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A Need for Sufficiency in the Built Environment: Prospective Life Cycle Assessment of the Austrian Building Stock

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A Need for Sufficiency in the Built Environment: Prospective Life Cycle Assessment of the Austrian Building Stock

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Abstract. Around 38% of global greenhouse gas (GHG) emissions are related to buildings. In Austria, most building-related industries designed roadmaps to net zero GHG emissions by 2050. However, there is little evidence whether this will be enough to stay within the climate limits, or if a more drastic approach is needed. In this paper we investigate the potential need for sufficiency in the built environment to stay within the latest 1.5-2°C carbon budget, including expected future technological developments. We implement a set of energy and industry transition scenarios to a building stock model, including an increase in circularity, and compare the resulting carbon emissions (both operational and embodied) with the carbon budget. Results show that, even with ambitious decarbonization pathways for Austrian industry, the projected rates of construction do not allow for staying within the carbon budget. On the contrary, additional sufficiency measures such as slightly reducing the average living area per person are a great lever for reducing GHG emissions and, with carbon removal, might be the only options left to comply with the climate targets.

1. Introduction

As part of the Paris Agreement, also known as COP21, 197 nations have committed to limiting global warming to 1.5-2°C above pre-industrial levels [1]. To achieve this, great efforts must be made to define and implement emission reduction plans for high-emitting industries. In Austria, previous work has shown that building-related GHG emissions over the life cycle amount to around 20.4-29.2 $MtCO_2eq$ in 2014, depending on the underlying assessment method, namely process-based or input-output Life Cycle Assessment (LCA) [2]. Drastic emission reductions are required to achieve the goals of the Paris Agreement. Recent calculations show that Austria's consumption-based emissions would have to be halved every three years to meet the remaining carbon budget for a 1.5°C target [3]. However, due to the cross-sectoral and international nature of building-related activities, represented by their "field of action" [2], assessing the whole field of action of buildings is not a trivial task. In any case, given the high contribution of buildings to climate change, it is clear that reducing the environmental impacts associated with buildings is necessary to secure Austria's path toward a Paris-compatible vision.

In order to properly assess the potential to reduce GHG emissions related to the field of action of buildings, it is essential to collect information on the existing building stock, and building stock models are being developed for this purpose. This is particularly important for assessing the potential of refurbishments with regard to improving the energy efficiency of existing buildings. Several countries have already produced detailed models of their building stock [4]. Similarly, initial developments have

been carried out on the building stock of certain Austrian cities or regions [5,6]. However, most of these studies focus on the development of the building stock itself, without necessarily linking it to a scientific environmental assessment method for calculating GHG emissions, such as LCA. Models for existing buildings that include GHG emissions typically do not follow a life cycle perspective and omit embodied GHG emissions (which include the production of building materials, transport, end of life, etc.), especially in view of new construction activity in the coming decades [4]. Given the strong focus on renovation in the European Union [7], it is understandable that most modeling focuses initially on operational GHG emissions. Nevertheless, the importance of assessing and managing potential trade-offs between embodied and operational emissions to improve the life cycle performance of buildings has been emphasized in several studies [8].

In Austria, operational energy consumption in buildings and embodied emissions from buildings are generally assessed within the two sectors "buildings" and "industry." Future scenarios and roadmaps have recently been drawn up for both economic sectors. Indeed, most building-related industries have designed roadmaps to net zero GHG emissions by 2050 (Scope 1 emissions). As the production of building materials is energy-intensive, most industrial roadmaps to reduce emissions include a switch to renewable energy and electrification of the production process [9]. National projects such as NEFI have also drawn up possible decarbonization scenarios for the various industries [10]. Only recently, the Austrian National Environment Agency also developed new energy scenarios for Austria that include energy consumption in buildings and industry [11]. However, these scenarios have never been combined in a model that attempts to cover the entire building sector and compared with a carbon budget for buildings. Therefore, there is also little evidence as to whether these roadmaps and scenarios are sufficient to stay within climate limits or whether a more drastic approach is required.

