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# Ecological Potential of Building Components in Multi-Storey Residential Construction: A Comparative Case Study between an Existing Concrete and a Timber Building in Austria

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**Abstract:** With the introduction of energy-efficient buildings, the importance of embodied energy in new buildings has become increasingly relevant to minimising the impact of climate change. This study compares two existing four-storey residential buildings: one building has a reinforced concrete (RC) structure and the other has a timber structure. The study's aim is to find out which building components are responsible for the largest embodied impacts and whether there are differences between the two construction methods. The specificity of the wooden building is the combined use of solid and lightweight timber elements. The methodology consists of a general life cycle assessment (LCA) and a more detailed analysis of the product stage using the eco2soft software. The heating and cooling energy demand was calculated using the WUFI Plus software with recent regional climate data sets. The results show that for both types of construction in multi-storey buildings, it is not only the superstructure that needs to be considered, but also the floor structures, which have a major influence on the embodied impact. The timber building requires less energy to maintain the indoor climate within the set temperatures. As climate change has progressed rapidly in Austria in recent years, it is recommended that the standards for climate models be updated more quickly to allow realistic prediction of thermal comfort at the design stage.

**Keywords:** comparative LCA; timber construction; building components; embodied impacts; energy demand

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## 1. Introduction

The environmental impact of buildings is large and diverse; thus, greening the entire building sector is a hugely important step in mitigating and adapting to climate change [1]. In recent years, many studies have identified the use stage of a building as the stage with the highest environmental impact [2–4]. With the establishment of passive, low- and plus-energy houses, and in particular through the use of renewable energy sources, the main impacts of new buildings are often no longer in the use stage but as embodied impacts in the product stage [5–7]. For low- and nearly-zero-energy buildings, the share of embodied energy is 26–57% and 74–100%, respectively [5]. Globally, materials used in buildings are estimated to account for 9% of total $CO_2$ emissions [1].

This increases the importance of using environmentally friendly building materials that have a small environmental footprint. Ecological building materials are defined as being renewable, resource-friendly, reusable, regional and durable. These characteristics are usually compared in a life cycle assessment (LCA) and can be determined by various parameters at different stages of a life cycle. They are divided into product and construction stage (module A), use stage (module B), end of life stage (module C) and benefits and loads beyond the system boundary (module D) [8].

### *1.1. Literature Review*

Comparative LCAs of timber structures and reinforced concrete (RC) structures have been carried out many times. For example, Duan et al. analysed 62 such comparative LCAs of buildings with different building heights in different countries. The global warming potential (GWP) was on average 42.68% higher for RC buildings than for timber buildings [9]. Hafner et al. investigated the relationship between building height and GWP [10]. Multi-storey buildings tend to have a higher GWP because more mineral-based building materials are used due to fire protection regulations. For multi-storey residential buildings, a reduction in GWP of 9–48% was found when buildings were constructed with wood-based rather than mineral-based materials. Chen et al. were able to show that for the modules A to C, even a 12-storey building made mainly of wood can save 20% of $CO_2$ emissions compared to a RC building [11]. Rinne et al. examined the differences between timber, hybrid and RC buildings; the timber building emits the least $CO_2$ emissions over its entire life cycle, while the hybrid building also performs better than the RC building [12]. The predominant use of wood in building construction, therefore, fundamentally reduces the $CO_2$ footprint, regardless of the height of the building.

The balance of embodied energy is less clear in scientific studies. Duan et al. found an average of 23% higher embodied energy for mass timber constructions [9]. Felmer et al. calculated the embodied energy of a five-storey solid timber building to be as much as 37% higher than that of an equivalent RC building [13]. However, a reduction in embodied energy through the use of wood in construction has been reported by several authors. For example, Tettey et al. calculated that the primary energy of a mass timber building is 20% lower than that of a RC building, while that of a lightweight timber building is 9% lower [2]. Overall, studies often show higher primary energy for wooden buildings when the environmental assessment does not distinguish between renewable and non-renewable primary energy. This fact is also noted by Minunno et al. [14]. Indeed, this distinction is often useful; in Austria, for example, many companies in the wood industry use their by-products as fuel or energy sources [15]. This means that energy can be produced locally and without the use of fossil fuels.

The heating and cooling demand is also strongly linked to the choice of materials used for construction. These differences are mainly caused by the thermal mass of the load-bearing materials and the thickness and properties of the thermal insulation. In Müller et al. [16], the different energy demands for cooling and heating of timber and RC structures are modelled using WUFI software based on a one-room model. The results show that the cooling energy demand is higher for both timber frame and mass timber construction compared to precast concrete, while the heating energy demand is slightly lower. Dodoo et al. calculated that the energy demand for space heating in the RC building was about 0.2% lower than in the wooden building due to the thermal mass [17]. It is suggested that such contrasting results are due to assumptions made about hypothetical buildings. The example given here allows a comparison based on two realised buildings, where no assumptions must be made about the building structures.

In LCAs carried out so far, the two parameters GWP and primary energy content dominate the calculation of resource consumption and emissions [9,18]. The results can vary considerably depending on which indicators, stages and calculation methods are used [18–20]. There are also large differences due to different national standards [21]. However, these two parameters by no means cover all the environmental assets that need to be protected. To cover as many protected assets as possible, more than two parameters must be used in the assessments. The results of other studies show that the level of other common parameters, such as acidification and ozone depletion are influenced by regional aspects. In China, for example, the wood used in cross laminated timber (CLT) production is often imported from Europe, which is why an examined wood building had higher values for ozone depletion, acidification, smog and fossil fuel depletion [22].

### *1.2. Objectives and Novelty of the Study*

Most studies compare two buildings where one of them is hypothetical. To avoid uncertainties that arise due to theoretical assumptions about buildings, two existing buildings in Vienna were used as case studies. The biggest difference between the hypothetical buildings is the mix of timber frame and solid timber elements. The outer wall is made of lightweight timber elements. This method has the advantage of allowing greater building heights without having to make all the elements from the more resource-intensive CLT. Previous LCAs have often focused on either multi-storey buildings, where each component is made of CLT or lightweight timber construction. Part of the research question is whether the mixed construction method used here is a particularly ecological construction method.

The main objective is to find out which of the building components used in the two compared buildings are responsible for the greatest embodied environmental impacts and whether there are any differences between the two construction methods in this respect. This ranking of building elements is a novelty as previously most comparisons have been made between specific building elements, such as exterior walls [23–26], non load-bearing interior walls [27,28] or flooring systems [19,29]. LCAs of whole buildings, on the other hand, have often only looked at individual parameters, such as GWP or energy demand. To represent a range of environmental issues, seven different indicators are compared.

In Austria, simplified assumptions according to ÖNORM B 8110 are sufficient for the calculation of the heat energy demand for the preparation of energy performance certificates. This includes monthly averages for the calculation of the thermal performance with data sets up to the year 2007 [30]. To prevent energy poverty in the future, recent regional temperature changes due to climate change must also be taken into account [31]. As the climate in Austria has changed considerably in recent years, the question arises as to whether the data sets used still adequately predict the energy demand and thermal comfort for both buildings. The existing calculation of the energy performance certificate integrates the thermal mass of the building in a very simplified way. The hygrothermal simulation with WUFI Plus software allows a precise hourly calculation using the exact structures.

