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Towards Assessing Embodied Emissions in Existing Buildings LCA—Comparison of Continuing Use, Energetic Refurbishment versus Demolition and New Construction

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Abstract: One of the main objectives facing climate protection targets is how to deal with the existing building stock. Refurbishment measures are essential to ensure sustainable urban transformation. Life cycle assessments (LCAs) enable refurbishment measures to be evaluated holistically at the environmental level. However, there is still no sufficient methodological basis for the uniform evaluation. This present paper proposes a new perspective for comparing the continuing use with refurbishment as well as the demolition and new construction of a building. Thus, two new indicators are presented and elaborated regarding refurbishment measures: sustained emissions and the avoidance potential. To verify and validate the newly developed methodology, we implement it as part of this case study. We compare the environmental impact of a building's continuing use with refurbishment measures as well as demolition and a replacement building with functional equivalence. The results indicate the environmental benefits of refurbishment measures compared to other approaches towards existing buildings. Although new buildings typically possess a superior energy standard, nevertheless, irrespective of the major impact of operational energy, refurbishment measures appear to be the most viable option for dealing with existing buildings over their life cycle.

Keywords: embodied emission; operational emission; LCA; refurbishment; GHG emission; building stock

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1. Introduction

Anthropogenic climate change is becoming one of the most challenging problems facing modern society. Only 400 Gt of CO_2 emissions remain in the coming years to meet the 1.5 °C target with a high probability as specified in the Paris Climate Agreement in 2015 [1]. With the Green Deal in 2019, the European Commission set a common direction for the EU, specifying an emission reduction of 55% by 2030 compared to the year 1990 to secure this path. Requirements and guidelines are provided for all sectors. The key reduction targets for emissions and energy demand are accompanied by economic and social challenges. Sustainable transformation obviously must be pursued at various scales and requires a holistic approach at all times. Nevertheless, it is essential to address individual disciplines first to subsequently develop specific approaches. Integration and adaptation into the other sustainability dimensions are then mandatory.

Of the global energy-related CO_2 emissions, approximately 37% are accounted for by the building sector [2]. The energy demand of the building stock is largely influenced by the heating and cooling of spaces, domestic hot water, lighting, as well as cooking and other uses. Together, these components account for about 30% of the total final energy demand, although the figures have been steadily increasing for years [3]. Fossil fuels provide significantly more than half of the heat (around 57%) produced in European households and houses. In particular, gas with 39%, oil with 15% and coal with 4% were used for energy supply [4]. Conventional heating systems and energy sources are largely contributing to the high emission levels in the building sector. However, emissions from the production, use and demolition of building materials are not precisely captured, likely resulting in a higher overall level for a holistic assessment of the building sector. Since not only new buildings with optimized energy efficiency are being constructed, existing buildings require sustained refurbishment to meet climate protection targets. Embodied emissions are increasingly relevant and provide a new approach to the whole-life carbon emission consideration. Depending on building age as well as energy efficiency, the shares of operational and embodied energy may vary considerably. In low-energy buildings, the embodied energy share, for instance, ranges between 26% and 57%, whereas the proportion in higher-performance passive houses is estimated to range between 11% and 33% by Chastas et al. [5]. Conventional buildings yield embodied energy ratios of between 6% and 20%, whilst the varying influences for refurbished existing buildings have not been investigated yet [6]. Moreover, the significance of the extended consideration of embodied emissions in the existing building stock and refurbishment measures becomes evident once the fact that about 80% of the buildings in the EU already existing today will remain in 2050 [7] is considered. Focusing further on a national level in Germany, the majority of the buildings were erected before the first comprehensive regulation was enacted and hence were not subject to any regularisation for energy-efficient buildings [8]. Thus, the implementation of energy-efficient refurbishment measures requires an integrated consideration of operational as well as embodied emissions. As a result, the energy supply can be optimized on the one hand, but particular environmental impacts can be minimised by the choice of building materials.

However, not only refurbishment measures as actions for the subsequent interaction with the existing building stock require a fundamentally integral approach. Considerations for dealing with existing buildings require rethinking and regulation overall. In this paper, the building stock, in general, will be the focus of comparing scenarios and how to proceed with existing buildings for further use or demolition and new building projects. One decisive criterion within this consideration is the embodied emissions of the existing building stock that have already occurred in the past and can help with the avoidance of new emissions in the future.

This present paper proposes a methodology for the comparative LCA study of different building use scenarios. In particular, the different consideration of refurbishment measures in contrast to the demolition and new construction of a functionally equivalent building forms the central focus. Moreover, the continuing use of a building without any intervention provides a basis for further comparison. Since the assessment of existing buildings has not yet been harmonized and special features apply to already built structures as well as to already caused environmental impacts, new approaches are proposed in this paper. On the one hand, the scope of LCA is enhanced to include the avoidance potential of emissions via the continued use of existing buildings. Moreover, sustained emissions serve as a quantification of the environmental impact potential of the remaining materials based on the avoidance potential calculations. As a comparison unit, the Global Warming Potential (GWP) is used, which is presented in the GWP total on the one hand but also differentiated in GWP fossil and biogenic on the other [9].

After an overview of the latest challenges is provided in the first part of this paper, the current state of research as well as research gaps and requirements are presented. Subsequently, the methodology for assessing the comparative data is illustrated. To validate the methodology, an example building is examined. This building will be briefly presented, and key structural aspects will be highlighted.

The results of the different assessments are presented and described in detail in the third chapter. Following the presentation of the results, a discussion is carried out that coherently describes the essential findings and raises critical points where necessary.

Finally, the conclusion provides a comprehensive overview and highlights the implications of the results as well as their relevance regarding future studies.

1.1. Life Cycle Assessment of Buildings

Life cycle assessment (LCA) is an established tool for considering and quantifying the potential environmental impacts of human-made processes and activities. Basic principles are defined in EN ISO 14040:2021-02 [10] and EN ISO 14044:2021-02 [11]. A specified assessment of the environmental performance of buildings is enabled in EN 15978:2021-09 [12], providing details of the system boundaries and procedures for the building level. By considering individual life cycle modules separately, the entire life cycle of a building can be assessed. Figure 1 illustrates the composition of the life cycle for buildings, with Module A representing the manufacturing and construction, Module B the operation, and Module C the disposal phase. Module D contains separate information on recyclability. The modules framed in red are considered relevant for the assessment presented in this paper.

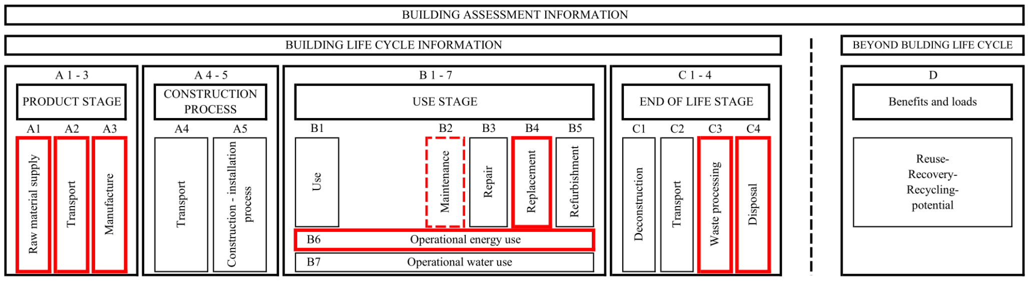

Figure 1. Life cycle phases of buildings adapted with permission from [13].

