leuven (Flemish region of Belgium). The case study is representative of an important share of the housing stock in Flanders that will need to be renovated in the near future. A total of 26% of the residential building stock in Flanders consists of terraced houses and 11% of the dwellings were constructed between 1946 and 1970 [27]. The case study building has a label F on its Energy Performance Certificate (EPC), which is the case for 28% of the single family houses in Flanders [28]. With an assumed energy use higher than 500 kWh/(m² y), this dwelling belongs to the worst performing houses.

For each of the circular renovation strategies and for the common practice renovation, buildups for 1 m² of floor on ground, external wall, pitched roof and window have been defined, based on materials that are on the market in Flanders and are technically feasible. For the common practice renovation approach, a buildup from the TOTEM library [29] consisting of conventional materials is selected.

In the circular approaches, the materials in the common practice buildup have been replaced by alternative materials, i.e., reclaimed, recycled or bio-based, provided that these are available on the market. For the avoiding materials approach, a renovation strategy that requires minimal material use is searched for. While to date often new materials that can be reused in the future are applied in the construction sector, this study only assessed the application of reclaimed materials during renovation. This is to lower the carbon spike at the moment of renovation.

The buildups for the existing and renovated elements are presented in Figure 2 for the floor on ground, in Figure 3 for the external wall, in Figure 4 for the pitched roof and in Figure 5 for the windows. Tables describing the buildups for each element are included in Appendix A. The buildups for the bio-based and circular renovation approaches are based on sources from the literature [29–31] and expert judgement. The selected ecoinvent records to model the materials used in the renovation approaches are included in the Supplementary Materials. Note that the heating system and internal elements are kept unchanged (not part of the renovation assessed in this paper).

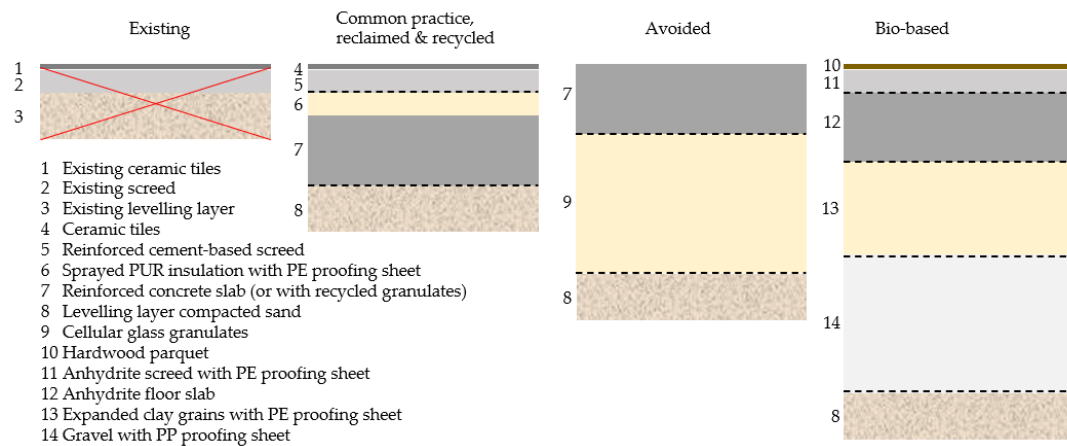


Figure 2. Buildup of the existing floor on ground and renovation approaches (U-value 0.24 W/m²K).

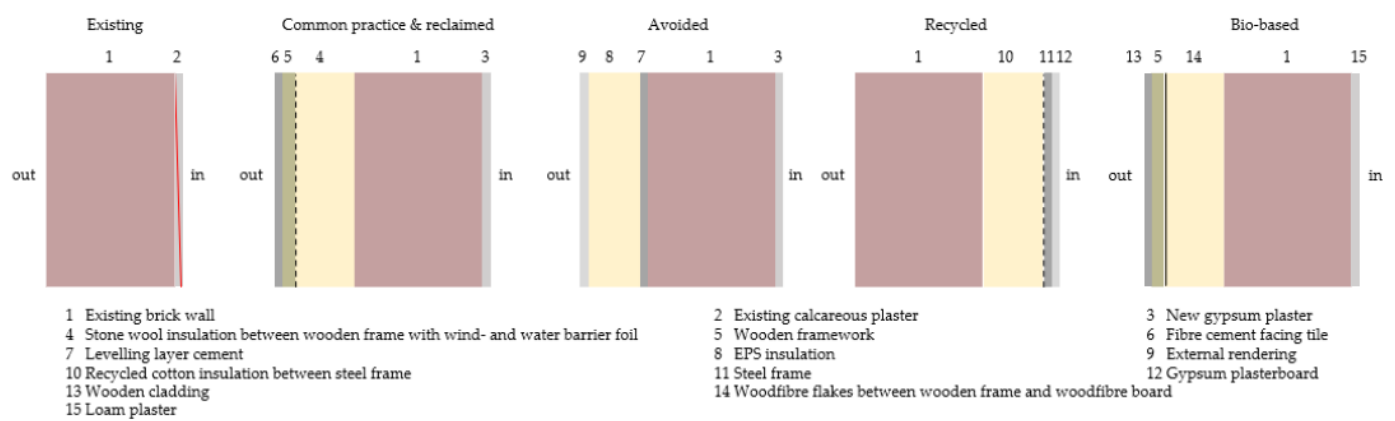


Figure 3. Buildup of the existing external wall and renovation approaches (U-value 0.24 W/m²K).

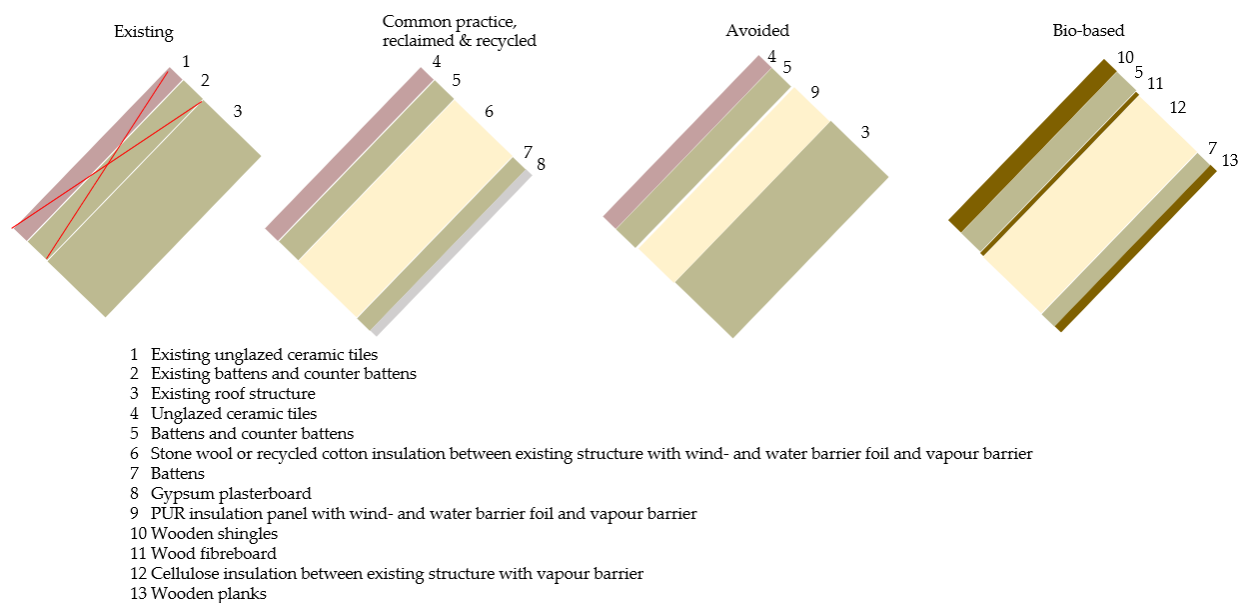


Figure 4. Buildup of the existing pitched roof and renovation approaches (U-value 0.24 W/m²K).

For the floor on ground, the common practice renovation solution is to demolish the existing tiles and screed and replace them by a new concrete slab, PUR insulation, a new cement-based screed and new ceramic tiles. The circular approaches with reclaimed and recycled materials are similar. In these approaches, the ceramic tiles are replaced by reclaimed or recycled ceramic tiles, reclaimed sand is used for the levelling layer, and the

concrete slab is assumed with recycled granulates. In the avoided materials approach, it is assumed that the concrete slab is polished to avoid the screed and ceramic tiles. This requires an insulation layer below the concrete slab. To this purpose, cellular glass granulates [32] are applied. In the bio-based approach, the ceramic tiles are replaced by wooden parquet and the cement screed and concrete slab are replaced by an anhydrite screed and slab. The PUR insulation is replaced by expanded clay grains on a gravel layer [29].

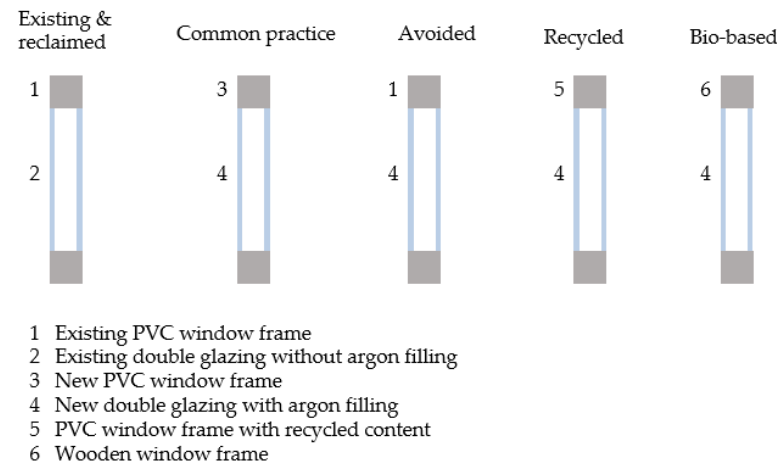


Figure 5. Section of the existing window and renovation approaches (U-value variable).