## 2. Materials and Methods

### *2.1. Compared Buildings*

The subjects of the study were two buildings of the same size and volume that were realised within a building complex in Baranygasse, 1220 Vienna. One of them was built in timber construction and the other in RC construction. In both cases, the façade was plastered so that the differences in the superstructures were not visible from the outside. The requirements for each building were exactly the same: a four-storey residential building with the same requirements for fire safety, sound insulation, summer heat protection and thermal insulation. Both buildings were completed in 2021. The location and external views of the two buildings are shown in Figure 1. Full documentation is available for both buildings.

#### 2.1.1. Wood-Based Building

The load-bearing structure is made of wood. The exterior walls were made of timber frames with mineral wool insulation, while the load-bearing interior walls and all floor structures, except the ground floor, were made of CLT. The fire protection requirements were met either by the thickness of the timber elements or by cladding with plasterboard. In the interior, the solid timber elements were partly visible. The separating floors between the storeys mainly consisted of a CLT slab, a levelling layer, XPS and footfall insulation made of mineral wool. Parquet flooring was laid on a screed in the living areas and tiles in the wet areas. The flat roof consisted mainly of a CLT slab and rigid foam boards or EPS for thermal insulation, followed by the waterproofing, a rubber granulate mat and gravel. The walkable areas of the roof were covered with tiles, while the non-walkable areas were covered with gravel. To prevent water vapour from diffusing from the interior into the structure, vapour-retarding membranes were used in both the ceilings and the exterior walls. The partition walls were partly made of a wooden frame and mineral wool and partly made of steel sheet and plasterboard, filled with mineral wool.


**Figure 1.** Rendering of the two realised buildings with a timber and a reinforced concrete (RC) superstructure in Vienna. © UBM Development AG/eleven visualisation.

#### 2.1.2. RC Building

The external walls were made of reinforced concrete with EPS insulation and plaster. The floor structures of the separating floors were made of concrete, followed by cement-bound EPS and a footfall insulation made of EPS. Parquet flooring was laid on a screed in the living areas and tiles in the wet areas. The flat roof construction consisted of a concrete slab with EPS between sealings followed by gravel. Vapour-retarding membranes were used in both the ceilings and the exterior walls. The interior partition walls were made from conventional lightweight steel sections covered with gypsum plasterboards and lined with glass wool. All interior surfaces were plastered.

### *2.2. Life Cycle Assessment and System Boundaries*

Two different methods were used for the environmental calculation. The first method was a general LCA of the modules A1–A4, B4, B6 and C1–C4. The second one was a more detailed consideration of the product stage (module A1–A3). The Austrian platform baubook [32] was used as the database for both calculations. This database accessed the ecoinvent datasets. As the basement was not directly under the building but extended over a large part of the terrain of the building assembly, both calculations excluded the basement and were calculated from the floor slab upwards. Balconies, windows and building services were not considered as they were the same in both buildings. Timber fixings were not included as no information was available. Partition walls were included as they were partially different in the two variants.

#### 2.2.1. Functional Equivalent

According to EN 15978, the "functional equivalent" is defined as "quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison" [8]. At the building level, there are certain design criteria that allow a meaningful comparison to be made. In this case, these criteria are the same cubature, floor area and building physics requirements. These basic assumptions for both buildings were based on the energy performance certificate and ensure comparability for the LCA:

- Floor area: 1143 $m^2$;
- A/V: 0.42 1/m;
- Mean U-Value: 0.3 W/$m^2$K;
- Energy demand for heating water: 13 kWh/$m^2$a;
- Energy demand for space heating: 58 kWh/$m^2$a;
- Energy demand for electrical appliances: 16 kWh/$m^2$a;
- Heating energy demand: 30 kWh/$m^2$a.

#### 2.2.2. Indicators

The following indicators were used for the ecological calculation, as listed in Table 1.

**Table 1.** Indicators for calculating the ecological impacts.

| Abbreviation | Indicator | Unit |
|---|---|---|
| GWP | Global warming potential | kg $CO_2$ eq. |
| PERT | Primary energy, renewable, total | MJ |
| PENRT | Primary energy, non-renewable, total | MJ |
| ODP | Ozone depletion potential | kg CFC-11 |
| AP | Acidification potential | kg $SO_2$ eq. |
| EP | Eutrophication potential | kg $PO_4{}^{3-}$ |
| POCP | Photochemical ozone creation potential | kg $C_2H_4$ |

#### 2.2.3. Whole Life Cycle

The modules A1-A4, B4, B6 and C1-C4 were considered, which are specified in ÖNORM EN 15978-1 [8]. A period of 100 years was chosen for consideration.

For space heating and hot water production, the natural gas energy source (low-NOx boiler) was compared with district heating for both types of construction. District heating is a system for the distribution of thermal energy produced by a central energy plant. In Austria, about 28% of all dwellings are supplied with district heating; in buildings built after 2000 and with 20 or more dwellings, the share of district heating is almost 81% [33]. Depending on the location in Austria, the energy for the district heating can be obtained from waste incineration plants, combined heat and power plants or renewable energies. In this calculation, the most environmentally friendly option (district heating with combined heat and power from 100% biomass energy source) was chosen. The Austrian consumption mix for household electricity was used for both construction methods.

For module A4 (transport to site), the following distances were assumed. In the absence of specific data on transport routes, the average values, as published in the EPDs of the surrounding building material manufacturers, were used.

- Concrete, screed, gravel, plaster, timber frame, CLT, OSB: 100 km;
- Plaster board, tiles, glass wool insulation, EPS, XPS: 200 km.

For module B4 (replacement of building components), the following lifetimes were assumed:

- Load bearing superstructure (concrete, CLT): 100 years;
- Interior walls, thermal insulation: 50 years;
- Sealings, membranes, plaster: 35 years;
- Flooring, gypsum fiber boards and wall coatings: 25 years.
- For module C, the assumptions are based on the data sets provided by eco2soft:
- Concrete, gravel, screed, plaster board, tiles, plaster, insulation, sealings, glass wool: landfill disposal;
- Timber, CLT, EPS, XPS, rigid foam panels: waste incineration plant;
- Steel: recycling.

2.2.4. Product Stage (Module A1–A3)

In the second step, the embodied impacts of different building components during the product stage were investigated and compared. For this purpose, the data was taken from the same software, categorised into building components and calculated in an Excel file. As shown in Figure 2, all building materials were divided into two main groups: the shell and the interior.