A standardized data basis is defined in EN 15804:2022-03 [9], specifying the basic rules for the life cycle assessment of construction products. Environmental Product Declarations (EPD) provide information on resource consumption or environmental impacts and are predefined as uniform for construction products. The German online database ÖKOBAUDAT is provided publicly as a central platform for EPD in compliance with EN 15804 [14]. Essential information for the impact assessment can be found aggregated within the database. In addition, service lives for building structures are used to model replacement intervals throughout the life cycle of buildings. A consistent base [15] has been established by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development and provides information about the service life of common building components and structures.

For new buildings, LCAs have been studied in detail and are standardized in the previously mentioned standards. However, there are still major gaps in research for refurbishment measures. Hafner and Storck [16] have developed a methodology for LCA of vertical building extensions with equivalent applicability to the analysis of refurbishment measures of buildings. Recently, EN 15978-1:2021-09 [12] was amended accordingly and is now under review. The elevation of the building level and expansion of the system boundaries to the neighbourhood and municipal level were then methodologically specified by Slabik et al. [17,18]. Large-scale refurbishment projects are the focus and can be compared in a consistent manner using a unified approach. Transforming the building stock in fact requires consideration of larger systems, albeit based on building data.

Most LCA approaches for refurbishment measures, however, only include the impact of the building materials brought in during the measure and the improvement of energy efficiency. In this present paper, we will focus on how exactly to handle the existing building stock and the emissions that have already been caused.

1.2. Current State of Research

In the scientific literature, several studies concerning the environmental impact of the continuing use of existing buildings have been carried out. Most recently, the studies have focused on the saving potential of embodied energy and environmental impacts.

Still, Vilches et al. found that there is a lack of studies applying the LCA approach to building renovations, and they recommend further research in this field [19]. Similar conclusions can be drawn from the results of Schwartz et al. [20]. Based on the LCA results available in the literature, the authors statistically investigated whether renovated buildings or new buildings show higher environmental impacts over their life cycle. If only residential buildings from one geographical region are considered, the environmental impacts of renovated buildings are on average statistically significantly lower, but there are still new buildings that perform better than the best renovations examined. The authors, therefore, conclude that it is still difficult to classify an alternative as “better” on the basis of the available data [20]. These results show that, based on the currently available sources in the literature, no clear statement can be made as to whether new construction or renovation is to be preferred regarding their environmental impacts. One aim of this paper is to provide further results to answer this question.

Besides the statistical evaluation of the available sources by Schwartz et al., there are a number of case studies that have dealt with the question of the environmental impacts of demolition and new construction or the continued use of a building on the basis of an exemplary building [21–35].

When examining the case studies, the methodological approaches for the comparison of demolition and new construction or continued use of buildings differ greatly, which influences the results and hinders comparability. While some studies only consider embodied environmental impacts [21–25], others also include the operation of the building in their considerations [26–35].

Vilches et al. have found significant differences in the life cycle modules included when comparing different LCA results of renovation measures. They found particularly significant differences in the handling of the EoL scenarios [19]. A closer examination of the existing case studies comparing refurbishment measures with demolition and new construction supports the findings of Vilches et al. Hasik et al. have developed a methodology for comparing both scenarios based on a literature review [24]. Their method considers the entire life cycle of the newly installed materials as well as the use phase of the reused materials. Deconstruction for renovation or the necessary demolition for new construction is not included, and the operational energy use is not considered. The results show a GWP saving of 75% by continuing the use of the building compared to a new construction [24]. In contrast to Hasik et al., Zimmermann et al. propose to include the demolition of existing structures in a framework for comparing new construction and continued use. They introduce the new LCA modules, C1 and D1, and the results are given as the sum of C1 and D1. The components installed during the construction of the new building or renovation of the existing one are reported in Module A. All newly installed and reused components remaining in the building after the initial construction work are analysed in modules B, C and D. Based on this framework, they conduct a case study of the continued use, renovation, demolition and new construction of a school building. They come to the conclusion that renovation shows the lowest environmental impacts over the life cycle, while new construction and continued use show very similar slightly higher results [28]. In a study by Slabik et al., a methodical approach for assessing refurbishment measures is elaborated. As a result, the demolition of existing building parts is calculated in Module C at time zero (C_0); Module D was not considered over the life cycle [17]. The methodology of Slabik et al. will be used in this paper and is described in detail in Section 2. The literature examples illustrate how relevant it is to establish and apply a uniform framework for comparing the results of demolition and new construction with the continued use of a building. While Hasik et al. arrive at about 75% lower CO_2 emissions for the alternative of continued use, Zimmermann et al., including both modules, arrive at a reduction of only 15–20% [24,28].

The results of other studies are also subject to significant variation. For example, the results of different studies on the saving potential of embodied carbon for renovations compared to demolition and new construction range between 13 and 92% [21–24,26,29,32,34]. The relatively large range of variation can be explained on the one hand by the unique character of the buildings and measures examined but, on the other hand, by the inconsistency in the treatment of LCA modules already mentioned above.

In studies that consider both embodied carbon and operational emissions, significant differences in the results can be observed as well. Weiler et al. conclude that compared to continued use, refurbishment measures are advantageous in terms of environmental impact after 4.5 years and new construction after 7.5 years, while Berg et al. see an advantage for refurbishment after only 6 months [27,29]. When comparing demolition and new construction with refurbishment, the influence of the energy mix during the use phase becomes evident.

Berg and Fuglseth come to an environmental payback time of the additional expenses of the new building in the construction phase via a lower energy demand in the use phase compared to the refurbished existing building after 52 years [29]. Fufa et al. and Plavina and Gruner concluded that when a heat pump is used for heating, supplied by the Norwegian electricity mix, there is no amortisation of the additional expenses coming from the construction of the new building over the 60-year life cycle when compared to the refurbished existing building. If the European electricity mix is used as a basis for operating the heat pump, the new construction will be amortised after 5 or 22 years, respectively, due to the significantly lower operating emissions of the new building in this case [26,30]. These results clearly illustrate the relevance of emission factors during operation for the comparison of demolition and new construction and continued use of a building. In the case of high emission factors, higher operating energy requirements of the renovated building compared to a newly constructed one can lead to higher total emissions over the life cycle for the renovation scenario. In the case of lower emission factors, this relationship can be reversed.

In the literature, no paper could be identified that deals with the influence of different construction options of new buildings compared to continued use. In particular, the comparison of the continued use of an existing mineral building with a new timber construction has not yet been carried out. Even though different building materials show clear differences in their environmental impacts [13]. A question directly linked to the integration of biogenic building materials into an LCA is how to deal with the biogenic carbon content of refurbishment in buildings. Besana and Tirelli discuss different ways of dealing with this problem in their case study and recommend further research on the topic for all life-cycle modules [22].

Similarly, there is no concept yet to describe the environmental potential through the continued use of an existing building. This potential could attribute an ecological value to an existing building, even though the continuing use does not cause or save direct emissions.