In this paper we investigate the potential need for sufficiency in the built environment to stay within the latest 1.5-2°C carbon budget by linking, for the first time in the case of Austria, future energy and technological developments in the field of action of buildings. We implement a set of energy and industry transition scenarios to a building stock model, including an increase in circularity, and compare the resulting carbon emissions (both operational and embodied) with the carbon budget. The building stock model used in this study is described in detail in another publication [12]. The gap between the scenarios and the carbon budget is then bridged with sufficiency measures. Apart from the national novelty of the study, the international relevance stems from: (i) The focus on sufficiency at the building stock level, including the embodied emissions perspective. (ii) The model employed, which offers rather complete coverage in terms of life cycle stages and buildings. (iii) The prospective LCA framework applied to the building stock model, which allows for both foreground and background modifications of the LCA database.

2. Methods

2.1. Overview

This section describes the methods used in this paper. An overview can be found in Figure 1. Two future scenarios are created based on projections by the Austrian National Environmental Agency [11]. They are applied to a representative building stock model for Austria [12], which projects the annual material and energy flows of all Austrian buildings. The life cycle GHG emissions are then assessed and compared with the remaining carbon budget [13]. To bridge the emissions gap, sufficiency measures are introduced.

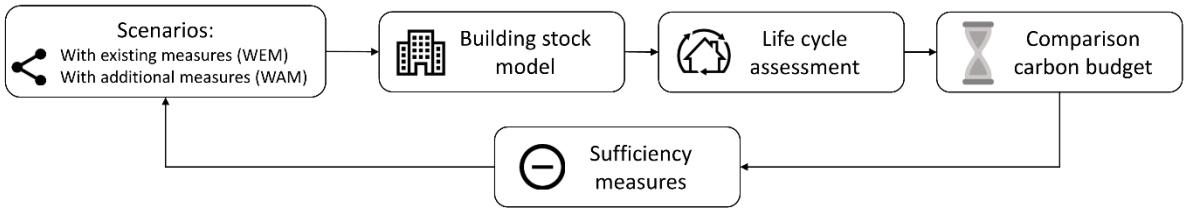

Figure 1. Overview of the methodology followed in this paper.

2.2. Building Stock Modeling

Building stock models aim to systematically represent the entire collection of buildings within a specific area, e.g. a country. The building stock model used in this study is representative for Austria and its creation is fully described in detail in another publication [12]. It is a Python-based, open source model. The model is typically bottom-up and based on 154 building archetypes. These archetypes were defined in earlier European projects [14]. They contain specific information about the building, such as geometry, energy consumption or materials. This approach is especially recommended to maintain comparability between the studies and harmonizing building stock modeling approaches [4]. Each archetype is divided into components (e.g., external walls) and materials (e.g., plaster, concrete, insulation, etc.). 366 components were created for new buildings or renovations and are based on 339 products (or materials). The output of the building stock model is the annual inflow and outflow of materials as well as the annual energy and water consumption, from 2023 to 2050. In other words, the model calculates how many tons of materials such as concrete or rock wool insulation are used annually for new buildings, the replacement of materials or the renovation of existing buildings, but also how much of these materials come from the demolition of buildings. In addition, the total energy consumption of the building stock (based on heating, cooling and electricity consumption) and water consumption are calculated. These calculated quantities are then linked to a prospective LCA framework, as explained in the next section.

2.3. Life Cycle Assessment

LCA is used to translate the results of the building stock model (as described in the previous section, annual quantities of materials, energy and water consumption) into environmental impacts, such as GHG emissions. It is linked to the building stock model via the open source framework for LCA brightway2 [15]. LCA is performed following the European standard EN 15978 [16]. This is an attributional, process-based approach. The ecoinvent database v3.9.1 cut-off [17] was used as a background database. From the prospective LCA perspective, *premise* was used to consistently modify the electricity generation in all foreground and background processes accordingly to scenarios from the REMIND integrated assessment model. This means, for example, that the electricity used in the production of all materials, or the fuel used in the trucks that transport these materials, is also changed annually, following the scenarios defined in the integrated assessment model. More information can be found in the original publication [18]. The impact assessment is conducted using the EF v3.0 EN15804 method [19], but only the global warming potential (fossil) is used in this study so as to be able to make a comparison with the remaining carbon budget. Concerning the scope of the LCA, using the life cycle modules from EN15978, A1-A3 (production of materials), A4-A5 (transport and construction), B4 (replacement), B5 (refurbishment), B6-B7 (operational energy and water use), and C1-C4 (end-of-life) are included.