The existing external wall is a brick wall with an internal calcareous plaster that is replaced during renovation. For the renovation with conventional materials, it is assumed that external insulation between the wooden rafters is added, as well as a wind and water barrier foil and a fibre cement cladding on a double wooden frame. In the reclaimed materials approach, the wood and insulation are substituted by reclaimed materials. In the bio-based approach, the insulation is replaced by a woodfibre insulation [33], finished with wooden cladding. Another frequently used insulation approach is the ETICS approach [29] with EPS insulation and external rendering; this is assumed as the avoid materials approach. Finally, internal insulation with recycled cotton [34] finished with a gypsum plasterboard with recycled content [35] is assumed in the recycled materials approach.

As the existing pitched roof is not insulated and no wind and water barrier foil is installed, the unglazed ceramic tiles and battens and counter battens are replaced during renovation. The common practice is filling the existing structure with insulation and the corresponding wind and water barrier foil and vapour barrier foil and finishing the roof with a gypsum plasterboard on the inside. The reclaimed and recycled approaches have a similar buildup where in the reclaimed approach the insulation, wooden battens and unglazed ceramic tiles are assumed to be reused and in the recycled approach a recycled cotton insulation [34] and a gypsum plasterboard with recycled content [35] is assumed. For the bio-based renovation approach, cellulose insulation is blown in between the existing structure, a woodfibre board is applied as a wind and water barrier and a vapour barrier and finishing with wooden planks is assumed on the inside. A sarking roof principle with PUR insulation [36] on the outside of the existing structure is assumed in the avoided materials approach.

For the existing window, a PVC window frame and double glazing without argon filling are assumed, resulting in a U-value of $3.5 \text{ W/m}^2\text{K}$. Common practice is to replace the window with a new window with a PVC frame and double glazing with argon filling with a U-value of $1.50 \text{ W/m}^2\text{K}$, corresponding with the EPBD regulation [17]. In the avoid material approach, it is assumed that only the glazing is replaced, resulting in a U-value of $2.7 \text{ W/m}^2\text{K}$, while for the recycled material approach a new PVC frame with recycled

content and double glazing with argon filling is assumed and for the bio-based approach a wooden frame and double glazing with argon filling is assumed. As the windows in the recycled and bio-based approaches are new, a U-value of $1.50 \text{ W/m}^2\text{K}$ is assumed. For the reclaimed material approach, the existing window is preserved. Improvement of the airtightness of the connection between the windows and the external wall after renovation is not considered in this study.

3. Results

An in-depth discussion of the considered renovation strategies for the renovated elements of the building envelope is presented, followed by a comparison of the results of the renovation strategies for all elements. Finally, the results of additional assessments are discussed.

3.1. Comparison of the Renovation Approaches for Each Element of the Building Envelope

3.1.1. Renovation Approaches of the Floor on Ground

Figure 6 presents the life cycle embodied carbon footprint for the common practice renovation approach. The impact is due to the production (life cycle stage A1–A3) of the new concrete slab, ceramic tiles, insulation, and screed. For those materials, an alternative is searched for in the circular renovation approaches. The results for Module D are included in the graphs to assess the possible effect of recycling and reuse. The results for module D are negative when the benefit of avoiding virgin materials by reusing or recycling is higher than the burden of the recycling process. The impact is positive when the recycling process has a higher impact than the avoided impact.

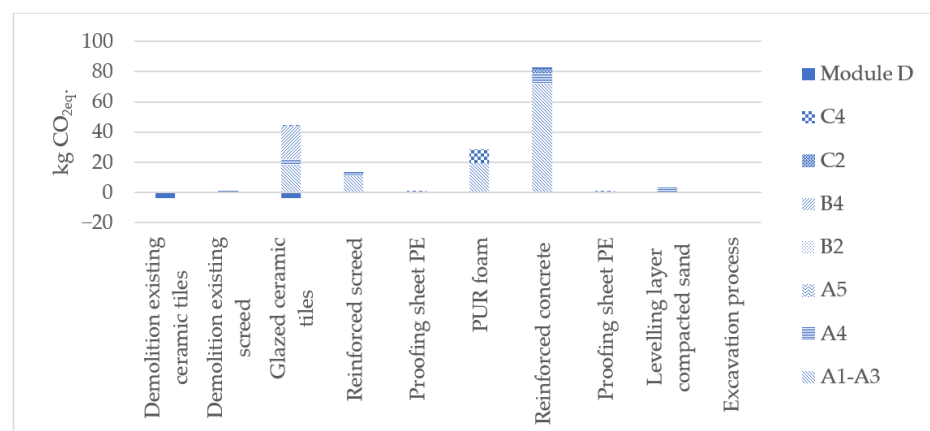


Figure 6. Life cycle embodied carbon footprint for the common practice renovation approach for the floor on ground, assuming a service life of 60 years.

In the avoid material use (polished concrete floor), the impact of the ceramic tiles and screed is avoided. As shown in Figure 7a, the remaining impact is due to the concrete slab. In the reclaimed material use approach, a reduction in the impact for the floor finishing is noticed as only the impact of the mortar for installing the tiles remains. In the recycled material use (recycled granulates in tiles and concrete), no significant decrease in the impact is found. Finally, in the bio-based material use variant, the impact of the wooden parquet, expanded clay grains and anhydrite floor slab proves to be lower than the impact of the ceramic tiles, PUR insulation and concrete slab.

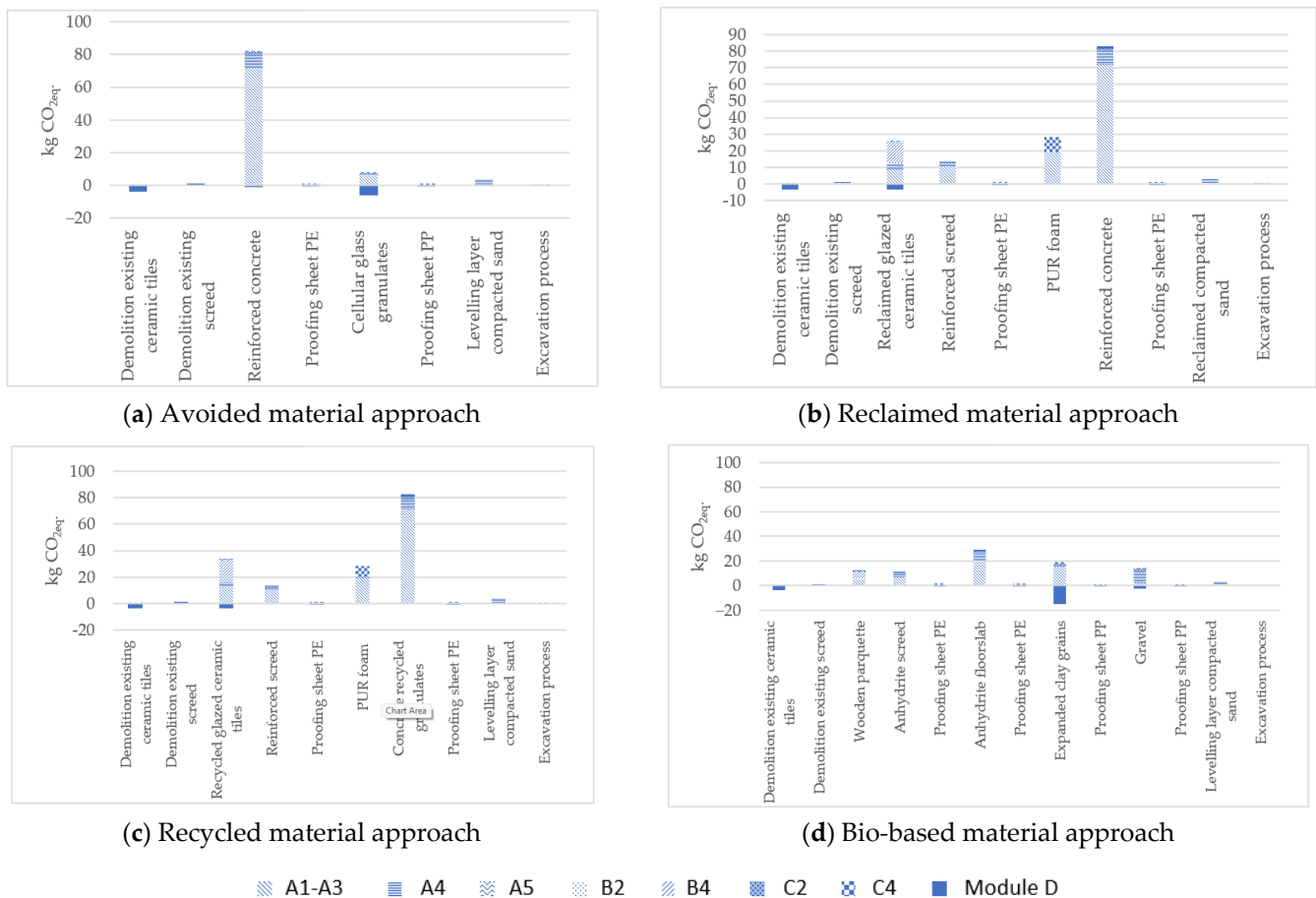


Figure 7. Life cycle embodied carbon footprint (kg CO_{2eq}) for the circular renovation approaches for the floor on ground, assuming a service life of 60 years.

In Figure 8, the results (life cycle carbon footprint) for the various renovation approaches of the floor on ground are compared to the existing floor. When considering the full service life of the building, the benefit of the energy reduction is most important. The reduction in the whole life cycle carbon footprint after 60 years is 87% in the common practice approach and the recycled material approach, 88% in the reclaimed material approach, 90% in the avoided material approach and 91% in the bio-based approach. However, although the energy use significantly decreased after renovation, the aspired 55% reduction by 2030 is not achieved in any of the renovation approaches. However, when the benefits reported in module D are accounted for, the bio-based materials approach results in a decrease in the life cycle carbon footprint after five years of 58%. The latter is, however, very uncertain as the benefits reported in Module D are based on future recovery and recycling scenarios. For all approaches, the embodied impact is mostly due to the production (A1–A3) of the materials (the diagonally dashed bars in the graph). The higher benefits in Module D in the avoided material use and bio-based approaches are due to the assumed EoL scenario of reuse for the cellular glass granulates and gravel. As only few materials can be reused or recycled, the reduction in the carbon footprint for these renovation approaches is limited. The reduction in the embodied carbon footprint compared to the common practice renovation approach is significant in the avoided material use approach (−44%) and bio-based approach (−47%). Here, significant changes in the buildup are assumed.