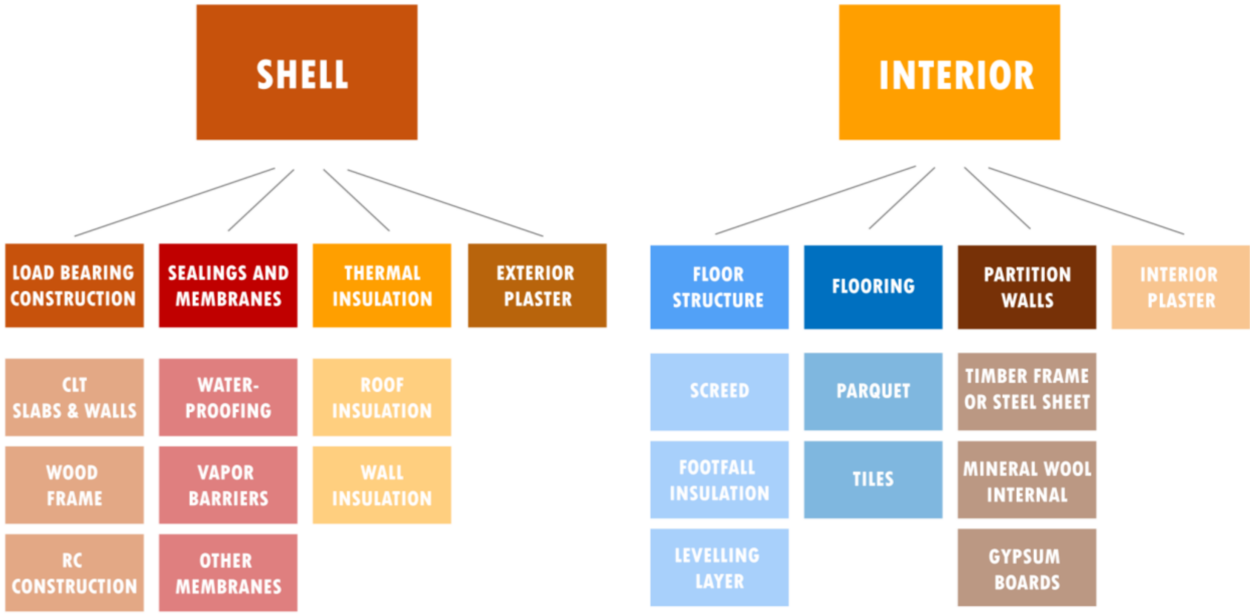


**Figure 2.** Building components.

For the wooden building, both the timber framing of the external walls and CLT load-bearing walls and CLT slabs were added together for the building component "load-bearing construction". "Sealings and membranes" included the waterproofing, the water vapour-retarding membranes, water vapour barriers and separating Polyethylen membranes. The building component "floor structure" excluded the load-bearing slab, but included the necessary materials for footfall insulation, the levelling fill and screed. The "flooring" included parquet and tiles. The building component "partition walls" consisted of either a wooden frame filled with mineral wool or steel sheet covered with plasterboard and filled with mineral wool.

*2.3. Heating and Cooling Energy Demand*

The heating and cooling energy demand was calculated using the WUFI Plus software. WUFI Plus is a tool for calculating the hygrothermal properties of building components, the indoor climate and the energy demand. A simplified model was used for the simulation, which did not include balconies or terraces. The simulation model is shown in Figure 3. The external dimensions of the building were identical for both buildings at 18.6 × 18 m. The floor height was 2.8 m and 4 floors are simulated. The roof geometry was chosen as a flat roof with attica. The gross floor area in this model was 1339 m$^2$ due to the simplifications made. This figure differs by 196 m$^2$ from the actual constructed area of 1143 m$^2$. The ceilings were inserted at the appropriate floors. The interior walls were specified as additional storage mass without a specific location in the building. Since inhomogeneous constructions cannot be created in WUFI Plus, the insulation was assumed to be without wooden studs in the exterior walls of the simplified model. The heat transfer coefficient (U-value) was then adjusted to match the real U-value.

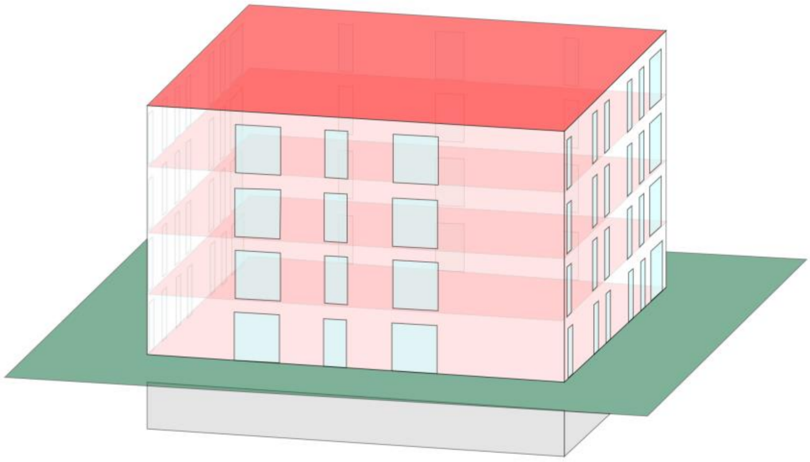

**Figure 3.** Simplified model of the simulated building in WUFI Plus.

The material data for the simulation in the software WUFI Plus are shown in Table A1 in Appendix A. For the outdoor climate, three different data sets for Vienna were used. The first set represented an average of the climate data from 1976–2005 and was available in the WUFI software. This results in a maximum temperature of 32.4 °C and a minimum temperature of −10.9 °C. The average temperature is 10.35 °C. The second and third climates were the measured climate of Vienna in 2018 and 2022. These climate files were generated from local weather data from Central Institute for Meteorology and Geodynamics (ZAMG). The year 2018 was chosen because it was one of the warmest years in Austria, while 2022 was chosen because it was the most recent year of data available at the time of publication. In 2022, the highest temperature in Vienna was 36.2 °C and the minimum temperature −6.8 °C. The average temperature was 12.38 °C. In 2018, the highest temperature in Vienna was 35 °C and the minimum temperature −12.2 °C. The average temperature was 12.58 °C.

The limits of the indoor climate were set at 20 °C and 27 °C. A daily profile of a residential building during the week in common rooms was chosen as the internal load. The air exchange rate was assumed to be constant at 0.5 [1/h]. The heating capacity of 350 kW was taken from the energy performance certificate. The cooling capacity was assumed to be 50 kW as no cooling units were installed in the realised buildings. The basement was simulated as unheated, while the temperature was approximated by a sinusoidal curve with a mean value of 18 °C and an amplitude of 2K. The relative humidity was also represented by a sinusoid with a maximum value of 45% and an amplitude of 15%. The simulation period was one year.

## 3. Results and Discussion

### 3.1. Material Contribution

The building mass by material is shown in Table 2. In both buildings, reinforced concrete is the largest contributor to the mass of the building, followed by screed and gravel. A linked representation of mass and environmental impacts can be found in Section 3.3.3.