2. Methodology

For LCA of existing buildings and activities incurred as part of refurbishment measures, the reuse of already installed and thus existing building materials needs to be accounted for as well during the construction of existing buildings energies and emissions occurred in the past, which are not currently being considered in the existing approaches. However, these expenses must not be neglected, although they have no additional impact on the environment, neither now nor in the future, and nor can they be reclaimed. Reusing existing building materials and structures, on the other hand, offers two major benefits: reducing the production of additional building materials and postponing the disposal of existing structures. Although EN 15978:2021-09 [12] proposes preservation and reuse of building components by crediting Module A impacts to Module D, this only provides theoretical savings over a fictional replacement option and is not calculated within the boundaries of the product system. Moreover, only the savings from reduced demand for building products are covered in this approach.

To assess and compare environmental impacts of refurbishment measures, a clear methodology is needed. Previous research [17] in this field leads to the methodology shown in Figure 2, as described in Section 1.2. The starting point of consideration for the entire building is the time of the actual refurbishment at time zero. Materials, which are removed from the building, are assessed in Module C3-4 at time zero (C_0), whereas new materials, such as insulation or windows, are covered in Module A1-3 at time zero (A_0). The modules and sub-modules used are shown in Figure 1**.** After the refurbishment, the assessment period is set to 50 years as a further life cycle of the building. Setting the life cycle to a fixed value of 50 years mainly follows the design working life recommended in EN 1990 and established sustainability certification systems [13,36]. Within this time frame, components are maintained and replaced in accordance with their service life (Modules B2-4), resulting in two different replacement cycles depending on the origin of the materials considered. First, the new components, are replaced following the replacement cycle rules of new buildings. Secondly, materials remain in the building stock but have a shorter lifespan than the estimated 50 years. The replacement cycles for the stock materials are based on the year of construction of the existing building, and the following replacement cycles are considered. Module B6 as the operational energy use is assessed over the life cycle. After 50 years, the entire building consisting of stock and new materials is assessed in Module C at time 50 (C_{50}). Module D is not considered according to the valid standards.

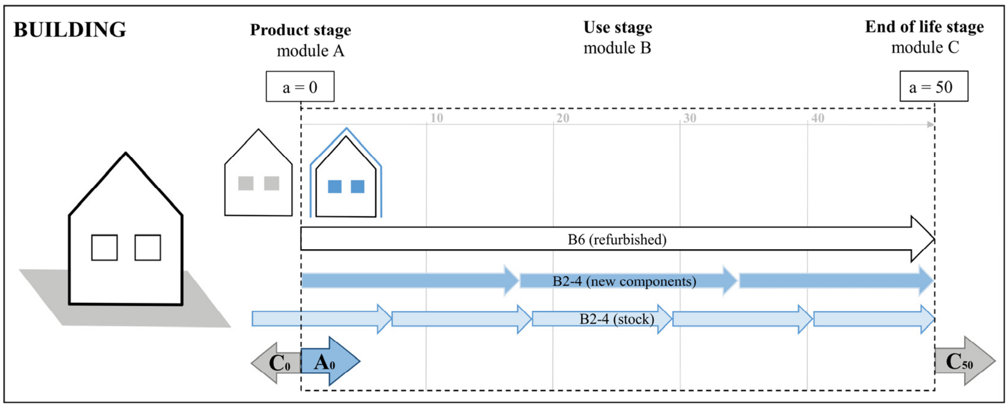

Figure 2. LCA methodology for refurbishment on the building level [17].

The savings in embodied emissions represent a comparison between two different variants. In particular, the comparison between the continued use of a building versus the demolition and new construction of the same building as a substitute becomes relevant. It is assumed that the impacts from Modules A_0 and C_0 will be significantly higher in the case of demolition and new construction since considerably more new materials must be disposed of and produced. However, continued use appears to have a reasonable potential because the impacts from Modules A_0 and C_0 are expected to be less since existing structures will continue to be used, and no or comparably fewer new building materials and constructions will have to be constructed and removed.

It should be noted that the continued use of existing structures does not result in actual savings of emissions or energy but rather causes additional environmental impacts. For instance, the production of insulation materials needed for refurbishment initially generates emissions and requires energy. However, actual energy and emission savings ("avoided impacts") are derived when considering the life cycle of the building, particularly when Module B6 is accounted for.

The biogenic carbon content of materials can lead to bias of results in GWP results. In particular, Module C_0 and the biogenic carbon content of stock materials can distort comparability of scenarios, if not assessed correctly. According to [37], at the time of complete oxidation, the quantity of CO_2 bound in the biomass and the equivalent amount of CO_2 emissions from the biomass results in a net CO_2 emission value of exactly zero when integrated over time. The normative base for estimating the biogenic carbon content is provided in EN 16449:2014-06 [38]. In assessing environmental impacts of refurbishments of buildings, the overall net zero emissions approach must be ensured [39]. Firstly, components of the existing building, which have a biogenic carbon content, are transferred into a new product system. The carbon content is assessed as -1 kg CO_2-eq/kgCO_2 negatively in the new product system. At the end of the life cycle, the same amount of +1 kg CO_2-eq/kgCO_2 is considered, as described in [37], to ensure net zero emissions. The carbon content of removed materials in Module C_0 is assessed negatively in the product system but is also removed as a positive value from the system simultaneously, resulting in net zero emissions. Thus, the biogenic carbon content of dismantled materials is not considered. For new materials (Module A_0), the carbon content is calculated as in the case of new buildings, leading to -1 kg CO_2-eq/kgCO_2 at time zero and +1 kg CO_2-eq/kgCO_2.

The advantages of energetic refurbishment of buildings or demolition and new construction of buildings are linked with the savings in the use stage as operational emissions as well as emissions from maintenance and replacement compared to the emissions caused by the material input in the first place (upfront emissions). Therefore, the number of years required to recover the material emissions (C_0 and A_0) in comparison to emissions caused by operational energy demand ($B6$) and maintenance and replacement ($B2$-4) gives an overview of the effectiveness of the variants. To estimate the environmental payback time of the scenarios, the following formula is used:

$$\left| \frac{(C_0 + A_0)_{Var1} - (C_0 + A_0)_{Var2}}{(B2\text{-}4 + B6)_{Var1} - (B2\text{-}4 + B6)_{Var2}} \right| = \left| \frac{\Delta(C_0 + A_0)}{\Delta(B2\text{-}4 + B6)} \right| \tag{1}$$

Here, Modules $B2$-4 and Module $B6$ are assessed as emissions per year, whereas C_0 and A_0 are assessed as absolute values since they only occur once in the life cycle. The greater the difference between operational energy emissions, the shorter the environmental payback. On the other hand, greater material-related emissions can result in a longer environmental payback time.

2.1. Avoidance Potential

The "avoidance potential" (AP) constitutes the highest possible savings potential of embodied energy and environmental impacts via the continued use of an existing building. It combines the expenses from Module A, which would be necessary to construct the existing building today, and the sum of the expenses from Module C, which would be required to demolish the existing building entirely.

- AP I: Total expenditure from Module A necessary to construct the existing building today.
- AP II: Total expenditure from Module C required to demolish the existing building.

Both the environmental impacts of the delayed demolition and the avoidance of new building material production required for an equivalent building are included. The AP can provide a building with an environmental value and can be used as an informative parameter to determine the further use or the demolition of an existing building, for instance. However, the value is to be interpreted as a theoretical value and does not represent a complete LCA of different scenarios.