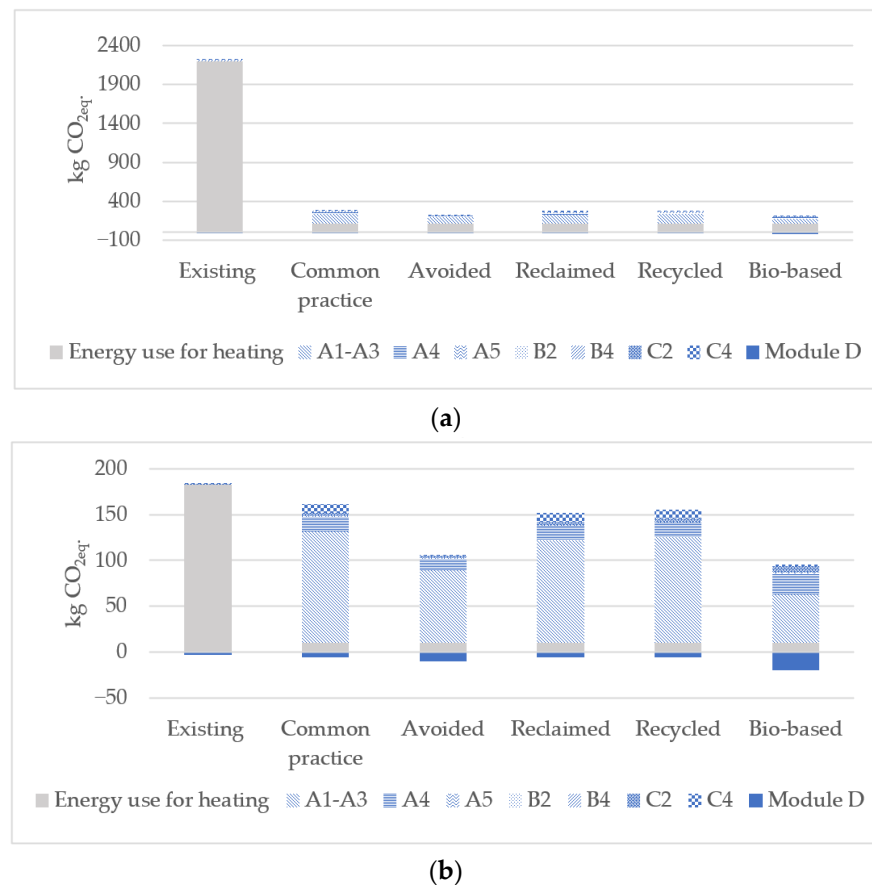


Figure 8. Comparison of the life cycle carbon footprint for renovation approaches for the floor on ground over 60 years (a) and over 5 years (b).

3.1.2. Renovation of the External Wall

Figure 9 presents the life cycle embodied carbon footprint for the common practice renovation approach for the external wall. The impact is due to the production (life cycle stage A1–A3) of the new fibre cement facing tiles and the gypsum plaster for internal finishing. For the latter, the maintenance and replacement are moreover important. In the circular renovation approaches, alternatives are sought for the finishing layers and the insulation.

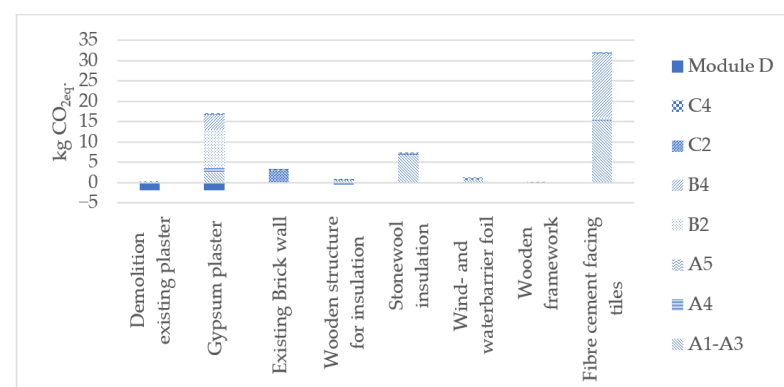


Figure 9. Life cycle embodied carbon footprint for the common practice renovation approach for the external wall, assuming a service life of 60 years.

The remaining impact of the avoid material use approach (rendering on insulation) is due to the internal finishing, the production of the insulation and external rendering, and

the waste treatment of the insulation (Figure 10). In the reclaimed material use approach, the high impact of new fibre cement tiles is avoided by using reclaimed tiles. In the recycled material approach, both the internal and external finishing are replaced, leading to a significant impact reduction. In the bio-based material approach, the remaining impact is due to the loam plaster and woodfibre board; however, this impact is smaller than the impact of the calcareous plaster and fibre cement tiles.

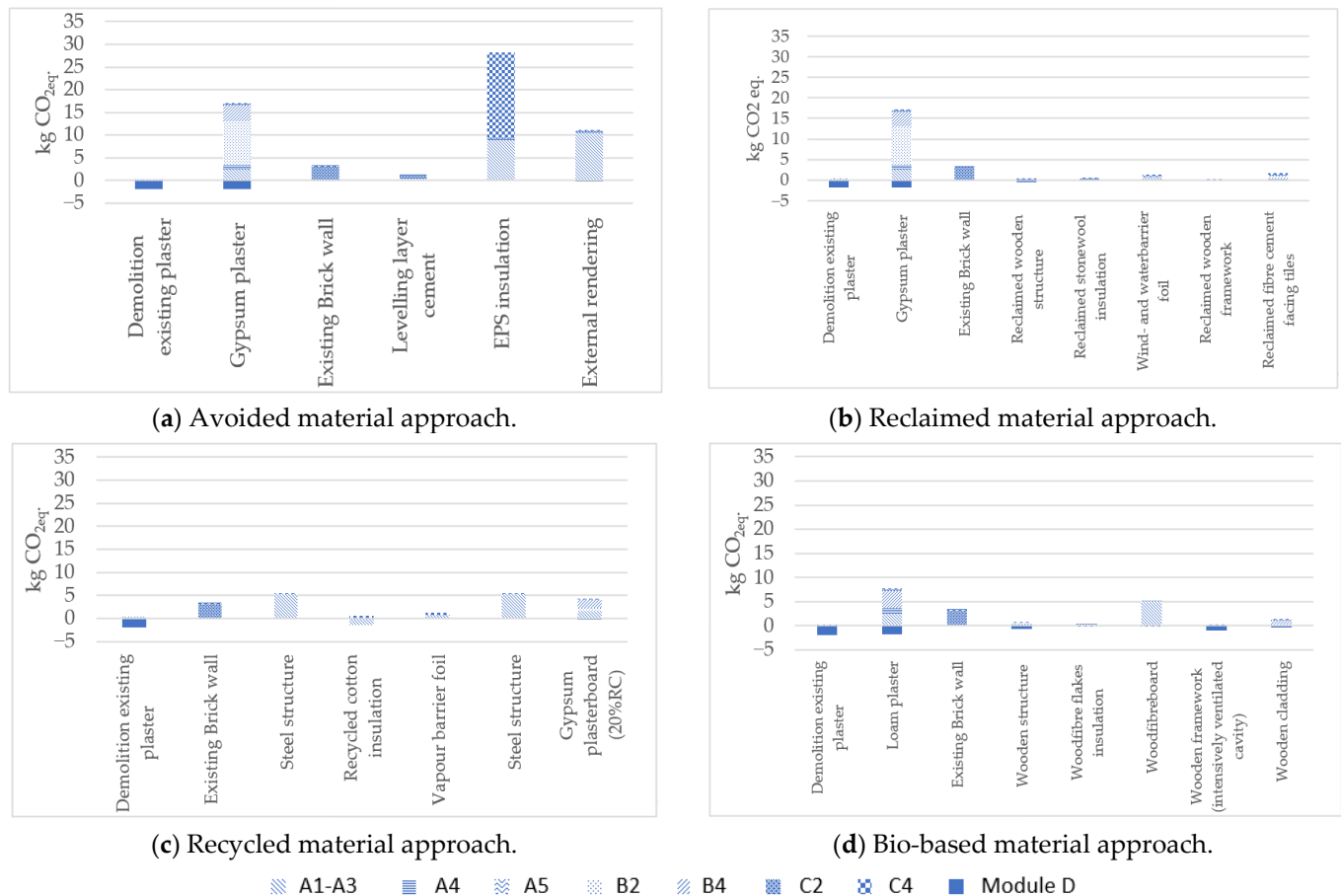


Figure 10. Life cycle embodied carbon footprint (kg CO_{2eq.}) for the circular renovation approaches for the external wall, assuming a service life of 60 years.

In Figure 11, the results for the different approaches for the renovation of the external wall are compared to the existing external wall. When the full service life (60 years) is considered, the whole life cycle carbon footprint of the external wall is decreased by 73% in the common practice and avoided material approaches, by 79% in the reclaimed material approach and by 80% in the recycled and bio-based approach. The embodied impacts are due to the production (A1–A3) and replacement (B4) of the materials. The avoided material approach leads to a limited reduction in embodied carbon footprint (−2%) compared to common practice renovation. The reason is that the selected materials have a high embodied impact for the production and EoL treatment. Due to the high impact of the fibre cement façade tiles in the common practice renovation approach, using reclaimed fibre cement façade tiles reduces the embodied carbon footprint significantly, −61%, compared to the common practice approach. As in the recycled and bio-based material approaches, both the façade tiles and gypsum plaster are replaced; these renovation approaches result in the highest reduction in the embodied carbon footprint, −70%, compared to the common practice renovation approach for both approaches.