2.4. Scenarios

Two main parameters are necessary to project the building stock from 2023 to 2050: the projected population development and the average living space per person. For Austria, both forecasts are taken from national statistics and institutions [20]. These are used to calculate the number of new buildings.

The number of demolished buildings is based on a Weibull distribution function following previous work [21], with parameters depending on typology and age. The number of replacements depends on typical lifetimes of building materials [22]. Regarding the energy-related scenarios, two main scenarios were recently developed by the National Environment Agency:

- **WEM** ("With Existing Measures"): This scenario considers political measures as of 01.01.2022 and follows current trends in all economic sectors.
- **WAM** ("With Additional Measures"): This scenario is based on the WEM but includes additional measures as recommended by the working groups on the National Energy and Climate Plan 2023 [23].

A third scenario called "Transition" was developed which shows a possible phase-out of fossil fuels in the Austrian energy system by 2040. As this scenario differs from the other two in that it is more normative and is considered less realistic, it was not included in the analysis.

The parameters used in the model to represent the two selected scenarios, such as renovation rates, are described in Table 1. The assumptions behind these scenarios not being fully transparent or made available to the public, best efforts were made to recreate them in the model, but some slight variations might occur. Due to this fact, the final energy consumption can vary for a specific year between our model and the original calculation, but cumulatively, over the years, the difference is less than 5%. Considering the embodied emissions, *premise* is used to systematically adapt the background LCA database. It includes the evolution of the energy, transport, as well as specific strategies for cement and steel, such as carbon capture and storage. These scenarios are from the REMIND integrated assessment model. For coupling with the WEM, the LCA background scenario SSP2-NDC is used, which is an extrapolation of historical developments, combined with the Nationally Determined Contributions (NDCs) from the Paris Agreement. For coupling with the WAM, which represents a stronger political ambition to reduce operational emissions from buildings, the SSP2-PkBudg500 scenario is used as LCA background, which envisages rapid penetration of renewable energies in order to achieve the Paris Agreement target (1.2-1.4 °C).

Table 1. Overview of the investigated scenarios and their main parameters

	WEM	WAM
Population	From 9,051,520 (2023) to 9,625,622 (2050)	
Renovation rate	Up to 1.4%	Up to 2.5%
Phase out of oil boilers	No	Yes, by 2040
Phase out of gas boilers	No	Yes, by 2050
Repartition of energy standard new buildings [standard, advanced, NZEB]	[10%, 20%, 70%]	[0%, 0 %,100%]
Share of renewable energy [2023, 2030, 2040]	[36%, 43%, 48%]	[36%, 53%, 69%]
Share of renewable electricity* [2023, 2030, 2040]	[76%, 96%, 87%]	[76%, 101%, 96%]
Background LCA database	SSP2-NDC	SSP2-PkBudg500
Increased circularity	No	Yes
*Imports/exports may lead to percentages over 100%, or decrease in the share of renewable electricity.		

Considering that the WAM scenario includes additional circular economy efforts within industry, the model simulated an increased circular economy for this scenario, based on current literature assessed within the INTEGRATE[1] project. The main recycling routes for the materials are: for wood waste, as wood panels [24]. For brick and concrete waste, respectively, as supplementary cementitious materials, with a maximum clinker replacement of 30% today and 50% in 2050 [25], or as recycled aggregates

[1] https://wegcwp.uni-graz.at/integrate/

with a limit of 30% [26]. For polystyrene insulation, for the same purpose [27]. For sand and aggregates, reused for the same purpose. For metals (including reinforcing steel) and flat glass, 95% of which is already recycled [28], no additional scenario.