2.2. Sustained Emissions

The impact of various measures in existing buildings can be quantified using the "sustained emissions" (SE). SE describe the environmental impact potentials of remaining materials, following the calculations of the AP. Whether the reason for the measure is a refurbishment for energetic improvement, an extension for providing new living space or the removal of pollutants is irrelevant. In all cases, it is only important that existing structures are preserved, and others are demolished. Ultimately, the level of intervention of the corresponding measure determines how much of the original AP can effectively be achieved. The SE consists of the sum of the following shares:

- SE I: Total expenditure from Module A necessary to construct the components of the original building stock still remaining after the measure.

- SE II: Total expenditure from Module C that it would take to demolish the remaining components.

The SE allow an assessment of the environmental impacts of the original building, which are still present in the existing building, e.g., after a refurbishment. Thus, environmental impacts can be quantified and compared for different utilisation or refurbishment measures. In particular, for the comparison between the scenarios, (i) refurbishment and (ii) demolition and new construction, the preserved emissions can be used as a basis for contrasting emissions and environmental impacts. However, actual emission reductions when compared to the complete preservation of the building will be caused by the reduction or decarbonisation of the operational energy use.

2.3. Object of Investigation

In this present case study, the investigated building is a multi-family house from the year 1962 with three residential floors and a basement. The building has a gross floor area of 1659 m^2 and a net floor area of 1458 m^2. In Table 1, the structures of the existing building are presented under the scenario of continuing use. Both the stairs and the balconies of the house were constructed of reinforced concrete.

Table 1. Building constructions of different utilization variants.

Building Part	Continuing Use	Energetic Refurbishment	Demolition/New Construction Timber	Demolition/New Construction Mineral
Foundation	Reinforced Concrete Strip Foundation 30 × 30 and 30 × 45 cm Floor Slab: 20 cm	Reinforced Concrete Strip foundation 30 × 30 and 30 × 45 cm Floor Slab: 20 cm	Reinforced Concrete Floor Slab 35 cm on a Blinding Layer Insulation 6 cm XPS	Reinforced Concrete Floor Slab 50 cm
External Wall	1 cm Plaster 30 cm Brick wall 1.5 cm Plaster U =1.17 W/m^2K	1 cm Plaster 30 cm Brick Wall 16 cm EPS-insulation 1.5 cm Plaster U = 0.18 W/m^2K	1.5 cm Plaster board 5 cm Mineral Wool Insulation 2.2 cm OSB-Board 24 cm Insulated Wooden Frame 1.5 cm Gypsum Fibre Board Sealing and 2.2 cm Wooden Facade U = 0.14 W/m^2K	1 cm Plaster 42.5 cm Poroton Brick Wall 2 cm Plaster U = 0.18 W/m^2K
Windows	Plastic Windows U = 1.36 W/m^2K	Plastic Windows U = 1.1 W/m^2K	Plastic Windows U = 0.9 W/m^2K	Plastic Windows U = 0.9 W/m^2K
Internal Walls	Masonry Walls varying between 24, 17.5 and 11.5 cm	Masonry Walls varying between 24, 17.5 and 11.5 cm	Load bearing Wooden Walls and Drywalls of varying thickness	Load bearing Reinforced Concrete Walls and Drywalls of varying thickness
Ceiling	1 cm Plaster 20 cm Reinforced Concrete Ceiling 2 cm Sound Insulation 5 cm Floating Screed 0.4 cm Vinyl Flooring U = 0.95 W/m^2K	1 cm plaster 20 cm Reinforced Concrete ceiling 2 cm sound insulation 5 cm floating screed 0.4 cm vinyl flooring U = 0.95 W/m^2K	24 cm Cross Laminated Timber Ceiling 14 cm Gravel Fill 3.5 cm Sound Insulation 5 cm Heated Screed 1.5 cm Linoleum Flooring U = 0.24 W/m^2K	1 cm Plaster 24 cm Reinforced Concrete Ceiling 8 cm Mineral Wool Insulation Layer 3 cm Sound Insulation 5.5 cm Heated Screed 0.4 cm Linoleum Flooring U = 0.31 W/m^2K

Table 1. *Cont.*

Building Part	Continuing Use	Energetic Refurbishment	Demolition/New Construction Timber	Demolition/New Construction Mineral
Roof	20 cm Reinforced Concrete non-insulated Top Storey Ceiling Wooden Pitched Roof 5 cm Insulation Fibre Cement Plates U = 3.45 W/m^{2}K	20 cm Reinforced Concrete Top Storey Ceiling 24 cm Cellulose Insulation Wooden Pitched Roof Bitumen Roof Lining U = 0.15 W/m^{2}K	16 cm Cross Laminated Timber Ceiling 20 cm Mineral Wool Insulation 17 cm Mineral Wool Insulation (inclined) Bitumen Sealing 8 cm Green Roof Structure U = 0.09 W/m^{2}K	24 cm Reinforced Concrete Ceiling 14 cm Mineral Wool Insulation 24 cm Mineral Wool Insulation (inclined) Bitumen Sealing 3 cm EPS Insulation 8 cm Green Roof Structure U = 0.09 W/m^{2}K
Final Energy Demand	185.9 kWh/m^{2}a	61.4 kWh/m^{2}a	51.3 kWh/m^{2}a	51.3 kWh/m^{2}a

Based on an actual measure performed in 2015, the refurbishment scenario is described as follows. An EPS-based insulation system was installed, and the windows and the exterior doors were replaced. In addition, cellulose insulation was applied to the top floor ceiling, and a pollutant cleanup was carried out as well as the renewal of the roof. As part of the renovation, the existing reinforced concrete balconies were demolished and replaced with new steel balconies. Only minor changes were made to the interior of the building, with only the stairwells and basement being repainted and the basement floor repaired.

To examine the effects of demolishing and constructing a new building instead of continuing use of an existing building, two notional newly constructed buildings were modelled on the original building. These new buildings are functionally equivalent to the original building with identical cubic shape and net floor space, but with modern construction structures, whereby one new building variant is a timber construction, and the other is a mineral construction. The constructions used are shown in Table 1. Both variants feature reinforced concrete staircases, balconies, and exterior basement walls as well as green flat roofs.

For all variants investigated, district heating is used to supply the heat and hot water demand (Module B6.1). In the two continued use scenarios (continuing use and energetic refurbishment), radiators are used for space heating, while the new buildings feature underfloor heating. The plumbing and electrical installations were assumed to be identical for all buildings. The power consumption of residents was not considered, as it would result in similar consumptions for all variants in Module B6.3.

For the energy demand of the variants for continuing use and energetic refurbishment, data from the planning processes were used. The final energy demand for the new building variants is based on energy and thermal calculations. To improve comparability, the energy demand values for the new constructions were aligned.

3. Results

Following the pointed-out gaps in research in Section 1.2, the LCA results of the four scenarios are analysed firstly for the material-related emissions over the life cycle to show the potential environmental savings of continued use of material. Secondly, the impacts of calculating the biogenic carbon content of products are shown. Thirdly, the operational energy demand is added and displayed in relation to the overall LCA results, answering the questions of what influence the continued use of existing materials has compared to a new building in two different variants as well as what influence the operational energy demand has compared to material related savings over the life cycle.

