# Greenhouse gas reduction strategies for building materials

*A reality check with the climate targets*

Alaux, N.; Truger, B.; Hoxha, E.; Saade, M. Ruschi Mendes; Passer, A.

*Published in:*
IOP Conference Series: Earth and Environmental Science

*DOI (link to publication from Publisher):*
10.1088/1755-1315/1078/1/012050

*Publication date:*
2022

*Document Version*
Publisher's PDF, also known as Version of record

*Citation for published version (APA):*
Alaux, N., Truger, B., Hoxha, E., Saade, M. R. M., & Passer, A. (2022). Greenhouse gas reduction strategies for building materials: A reality check with the climate targets. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), [012050]. https://doi.org/10.1088/1755-1315/1078/1/012050

IOP Conference Series: Earth and Environmental Science

# Greenhouse gas reduction strategies for building materials: A reality check with the climate targets

To cite this article: N Alaux *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1078** 012050

# Greenhouse gas reduction strategies for building materials: A reality check with the climate targets

**N Alaux[1*], B Truger[1], E Hoxha[1,2], M Ruschi Mendes Saade[1] and A Passer[1*]**

[1]Graz University of Technology, Institute of Structural Design, Working Group Sustainable Construction, Waagner-Biro-Straße 100/XI, 8020 Graz, Austria.
[2]Aalborg University, Department of the Built Environment, A. C. Meyers Vaenge 15, 2450 Copenhagen SW, Denmark.

*nicolas.alaux@tugraz.at; alexander.passer@tugraz.at

**Abstract**. The increasing importance of the embodied emissions in the life cycle of buildings has led to a growing interest in strategies supporting their mitigation. In this paper are presented the environmental impacts of 10 variants of a single-family house assessed with the life cycle assessment (LCA) method. A set of potential technological improvements and strategies are applied at the material level. Their influence at the building level is discussed and the resulting global warming potentials are compared to the COP21 targets for Austrian buildings. Finally, potential trade-offs in 9 other environmental impact categories are explored. The results show that, when incorporating all of the assessed strategies for emission reduction, the embodied greenhouse gas (GHG) emissions could be reduced up to 87% at the material level and 50% at the building level. Carbon capture and storage and the use of bio-based materials are to be credited for the highest share of these reductions. However, there is no version of this building that fulfils the COP21 targets. Other pathways, which do not solely rely on material-related technological improvements, should be investigated. A more radical change of the building industry might even be necessary. Overall, the implementation of the strategies decreased the environmental impacts in almost every impact category, except for freshwater aquatic ecotoxicity.

**Keywords**: Buildings, life cycle assessment (LCA), greenhouse gas emissions (GHG), future technologies, mitigation strategies

## 1. Introduction

In 2015, 195 countries came to terms through the COP21, or the Paris Agreement, and decided to limit global warming to 1.5-2°C above pre-industrial levels. To achieve this objective, mitigation strategies must be identified in all sectors of the economy, starting with the most carbon-intensive ones. The building sector, which accounts for 37% of broader global greenhouse gas (GHG) emissions [1], is undeniably one of them. An approach that is often used to translate these global COP21 targets into specific goals for the building sector is the introduction of a carbon budget. This method aims to calculate a quota for GHG emissions that a country can spend by 2050 to ensure that it stays on the 1.5-2°C pathway. However, there is rarely complete agreement on the definition of a carbon budget, and different approaches to the calculation can be considered legitimate. Many European countries such as

Switzerland, the Czech Republic, or Denmark have already calculated carbon budgets for their respective building stocks [2]. In Austria, a first estimate was produced, combining top-down and bottom-up approaches. Considering new constructions and assuming a reference service life of 50 years, the calculated values would be 4 $kgCO_2eq/m^2a$ for the embodied emissions (production of materials, transportation, construction of the building, renovation, end-of-life treatment, etc.) and 1.8 $kgCO_2eq/m^2a$ for the operational emissions (HVAC, electrical equipment, etc.). These quotas were obtained by using the consumption-based emissions in Austria and assuming that they would have to be reduced to 1 t-$CO_2eq$/capita in 2050. Using statistical data and projections, the building-related emissions were then equally distributed between Austrian buildings and cross-checked with data from case studies [3].

Operational emissions have long been a focus of interest because they far exceeded embodied emissions during the life cycle of a building [4]. It is commonly expected that the greatest environmental impacts generated by (and within) a building occurs during its use, as a result of its long service life. Today, however, operational emissions can be drastically reduced with stricter regulations applying for new buildings and renovation measures [5]. The passive house standard [5] is an example of such a possible radical reduction in a building's operational emissions. As a result, embodied emissions are gaining importance, not only due to the mere decrease in the relative share of operational emissions, but also due to increased material needs, such as e.g. additional thermal insulation [6]. There is growing interest in the investigation of strategies, new technologies and innovative building practices which would help reduce the embodied emissions of buildings [7–9]. Among these approaches, interventions at the material level have been considered to be the most effective strategies for reducing embodied GHG emissions [10]. Various promising strategies aiming in this direction, which have the potential for implementation in the manufacturing process of construction materials by 2050, have been pointed out, such as the use of renewable electricity, the use of bioenergy, improvements in energy efficiency, the implementation of carbon capture and storage (CCS), and the use of renewable fuel for transportation [7]. Additionally, other approaches such as an increased use of bio-based or recycled materials, could complement these technological improvements [9]. The practical possibility of achieving the COP21 objectives (for the embodied emissions) based on these strategies, however, has yet to be determined.