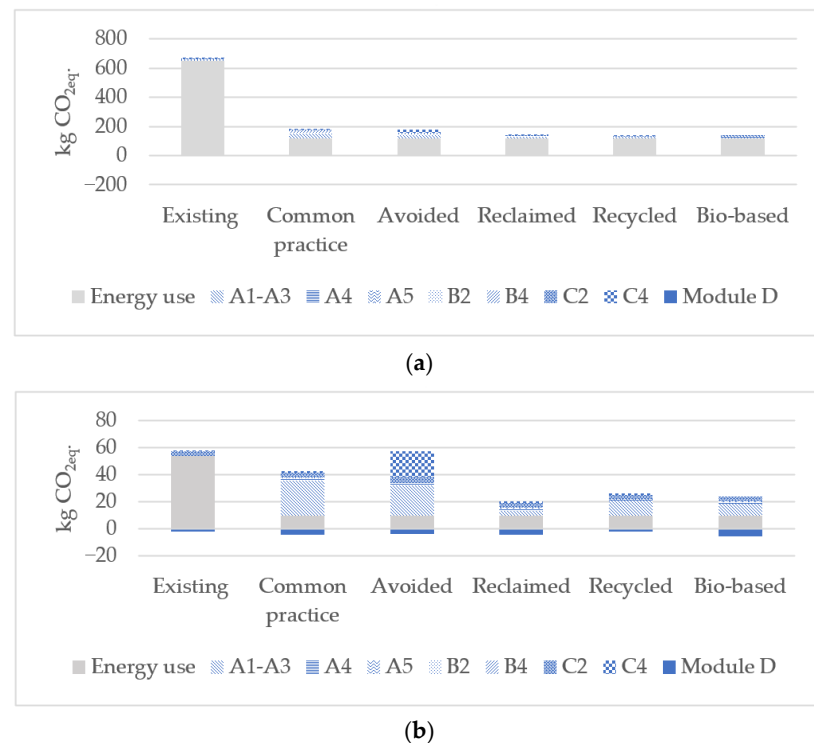


Figure 11. Comparison of the life cycle carbon footprint for renovation approaches for the external wall over 60 years (a) and over five years (b).

When considering a five year service life, the reduction target of -55% by 2030 is achieved in the recycled (-65%) and bio-based (-58%) materials approaches. For the common practice and the reclaimed materials approaches, the life cycle carbon footprint decreased respectively by 26% and 54%. In the avoided material approach, the carbon footprint resulted in a life cycle carbon footprint comparable to the unrenovated wall due to the embodied impact of the materials. In this approach, the embodied impact is not compensated by the benefit of the reduction in energy for heating over a period of five years.

3.1.3. Renovation of the Pitched Roof

Figure 12 presents the life cycle embodied carbon footprint for the common practice renovation of the pitched roof. The impact is mainly caused during the production (life cycle stage A1–A3) of the new ceramic roof tiles and the stone wool insulation. For those materials, an alternative is searched for in the circular renovation approaches.

Figure 13 presents the results for the circular renovation approaches. In the avoid material approach, the carbon footprint has increased due to a higher impact of the waste treatment of the PUR insulation compared to stone wool. In the reclaimed material use approach, the carbon footprint is reduced significantly due to the avoided impact of the roof tiles (and insulation). The additional thickness of the insulation materials, due to the higher default lambda value for reclaimed materials, has no significant impact on the result. The recycled material approach results in a lower carbon footprint for the insulation. The ceramic tiles, on the other hand, are assumed as new materials and therefore no decrease in the carbon footprint is shown. In the bio-based material approach, the ceramic tiles are replaced by wooden shingles resulting in a decrease in the carbon footprint. The remaining impact is due to the insulation, the woodfibre board as wind and water barrier, and the wooden shingles.

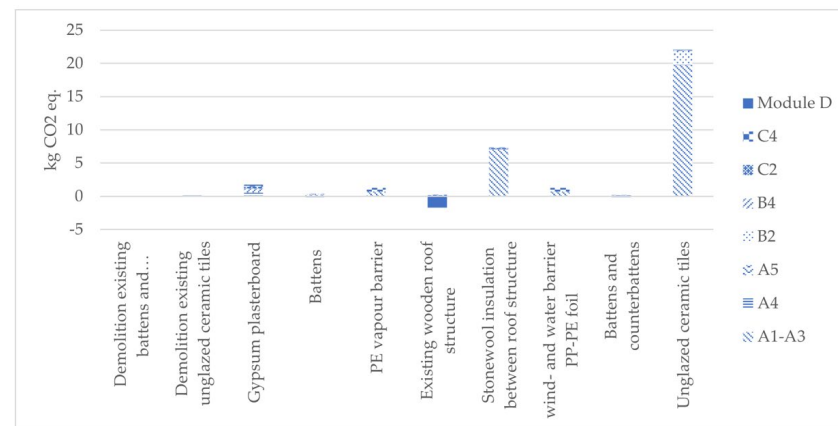
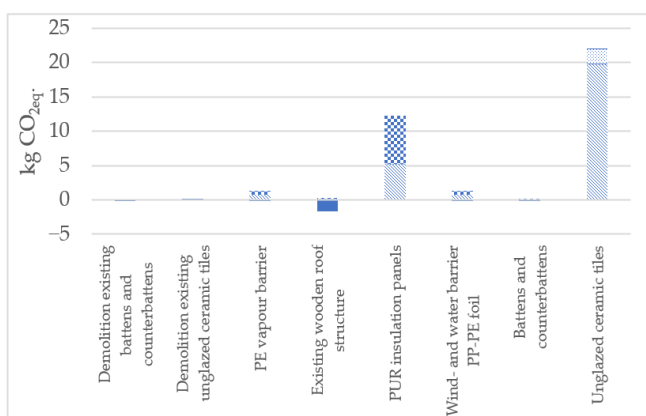
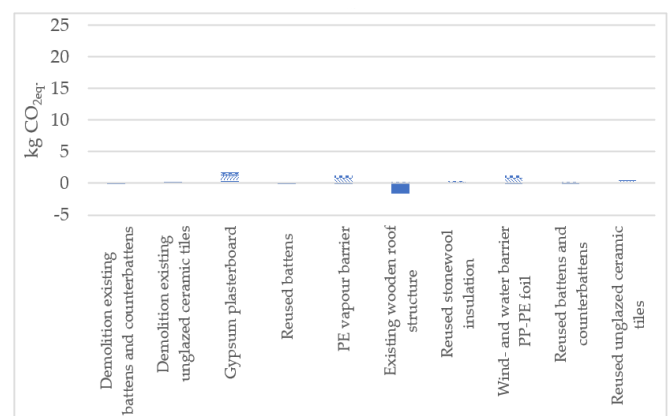


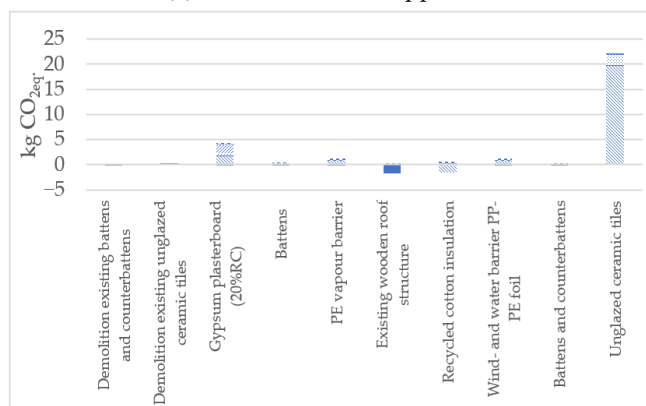
Figure 12. Life cycle embodied carbon footprint for the common practice renovation approach for the pitched roof, assuming a service life of 60 years.



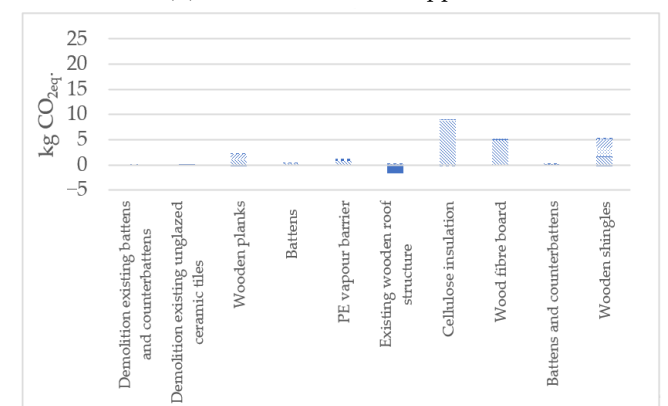
(a) Avoided material approach



(b) Reclaimed material approach



(c) Recycled material approach



(d) Bio-based material approach

/// A1-A3 ■ A4 /// A5 /// B2 /// B4 ■ C2 /// C4 ■ Module D

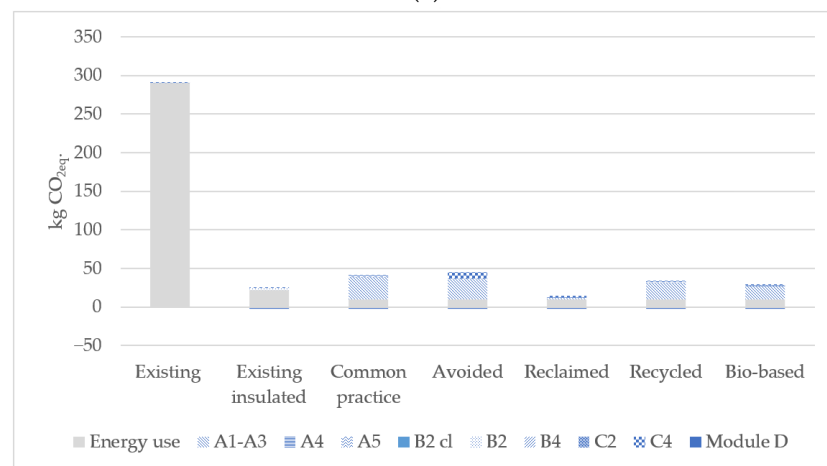
Figure 13. Life cycle embodied carbon footprint (kg CO_{2eq}.) for the circular renovation approaches for the pitched roof, assuming a service life of 60 years.