As the investigated scenarios might overshoot the remaining carbon budget, a sensitivity analysis is performed with a sufficiency measure. The main investigated measure is the optimized use of space in buildings, which is modeled by changing the average living floor area per person, which is currently about 46 m² in Austria. The national long-term renovation strategy expects an increase up to 55.3 m² by 2050 [20], which is used in the WEM and WAM scenarios, while national projects also estimate a possible reduction to about 44 m² when consulting relevant stakeholders [29]. An additional scenario, called "WAM-SUF", based on the WAM scenario but for which the living floor area per person is decreased to 44 m², is therefore additionally investigated.

2.5. Carbon Budget

The remaining global carbon budget represents the total global amount of CO_2 that can still be emitted in order to remain within a specific global warming limit with a certain probability. It is quantified globally by the Intergovernmental Panel on Climate Change (IPCC) [30]. The challenge usually resides in translating this global carbon budget into specific budgets for buildings or building stocks. This was addressed in a previous publication, in which the authors of this study have recently developed a methodology to establish consistent carbon budgets specifically for life cycle emissions of the national building stock and applied it to the case study of Austria [13]. The outcome of this research is a carbon budget for the life cycle emissions of the Austrian building stock, which can be translated into a GHG budget assuming that 5% of GHG emissions of buildings are non-CO_2 emissions (as stated by the IPCC) [31]. The carbon budget can be given as a range, depending on the likelihood to reach the temperature target and the allocation mechanism used to derive the carbon budget. More information and discussion on the allocation mechanisms can be found in the original paper [13]. They are provided below for three target temperatures: -21 to 142 $MtCO_2$ for global warming of 1.5°C, 73 to 273 $MtCO_2$ for global warming of 1.7°C, and 204 to 461 $MtCO_2$ for global warming of 1.7°C. As explained above, non-CO_2 gases are added by increasing these amounts by 5%. In addition, as explained in the original study [13], due to the fact that a 30% difference in GHG emissions was found between the input-output and process-based LCA results at the building stock level, and that the carbon budget is based on input-output data, it was reduced by 30% for use in this study, which uses process-based results. This gives a maximum budget of 104, 201, 339 $MtCO_2$ for temperature targets of 1.5°C, 1.7°C, and 2.0°C respectively. The term "carbon budget" will be used consistently in the paper, although it now actually refers to a "GHG budget" in $MtCO_2eq$, calculated from the "CO_2 budget" $MtCO_2$ (by including non-CO_2 gases as explained above).

3. Results and Discussion

3.1. Life Cycle GHG Emissions of the Austrian Building Stock

The building stock model in addition to the created scenarios can be used to derive the annual GHG emissions of the Austrian building stock. Figure 2 illustrates the development of both operational and embodied emissions for the WEM, WAM and WAM-SUF scenarios for the years 2023 (starting year of the model), 2030, 2040, and 2050. The model has an annual resolution, but in order not to clutter the presentation of results, only these four years are shown. It can be seen that operational emissions (B6) largely dominate in the first years, accounting for around 70-71% of total emissions in 2023 and 62-65% in 2030 for the WEM and WAM scenarios. However, with efforts to increase the share of renewable energy use in both scenarios, the share of embodied emissions is projected to increase dramatically in the period to 2050, accounting for around 36-55% of total GHG emissions for the WEM and WAM scenarios. This trend becomes all the more pronounced the more emissions are reduced in the energy mix, as can be seen in the WAM scenario. Most embodied emissions are expected to come from the production of materials for new buildings (A1-A3) and replacement and renovation measures (B4-B5).

Thanks to the diffusion of greenhouse gas reduction technologies and increased circular economy measures that impact embodied emissions, especially in the WAM scenario, the results indicate a 30% reduction in embodied emissions by 2050 compared with the WEM scenario. Looking at the remaining operational emissions in 2050, in the WEM they are attributable to oil and gas heating systems, which are not being phased out completely, and in the WAM, mainly to district heating, which is still considered gas-fired according to the projections of the Austrian National Environmental Agency [11]. The WAM-SUF scenario achieves significantly lower GHG emissions from the construction of new buildings thanks to the reduction in average living area per person. Overall, the WAM-SUF scenario emits 52% less embodied GHG emissions than the WAM scenario. The energy consumption of the building stock is also reduced by 11% in 2050 in the WAM-SUF scenario compared to the WAM scenario, which leads to an additional reduction in GHG emissions.