The goal of this study is to investigate the influence of these identified strategies on the embodied GHG emissions of building case studies, to question their suitability to reach the climate (or COP21) goals, and to explore potential trade-offs within the other environmental impact categories.

## 2. Methods

### 2.1. *Overall methodology*

The overall methodology of this article can be described as follows: the environmental impacts of 10 variants of a single-family house are assessed using life cycle assessment (LCA), considering 10 impact categories. A set of potential future technological improvements and strategies identified in the literature at the material level are applied to these variants and the influence of each strategy at the building level is discussed for the global warming potential (GWP). The ensuing GWP results are then compared to the COP21 targets which were previously calculated for Austria [3]. Finally, potential trade-offs triggered by these strategies in other environmental impact categories are explored.

### 2.2. *Life cycle assessment (LCA)*

LCA is performed for construction materials following the EN-15804 standard [11], and at the building level in accordance with the EN-15978 standard [12]. The goal of the analysis is to compare the GHG emissions of different building variants to the climate targets, considering future material-related technological improvements and strategies identified in the literature, as well as to explore potential trade-offs triggered by these strategies in other environmental impact categories. The functional unit is the square meter net floor area (NFA) of a single-family house (SFH) built with current construction techniques, excluding its surroundings. The system boundaries include the product stages (A1-A3), the construction process (A4-A5), replacement (B4), operational energy use (B6), and the end-of-life stages

(C1-C4). The distances used in A4 are based on transportation data from a recently completed building project in Austria [13]. The A5 and C1 modules are roughly calculated using typical ratios of the product stages (respectively 5% and 2%) [14]. B4 is based on the available Austrian data for the service life of building components [15]. For B6, the impacts of heating, cooling, ventilation, hot water, lighting and appliances are included and are calculated according to Austrian requirements for energy certificates of buildings [5]. Regarding C2-C4, usual end-of-life scenarios are used [16]. For this study, the 'cut-off approach' of the Swiss ecoinvent database v.3.8 [17] is chosen and is accessed from the simapro LCA software v.9.3. The impact assessment is performed with the CML 2001 baseline method version 3 and includes its 10 impact categories [18].

### *2.3. Case studies*

The investigated case study is a single-family house (SFH), designed in a previous research project by a consortium including the Austrian research institutes and associations for construction materials [19]. Based on a project planning, inventories were elaborated for 45 different variants with varying building techniques, energetic class and technical equipment [19]. The external dimensions, the basement and the roof designs were kept identical between all variants. The gross floor area (GFA) is of 221m$^2$ for all variants, but the net floor area (NFA) slightly varies (between 159 and 173m$^2$), depending on the thickness of the exterior walls required to fit the insulation needs of each energetic class. The NFA will be consistently used in this paper when mentioning the floor area. This house typology is particularly relevant in the Austria context, as SFHs accounted for 66% of the new constructions in 2020 [20].

For this study, which is focused on the embodied environmental impacts, it was important to reflect the diversity of the construction practices, which is why the brick, concrete and wood variants of this SFH were considered. Keeping this aspect in mind, the variants for which the operational GHG emissions were lower than the climate targets of 1.8 kgCO$_2$eq/m$^2$a [3] were selected for further analysis. Table 1 presents the houses which came out of this selection process. Their energetic classes are defined based on a heat-demand perspective, in accordance with Austrian standards [21]. The passive house and plus-energy house standards both have a heating demand of 10 kWh/m$^2$a, but the latter one includes 61m$^2$ of photovoltaic panels built on the house [19]. The generated electricity is assumed to cover the entire personal consumption but does not bring additional benefits in the calculations. The operational emissions are not further discussed in this paper and their impact is not calculated for other impact categories, as their main purpose was to select the different case studies which would then be further investigated in this study, from an embodied emissions point of view.

**Table 1.** Overview of the different variants of the case study which are investigated in this study [19].

| Case study number | Building technique | Technical equipment | Energetic class | Operational GHG emissions |
|---|---|---|---|---|
| 1 | Bricks external insulation | Heat pump | Passive house | 1.2kg CO$_2$eq/m$^2$a |
| 2 | Bricks single shell | Heat pump | Passive house | 1.2 kgCO$_2$eq/m$^2$a |
| 3 | Concrete | Heat pump | Passive house | 1.2 kgCO$_2$eq/m$^2$a |
| 4 | Solid wood | Heat pump | Passive house | 1.2 kgCO$_2$eq/m$^2$a |
| 5 | Frame wood | Heat pump | Passive house | 1.2 kgCO$_2$eq/m$^2$a |
| 6 | Bricks external insulation | Heat pump | Plus-energy house | 0 kgCO$_2$eq/m$^2$a |
| 7 | Bricks single shell | Heat pump | Plus-energy house | 0 kgCO$_2$eq/m$^2$a |
| 8 | Concrete | Heat pump | Plus-energy house | 0 kgCO$_2$eq/m$^2$a |
| 9 | Solid wood | Heat pump | Plus-energy house | 0 kgCO$_2$eq/m$^2$a |
| 10 | Frame wood | Heat pump | Plus-energy house | 0 kgCO$_2$eq/m$^2$a |