3.1. Results of Embodied Emissions and Material-Related Potentials of Continuing Use

Figure 3 displays the benefits of continuing use of existing structures. The embodied emissions of the building are presented before construction, during construction and after the construction phase for four different scenarios. Here, all emissions from demolition and new buildings C_0 and A_0 and the future demolition C_{50} are considered equivalent new buildings, as described in Section 2.1 (AP) previously. Maintenance and replacement are not accounted for. The SE are those that will remain in the building during construction, for instance, in the case of energetic refurbishment. The results are calculated without the biogenic carbon content for all constructions, which is equivalent to GWP fossil according to EN 15804:2022-03 [9]. The continuing use of the building has no influence on the embodied emissions, while the energetic refurbishment parts of the building must be removed and more materials added to the building during the refurbishment measure. For the case of demolition and new construction, the embodied emissions are zero at the point of construction and depending on the use of material, rise again to a certain point after construction.

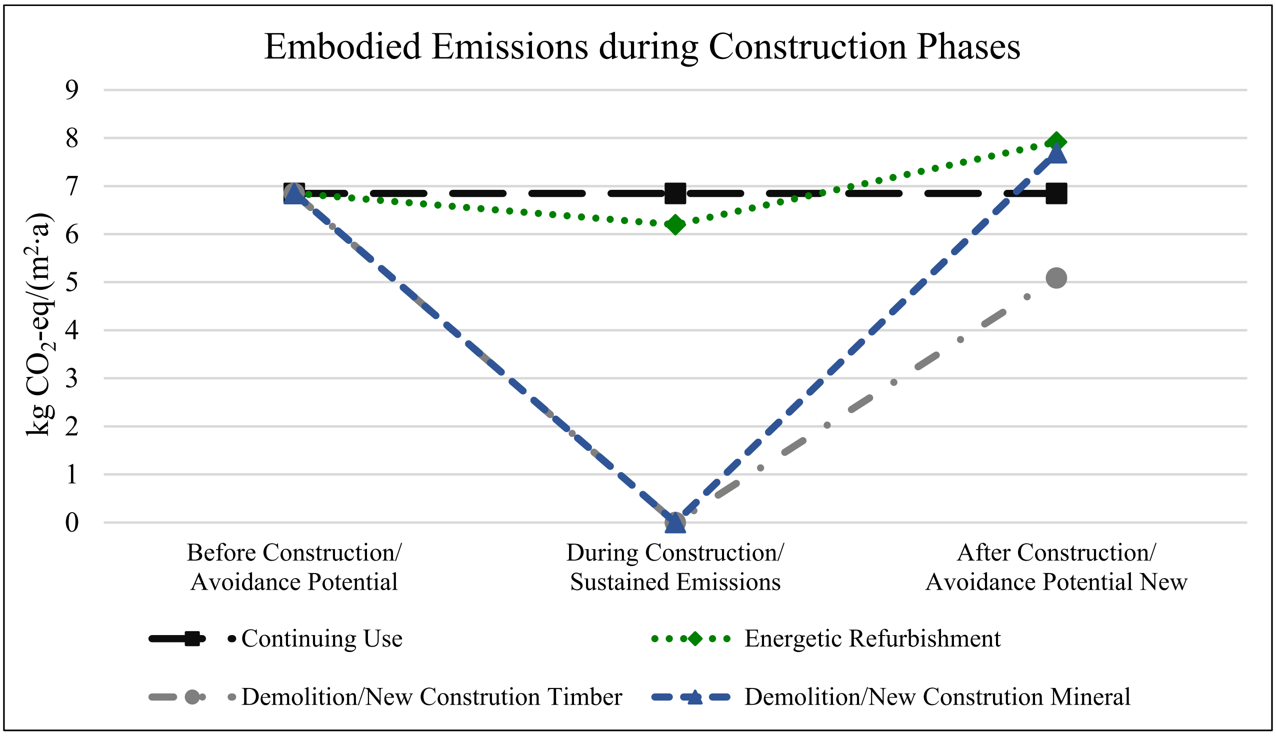

Figure 3. Material emissions during the construction phases as a comparison of the four scenarios.

In Table 2, the results of the potential of continuing use of materials are shown. Emissions of AP of the existing building and SE after energetic refurbishment are assessed in Module C and Module A in comparison to the SE resulting from existing materials. As it turns out, Module A has a much higher impact on the AP and SE than Module C. Additionally, about 90% of the AP will remain in the building, which means that 90% of the potential embodied emissions can be prevented. Due to this correlation, the benefits of refurbishment measures compared to the construction of new buildings become evident for considering embodied energies and emissions.

Table 2. Avoidance potential and sustained emissions of energetic refurbishment.

	Emissions of Module C	Emissions of Module A	Total Emissions of Modules A + C
	GWP [kg CO_2-eq./m^2a]	GWP [kg CO_2-eq./m^2a]	GWP [kg CO_2-eq./m^2a]
Avoidance potential	0.98	5.87	6.85
Sustained emissions	0.76	5.44	6.20

The results of embodied emissions for all four variants over the life cycle stages are shown in Figure 4. Life cycle stages range from the demolition of the existing components (C_0), the new components added to the product system (A_0), the replacement of building components according to their service life (B2-4) to the demolition of the entire building after the estimated life cycle of 50 years (C_{50}). Biogenic carbon content is not considered, and the results are referred to one square meter of net area per year as a functional unit. According to the obtained results, Module A_0 holds the highest impact for new buildings, mostly for new buildings in mineral construction, followed by new buildings in timber. Modules C_0, B2-4 and C_{50} have only a minor impact on the overall results. Continuing the use of the building entails the lowest embodied emissions over the life cycle, while the highest material-related emissions are caused by demolition and new mineral construction.

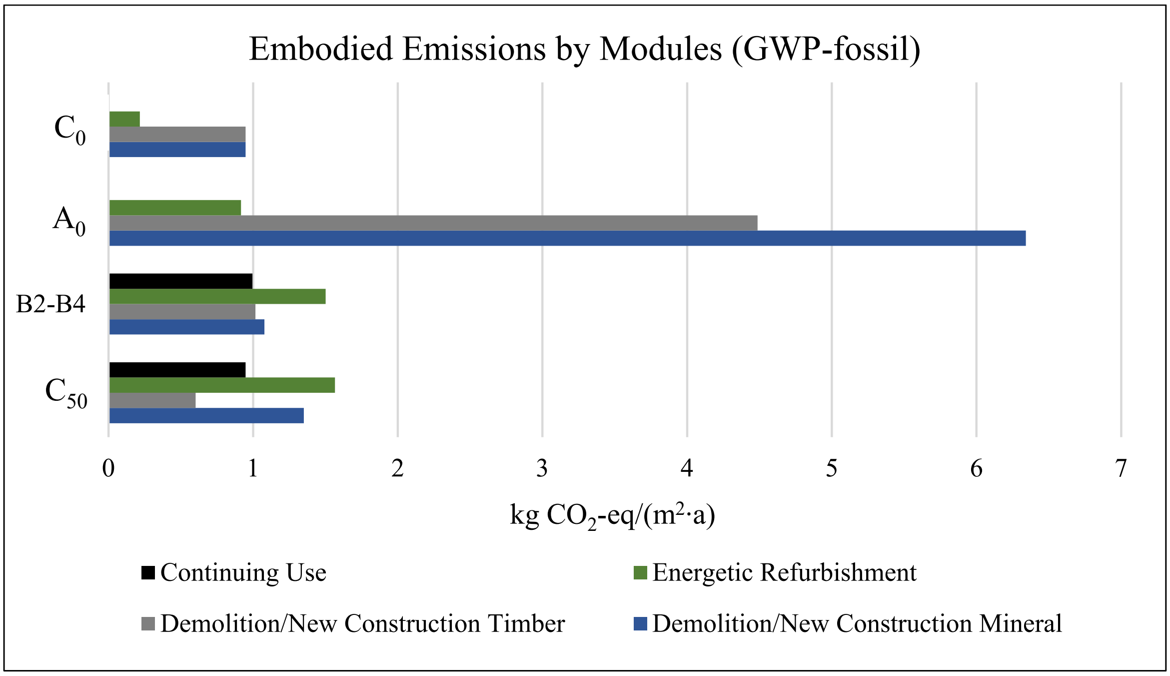

Figure 4. Embodied fossil emissions over the life cycle.