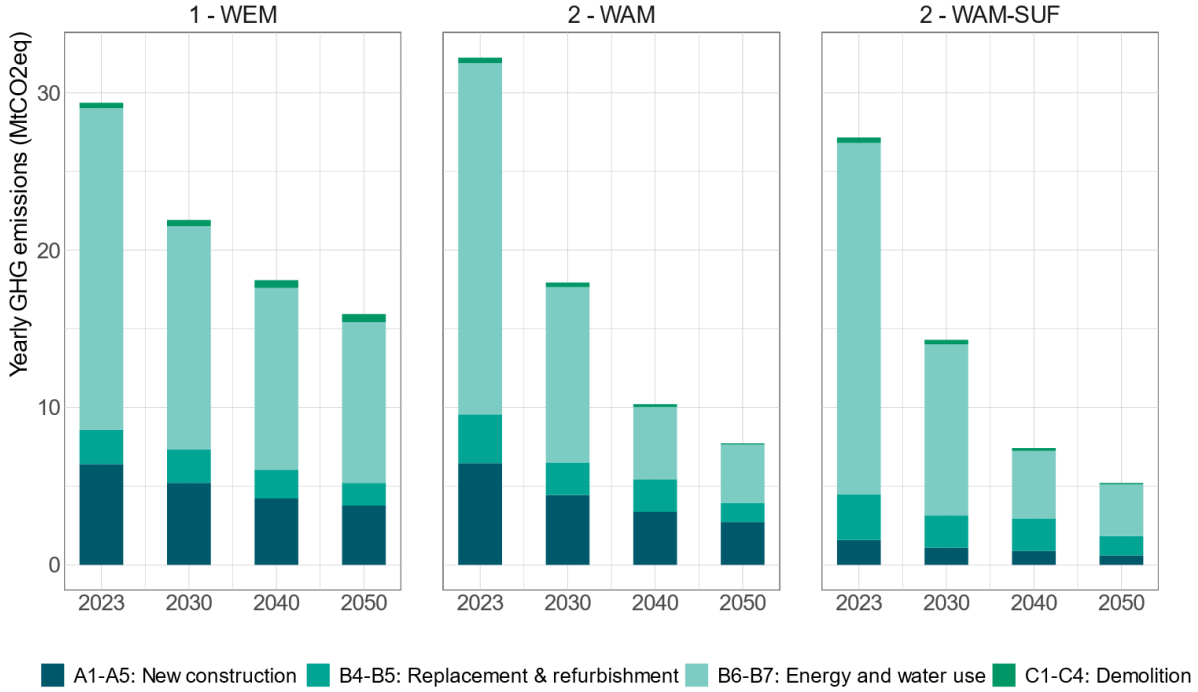

Figure 2. Annual life cycle GHG emissions of the Austrian building stock for the WEM, WAM and WAM-SUF scenarios, per life cycle module as defined in the EN 15978 [16].

3.2. Closing the Gap to the Carbon Budget

The cumulative emissions within the respective annual scenarios in the period 2023-2050 determine the consumption of the remaining carbon budget. The cumulative GHG emissions of the WEM, WAM and WAM-SUF scenarios are shown in Figure 3, alongside the remaining carbon budget. The GHG emissions from the WEM and WAM scenarios are far from the upper limit of the carbon budget, which is 339 MtCO2eq. Even the most ambitious scenario (WAM) exceeds this budget by almost 100 MtCO2eq. The results of these scenarios show that more ambitious measures are needed for the building industry to limit global warming to 1.5°C or even 2.0°C. This need has already been highlighted in previous studies [32]. Additional measures could include the use of fast-growing bio-based materials [33], new building designs or construction techniques such as rammed earth construction [34]. However, these solutions are limited by the availability of resources, a lack of expert knowledge or economic constraints, which limit their diffusion potential at such a large scale and also their GHG reduction potential. Previous research has thus emphasized the importance of sufficiency measures to successfully reduce GHG emissions in the building sector [35]. Given the large reduction in GHG emissions required to meet the carbon budget, strong sufficiency measures may be the only option left to meet such a target. As an example of a sufficiency measure in the WAM-SUF scenario, the average living space per person