### 2.4. *Investigated strategies*

This study builds on previous work from the literature in terms of identification and implementation of material-related strategies and technical innovation, in order to reduce the embodied GHG emissions of buildings. Most of the investigated strategies come from [7], a study on life cycle inventories for the future production of mineral, metallic, wood, and plastic building materials commonly used in the Swiss construction industry, based on industry data collection. These strategies, which all relate to the manufacturing stage, can be described as follows: an increased renewable electricity use, an intensified use of bioenergy, improvements in energy efficiency, the implementation of CCS, and the use of renewable fuel for transportation (biofuels or electricity, used for the A2 module). These datasets were adapted to the Austrian context and applied to common various structural and insulation materials (concrete, bricks, mortar, wood, stone wool, etc.). The materials were assumed to be produced in Austria, or in Europe. The exhaustive list of materials included in this analysis, as well as the and applied strategies, are provided in Figure 1. In particular, it is possible to visualize which strategies are applied to which materials and how certain materials are interconnected during the manufacturing process.

The use of renewable fuels for transportation was also applied to modules A4 and C2 to ensure consistency with A2. Additional strategies which are compatible with the afore-mentioned ones were also identified in the literature, such as the use of bio-based materials, the design of innovative cement mixes or the integration of circularity approaches [9]. We decided to include some of these strategies in the following way: the inclusion of bio-based materials was performed by replacing PVC windows by wooden ones. Plastic polystyrene insulation was also replaced by cellulose insulation, made out of recycled paper, which also integrates the circularity approach. This insulation replacement was adapted solely based on the thermal conductivities of the materials but did not consider any technical constraints in the building. Finally, an innovative cement mix with reduced clinker content was also modelled, based on predictions from the concrete industry and similarly to the International Energy Agency (IEA) strategies for concrete and cement [22].