The sum of all material-related emissions is displayed in Figure 5. The new construction in minerals has the highest embodied emissions over the life cycle, followed by timber construction and energetic refurbishment. The embodied emissions of the continuing use are only based on calculations for Modules B2-4 and C_{50}. Due to not regarding the operational energy consumption and the related emissions over the life cycle, the results cannot be interpreted enough for decision making. Also, the upfront emissions as the sum of A_0 and C_0 for construction are presented. A great share of overall material emissions is caused by the upfront emissions in the case of demolition and new buildings. Further, the biogenic carbon content of the timber construction can shift the results of the upfront emissions in comparison to GWP total and GWP fossil.

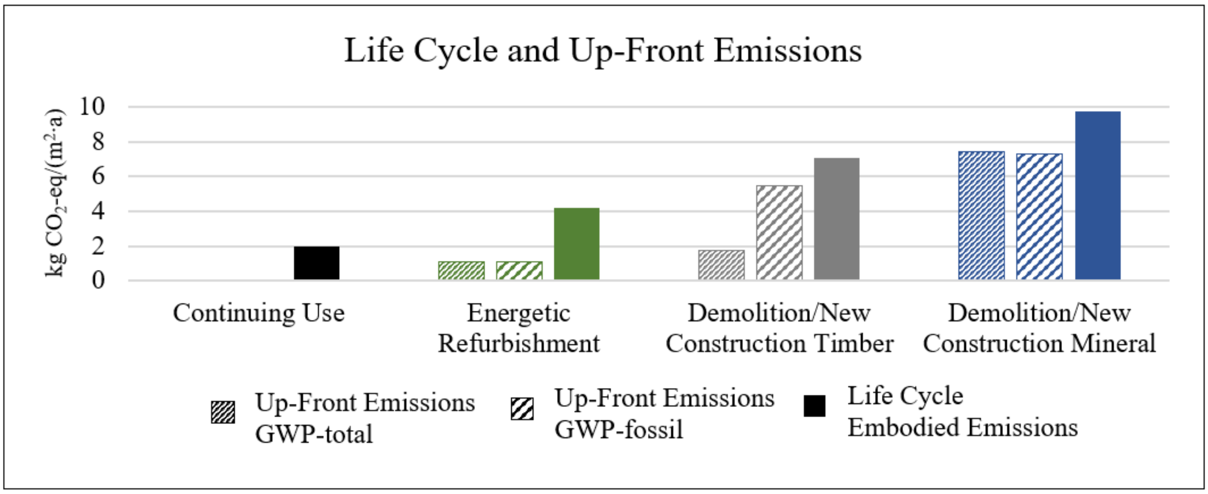

Figure 5. Comparison of the embodied emissions over the life cycle.

3.2. Impacts of the Biogenic Carbon Content on Embodied Emissions

Previously shown results mostly exclude the biogenic carbon content of different variants. Especially regarding the emissions of the demolition and new construction in timber, the biogenic carbon content has a great influence on the results. Thus, Figure 6 shows the influence of the biogenic carbon content on the life cycle modules. In Module C_0, the biogenic carbon content of the remaining parts is transferred to the subsequent product system for the case of continuing use and energetic refurbishment [37]. Comparing the biogenic carbon contents, which are transferred to the subsequent product system, the carbon content from the continuing use will always be equal or greater compared to the energetic refurbishment, which is due to products being dismantled for refurbishment measures. For materials that are disposed of during the construction, such as roof components, the biogenic carbon is calculated at -1 and +1 kg CO_2-eq./kg CO_2 as it enters and leaves the system at the same time and is, therefore, not assessed and displayed [37,39]. For new components, in the cases of energetic refurbishment and the two new construction variants, the biogenic carbon is assessed in Module A_0 negatively and in Module C_{50} positively with the same amount after 50 years. The biogenic carbon content of the new construction in timber is about 4 kg $CO_2/m^2{\cdot}a$, which is comparatively less than the fossil emissions for construction. The carbon content over the life cycle of the new construction is accounted for zero, but the actual emissions occur delayed over the life cycle, which is relevant for the assessment of GHG emissions on a national level [39]. The amount of biogenic carbon content is much higher for timber constructions in comparison to mineral constructions. For the case of energetic refurbishment, two biogenic carbon contents from the remaining parts of the building and the newly installed parts are calculated in C_{50}. To ensure future comparability in CO_2 emissions, it is recommended to use GWP fossil as an indicator.

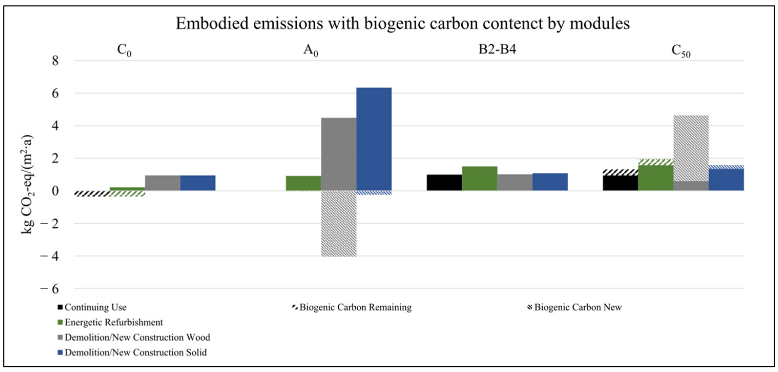

Figure 6. Embodied emissions with illustration of the biogenic carbon content.

3.3. Comparison Including the Operation Energy Emissions

In this section, the previously shown results are extended by adding the operational energy demand and the resulting emissions for the four variants over the estimated life cycle of 50 years, as shown in Figure 7. The x-axis shows the timeline of the life cycle, and the y-axis shows the cumulated fossil emissions of CO_2 equivalents. As expected, the energetic performance of the building has a significant influence on the overall results and should always be considered in cases of comparison. The variant of continuing use has the highest life cycle emissions with about 47 kg CO_2-eq/m^2·a, including embodied and operational emissions. The lowest total emissions are caused by the energetic refurbishment with about 19.62 kg CO_2-eq/m^2·a, followed by the new construction in timber with 19.95 kg CO_2-eq/m^2·a. The total emissions of the demolition and new construction in minerals is about 22.6 kg CO_2-eq/m^2·a, which is still less than half of the continuing use scenario. Module B6 represents the gradient of the graphs over the entire life cycle, while Modules B2-4 can be noted as small time-concentrated increases in specific years.