**Table 2.** Whole building mass by material.

| Material | Mass, Timber Building [kg] | Mass, RC Building [kg] |
|---|---|---|
| Reinforced concrete | 202,842 | 1,278,204 |
| Screed | 118,999 | 111,851 |
| Gravel | 168,140 | 40,840 |
| CLT | 130,740 | 0 |
| Gypsum plaster boards and gypsum fiber boards | 35,069 | 17,726 |

**Table 2.** *Cont.*

| Material | Mass, Timber Building [kg] | Mass, RC Building [kg] |
|---|---|---|
| Wood-based materials (except CLT) | 23,475 | 776 |
| Tiles | 12,666 | 13,083 |
| Cement based tiles | 12,649 | 16,403 |
| Plaster | 8250 | 13,114 |
| Parquet | 8140 | 7797 |
| Cement bound EPS | 1021 | 4965 |
| Polymer based insulation (EPS, XPS, rigid foam) | 5534 | 5752 |
| Sealings and membranes | 6825 | 6349 |
| Glass and stone wool | 3574 | 1276 |
| Steel | 1643 | 4407 |
| Total | 739,567 | 1,522,543 |

### *3.2. Comparison of the Ecological Impact—Whole Life Cycle*

Figure 4 shows seven indicators of the two construction methods: one time with gas as the energy source and one time with district heating as the respective energy sources for heating and warm water. The comparison is shown as a percentage value.

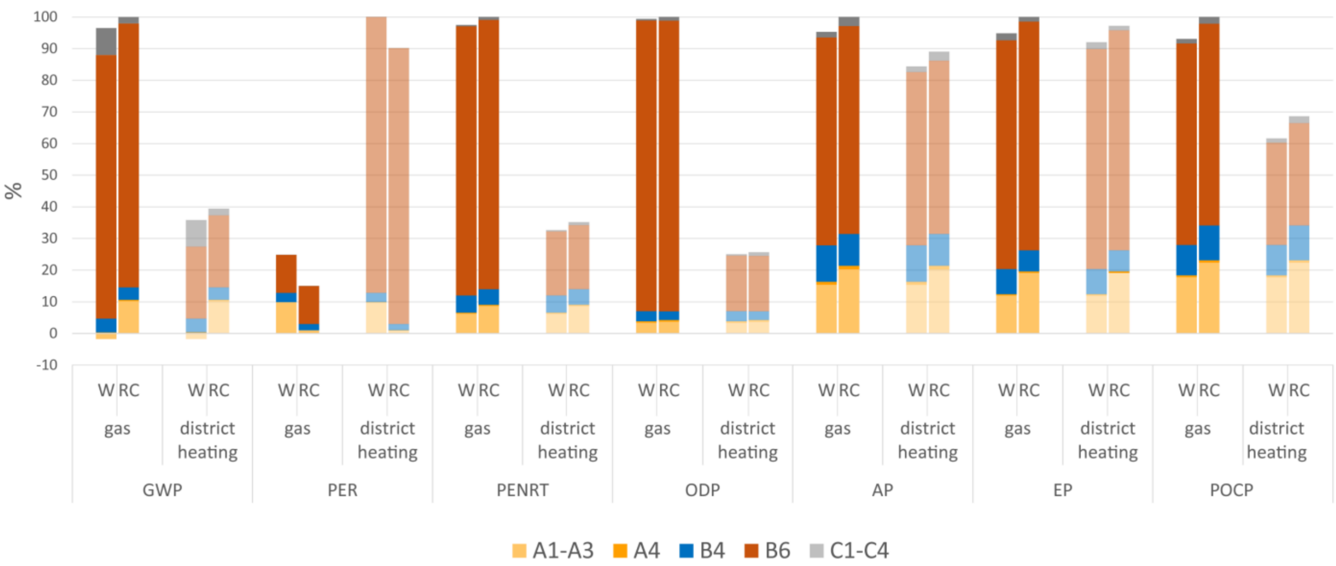


**Figure 4.** Comparison of ecological impacts of a wooden (W) and a reinforced concrete building (RC) with gas and district heating as energy source.

The results show that module B6 (operational energy use) is still the most decisive life cycle module for current new buildings in Austria, as long as the energy source is not replaced by more sustainable alternatives. The reduction in GWP and PENRT by more than 50% in the case of supply by district heating illustrates the large ecological impact of energy systems. However, such a high level of reduction is not evident for all the indicators. For the AP parameter, the impact is only reduced by 11% and the EP indicator by 2%. It shows that the exclusive calculation of GWP does not reflect the trend of all parameters.

In terms of embodied impacts, the product stage is responsible for the largest share of ecological impacts. The product stage of the wooden building has a negative GWP. Module B4 (replacement of building components) is responsible for a larger share than module C (end of life) with the assumed values; thus, the longevity of building components should be given a high relevance. Surprisingly, A4 (transport) does not account for more than 1% of any of the parameters. This result can be explained by the fact that many building materials, such as cement or wood-based products, are produced locally in Austria.

On average, the timber-based building causes 7% less environmental impact than the RC building in both energy supply variants.

The total values of all indicators divided into life stages are listed in Tables A2–A5 in Appendix A.

### 3.3. Comparison of the Ecological Impact—Product Stage

Figure 5 shows the embodied environmental impacts of the product stage by the means of seven indicators, each divided into shell and interior work. In the case of the timber building, the shell is responsible for the largest impact in five of the seven parameters. Only for the GWP indicator does it produce a negative value because the wooden construction stores $CO_2$. Due to this indicator, the interior has the greater environmental impact. In the case of PENRT, it is the interior work that dominates.

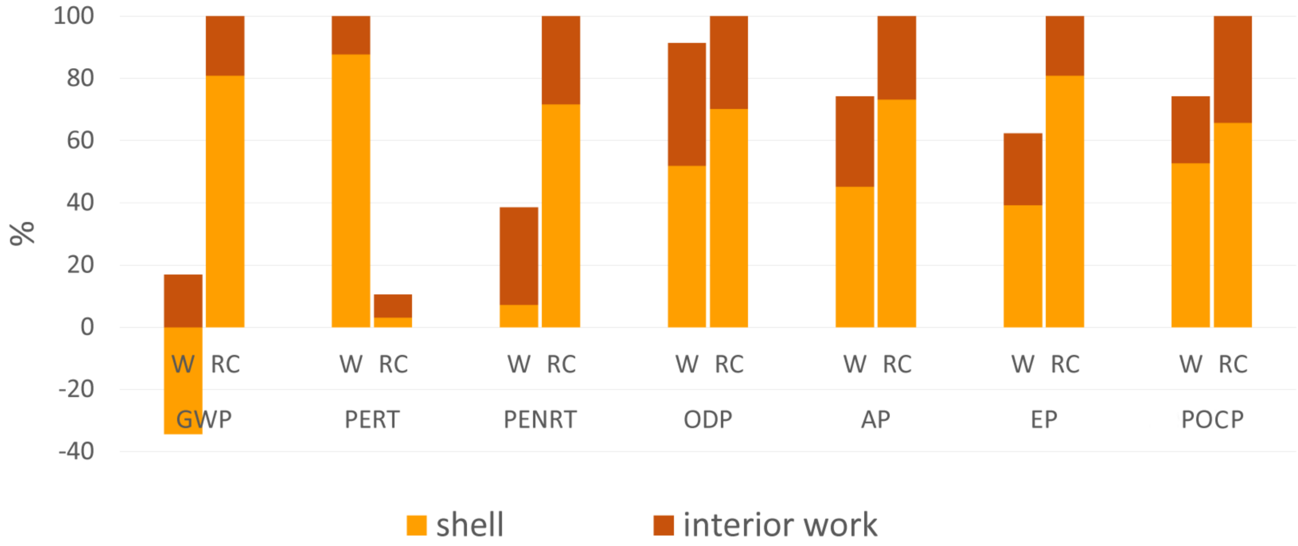


**Figure 5.** Embodied ecological impacts of the shell and interior work of a wooden (W) and reinforced concrete (RC) building.