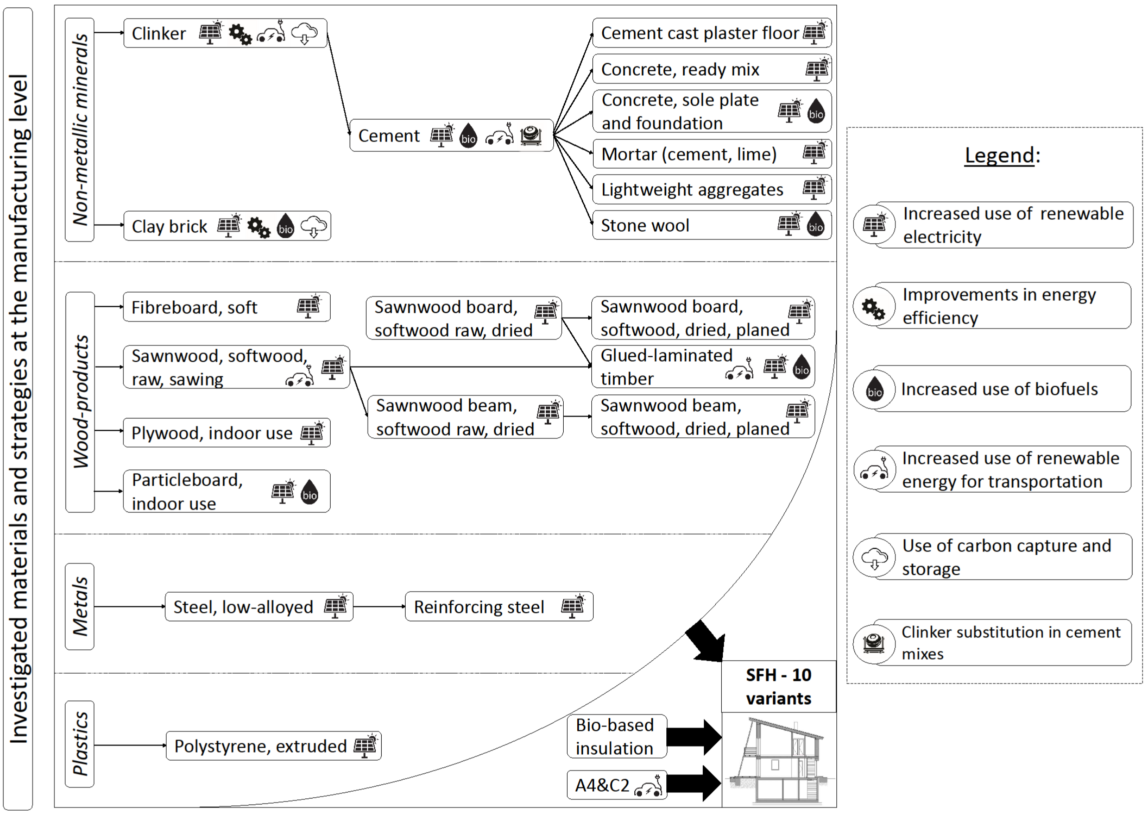

**Figure 1.** Overview of the investigated strategies and materials (based on [7,9,19]).

## 3. Results and discussion

### *3.1. Influence of the strategies on the GWP*

The influence of each strategy is first briefly discussed at the material level and shows that, when incorporating all of them, the GHG emissions coming from the manufacturing stage could be reduced by as much as 87%. These reduction percentages are presented in Table 2 for concrete, bricks, glued-laminated timber (glulam) and soft fibreboard, as an example. Results show that CCS is the main driver of the GHG emissions reduction for concrete and brick production, with a decrease of 63.2% and 49.3%, respectively. Efficiency improvements are also particularly relevant in brick production, as they contribute to 31.1% of the reduction. This is due to the fact that an early development-stage innovative brick firing technique, microwave-assisted gas firing [23], was included in the efficiency improvements. In the context of wood production, the role of renewable electricity in reducing emissions is notable, decreasing up to 26.1% of the emissions for glulam and 54.7% of the fibreboard. In the case of fibreboard, the use of biofuels contributes to a higher reduction than for glulam (20.1% versus 7.5%). These differences are also reflected in the maximum reduction potential for these materials, which is of 39.6% for the glulam and 74.7% for fibreboard.

**Table 2.** Influence of the strategies on four construction materials, expressed in percentage of reduction of the GHG emissions.

| | Renewable electricity | Renewable fuel for transportation | Efficiency improvements | Use of CCS | Use of biofuels | Reduced clinker content | All strategies combined |
|---|---|---|---|---|---|---|---|
| Concrete | 6.7% | 0.3% | 6.5% | 63.2% | - | 4.7% | 81.4% |
| Bricks | 5.4% | - | 31.1% | 49.3% | 5.0% | - | 87.4% |
| Glulam | 26.1% | 11.8% | - | - | 7.5% | - | 39.6% |
| Fibreboard | 54.7% | - | - | - | 20.1% | - | 74.7% |

The influence of these strategies was then further investigated in the 10 building case study variants and shows comparable effects between the variants, although some slight dissimilarities can be noticed. In Figure 2, each colour of the columns illustrates the GHG emissions which can theoretically be “saved” by applying one of the strategies. The case studies numbers directly refer to the ones defined in Table 1. Compared to the material level, the use of renewable fuel for transportation was also applied to the other transportation modules of the LCA (A4 and C2) for better coherence. Changing windows and insulation towards bio-based materials was also included, as a ‘bio-based’ strategy. When applying all of these strategies, the grey columns (referred to as “Remaining emissions” on the graph) remain. The achieved GHG reductions lie between 41% and 50% depending on the building type. Although the brick houses had the highest reductions, the wooden houses had the lowest embodied emissions to start with.

Among all the different strategies, CCS and the use of bio-based materials are to be credited for the highest share of the GHG reduction at the building level, for every house. CCS is the main driver in reducing the emissions (16-20%) for concrete and brick houses, while the bio-based strategy is the second biggest contributor (12-17%). The opposite trend can be observed for timber houses, with the bio-based strategy accounting for 13-15% of the reduction and CCS for 11-13%. The high influence of CCS on the mineral houses is in accordance with the results at the material level presented in Table 2. However, it is surprising that changing the insulation and the windows from plastics towards bio-based materials would lead so such high reductions over the whole life cycle. On examining the remaining strategies, their influence can be seen to differ slightly depending on the building type. Similar to the situation in the material level, efficiency improvements play a larger role in the brick buildings, while the effects from the use of renewable electricity is more noticeable in the timber buildings. However, the latter strategy, which is expected to have a significant role in the reduction of the operational emissions of buildings, is found to have a relatively low impact on the reduction of the embodied emissions (4-6% depending on the building type). This small reduction is partly due to the already relatively low impacts of the Austrian electricity grid, but also because a large share of the emissions in the construction industries come from raw material-related processes which are not energy-based (as pointed out in [2]). The use of renewable fuel for transportation in A2, A4 and shows a similar influence (3-6% depending on the building type). Finally, the use of biofuels for material production and the production of cement with reduced clinker content seem to be less significant and contribute to less than 3% of the emissions reduction.