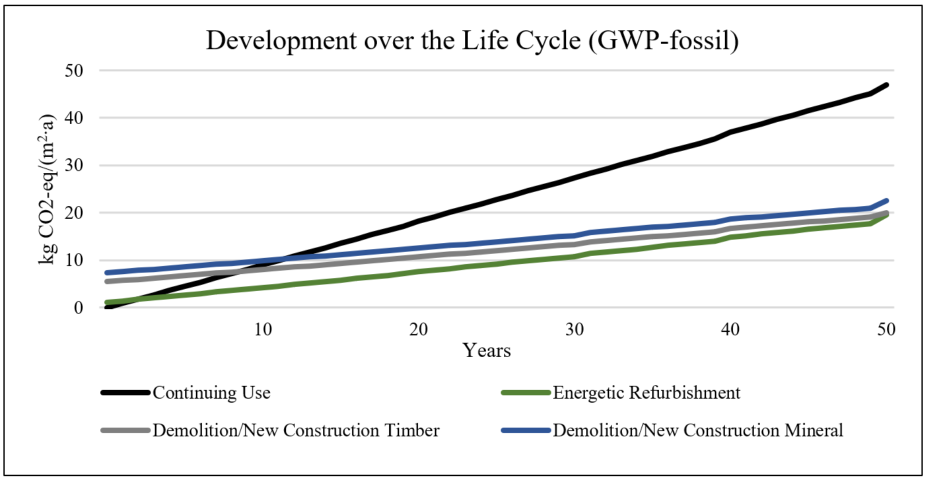

Figure 7. Display of the fossil emission development over the life cycle.

When comparing energetic refurbishment with demolition and new construction, outcomes need to be carefully evaluated. Savings in the construction (A_0) have an impact on the overall results, but a slightly less penetrating energetic refurbishment may result in poorer life cycle performance due to the operational energy demand. On the other hand, an energetic refurbishment resulting in a high energetic standard can very likely lead to fewer emissions over the life cycle compared to demolition and new buildings.

Table 3 shows the comparison of the three variants energetic refurbishment, demolition and new construction timber and demolition and new construction mineral. The absolute differences for the sum of the modules C_0 and A_0 range between 82.55 and 533.55 kg CO_2-eq., which is equivalent to the differences at time zero in Figure 5. To calculate the difference results of B2-4 and B6 in comparison to the case of continuing use, the sum of B2-4 and B6 was divided by 50 years for all variants and is presented in kg CO_2-eq. per year. The new construction variants result in a higher absolute and relative saving in the use phase in comparison to the energetic refurbishment, which is due to the difference in the energetic performance of the refurbished building. In Figure 7, this difference is shown as the gradients of the graphs over the life cycle. The relative savings between new construction and continuing use for modules B2-4 and B6 are about 70%. Additionally, the environmental payback time for the three variants in comparison to continuing use is displayed, as described in Section 2. Since the material input in the case of energetic refurbishment is comparatively low while the savings in heating energy demand are about 63%, the time of environmental payback between continuing use and energetic refurbishment is 1.9 years and equals the point of intersection of the graphs in Figure 7. In fact, this highlights the importance and benefits of refurbishment measures and provides a strong indication that refurbishment measures can achieve environmental benefits in a short period. The environmental payback time for demolition and a new building in timber is 8.5 years, while the payback time for the demolition and a new building in mineral constructions is about 11.4 years in comparison to continuing use. The results show the necessity to assess all life cycle stages consisting of upfront and future emissions to compare building scenarios, as described in [40].

Table 3. Results for absolute saving and environmental payback time in comparison to continuing use.

Scenario	Life Cycle Stage	Absolute Differences	Unit	Relative Differences [%]	Environmental Payback Time [Years]
Energetic refurbishment	$C_0 + A_0$	+82.55	kg CO_2-eq.		
	B2-4 + B6	−42.42	kg CO_2-eq./a	−63.20	
	Life Cycle	−27.40	kg CO_2-eq./m^2a	−58.20	
					1.9
Demolition/New Construction Timber	$C_0 + A_0$	+398.37	kg CO_2-eq.		
	B2-4 + B6	−46.85	kg CO_2-eq./a	−69.80	
	Life Cycle	−27.10	kg CO_2-eq./m^2a	−57.60	
					8.5
Demolition/New Construction Mineral	$C_0 + A_0$	+533.55	kg CO_2-eq.		
	B2-4 + B6	−46.76	kg CO_2-eq./a	−69.70	
	Life Cycle	−24.40	kg CO_2-eq./m^2a	−51.90	
					11.4

In terms of life cycle emissions, the continuing use represents the variant with the highest emissions. Improved performance in operating energies may result in short payback periods in CO_2 emissions. Table 4 shows the results of absolute savings, relative savings and environmental payback time for the comparison of both demolition and new construction scenarios with the refurbishment scenario. The additional emissions at the beginning of the life cycle range between 313.51 and 448.68 kg CO_2-eq. underline the potential of continuing use of existing materials. Regarding the emissions within the following life cycle, it appears that new constructions have advantages due to superior energy performance. The relative savings range between 17.6 and 18.0%. To estimate the environmental payback time, Module C_{50} was not considered, resulting in a payback time for demolition and new construction in timber of 70.7 years and for demolition and new construction in mineral materials of 103.3 years. In this case, the higher embodied emissions, especially in Module A_0, have a major impact on the environmental payback time compared to an energetic refurbishment.

Table 4. Results for savings and environmental payback time in comparison to energetic refurbishment.

Scenario	Life Cycle Stage	Absolute Differences	Unit	Relative Differences [%]	Environmental Payback Time [Years]
Demolition/New Construction Timber	$C_0 + A_0$	+313.51	kg CO_2-eq.		
	B2-4 + B6	−4.43	kg CO_2-eq./a	−18.00	
	Life Cycle	+0.33	kg CO_2-eq./m^2a	+1.60	
					70.7
Demolition/New Construction Mineral	$C_0 + A_0$	+448.68	kg CO_2-eq.		
	B2-4 + B6	−4.34	kg CO_2-eq./a	−17.60	
	Life Cycle	+3.00	kg CO_2-eq./m^2a	+15.30	
					103.3

An alternative approach to illustrate the origin of fossil emissions over the life cycle of the four variants is provided in Figure 8. Here, embodied and operational emissions over the life cycle are shown. The diameter of the pie charts mirrors the total emissions over the life cycle and leads to varying sizes of the corresponding charts. Almost all emissions of continuing use occur in Module B6 with 96% of emissions. The energetic refurbishment Module B6 accounts for 79% of the emissions and Modules B2-4 as well as C_{50} contribute about 8% of the total emissions. Since approximately 90% of material potentials have been saved in the building, the share of operational energy emissions increases. With demolition and new construction, the share of operational emissions decreases to 64% for timber construction and 57% for mineral construction. Meanwhile, the material further affects the overall results. The demolition of the existing building in Module C_0 accounts for between 4% and 5% of the results, whereas the new construction in Module A_0 is responsible for 22% of the emissions for timber construction and 28% for mineral construction. Modules B2-4 of the new buildings have a share of 5%, and the deconstruction of the entire building after 50 years (C_{50}) ranges between 3% for timber construction and 6% for mineral construction.