In Figure 14, the results for the various renovation approaches of the pitched roof are compared to the existing pitched roof. In all renovation approaches, the aspired reduction of 55% in life cycle carbon footprint is achieved by 2030. The majority of the embodied carbon footprint is caused by the production (A1–A3) of the materials. As the buildups for the pitched roof are very similar in the four renovation approaches, the results show little variation, except for the renovation approach with reclaimed materials. As the construction of a pitched roof allows for easy dismantling of materials, it is possible to reuse most of the

materials used for the construction of the pitched roof, resulting in a decrease in embodied carbon footprint of 80% compared to the common practice renovation approach, when considering a service life of 60 years.



(a)



(b)

Figure 14. Comparison of the life cycle carbon footprint for renovation approaches for the pitched roof over 60 years (a) and over five years (b).

To evaluate the effect of assuming an uninsulated existing roof, an additional assessment is made for an existing roof with six centimetres of stone wool insulation, resulting in a U-value of 0.55 W/m²K. As shown in Figure 14b, the aspired reduction of 55% in life cycle carbon footprint by 2030 could not be realised when the existing roof is insulated. On the contrary, the limited reduction in the operational carbon footprint cannot compensate for the embodied impact for the common practice, avoided, recycled and bio-based material renovation approach. Considering a service life of 60 years, as presented in Figure 14a, a reduction in the life cycle carbon footprint compared to the insulated existing roof of 44%, 43%, 55%, 46% and 48% is found for respectively the common practice and the avoided, reclaimed, recycled and bio-based materials renovation approaches.

3.1.4. Renovation of Windows

The life cycle carbon footprint of the windows is presented in Figure 15. When considering the full service life (60 years), the carbon footprint of the energy use is more important. As a result, the renovation approaches with a higher U-value, i.e., the avoided and reclaimed materials approaches, result in a smaller decrease in carbon footprint, namely −24% and −6%. A trade-off is noticed: the reduction in the embodied carbon

due to reclaiming the glass and/or window frame has been offset by the increase in the operational impact due to the higher U-value. The common practice and recycled materials approaches result in a decrease in the life cycle carbon footprint of 47% after 60 years for both approaches, while the bio-based materials approach results in a decrease of 53%. The results show that the embodied impact on $\text{CO}_{2\text{eq}}$ emissions for three of the five scenarios is mainly caused by the production and replacement of the window frame. For the reclaimed material approach, it is assumed that the window is replaced by another reclaimed window. Recycling part of the raw materials of the frame results in a limited decrease in the carbon footprint, i.e., 2%, because only part of the virgin raw materials can be substituted by recycled raw materials. Reclaiming the existing frame and replacing the glazing, the avoided material approach, results in a decrease of 61%, while reclaiming the whole window decreases the impact by 77% compared to the common practice. The bio-based approach has a 58% lower carbon footprint than the common practice.

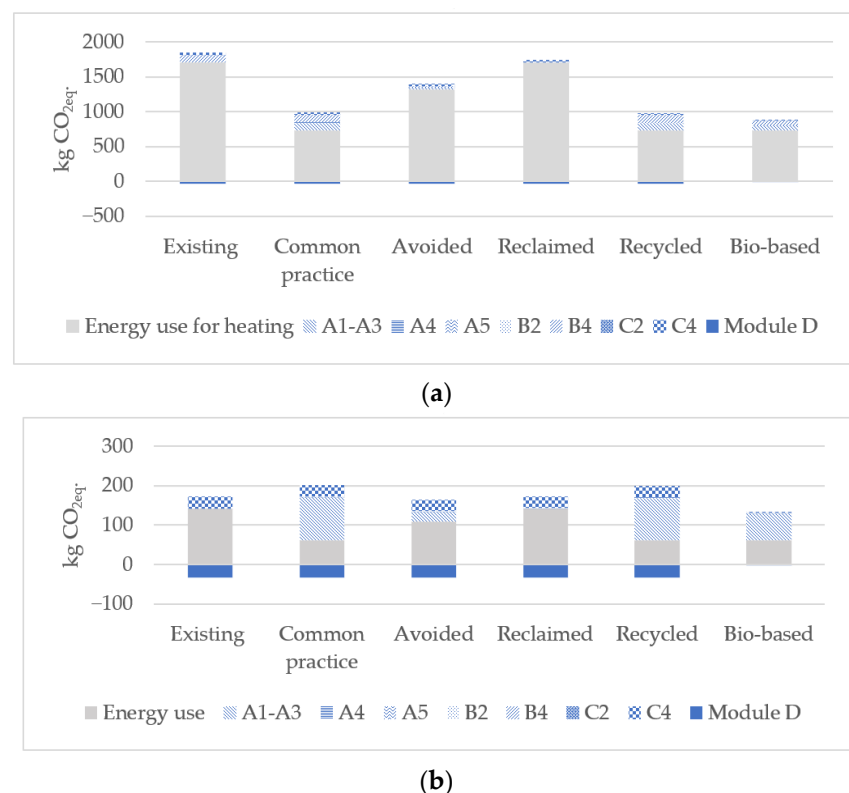


Figure 15. Comparison of the life cycle carbon footprint for renovation approaches for the windows over 60 years (a) and over five years (b).

For the shorter timeframe, the life cycle carbon footprint increased after renovation in the common practice, reclaimed and recycled materials approaches with respectively 18%, 1% and 16% compared to the existing window. In the avoided and bio-based materials approaches, the life cycle carbon footprint decreased with respectively 4% and 23%. The aspired policy goal for 2030 cannot be achieved in any of the renovation approaches.

3.2. Comparison of the Renovation Approaches for All Elements of the Building Envelope

Figure 16 compares the life cycle carbon footprint of the renovation strategies for all elements of the building envelope, over a period of five years (a) and over a period of 60 years (b). The results for Module D are not included in Figure 16 due to the high uncertainty as they are based on future scenarios.

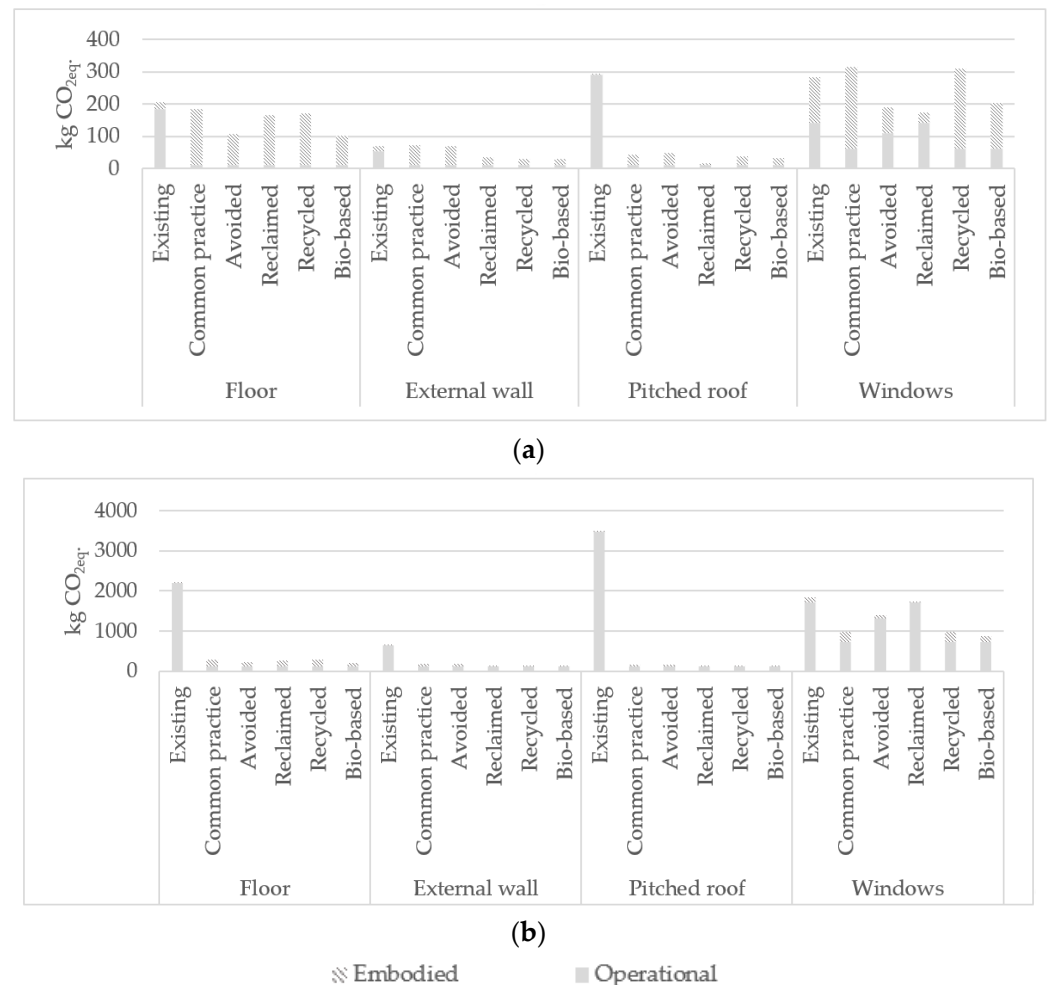


Figure 16. Comparison of whole life cycle carbon footprint for the renovation options of 1 m² for elements of the building envelope over five years (a) and over 60 years (b).

The results show that the floor on ground and the windows result in the highest life cycle carbon footprint after renovation. The reduction in the life cycle carbon footprint after renovation is the highest for the pitched roof. For the windows, the life cycle carbon footprint increased after renovation in the common practice and recycled material use approaches when a service life of five years is considered. After 60 years, however, the life cycle carbon footprint decreased after renovation in all approaches.