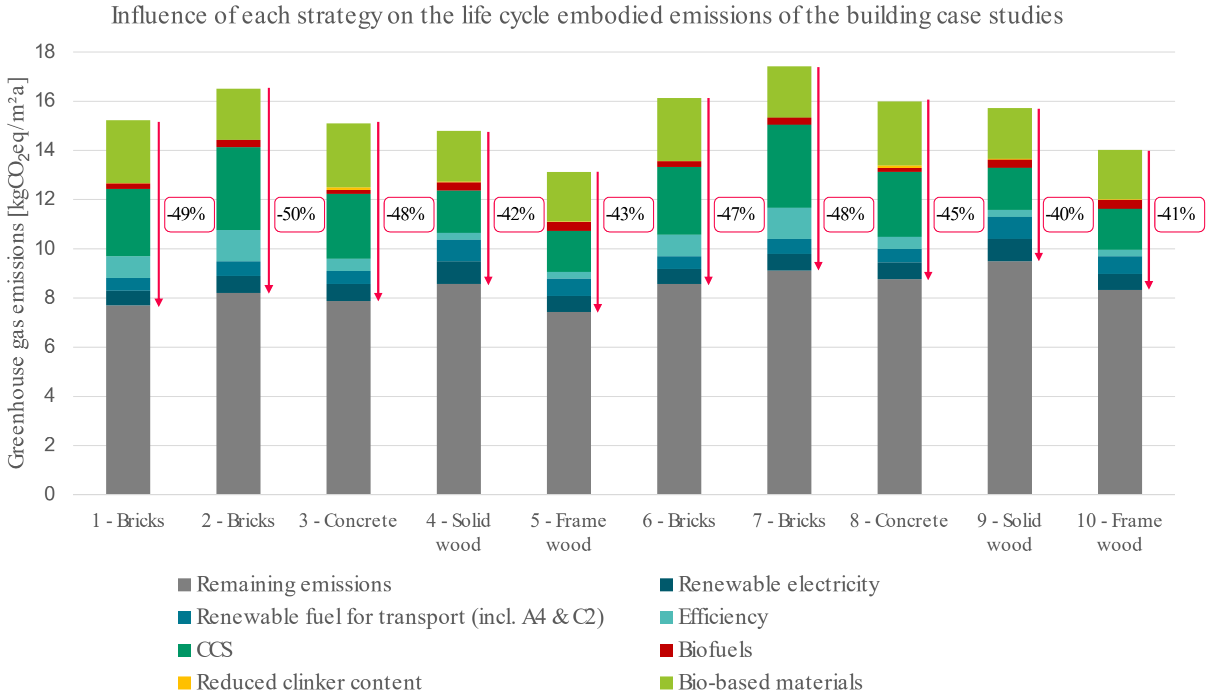

**Figure 2.** Influence of each strategy on the life cycle embodied emissions of the building case studies.

### 3.2. *GWP results in regard to the climate goals*

There are no versions of this building which fully fulfil the COP21 targets in terms of embodied GHG emissions, even with the implementation of all the identified strategies. Figure 3 presents the embodied GHG emissions of the case study variants, per LCA module, as well as the COP21 target for the total of all the embodied emissions (the orange dot on the graph). The bars reflect the variability of the results obtained from the different case study variants. It is clear that the total of the embodied emissions is far higher (at least twice as high in most cases) than the COP21 target. It should also be mentioned that two refurbishments of the building are included in this budget of 4 $kgCO_2eq/m^2a$ [3]. As module B5 was not part of our LCA calculations, the actual budget that we should consider for the embodied emissions should be even lower. In more than half of the cases, even the emissions coming from A1-A3 are already higher than the target. The house achieving the overall lowest embodied GHG emissions is variant number 5, the frame-wood passive house. When however, considering the operational emissions, which were used in Table 1, it is the frame-wood plus-energy house (variant number 10) which achieves the overall lowest GHG emissions. Even for these two best cases, their embodied emissions are far higher than the climate target. It should also be kept in mind that, in theory, this target must be met by every newly built building, starting now and up until 2050. This surely appears challenging if this target cannot be met in 2050 when these technologies (such as CCS) should become more widely available.

These results point towards the fact that a more radical change in the building industry should take place in order to reach the climate goals. Drastically reducing the number of new buildings and focusing on renovations might also be a way of success. Additional pathways, which do not solely rely on technological improvements at the material level should be investigated. For example, innovative building design practices could reduce the needed amounts of materials and, therefore, indirectly reduce the emissions coming from the manufacturing phase. Another approach could be closing the material loop in the buildings sector, by moving towards a complete circular economy. Finally, a broader discussion about sources and sinks of emissions should be addressed, in particular to investigate the potential role of fast-growing bio-based materials.