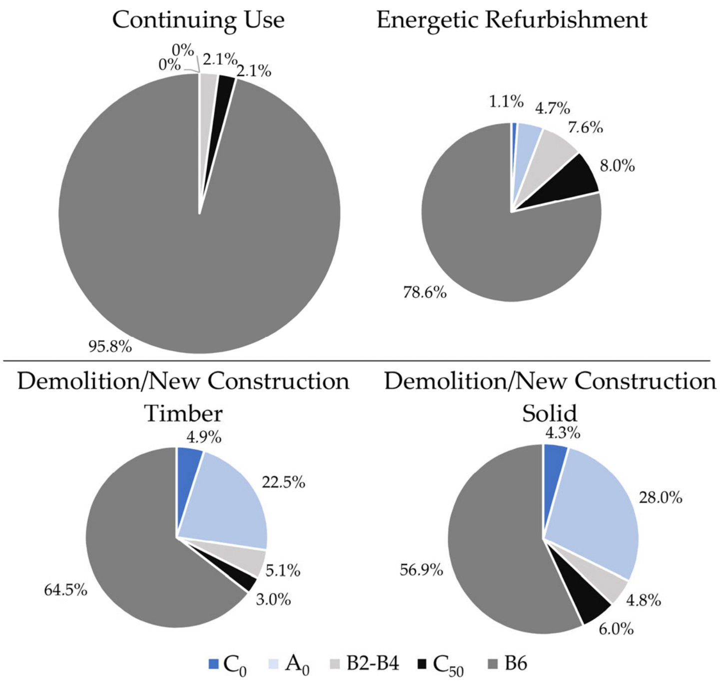

Figure 8. Distribution of the life cycle modules of the overall fossil emissions.

4. Discussion

This paper demonstrates how the continued use of existing building structures can be applied in building LCAs by determining the AP and SE of buildings. By validating the method on a building and by comparing different scenarios, the initial results indicating the benefits of refurbished existing buildings, compared to demolition and new construction scenarios, are provided. Further research is required to establish a valid database and to strengthen the obtained findings, as it was shown that studies differ in many basic assumptions regarding building LCAs. Uniform calculation rules and a standardised framework are crucial to ensure comparable LCA results. It was shown that basic assumptions for LCAs vary in the literature, and no framework has been established in terms of which life cycle modules or functional units are considered. This leads to a complicated comparison of the results to other literature results. A potential enhancement of the applicable international and European standards in this perspective could also be beneficial.

A substantial contribution to the overall emission calculations results from the operational energy. Emissions caused during the manufacturing or demolition phase have a comparatively small share in the life cycle emissions when considering the operational energy, which causes emissions over the life cycle of 50 years. Following the LCA guidelines, a static approach is used for the determination of the energy supply composition. Thus, the advancing decarbonization of energy systems and the increase in renewable energies are insufficiently accounted for in future scenarios. However, it is expected that with reduced emissions from Module B6, the refurbishment variant and refurbishments in general would perform comparatively better on average.

An additional important factor to be included in the decision-making process when comparing alternative options regarding environmental quality is the biogenic carbon content. It is essential to conduct the LCA calculations without the biogenic carbon content and use GWP fossil to avoid diffuse results and to operate in line with the relevant standards. However, the biogenic carbon content is still a useful indicator, which enables predictions to be obtained on the climate mitigation effects over the life cycle of buildings. Thus, it can be used as an informative indicator in future assessments of the AP and SE to compare different scenarios in the building sector in an integrated approach.

The results of this paper could help the policy framework by showing the environmental benefits of using already-existing structures compared to new buildings. The gathered information could be used to create funding instruments to keep existing structures instead of demolition and new buildings.

Finally, this paper addresses environmental considerations only, and environmental payback times were determined based on LCA results. However, in practice, these arguments are often neglected, and economic factors become increasingly relevant in the decision-making process. Various stimuli and funding instruments, as well as legal requirements, can be used to balance out financial aspects. The building sector has a crucial contribution to achieving international climate protection goals, which should be considered when addressing the building stock in future scenarios.

The shown results in this paper help to understand the benefit and assessment of the continued use in building LCA. Still, the results are limited to a certain context and cannot be extrapolated for all buildings. All data were calculated using the German database Ökobaudat. The results are, therefore, limited to a German context. The results in this paper are calculated for the indicator of global warming potential. Other environmental indicators, such as non-renewable energy use, water use or acidification potential, were not considered. It was shown that Module B6 plays a large role in the overall LCA results. The underlying energy mix, therefore, has a great influence on the results, as shown in the literature [26,30]. In this case, district heating was used and calculated for all variants. Future research should also consider different heating sources, energy sources, electricity mixes and the production and use of regenerative energies in the building.

Further, only environmental impacts were calculated. The benefits or disadvantages of continued use in terms of economic and social factors could not be considered. Factors such as the presence of hazardous substances or accessibility could play an important role in decision making.

5. Conclusions

This paper introduces the concepts of AP and SE to enable the comparison of different scenarios for the use and continuing use of buildings. Based on a methodology for the life cycle assessment of refurbishment measures, the existing building and the environmental impacts that have already occurred are integrated into the considerations and comparisons using this approach. The central aim is to transform the existing building stock with as little environmental impact as possible while, at the same time, using resources efficiently.

Methodological validation results from this case study indicate the relevance of the building stock. About 90% of the material-related emissions already caused can be further utilised. The emissions originate from a previous life cycle of the building and avoid the necessity of using new materials and the corresponding new environmental impacts. A comparison of the results with other scientific research could not be made since basic assumptions and LCA calculation rules differ in comparison.

The environmental payback time in terms of CO_2 emissions indicates the efficiency of the respective variant. Compared to continuing use without any action, the energetic refurbishment measure already yields an environmental payback after 1.9 years. The two new building scenarios, on the other hand, only return an environmental benefit after 8.8 years for timber construction and 11.4 years for mineral construction. Comparing the demolition and new construction scenarios in timber construction and mineral construction, the meaningfulness of refurbishment measures becomes even more evident. The first scenario would pay back after 70.7 years and the second after 103.3 years. From an environmental perspective, the long payback time illustrates that refurbishment measures are preferable in any case if carried out using a high energy standard. All measures required for the demolition and new construction of a building are disproportionate to the continuing use of an existing building undergoing refurbishment, especially in regard to limited CO_2 emission budgets.

The consideration and the observations of refurbishment measures and the continuing use of buildings just started, so this is still an early stage and the beginning of further investigations. Further studies to confirm the initial findings are required to gain a deeper understanding of the environmental impact and benefits of refurbishment measures. In addition, more detailed attention should be given to the energy system and the influence of different as well as renewable energy sources. Particularly towards an energy mix with a larger share of renewable energies, the impact of embodied emissions is expected to be larger compared to operational emissions. Approaches that encourage the circular use of building materials and products may also be included in further studies.

Apart from environmental impacts, future research should include other sustainability-related factors, such as social and economic factors, which could further influence decision making factors for the handling of existing building structures. An overall final statement, if energetic refurbishment compared to demolition and new construction can be classified as a better option, will most likely not be achieved, as it is building specific.

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