The RC building also clearly shows that the shell causes the highest environmental impacts for six out of seven indicators. The parameter for renewable energy shows higher impacts for the interior work. This result is due to the fact that parquet flooring is used extensively, yet relatively little renewable primary energy is used overall. When renewable and non-renewable primary energy are added together, the LCA gives a similar picture to previous studies, with concrete construction requiring less primary energy overall. However, most of the primary energy used in the timber building comes from renewable sources.

After the GWP, PERT and PENRT parameters, the biggest difference between the two buildings can be seen in the EP parameter. Eutrophication as an impact category in LCAs includes non-organic nutrients based on nitrogen and phosphorus; this process is a by-product of cement production [34].

It can be concluded that for both construction methods, the building shell is responsible for the largest embodied impact.

Figure 6 shows the effects of the product stage broken down by building components. The most significant differences between the two construction methods are in the load-bearing construction. This finding means that an accurate structural analysis and, thus, high material efficiency; it also suggests that the use of building materials with a low ecological footprint for the load-bearing structure can contribute enormously to the greening of buildings. This finding has been highlighted in other studies [3].

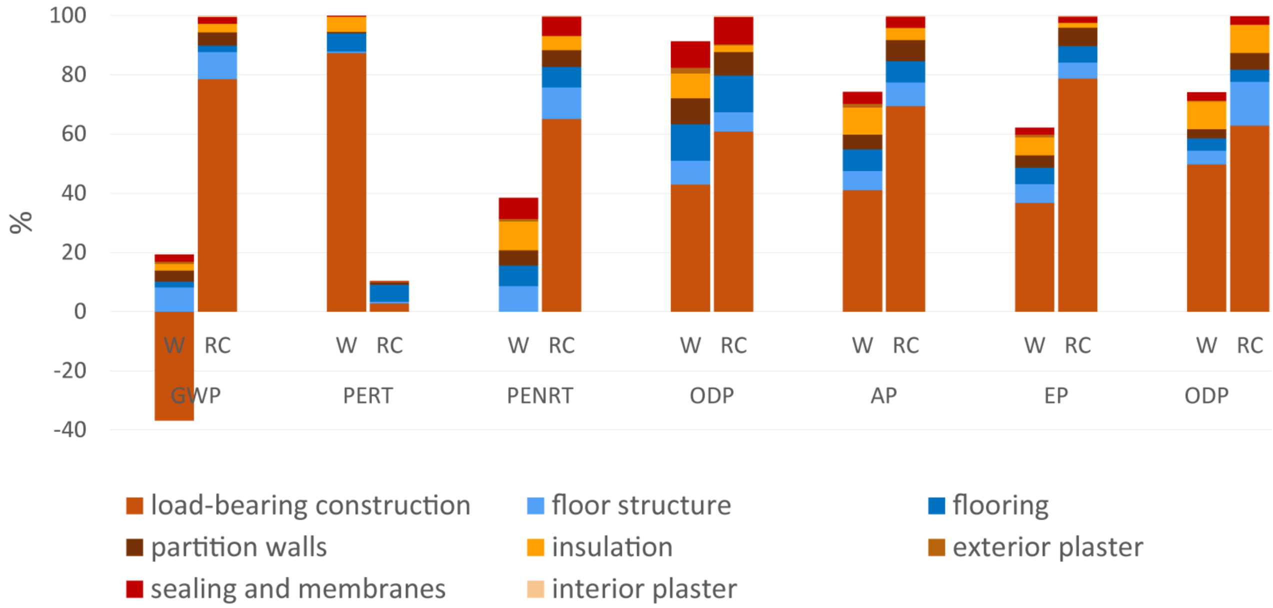


**Figure 6.** Embodied ecological impacts of building components of a wooden (W) and reinforced concrete (RC) building.

The second largest potential for ecological optimisation in both buildings is the floor structure. The analysed floor structure consists of a levelling fill made of cement-bound EPS, a water vapour-retarding membrane and footfall insulation made of EPS and cement-based screed. The development of an ecologically optimised floor structure that meets all current standards, therefore, represents a very relevant research potential.

Although the floor slab, foundations and basement were not included in the calculation, it is assumed that there is a large potential for ecological optimisation. Floor constructions with single or strip foundations, which are designed to avoid moisture damage and, thus, require fewer polymer-based sealing materials, can reduce $CO_2$ emissions by up to 82%, provided that such a design is possible in terms of structural requirements [19].

### 3.3.1. Embodied Impacts of the Wooden Building

Table 3 shows the total values of the seven parameters. Figure 7 shows that for five out of seven indicators, the supporting structure is responsible for more than half of the impact. For the PENRT indicator alone, construction accounts for about 20% of the total impact. As the timber construction has an overall negative $CO_2$ balance, the floor construction is responsible for the largest share of the GWP. Most of the primary energy is provided by renewable energy sources. Overall, CLT panels are responsible for over 90% of the renewable primary energy of the wooden building.

**Table 3.** Total values of the embodied impacts during product stage for the wooden building.

| | Load-Bearing Structure | Floor Structure | Flooring | Partition Walls | Insulation | Exterior Plaster | Sealings and Membranes |
|---|---|---|---|---|---|---|---|
| GWP | −133,983 | 29,815 | 7289 | 13,311 | 8329 | 2706 | 8730 |
| PERT | 3,042,078 | 20,634 | 209,773 | 18,146 | 178,092 | 2367 | 9853 |
| PENRT | 38 | 409,212 | 326,303 | 243,748 | 455,009 | 45,457 | 336,593 |
| AP | 464.13 | 72.65 | 81.73 | 55.99 | 104.15 | 13.79 | 45.25 |
| ODP | 0.00710 | 0.00132 | 0.00203 | 0.00147 | 0.00138 | 0.00031 | 0.00147 |
| EP | 231.88 | 39.48 | 34.95 | 26.48 | 38.09 | 5.96 | 14.87 |
| POCP | 123.67 | 11.39 | 10.49 | 7.38 | 23.25 | 0.95 | 7.02 |