in the WAM scenario is reduced from the current 46 m² (2023) to 44 m² by 2050, as explained in section 2.3, assuming a linear decrease. With only such a small reduction, the WAM scenario becomes compliant with the 2.0°C carbon budget with a value of just under 339 MtCO2eq. This underlines the importance of sufficiency measures for achieving the carbon reduction targets, even if these are not drastic measures but only a small reduction in living space per person. Combined with other measures, such as a reduction in vacancy, for example by creating a tax on empty dwellings or secondary residence, there is potential to stay within the remaining carbon budget.

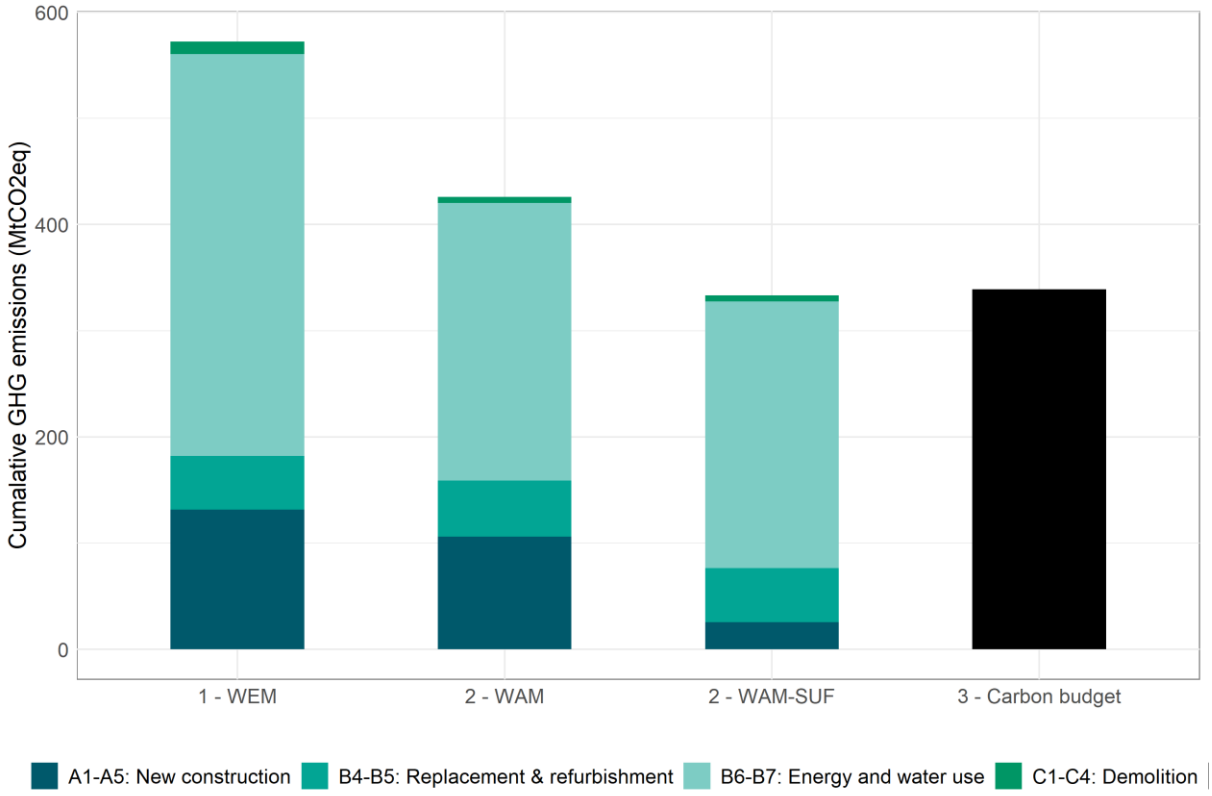

Figure 3. Cumulative GHG emissions of the WEM, WAM and WAM-SUF scenarios and remaining carbon budget.