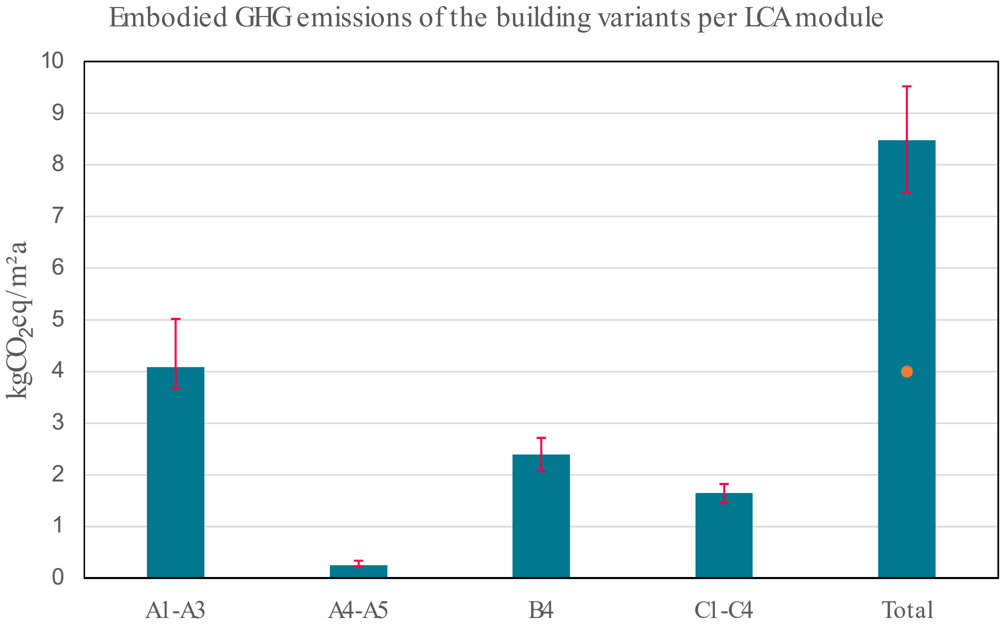

**Figure 3.** Embodied GHG emissions of the building variants per LCA module compared with the COP21 target (orange dot).

There are, however, multiple inherent uncertainties regarding these LCA calculations which should be considered when interpreting the results. The first relates to the availability of the discussed technologies. Some of the suggested strategies are only theoretical and their applicability has not been proven in practice. The implementation of CCS requires substantial economic investments, a fact that is frequently cited as one of its main barriers [24]. In addition, the IEA in its technology roadmap for cement foresees that a maximum of 25% of the cement-related emissions might be captured by 2050 [22]. In this paper, CCS was very optimistically applied and reduced almost 70% of the cement-related emissions, which is much higher than the IEA predictions. If investments in CCS technologies remain only modest, this would mean a drastic reduction in the real influence of CCS compared to the results of this paper. The same discussion can be held for microwave-assisted gas firing in brick production [23], which is still at an early development-stage and would of course require substantial investment, first to bring it to the market, and second to implement it in existing brick factories. The applicability of this technology to an actual brick factory still needs to be proven. Similarly, the possibility of a high clinker substitution in cement production also needs to be demonstrated in practice, at a larger scale than laboratory experiments. The considerations made in this paper are, therefore, based on a theoretical implementation of these early-stage strategies. In the context of other strategies such as the increase in renewable energy generation or biofuels, the achievement of these ambitions can also not be guaranteed despite the demonstration of strong political support at the European level [25].

Another source of uncertainty is associated with the choice of the investigated materials, as well as the LCA modelling of the strategies applied to these materials. It is very likely that there is an underestimation of the reduction potentials due to the fact that the strategies were not applied to all construction materials. For example, the decarbonization of the electricity grid will uniformly affect all materials for which electricity is needed during their manufacturing process. Therefore, its evolution should be uniformly applied to every material of the building. This also applies to the background processes on which the foreground system relies. In that regard, there is a strong temporal mismatch between the processes used in this LCA, which was found in some studies to have a noticeable influence on the final results [26]. This is a well-known challenge in prospective LCA studies, especially because it is usual to have a large majority of background processes among all unit processes [27]. Attempts to resolve this gap are currently being discussed in the literature [26–28]. In any case, one should keep in mind that the study presents a possible future, and one which may emerge subject to a specific set of assumptions [29]. In this possible future, the investigated strategies are not enough to meet the climate goals, but it is definitely not claimed that this is the only possible future.

### *3.3. Results regarding other impact categories*

Although the focus is usually put on the GWP, especially when discussing climate targets, it is possible that some strategies might trigger an increase in other environmental impact categories. Such 'trade-offs' could hinder the interest in implementing such technologies. Table 3 introduces a heatmap of the reduction percentage for each case study variant (as numbered in Table 1) and for each impact category of the CML 2001 baseline method version 3 [18]. This heatmap was obtained by comparing the impacts of the case studies before and after implementing all of the strategies (considering only the embodied impacts). The percentage of reduction in the impacts was calculated based on these results. When this percentage is positive, this means there is a reduction in the environmental impacts, but when it is negative, this means there has actually been an increase. The colour scheme is just a visual indication of the amount of the reduction, the highest reductions being achieved when the colour is dark green.