For a service life of five years, the common practice approach resulted in the highest life cycle carbon footprint for all building elements except for the pitched roof. Here, the avoided material approach has the highest life cycle carbon footprint. When a service life of 60 years is considered, similar results were found except for the windows where the reclaimed material approach has the highest life cycle carbon footprint after renovation, due to the impact of the energy use.

The results for the embodied impact show that reclaiming materials and using bio-based and recycled materials result in a significant reduction in the embodied carbon footprint compared to the common practice approach for all elements both for a service life of five and 60 years. Avoiding material use and using bio-based materials result in a different buildup for the element. Consequently, the embodied impact is highly dependent on the selected materials for the alternative buildup.

The absolute reduction in the life cycle carbon footprint per square metre over five years is the highest for the pitched roof, 276 kg CO_{2eq}. reduction (3360 kg CO_{2eq}. reduction

over 60 years), between the existing pitched roof and the reclaimed material renovation approach. This is due to the high U-value of the existing pitched roof, namely $7.14 \text{ W/m}^2\text{K}$.

It can thus be concluded that selecting the renovation approach with the lowest embodied carbon footprint for the pitched roof has the highest reduction potential, both for a service life of five and 60 years, while renovating the windows could increase the life cycle carbon footprint (over a short service life of 5 years). The renovation approaches with recycled and bio-based materials for the external wall and all renovation approaches for the pitched roof are in line with the policy ambition of reducing the life cycle carbon footprint by 55% by 2030.

3.3. Burden Shifting: Assessment of the Other Environmental Impact Categories

To investigate the risk of burden shifting, the results for all impact categories included in the EN15804+A2 standard have been assessed. The results of the assessment of the risk of burden shifting for the floor on ground are presented in Figure 17. The results show that the common practice renovation approach has the highest impact in all impact categories except for land use (Figure 17p). For the latter, the bio-based approach results in the highest impact due to the production and replacement of the parquet floor. This is in contradiction with the carbon footprint assessment, where the bio-based approach is the renovation approach with the lowest impact. Likewise, in the assessment for the windows, the common practice approach results in the highest impact for all impact categories except for land use where the renovation approach with bio-based materials has the highest impact. For the external wall, it was found that the renovation approach with recycled materials has the highest impact on ozone depletion, ecotoxicity fresh water and human toxicity cancer effects due to the production of the insulation material. The renovation approach with bio-based materials resulted in the highest impact for water use and land use, due to the production of the wooden structures. The assessment of the pitched roof showed that the renovation approach with recycled materials has the highest impact on climate change and human toxicity cancer effects due to the production of the insulation material, while the renovation approach with bio-based materials resulted in the highest impact for eutrophication fresh water, abiotic depletion, water use particulate matter, ionising radiation, ecotoxicity fresh water, human toxicity non-cancer effects and land use. Considering a single indicator can thus result in burden shifting.

A potential approach to allow for decision taking when being confronted with contradicting indicators is aggregating the various indicators into a single score. For the aggregation of indicators, their importance needs to be determined. For this purpose, normalisation and weighting factors have been provided in the European Product Environmental Footprint (PEF) method [37]. The weighted results show that the common practice renovation approach has the highest life cycle environmental impact for the renovation of the floor, external wall and window. For the pitched roof, the renovation approach with bio-based materials has the highest life cycle environmental impact, due to the high impact of the electricity use in the production of wood on the impact category water use and the high impact of the boric acid used in cellulose production on the depletion of abiotic resources—minerals and metals.

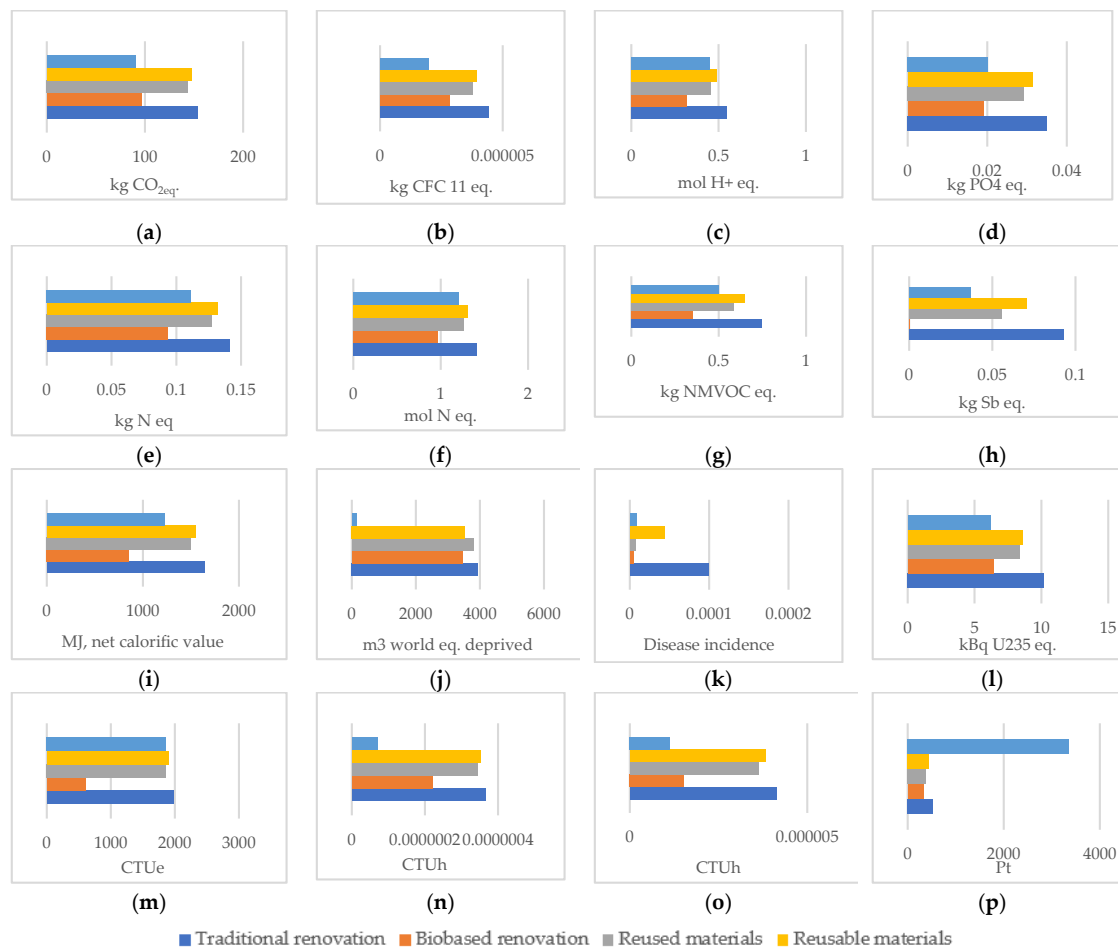


Figure 17. Overview of results for the life cycle embodied impact (60 years) of floor on ground for all renovation approaches on EN 15804 impact categories: (a) climate change total, (b) ozone depletion, (c) acidification, (d) eutrophication aquatic fresh water, (e) eutrophication aquatic marine, (f) eutrophication terrestrial, (g) photochemical ozone formation, (h) depletion of abiotic resources—minerals and metals, (i) depletion of abiotic resources—fossil fuels, (j) water use, (k) particulate matter emissions, (l) ionising radiation, human health, (m) ecotoxicity (freshwater), (n) human toxicity, cancer effects, (o) human toxicity, non-cancer effects, (p) land use.

3.4. Optimisation Potential: Alternative Materials

In this section, alternatives for the materials with the highest embodied carbon footprint are assessed. For the floor on ground, the materials generating the highest carbon footprint are in descending order the reinforced concrete slab, the anhydrite floor slab, glazed ceramic tiles, the PUR insulation, the expanded clay grains, and the cement screed. In the bio-based approach, the anhydrite floor slab, anhydrite screed and wooden parquet are modelled as alternatives for the concrete slab, the cement screed, and the ceramic tiles. The cellular glass granulates included in the buildup in the avoid materials approach could be used as an alternative for the gravel. In Figure 18a, the life cycle embodied carbon footprint over 60 years of stone wool, EPS and cork insulation are compared to the life cycle embodied carbon footprint over 60 years of PUR insulation to search for an alternative with a lower carbon footprint for the same heat resistance value. Both the stone wool and cork insulation result in a significant decrease in the carbon footprint, due to the lower impact of the EoL treatment.

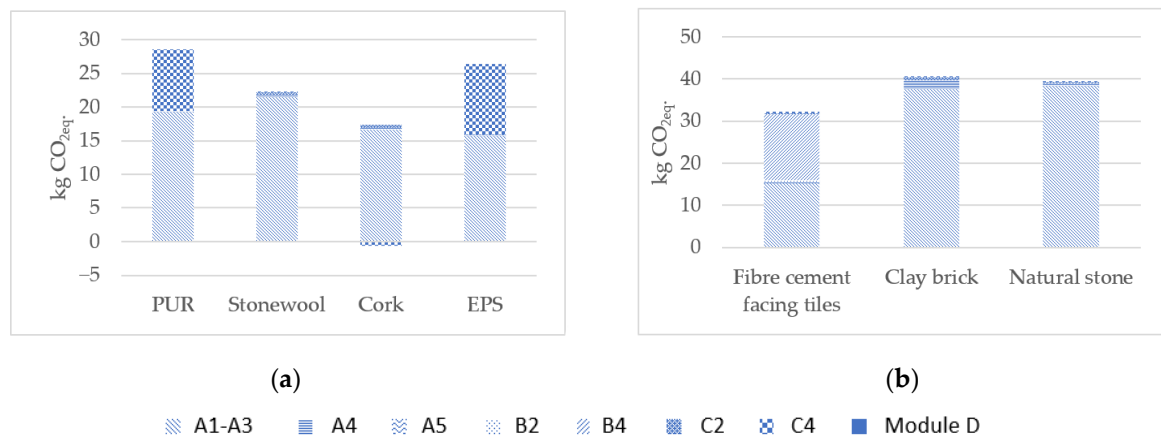


Figure 18. Comparison of the life cycle embodied carbon footprint over 60 years of floor insulation (a) and external wall finishing (b).