3.3. Limitations and Future Work

The model used for this analysis is based on assumptions that may naturally affect its results. As the assumptions underlying the WEM and WAM scenarios are not fully transparent, best efforts have been made to replicate them in the model, but there may be slight variations in operational energy demand and GHG emissions. An example of an obvious assumption that affects both operational and embodied emissions is the energy standard of new buildings, as shown in Table 1. Another example is the actual application of the renovation rate. Although a renovation rate of 1.4 or 2.5% is quite easy to communicate, there are different depths of renovations, and these actual renovation rates are usually achieved through a combination of several light renovations rather than comprehensive renovations. In the model used, three possible renovation depths are modeled for each archetype (light, medium or deep), and the distribution of the renovation rate between these possibilities has been assumed for each scenario, which is an additional source of uncertainty. A final assumption concerns district heating, for which it was decided not to consider the embodied emissions related to the district heating connection, as they are part of the infrastructure and therefore outside the system boundary [16]. This could of course lead to an underestimation of the actual embodied emissions associated with the renovation, but the total

infrastructure-related emissions would then need to be taken into account for consistency, which is not a typical approach when modeling the building stock.

The perspective of a field of action of buildings offers a concept for presenting the emissions of the national building stock on the basis of the construction and operation of buildings. This comprehensive view of emissions enables stakeholders to consider emissions over the entire life cycle of a building and thus reduce emissions in both the short and long term. It goes beyond the UNFCCC's national emissions accounting based on the territorial principle and includes cross-sectoral and international emissions. However, due to this interconnectedness of building-related activities, translating a national carbon budget into specific targets for buildings is not a trivial task. The concept of a carbon budget for buildings is not always unanimously accepted and there are different allocation mechanisms that can be considered appropriate. While the approach used in this paper attempted to address some of the consistency issues that have arisen in scaling down the budget from the global to the national level, as described in detail in the original contribution [13], it is still based on allocation decisions that can be criticized on the basis of fairness criteria. As a result, the carbon budget used in this study should not be seen as a fixed value but rather as an indicative range of necessary emission reductions to stay within planetary boundaries.

A main limitation of the study comes from the implementation of the GHG reduction strategies for the embodied emissions in the background LCA database. It is common in prospective LCA studies to have a time discrepancy in between the foreground and background processes. This happens, for example, when the evolution of the electricity mix is only applied to the foreground while the background is left static. This is a well-known challenge in prospective studies and has been shown to have a noticeable impact on the final results [36]. This was avoided in the present study by applying a consistent modification of the background database using *premise*. However, the scenarios used are the ones which come directly from the integrated assessment models, meaning that they have a rather regional resolution (Europe, or at best Central Europe) and are not Austrian-specific scenarios. A next step, using the user-specific option of *premise*, could be to create scenarios for the production of materials which are specific to Austria, which would increase the level of detail of the investigated scenarios.

4. Conclusion

This article presents an overview of future GHG reduction scenarios applied to a building stock model for Austria. The model includes an assessment of both embodied and operational GHG emissions using life cycle assessment. The main focus of the study is to investigate and evaluate possible scenarios to achieve carbon budget-compliant GHG emission reductions by 2050. The results show that even with ambitious decarbonization pathways for Austrian industry, the projected building rates are not sufficient to meet the carbon budget. On the contrary, additional small sufficiency measures such as a slight reduction in average living space per person are a major lever for reducing GHG emissions and, together with carbon removal, could be the only remaining options for meeting climate targets. Consequently, more ambitious policies are needed to accelerate the reduction of embodied emissions and achieve net zero targets. By looking at the entire life cycle of these buildings, the study provides, for the first time, valuable insights into the pathways to a low-carbon future for Austria's buildings.

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