**Table 3.** Heatmap representing the impact reduction for each case study variant and for each impact category of the CML 2001 baseline method version 3 [18]. The dark green colour represents the highest reductions in the environmental impacts, while the light green shades indicate smaller reductions, and the yellow colour indicates an increase in the impacts (hence the negative reduction percentage).

| Case study | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | 7% | 8% | 7% | 8% | 8% | 5% | 5% | 5% | 5% | 5% |
| Global warming (GWP100a) | 49% | 50% | 48% | 42% | 43% | 47% | 47% | 45% | 39% | 40% |
| Ozone layer depletion | 65% | 65% | 62% | 59% | 63% | 44% | 45% | 42% | 41% | 42% |
| Human toxicity | 14% | 15% | 10% | 11% | 11% | 8% | 9% | 6% | 6% | 7% |
| Fresh water aquatic ecotox. | -14% | -13% | -14% | -12% | -15% | -12% | -11% | -12% | -11% | -13% |
| Marine aquatic ecotoxicity | 48% | 58% | 25% | 13% | 11% | 45% | 55% | 23% | 11% | 10% |
| Terrestrial ecotoxicity | 0% | 1% | 2% | 2% | 0% | 0% | 1% | 1% | 2% | 0% |
| Photochemical oxidation | 38% | 26% | 38% | 13% | 17% | 34% | 23% | 35% | 12% | 15% |
| Acidification | 21% | 21% | 19% | 17% | 17% | 19% | 18% | 17% | 15% | 15% |
| Eutrophication | 25% | 25% | 23% | 17% | 20% | 24% | 23% | 21% | 16% | 19% |

Overall, the implementation of the strategies decreases the environmental impacts of almost every impact category, except for freshwater aquatic ecotoxicity. For the passive houses (numbers 1 to 5), the highest reductions are reached for the GWP, while for the plus-energy houses (numbers 1 to 10), it is the ozone layer depletion which benefits from the largest decrease in impacts, although this decrease is similar to the ones for the passive houses (39-50% of reduction). It is likely that the additional technical equipment needed for the plus-energy house standard (solar panels, etc.) will increase the embodied GHG emissions and therefore decrease the reduction potential for the GWP. The reductions in marine aquatic ecotoxicity and photochemical oxidation are high for the mineral buildings (numbers 1, 2, 3, 6, 7 and 8) with respectively 23-58% and 23-38% reduction, but relatively moderate for the other buildings (10-17% reduction). This is mostly linked to the biofuel strategy applied to brick production. It indicates that the use of biofuels has an additional benefit in brick production, and its influence is far higher than its influence on the GWP, which was relatively low (as noticeable in Figure 2). This effect is visible on all building variants because they all have bricks in their building elements (but to different extents based on the construction technique). Acidification and eutrophication also have moderate reductions for all buildings, respectively 15-21% and 16-25%. Regarding abiotic depletion and human toxicity, the reduction is noticeable but nevertheless relatively low for all buildings, respectively 5-8% and 5-15%. Terrestrial ecotoxicity remains almost neutral with less than a 2% reduction at best. Finally, freshwater aquatic ecotoxicity is the only indicator of the list for which the impacts have increased (hence the negative percentage). Previous studies already highlighted the increase in fresh water ecotoxicity and human toxicity in the case of CCS combined with electricity generation systems [30,31]. However, at the building level, the increase in human toxicity would appear to be compensated by another strategy, which could be the bio-based strategy. In any case, even if a direct comparison of the environmental indicators is impossible, the produced trade-offs seem to be relatively low when applying all of these strategies to the case studies, with a maximum increase of only 15% in freshwater aquatic ecotoxicity.

## 4. Conclusion

This study investigated the influence of identified strategies in the literature, which can be applied at the material level, on the embodied environmental impacts of 10 building case study variations. This was performed in the light of the climate targets calculated for Austria. The explored strategies, which affect the manufacturing of construction materials, can be defined as follows: an increased renewable electricity use, an intensified use of bioenergy, improvements in energy efficiency, the implementation of CCS, a reduction of the clinker content of cement and the use of renewable fuel for transportation. They were applied to various common structural and insulation materials (concrete, bricks, mortar, wood, stone wool, etc.). Additionally, the replacement of plastics by bio-based materials was considered at the building level. The results show that, when incorporating all of the strategies, the embodied GHG emissions could be reduced by as much as 87% at the material level and 50% at the building level. CCS and the use of bio-based materials are to be credited with the highest share in these reductions. The use of renewable electricity, which is expected to have a significant role in the reduction of operational emissions in buildings, has been found to have a relatively lower impact on the reduction of their embodied emissions. This is due to the already relatively low emissions of the Austrian electricity grid, but also because a large share of the emissions in the construction industries come from raw material-related processes which are not energy-based. However, despite the implementation of all these strategies, there are no versions of this building which fully fulfil the COP21 targets in terms of embodied GHG emissions. These results point to the fact that other pathways, which do not rely solely on technological improvements at the material level should be investigated, and that a broader discussion about sources and sinks of emissions should be addressed. It is also possible that a more radical change of the building industry could take place in order to reach the climate goals. Drastically reducing the number of new buildings and focusing on renovations might be a path to success here. In any case, one should keep in mind that the study presents a possible future with multiple inherent uncertainties and a lot of assumptions, which do not necessarily reflect the ‘real’ future. Finally, in terms of other impact categories, the implementation of the strategies decreases the environmental impacts of almost every one of them, except for freshwater aquatic ecotoxicity, for which a 15% maximum increase is observed.