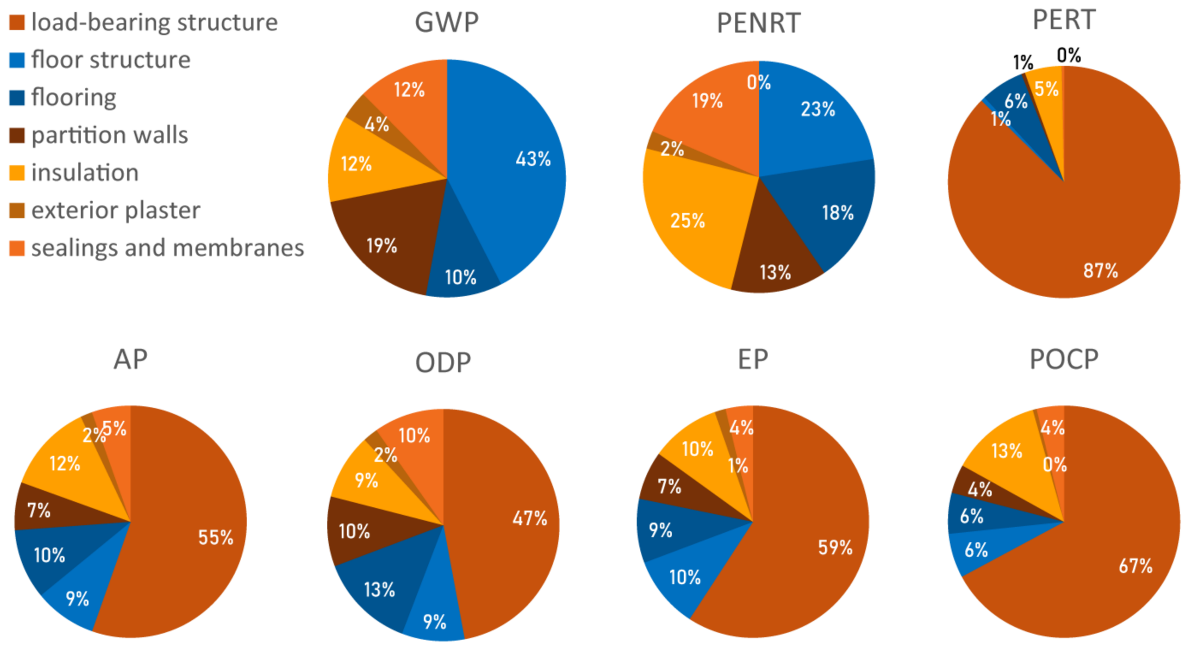


**Figure 7.** Embodied impacts in the product stage of the wooden building.

In this example, the greatest potential for environmental optimisation lies in the material efficiency of the superstructure. When the two categories "floor structure" and "flooring" are added together, they are jointly responsible for 7–53%, second only to the superstructure. This is followed by insulation with 5–25%. Here, ecological optimisation using renewable and/or low energy insulating materials could reduce the impact. Non-load-bearing interior walls contribute 1–19% and the waterproofing and foils contribute 0–19%.

The timber building has relatively low embodied energy, probably due to the efficient load-bearing structure, which is a combination of solid and lightweight timber elements. There are also great differences in the environmental performance of solid wood panels. For example, CLT uses up to 40% less energy than GLT (glued laminated timber) [35]. The combination of lightweight and solid timber construction used in the case study is, therefore, a particularly embodied energy-efficient and, thus, ecological construction method. Further ecological optimisation of the construction could be achieved by using glueless timber constructions. Further research is needed to calculate the ecological optimisation potential of such constructions.

### 3.3.2. Embodied Impacts of the RC Building

Table 4 shows the total values for the seven parameters. As shown in Figure 8, the load-bearing structure is also responsible for the majority of the embodied environmental impact in the RC building. As in the case of the timber construction, the floor covering added together with the floor structure places second with about 11–60 %. This is followed by interior walls with 4–9% and insulation with 2–9%. Waterproofing and foils account for 2–9%. Neither external nor internal plaster accounts for more than 1% of any indicator.

The exception is the PERT indicator. PERT is dominated by flooring, especially parquet, as it is one of the only available renewable materials.

The load-bearing structure of the RC building embodies a total energy (PERT+PENRT) of 2.6 GJ/m$^2$, while the timber building embodies 2.5 GJ/m$^2$. According to Duan et al. [9] the average embodied energy is 3.99 GJ/m$^2$ for solid wood buildings and 3.08 GJ/m$^2$ for RC buildings. For an 8-storey building, the primary energy is 4.6 GJ/m$^2$ for a reinforced concrete building and 4.6 and 4.9 GJ/m$^2$ for two hybrid buildings, according to Pierobon et al. [36]. As the RC building has a higher absolute impact and a larger proportion of the load-bearing structure compared to the other building components, efficient planning and use of the material should be a priority. When reinforced concrete is used as a construction material, $CO_2$ can be minimised or stored, for example, by using recycled aggregates that have previously stored $CO_2$ from carbonation [37,38].

**Table 4.** Total values of the embodied impacts during product stage for the RC building.

| | Load-Bearing Structure | Floor Structure | Flooring | Partition Walls | Insulation | Exterior Plaster | Sealings and Membranes | Interior Plaster |
|---|---|---|---|---|---|---|---|---|
| GWP | 286,318 | 33,263 | 8179 | 15,869 | 10,368 | 580 | 8078 | 1469 |
| PERT | 98,166 | 17,596 | 201,774 | 31,368 | 3130 | 1417 | 9051 | 2745 |
| PENRT | 3,067,690 | 501,231 | 329,063 | 269,918 | 216,024 | 8647 | 306,340 | 13,727 |
| AP | 783.54 | 90.08 | 81.78 | 80.14 | 45.16 | 1.67 | 42.54 | 3.34 |
| ODP | 0.01006 | 0.00108 | 0.00204 | 0.00130 | 0.00038 | 0.00006 | 0.00153 | 0.00006 |
| EP | 495.94 | 33.99 | 35.15 | 38.60 | 9.98 | 0.69 | 13.23 | 1.72 |
| POCP | 155.94 | 36.72 | 10.41 | 13.81 | 23.59 | 0.20 | 7.03 | 0.47 |