The materials with the highest carbon footprint in the external wall are the fibre cement facing tiles and the gypsum plaster. In the bio-based approach, the loam plaster is modelled as an alternative for the gypsum plaster; in Figure 18b, the life cycle embodied carbon footprint over 60 years of an external wall finishing with facing brick and natural stone plate are compared to the life cycle embodied carbon footprint over 60 years of the fibre cement facing tiles. Both the finishing with brick and natural stone have a higher carbon footprint than the fibre cement facing tiles.

For the pitched roof, the embodied carbon footprint is due to the ceramic roof tiles and stone wool insulation. In the bio-based approach, the wooden shingles and cellulose insulation are assessed as an alternative.

4. Discussion

The findings of this paper are compared to the findings on the reduction potential of circular renovation strategies found in the literature. Nußholz et al. [13] found a variation in reduction between −2% and −80% of the life cycle embodied emissions compared to common practice. In this paper, a reduction in the embodied carbon footprint over 60 years of 2% compared to the common practice was found in the avoided material approach for the renovation of an external wall and in the recycled material approach for the renovation of a window. The highest reduction in embodied impact over 60 years compared to common practice, −87%, was found in the reclaimed materials approach for the renovation of a window. The additional assessment considering multiple impact categories revealed a high impact on land use for the bio-based materials. This is in line with the findings of Mouton et al. [31]. Although different LCA methods and databases were used in the studied articles, the literature review of Dinh et al. [38] found a lower GWP impact for bio-based and circular materials.

To assess the effect of the assumptions in the scenarios for transport distances (life cycle stage A4) and EoL treatment (life cycle stage C4), i.e., the two most important life cycle stages besides the production stage, on the results, a sensitivity assessment is done where the transport distances are doubled and halved and where no impact for the EoL treatment is included assuming that all materials will be reused at the end of their service life. For the renovation of the floor on ground, reducing the transport distance or assuming no impact for EoL treatment has no effect on the ranking of the renovation approaches. When the transport distances are doubled, the embodied carbon footprint of the renovation scenario with avoided materials is similar to the embodied carbon footprint of the renovation scenario with bio-based materials. For the pitched roof, changing the transport distance has

no impact on the ranking of the renovation approaches, while considering no impact for the EoL treatment results in a higher embodied impact for the common practice approach compared to the renovation approach with avoided materials. For the external wall and windows, changing the transport distance or assuming no impact for EoL treatment has no effect on the ranking of the renovation approaches. The assumptions in this research have thus minor effect on the results.

5. Limitations of the Study

In this paper, it is assumed that all reclaimed materials fulfil the structural and technical requirements without the need for any additional repair or treatment. As findings in the literature show possible degradation when reclaiming insulation materials [39], a higher lambda value and hence higher material need to obtain the requested U-value was assumed in the calculation of the energy use for heating, in line with the EPBD guideline.

This study moreover included a limited set of materials, while many more options are on the market to date. This limitation was partially overcome by including an optimisation step for the most impactful (high carbon footprint) materials by assessing alternative materials for these. A more extensive analysis of other more innovative solutions is, however, recommended in future research.

This study was limited to assessing the renovation of the building envelope by focussing on various building elements (floor, roof, façade and windows). For the opaque elements, the functional unit was defined as 1 m² of element with a U-value of 0.24 W/m²K and a specified service life (5 years and 60 years). For the windows, the functional unit was defined as 1 m² of element with a specified service life (5 years and 60 years) and the corresponding energy use for heating. The existing structure of the renovated building was kept unchanged in this study, while in deep renovations a renewal or adaptation of the structure might be needed. Although the replacement of the structure is not in the scope of this paper, the authors acknowledge that additional safety coefficients are used in practice when reclaimed materials are used for structural purposes. Additionally, no variation in the existing buildups nor in the construction period was studied. These assumptions simplified the assessment, but a more extensive study including multiple materials for the building structure refurbishment would be needed to generalise the conclusions.

The consequences for the renovation of the full building were out of the scope of this paper. However, the literature on renovation with bio-based and reclaimed materials shows a possible reduction in the carbon footprint of an uninsulated single family house by 75% [40]. The potential GWP reduction by renovating the building stock was also not part of this research. This was, however, investigated in previous research [41]. A consultation of the WLC scenario explorer web tool [42], developed as part of that former study, shows a potential reduction in carbon footprint of single family houses in Belgium of 85% compared to business as usual when a scenario with maximal increase in circularity measures, a maximal shift to low carbon and bio-based solutions, and maximally reduced operation emissions is applied.

Finally, the uncertainty of the LCI data and assumed scenarios and the consequences of this uncertainty on the LCA results were not addressed in this paper.

6. Conclusions

As buildings are responsible for an important share of the energy use and related GHG emissions in Europe, renovation of the building stock is a key priority in the coming decades. However, as these large-scale renovations will require a vast amount of materials, sustainable solutions for material use in renovations must be searched for. To date, the use of circular materials is put forward to reduce the embodied impact of building renovations.

This paper investigates whether the EU emission reduction goals could be achieved when renovating a single family house through implementing circular materials in renovation strategies and what would be the most effective strategy. To this end, four circular renovation approaches are studied: (1) avoiding material use, (2) applying reclaimed materials, (3) applying recycled materials and (4) applying bio-based materials.

The comparison of the four circular renovation approaches presented in this paper provides insight into the benefits and burdens of each approach in the overall aim to support decision taking in building renovation. The paper aspires to answer the following research questions: (1) what is the short- and long-term reduction potential of various circular renovation approaches, and (2) which renovation approach results in the aspired emission reduction? To this end, the embodied carbon footprints of a common practice and the four circular renovation approaches are studied using the current European LCA standards. The assessment includes all life cycle stages from the production stage to the end of life stage. Additionally, the results for Module D, benefits and burdens outside the system boundary are reported showing the burdens and benefits of reuse and recycling of materials. To avoid burden shifting, an additional assessment including all impact categories of the EN15804:2012+A2:2019 standard is conducted.

The results for the floor on ground show that, although the energy use significantly decreased after renovation, the aspired 55% reduction by 2030 is not achieved in any of the renovation approaches. However, when the benefits reported in module D are accounted for, the bio-based materials approach results in a decrease in life cycle carbon footprint after five years of 58%. When considering the full service life of the building (60 years), the benefit of the energy reduction is more significant and, consequently, the reduction in the whole life cycle carbon footprint after 60 years is between 87% and 90%. When considering a five year service life for the external wall, the reduction target of -55% by 2030 is achieved in the recycled (-65%) and bio-based (-58%) materials approaches. For the common practice and the reclaimed materials approaches, the life cycle carbon footprint decreased respectively with 26% and 54%. In the avoided material approach, the carbon footprint resulted in a life cycle carbon footprint comparable to the unrenovated wall due to the embodied impact of the materials. For the pitched roof, the aspired reduction of 55% in life cycle carbon footprint by 2030 is achieved in all renovation approaches. However, when the existing roof is assumed as insulated, the reduction in the operational carbon footprint after renovation could not compensate for the increased embodied carbon footprint of the common practice, avoided, recycled and bio-based material renovation approaches. For the windows, the life cycle carbon footprint over five years increased after renovation in the common practice, reclaimed and recycled materials approaches with respectively 18%, 1% and 16% compared to the existing window. In the avoided and bio-based materials approaches, the life cycle carbon footprint decreased with respectively 4% and 23%. The aspired policy goal for 2030 cannot be achieved in any of the renovation approaches. When the full service life (60 years) is considered, the carbon footprint of the energy use is more important. As a result, the renovation approaches with a higher U-value, i.e., the avoided and reclaimed materials approaches, resulted in a smaller decrease in carbon footprint, namely -24% and -6% . The common practice and recycled materials approaches result in a decrease in life cycle carbon footprint of 47% after 60 years for both approaches, while the bio-based materials approach results in a decrease of 53%.

For a service life of five years, the common practice approach resulted in the highest life cycle carbon footprint for all building elements except for the pitched roof. Here, the avoided material approach has the highest life cycle carbon footprint. When a service life of 60 years is considered, similar results were found except for the windows where the

reclaimed material approach has the highest life cycle carbon footprint after renovation, due to the impact of the energy use.

The results for the embodied impact show that reclaiming materials and using bio-based and recycled materials result in a significant reduction in the embodied carbon footprint compared to the common practice approach for all elements both for a service life of five and 60 years. Avoiding material use and using bio-based materials result in a different buildup for the element. Consequently, the embodied impact is highly dependent on the selected materials for the alternative buildup.

It can thus be concluded that selecting the renovation approach with the lowest embodied carbon footprint for the uninsulated pitched roof has the highest reduction potential, both for a service life of five and 60 years, while renovating the windows or an insulated pitched roof could increase the life cycle carbon footprint (over a short service life of 5 years). The renovation approaches with recycled and bio-based materials for the external wall and all renovation approaches for the uninsulated pitched roof are in line with the policy ambition of reducing the life cycle carbon footprint by 55% by 2030. The most important reason for not achieving the 2030 goals is the limited reduction in the operational carbon footprint over five years. This is often not enough to compensate for the additional embodied impact due to the materials used in the renovation. To mitigate the impact of the building sector on climate change more efficiently, applying reclaimed and bio-based materials should be better enabled by the market and could be supported by policy. However, the results of an additional assessment show a risk for burden shifting towards land use when bio-based materials are applied for renovation.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/buildings16040722/s1>. The ecoinvent records and the life cycle scenarios are described per installed material for all elements and all renovation approaches in the Supplementary Materials.