## Acknowledgements

This paper was developed in the course of the ongoing research project “Transition of the procurement process towards Paris compatible public buildings” (ParisBuildings), conducted by the Working Group on Sustainable Construction from the Graz University of Technology and financially supported by the Klima- und Energiefonds, ACRP11 KR18AC0K14693. The analysis and results described in this paper also build upon the “Ökovergleiche” project (see http://www.hausderzukunft.at/results.html/id6530).

## References

[1] United Nations Environment Programme (UNEP) 2021 *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector* (Nairobi: UNEP) p 15

[2] Habert G *et al* 2020 *Buildings and Cities* **1** 429–52

[3] Hoxha E, Röck M, Truger B, Steininger K and Passer A 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 032052

[4] Lasvaux S, Lebert A, Achim F, Grannec F, Hoxha E, Nibel S, Schiopu N and Chevalier J 2017 *Int J Life Cycle Assess* **22** 657-74

[5] Österreichisches Institut für Bautechnik 2015 *OIB-Richtlinie 6: Energieeinsparung und Wärmeschutz*

[6] Röck M, Ruschi Mendes Saade M, Balouktsi M, Nygaard Rasmussen F, Birgisdottir H, Frischknecht R, Habert G, Lützkendorf T and Passer A 2020 *Applied Energy* **258** 107–14

[7] Alig M, Frischknecht R, Krebs L and Ramseier L 2020 *LCA of climate friendly construction materials* (Uster: treeze Ltd)

[8] Zhong X, Hu M, Deetman S, Steubing B, Xiang Lin H, Aguilar Hernandez G, Harpprecht C, Zhang C, Tukker A and Behrens P 2021 *Nature Communications* **12** 6126

[9] Alaux N, Hoxha E, Ruschi Mendes Saade M and Passer A 2021 *J. Phys.: Conf. Ser.* **2042** 012165

[10] Pomponi F and Moncaster A 2016 *Journal of Environmental Management* **181** 687-700

[11] European committee for standardization 2019 *EN15804+A2:2019: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*

[12] European committee for standardization 2012 *EN15978:2012: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*

[13] Hoxha E, Maierhofer D, Ruschi Mendes Saade M and Passer A 2021 *Int J Life Cycle Assess* **26** 852-63

[14] Lützkendorf T, Balouktsi M and Frischknecht R 2016 *Guideline for Design Professionals and Consultants Part 1: Basics for the Assessment of Embodied Energy and Embodied GHG Emissions* (Birmingham: Institute for Building Environment and Energy Conservation)

[15] Landesverband Steiermark und Kärnten 2020 *Nutzungsdauerkatalog 2020*

[16] Allacker K, Debacker W, Delem L, de Nocker L, de Troyer F, Janssen A, Peeters K, Servaes R, Spirinckx C and Van Dessel J 2017 *Environmental profile of building elements* (Mechelen: OVAM)

[17] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E and Weidema B 2016 *Int J Life Cycle Assess* **21** 1218-30

[18] Guinée JB 2002 *Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards* ed H de Bruijn *et al* (Dordrecht: Springer)

[19] Sölkner PJ, Oberhuber A, Spaun S, Preininger R, Dolezal F, Mötzl H, Passer A and Fischer G 2014 *Innovative Gebäudekonzepte im ökologischen und ökonomischen Vergleich über den Lebenszyklus* (Vienna: Bundesministerium für Verkehr, Innovation und Technologie)

[20] STATISTIK AUSTRIA 2021 *Baumaßnahmenstatistik*

[21] Austrian Standard Institute 2011 *ÖNORM H 5055:2011 08 05 – Gesamtenergieeffizienz von Gebäuden - Begleitende Dokumente zum Energieausweis - Befund, Gutachten, Ratschläge und Empfehlungen*

[22] International Energy Agency (IEA) 2018 *Low-Carbon Transition in the Cement Industry - IEA Technology Roadmaps* (Paris: IEA)

[23] Danish Technological Institute (DTI) 2013 *Sustainable manufacture of brick and tiles with microwave energy* (Aarhus: DIT)

[24] Salas DA, Ramirez AD, Rodríguez CR, Petroche DM, Boero AJ and Duque-Rivera J 2016 *J Clean Prod* **113** 114-22

[25] European Commission 2021 *Communication on "Fit for 55": delivering the EU's 2030 climate*

*target on the way to climate neutrality* (Brussels: European Commission)
[26] Mendoza Beltran A, Cox B, Mutel C, Vuuren DP van, Vivanco DF, Deetman S, Deetman S, Edelenbosch OY, Guinée J and Tukker A 2018 *Journal of Industrial Ecology* **24** 64-79
[27] van der Giesen C, Cucurachi S, Guinée J, Kramer GJ and Tukker A 2020 *J Clean Prod* **259** 120904
[28] Adrianto LR *et al* 2021 *Int J Life Cycle Assess* **26** 1541-4
[29] Frischknecht R, Büsser S and Krewitt W 2009 *Int J Life Cycle Assess* **14** 584-8
[30] Singh B, Strømman AH and Hertwich EG 2011 *Int J Greenh Gas Con* **5** 911-21
[31] Koornneef J, van Keulen T, Faaij A and Turkenburg W 2008 *Int J Greenh Gas Con* **2** 448-67