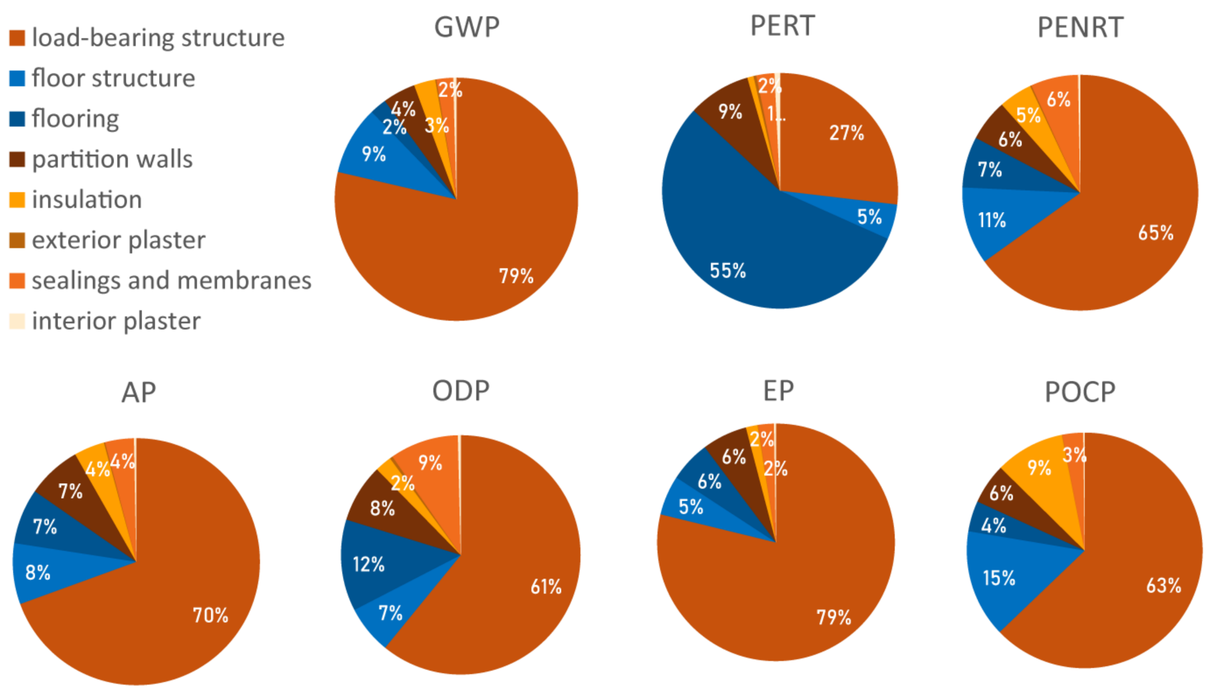


**Figure 8.** Embodied impacts in the product stage of the RC building.

### 3.3.3. Comparison by Mass

Figure 9 shows the different parameters on the *y*-axis and the magnitude of the effect on the *x*-axis, scaled logarithmically. The size of the circle represents the mass of the respective component category. Negative values are not shown.

The component category with the highest mass also has the highest impact. Most of the categories for the two construction methods are below the 10% mark; thus, the environmental relevance of the load-bearing elements is also illustrated by this graph.

Particularly in the case of timber construction, it is useful to distinguish between renewable and non-renewable primary energy content. In this case study, mass allows a rough estimation of most of the environmental indicators used.

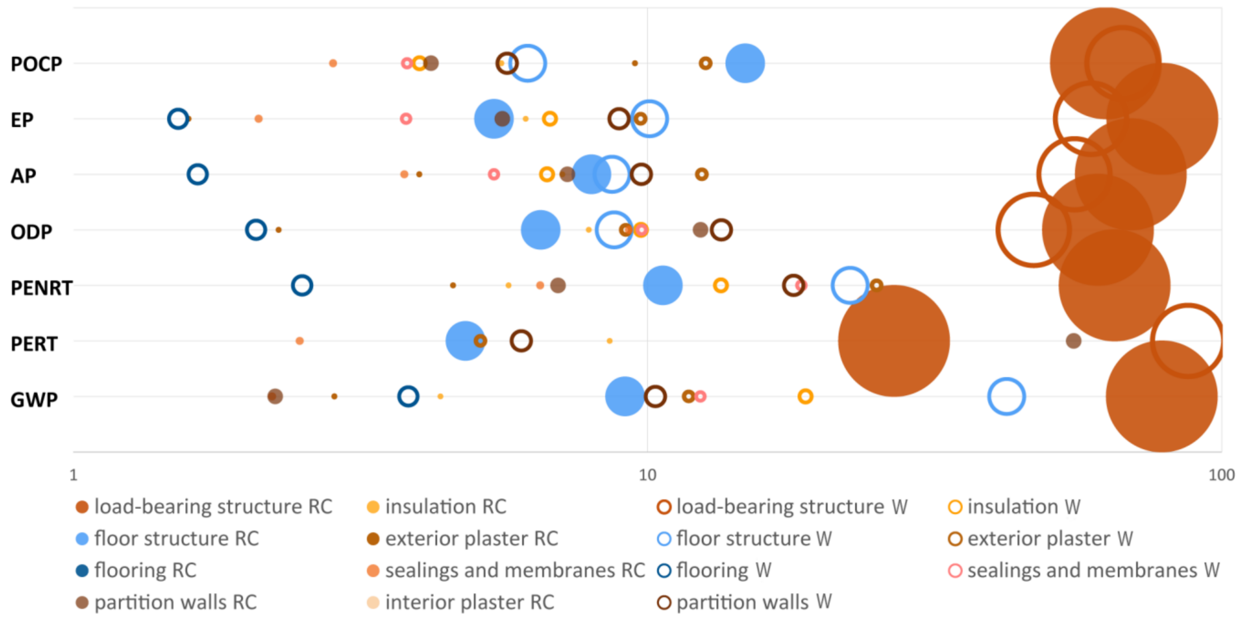


**Figure 9.** Comparison of embodied impacts by mass of a wooden (W) and reinforced concrete (RC) building.

### 3.4. Comparison of Heating and Cooling Energy Demand

Table 5 shows the results of the simulations assuming the temperature does not fall below 20 °C and does not rise above 27 °C.

**Table 5.** Heating and cooling load of two construction methods in different climates.

| | Climate 20–27 °C | Heating Load [kWh/m$^2$a] | Cooling Load [kWh/m$^2$a] |
|---|---|---|---|
| Wooden building | Vienna, 1976–2005 | 49.4 | 0.08 |
| | Vienna, 2018 | 43.3 | 1.03 |
| | Vienna, 2022 | 40.6 | 1.17 |
| RC building | Vienna, 1976–2005 | 52.5 | 0 |
| | Vienna, 2018 | 46.0 | 0.44 |
| | Vienna, 2022 | 43.1 | 0.46 |

It can clearly be seen that the results for both buildings with the two current climate data differ from the older climate data. In both assumed outdoor climates, the wooden building needs to be cooled slightly more to achieve the target temperature. In winter, the RC building needs to be heated more to maintain 20 °C throughout. Thus, even if the timber building is actually cooled in the summer, more energy would have to be used to keep the reinforced concrete building's indoor climate within the set temperatures. For both buildings, it can clearly be seen that the annual heating energy consumption decreases over time, while the cooling demand increases. The link between temperature rise and the different heating and cooling demand is clear. To correctly calculate this demand at the planning stage of a building, the effects of climate change need to be included in the standards on an ongoing basis.

### 3.5. Limitations

It is clear that this LCA has its limitations. One of these is that specific modules are not considered, such as module D. For module C, only very simplified information was available in the eco2plus software; thus, only one scenario per material could be calculated. Another limitation is the choice of indicators. The use of different LCA methodologies can significantly affect the results. One study shows that the results can be affected by a factor of 10 [39]. Other factors, such as geometry, size and building type, also have a significant impact on the environmental performance of buildings [40].

The main limitation is that future technological progress is not taken into account. During the 100-year period considered, there may be profound changes not only in the technology for heating, cooling, electricity and hot water production, but also in the materials used.

The results can be extrapolated to cover similar construction methods and building heights. However, it is important to consider whether the climate is similar to that in Vienna and, if not, the potential consequences of these changes.

## 4. Conclusions

The great potential of timber buildings in the context of the challenging environmental impacts of all buildings has been known for some time. The analysed construction, which consists of both lightweight and solid timber elements, represents a particularly ecological variant in multi-storey timber construction.