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Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GHG	Green House Gas
LCA	Life Cycle Assessment
UN	United Nations
COP	Conference of the Parties (Climate Change Conference)
CE	Circular Economy
EPBD	Energy Performance and Building Directive
TOTEM	Tool to Optimise the Total Environmental impact of Materials
EoL	End of Life

MMG	Milieugerelateerde Materiaalimpact van Gebouw(element)en
PUR	Polyurethane
ETICS	ETICS
EPS	Expanded Polystyrene
PVC	Poly Vinyl Chloride

Appendix A

Appendix A.1

In this appendix, Table A1 presents the detailed buildups for the floor on ground.

Table A1. Buildups for renovation of floor on ground (U-value 0.24 W/m²K).

	Material/Process	Thickness (m)	Lambda Value (W/mK)
Traditional renovation approach	Glazed ceramic tiles	0.01	0.83
	Reinforced cement-based screed	0.05	1.35
	Proofing sheet PE	0.002	n.a.
	PUR foam	0.11	0.028
	Reinforced concrete	0.15	1.7
	Proofing sheet PE	0.02	n.a.
	Levelling layer compacted sand	0.1	n.a.
	Levelling process	n.a.	n.a.
	Excavation process	0.26	n.a.
	<i>Demolition existing ceramic tiles</i>	<i>n.a.</i>	<i>n.a.</i>
	<i>Demolition existing screed</i>	<i>n.a.</i>	<i>n.a.</i>
Avoided material approach	Reinforced concrete	0.15	1.7
	Proofing sheet PE	0.002	n.a.
	Cellular glass granulates	0.33	0.082
	Proofing sheet PP	0.005	n.a.
	Levelling layer compacted sand	0.1	n.a.
	Levelling process	n.a.	n.a.
	Excavation process	0.42	n.a.
	<i>Demolition existing ceramic tiles</i>	<i>n.a.</i>	<i>n.a.</i>
Reclaimed material approach	Reclaimed glazed ceramic tiles	0.01	0.83
	Reinforced cement-based screed	0.05	1.35
	Proofing sheet PE	0.002	n.a.
	PUR foam 11 cm	0.11	0.028
	Reinforced concrete 15 cm	0.15	1.7
	Proofing sheet PE	0.02	n.a.
	Levelling layer reclaimed compacted sand	0.1	n.a.
	Excavation process	0.26	n.a.
	<i>Demolition existing ceramic tiles</i>	<i>n.a.</i>	<i>n.a.</i>
	<i>Demolition existing screed</i>	<i>n.a.</i>	<i>n.a.</i>
Recycled material approach	Recycled glazed ceramic tiles	0.01	0.83
	Reinforced cement-based screed	0.05	1.35
	Proofing sheet PE	0.002	n.a.
	PUR foam 11 cm	0.11	0.028
	Reinforced concrete with recycled granulates 15 cm	0.15	1.7
	Proofing sheet PE	0.02	n.a.
	Levelling layer compacted sand	0.1	n.a.
	Excavation process	0.26	n.a.
	<i>Demolition existing ceramic tiles</i>	<i>n.a.</i>	<i>n.a.</i>
	<i>Demolition existing screed</i>	<i>n.a.</i>	<i>n.a.</i>

Table A1. Cont.

	Material/Process	Thickness (m)	Lambda Value (W/mK)
Bio-based material approach	Hardwood parquet	0.02	0.12
	Anhydrite screed	0.08	1.35
	Proofing sheet PE	0.002	n.a.
	Anhydrite floor slab	0.16	0.07
	Proofing sheet PE	0.02	n.a.
	Expanded clay grains	0.2	0.104
	Proofing sheet PP	0.05	n.a.
	Gravel	0.3	n.a.
	Proofing sheet PP	0.05	n.a.
	Levelling layer compacted sand	0.1	n.a.
	Levelling process	n.a.	n.a.
	Excavation process	0.77	n.a.
	Demolition existing ceramic tiles	n.a.	n.a.
	Demolition existing screed	n.a.	n.a.

Appendix A.2

In this appendix, Table A2 presents the detailed buildups for the external wall.

Table A2. Buildups for renovation of external wall (U-value 0.24 W/m²K).

	Material/Process	Thickness (m)	Lambda Value (W/mK)
Traditional renovation approach	Calcareous plaster	0.0125	0.69
	Existing brick wall	0.34	0.59
	Wooden structure (10%)	0.08	n.a.
	Stone wool insulation (90%)	0.14	0.036
	Wind and water barrier foil	0.0025	n.a.
	Wooden framework (intensively ventilated cavity)	0.035	n.a.
	Fibre cement facing tiles	0.02	n.a.
	Demolition existing plaster	n.a.	n.a.
Avoided material approach	Calcareous plaster	0.0125	0.69
	Existing brick wall	0.34	0.59
	Levelling layer cement	0.02	n.a.
	EPS insulation	0.12	0.034
	External rendering	0.015	0.35
	Demolition existing plaster	n.a.	n.a.
Reclaimed material approach	Calcareous plaster	0.0125	0.69
	Existing brick wall	0.34	0.59
	Reused wooden structure for insulation (10%)	0.2	n.a.
	Reused stone wool insulation (90%)	0.2	0.05
	Wind and water barrier foil	0.0025	n.a.
	Reused wooden framework (intensively ventilated cavity)	0.035	n.a.
	Reused fibre cement facing tiles	0.04	n.a.
	Demolition existing plaster	n.a.	n.a.

Table A2. Cont.

	Material/Process	Thickness (m)	Lambda Value (W/mK)
Recycled material approach	Existing brick wall	0.34	0.59
	Steel structure (10%)	0.14	n.a.
	Recycled cotton insulation (90%)	0.14	0.036
	Vapour barrier foil	0.0025	n.a.
	Steel structure	0.06	n.a.
	Gypsum plasterboard with recycled content	0.0125	n.a.
	<i>Demolition existing plaster</i>	<i>n.a.</i>	<i>n.a.</i>
Bio-based material approach	Loam plaster	0.02	0.8
	Existing brick wall	0.34	0.59
	Wooden structure (10%)	0.08	n.a.
	Woodfibre flakes insulation (90%)	0.08	0.038
	Woodfibre board	0.07	0.04
	Wooden framework (intensively ventilated cavity)	0.06	n.a.
	Wooden cladding	0.02	n.a.
	<i>Demolition existing plaster</i>	<i>n.a.</i>	<i>n.a.</i>

Appendix A.3

In this appendix, Table A3 presents the detailed buildups for the pitched roof.

Table A3. Buildups for renovation of pitched roof (U-value 0.24 W/m²K).

	Material/Process	Thickness (m)	Lambda Value (W/mK)
Traditional renovation approach	Gypsum plasterboard	0.012	0.24
	Wooden battens	0.035	0.14
	PE vapour barrier	0.020	n.a.
	Existing wooden roof structure	0.18	n.a.
	Stone wool insulation between roof structure	0.14	0.036
	Wind and water barrier PP-PE foil	0.0025	n.a.
	Battens and counter battens	0.06	n.a.
	Unglazed ceramic roof tiles	0.04	n.a.
	<i>Demolition existing battens and counter battens</i>	<i>n.a.</i>	<i>n.a.</i>
	<i>Demolition existing unglazed ceramic roof tiles</i>	<i>n.a.</i>	<i>n.a.</i>
Avoided material approach	PE vapour barrier	0.020	n.a.
	Existing wooden roof structure	0.18	n.a.
	PUR insulation panels	0.12	0.022
	Wind and water barrier PP-PE foil	0.0025	n.a.
	Battens and counter battens	0.06	n.a.
	Unglazed ceramic tiles	0.04	n.a.
	<i>Demolition existing battens and counter battens</i>	<i>n.a.</i>	<i>n.a.</i>
Reclaimed material approach	<i>Demolition existing unglazed ceramic roof tiles</i>	<i>n.a.</i>	<i>n.a.</i>
	Gypsum plasterboard	0.012	n.a.
	Reused battens	0.035	n.a.
	PE vapour barrier	0.020	n.a.
	Existing wooden roof structure	0.18	n.a.
	Reused stone wool insulation	0.18	0.05
	Woodfibre board	0.022	0.04
	Reused battens and counter battens	0.06	n.a.
	Reused unglazed ceramic tiles	0.04	n.a.
	<i>Demolition existing battens and counter battens</i>	<i>n.a.</i>	<i>n.a.</i>
	<i>Demolition existing unglazed ceramic roof tiles</i>	<i>n.a.</i>	<i>n.a.</i>

Table A3. Cont.

	Material/Process	Thickness (m)	Lambda Value (W/mK)
Recycled material approach	Gypsum plasterboard (20%RC)	0.012	n. a
	Battens	0.035	n.a
	PE vapour barrier	0.020	n.a
	Existing wooden roof structure	0.18	n.a
	Cotton insulation	0.12	0.037
	Wind-and water barrier PP-PE foil	0.022	0.04
	Battens and counter battens	0.06	n.a
	Unglazed ceramic tiles	0.04	n.a
	Demolition existing battens and counter battens	n.a.	n.a.
	Demolition existing unglazed ceramic roof tiles	n.a.	n.a.
Bio-based renovation approach	Wooden planks	0.013	0.24
	Wooden battens	0.035	0.14
	PE vapour barrier		n.a.
	Existing wooden roof structure	0.18	n.a.
	Cellulose insulation	0.14	0.038
	Woodfibre board	0.022	0.04
	Battens and counter battens	0.06	n.a.
	Wooden shingles	0.08	n.a.
	Demolition existing battens and counter battens	n.a.	n.a.
	Demolition existing unglazed ceramic roof tiles	n.a.	n.a.

Appendix A.4

In this appendix, Table A4 presents the detailed buildups for the windows.

Table A4. Buildups for renovation of windows.

	Material/Process	U-Value (W/m ² K)
Traditional renovation approach	New PVC window frame	1.50
	New double glazing with argon filling	
Avoided material approach	Existing PVC window frame	2.70
	New double glazing with argon filling	
Reclaimed material approach	Reclaimed PVC window frame	3.50
	Reclaimed double glazing without argon filling	
Recycled material approach	PVC window frame with 50% recycled content	1.50
	New double glazing with argon filling	
Bio-based material approach	New wooden window frame	1.50
	New double glazing with argon filling	

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