Within the entire life cycle, module B6 (operational energy use) still contributes the most to the indicators for both buildings. The district heating alternative shows a significant improvement and underlines the assumption that the relevance of embodied emissions increases significantly with the use of efficient and renewable energy sources. However, such a high level of reduction is not evident for all the indicators. Although the two parameters (GWP and primary energy content) are considered the two most commonly used indicators, they cannot be used as leading indicators.

Module A4 (transport to site) makes up a very small share of the environmental impacts, while B4 (replacement of building components) has a larger impact than expected. Therefore, in the future development of building structures, special attention should be paid to fault tolerance and durability to maintain all parts of the building components for as long as possible.

The ranking of the ecological impact of the building components shows that not only does the superstructure need to be taken into account, but in multi-storey buildings the floor structures also have a major influence on the environmental impact. Standard structures, as used in this case study in Austria, consist of a levelling layer, impact sound insulation, screed and flooring. These materials are often based on polymer and cement. There are currently no environmentally friendly alternatives that have the same technical properties and are economically affordable. The development of ecological floor structures is, therefore, of great importance.

Although the timber building would require more cooling in the summer, it requires less heating energy in the winter. Thus, despite climate change and the associated higher outdoor temperatures in summer, timber construction will continue to prove its worth in Austria. For current software and standards, climate data are often more than 10 years old. As climate change has progressed rapidly in recent years and is more severe in Austria than the global average, it is recommended that the standards for climate models be updated more quickly to allow realistic prediction of thermal comfort at the design stage.

### *Future Research*

To reduce the embodied impact of new buildings, further case studies should be calculated. It would be interesting to see how the buildings' ecological footprint could be reduced by glueless timber construction and the use of recycled materials.

In the development of ecological floor constructions, special attention should be paid to sound protection. Sound insulation is a key consideration in the development of ecological floor structures as it is often the reason for the use of conventional materials with high environmental impacts.

A general increase in the proportion of natural building materials in buildings should not only consider the effects on the life cycle assessment, but also the effects on human health and social acceptance.

To construct buildings that are adaptable to climate change, low-tech energy solutions and their impact on the environmental footprint will play a major role in the future. This approach can make a significant contribution to the design and construction of resilient buildings for the future.

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## Appendix A

**Table A1.** Material data for WUFI Plus simulation.

| Material | Density [kg/m$^3$) | Specific Heat Capacity c [J/kgK] | Thermal Conductivity λ [W/mK] |
|---|---|---|---|
| CLT | 410 | 1000 | 0.7 |
| Concrete | 2104 | 1300 | 0.098 |
| Timber frame with mineral wool | 25.2 | 1000 | 0.035 |
| Gravel | 1400 | 1000 | 0.7 |
| OSB (airtight sealed) | 553 | 1700 | 0.12 |
| Wood fiber board | 155 | 2000 | 0.042 |
| EPS | 20 | 1500 | 0.17 |
| XPS | 20 | 2300 | 2.3 |
| Plaster board | 850 | 850 | 0.2 |
| screed | 1970 | 1500 | 0.13 |
| Mineral wool | 25.2 | 850 | 0.2 |
| Interior plaster | 850 | 850 | 0.2 |
| Parquet | 650 | 1300 | 0.098 |
| Rubber granulate mat | 83 | 840 | 0.035 |
| Bituminous sealing | 1100 | 840 | 0.035 |
| Bituminous water vapour barrier | 130 | 1500 | 0.04 |
| Silicate plaster | 1900 | 850 | 0.8 |
| Cement-bound EPS | 700 | 850 | 0.26 |
| Polyethylen foil (sd = 50 m) | 130 | 850 | 1.6 |

**Table A2.** Total values of GWP and PER for both buildings divided into life stages over 100 years.

| | GWP | | | | PER | | | |
|---|---|---|---|---|---|---|---|---|
| | Gas | | District Heating | | Gas | | District Heating | |
| | W | RC | W | RC | W | RC | W | RC |
| A1–A3 | −55.6 | 319 | −55.6 | 319 | 3047 | 320 | 3047 | 320 |
| A4 | 11.4 | 12.9 | 11.4 | 12.9 | 2.39 | 2.98 | 2.39 | 2.98 |
| B4 | 135 | 124 | 135 | 124 | 896 | 598 | 896 | 598 |
| B6 | 2598 | 2598 | 709 | 709 | 3679 | 3679 | 26,756 | 26,756 |
| C1–C4 | 263 | 64.6 | 263 | 64.6 | 2.03 | 3.82 | 2.03 | 3.82 |

**Table A3.** Total values of PENRT and ODP for both buildings divided into life stages over 100 years.

| | **PENRT** | | | | **ODP** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Gas** | | **District Heating** | | **Gas** | | **District Heating** | |
| | W | RC | W | RC | W | RC | W | RC |
| A1–A3 | 2947 | 4122 | 2947 | 4122 | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ |
| A4 | 177 | 202 | 177 | 202 | $2 \times 10^{-6}$ | $2 \times 10^{-6}$ | $2 \times 10^{-6}$ | $2 \times 10^{-6}$ |
| B4 | 2561 | 2302 | 2561 | 2302 | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ | $1 \times 10^{-5}$ |
| B6 | 40,344 | 40,344 | 9597 | 9597 | 0.0004 | 0.0004 | $7 \times 10^{-5}$ | $7 \times 10^{-5}$ |
| C1–C4 | 184 | 433 | 184 | 433 | $2 \times 10^{-6}$ | $5 \times 10^{-6}$ | $2 \times 10^{-6}$ | $5 \times 10^{-6}$ |

**Table A4.** Total values of AP and EP for both buildings divided into life stages over 100 years.

| | **AP** | | | | **EP** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Gas** | | **District Heating** | | **Gas** | | **District Heating** | |
| | W | RC | W | RC | W | RC | W | RC |
| A1–A3 | 0.749 | 0.987 | 0.749 | 0.987 | 0.345 | 0.55 | 0.345 | 0.55 |
| A4 | 0.0439 | 0.0528 | 0.0439 | 0.0528 | 0.0117 | 0.0141 | 0.0117 | 0.0141 |
| B4 | 0.559 | 0.486 | 0.559 | 0.486 | 0.229 | 0.192 | 0.229 | 0.192 |
| B6 | 3.19 | 3.19 | 2.66 | 2.66 | 2.08 | 2.08 | 2 | 2 |
| C1–C4 | 0.0841 | 0.139 | 0.0841 | 0.139 | 0.063 | 0.0413 | 0.063 | 0.0413 |

**Table A5.** Total values of POCP for both buildings divided into life stages over 100 years.

| | **POCP** | | | |
|---|---|---|---|---|
| | **Gas** | | **District Heating** | |
| | W | RC | W | RC |
| A1–A3 | 0.172 | 0.217 | 0.172 | 0.217 |
| A4 | 0.006 | 0.0074 | 0.006 | 0.0074 |
| B4 | 0.0925 | 0.106 | 0.0925 | 0.106 |
| B6 | 0.617 | 0.617 | 0.313 | 0.313 |
| C1–C4 | 0.0134 | 0.0208 | 0.0134 | 0.0208 |

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