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Future trends in materials manufacturing for low carbon building stocks: A prospective macro-scale analysis at the provincial level

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ABSTRACT

In order to reduce the greenhouse gas (GHG) emissions of buildings, the literature has investigated many strategies to tackle operational emissions, which are traditionally the largest contributor to overall emissions. As a result, embodied emissions are gaining increased attention, not only due to the decrease in the relative share of operational emissions but also due to increased material needs, e.g. the use of additional thermal insulation in buildings. Some of these strategies, such as the decarbonisation of the energy grid, could also help decrease the embodied emissions of building materials. The objective of this paper is to investigate the influence of increased renewable electricity use in building material production. It also examines future trends in the manufacturing processes – such as an intensified use of bioenergy, improvements in energy efficiency and the introduction of carbon capture and storage – on the GHG emissions of buildings. These strategies are analysed in a combined "future materials" scenario on a macro scale within the Tyrol province in Austria. With a focus on new residential constructions, six design variations of two building case studies are assessed using life cycle assessment. They are then projected to 2050 at the provincial level. The results of the future materials scenario point towards a promising embodied GHG reduction, up to 19% in this analysis. Larger mitigation effects would appear in the 2040s and 2050s, meaning future manufacturing technologies can be seen as a long-term investment. Their reduction potential surpasses the potential impact of an increase in wooden constructions. The latter achieved up to 7% reduction in GHG emissions, which would be mostly visible in the early decades rather than in later ones. These reduction percentages remain lower than those which could be attained at the operational energy level, with reductions of up to 72%. The obtained results are discussed in the light of other published regional and global studies to identify the possible sources of variations. Critical reflections on carbon capture and storage, as well as renewables, additionally highlight the intrinsic challenges of such key technologies.

1. Introduction

The great contribution of buildings to anthropogenic greenhouse gas (GHG) emissions and, consequently, climate change, is undeniable (IEA, 2021). Recent data shows that, in 2020, buildings were responsible for 37% of global GHG emissions (UNEP, 2021), either directly or indirectly. To curb buildings' contribution to increased global temperatures, many reduction strategies have been proposed in recent decades. Focus has been mostly placed on the use (or operational) stage of the building (Hoxha et al., 2017; Lasvaux et al., 2017; Drouilles et al., 2019). Due to their long service life, it is common to expect that the greatest number of environmental impacts generated by (and within) a building happens during this period. Moreover, if one considers the electricity and heating demands of buildings, which require consumption of resources (and generation of emissions) over multiple decades, the focus on buildings' use is confirmed as a sound strategy (Jusselme et al., 2016).

Still, as their operational emissions were increasingly controlled, buildings' embodied emissions, associated mostly with material manufacturing, drew increased attention both as a result of the decrease of the relative share of operational emissions and increased material

Abbreviations: LCA, Life cycle assessment; LCIA, Life cycle impact assessment; GWP, Global warming potential; GHG, Greenhouse gas; CCS, Carbon capture and storage; SFH, Single-family house; MFH, Multi-family house; GFA, Gross floor area; BAU, Business-as-usual; EPS, Expanded polystyrene.

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needs (Röck et al., 2020). Increased thermal insulation requirements or the use of technical on-site equipment to generate renewable energy are called for to provide energetic efficiency. Tackling embodied emissions has therefore recently become a focus in order to mitigate the built environment's contribution to climate change (Röck et al., 2020). While the future trends that affect mostly a building's operational stage are fairly regulated (European Parliament and Council, 2012, 2018), there is a significant lack of solid policies directed towards the sectors that contribute to building's embodied emissions. Considering the confirmed contribution of buildings to climate change, as the largest contributor to GHG emissions in 2020 (37% compared to 23% for the transport sector) (UNEP, 2021), and the challenge of reducing carbon lock-in effects (IEA, 2021; Habert et al., 2020; Corvellec et al., 2013), the examination of future trends in building material production is of paramount importance.

In this context of reducing the future embodied GHG emissions of the construction sector, the literature had proposed various solutions, depending on the scope of the analysis (material, building or district scale), the assessed technologies, and the level at which they can be implemented. Interventions at the material level have, however, been identified as the most effective strategies to reduce embodied GHG emissions (Pomponi et al., 2020). Alig et al. (2020) created life-cycle inventories for the future production of mineral, metal, wood and plastics construction materials commonly used in Switzerland in the construction industry, based on data collection from the industry. They also considered future energy supplies in the future modelling of the manufacturing processes. When implementing all of the investigated strategies, an average of 65% GHG reduction was reached in 2050 at the material level, compared to the current manufacturing technologies. Several other future-oriented strategies for single materials can also be found in the literature. One example is the case of cement production, for which Salas et al. (2016) identified four improvement possibilities for the manufacturing of cement: improvements in energy efficiency, use of alternative fuels, clinker substitution and carbon capture and storage (CCS).

Looking at the building level, Karlsson et al. (2021) explored the best available technologies and construction practices for multi-family residential buildings which could be available by 2045, at different parts of the construction supply chain. Considering the embodied GHG emissions in the system boundary, they calculated an 85–93% reduction in 2045, depending on their scenarios. Although operational energy is not considered in their analysis, a large number of materials and embodied emissions reduction strategies are identified and included. Ayagapin et al. (2021) focused on the impact of decarbonizing the electricity mix on single-family houses in Reunion Island, a French overseas region. By integrating the political ambitions of electricity production by 2045, they achieve an 83% reduction of the global warming potential (GWP) in the operational phase in their scenario, but only 1% reduction in the GWP of the structural materials, which mainly come from imports. The operational phase is featured as the biggest contributor to the impacts of the houses over the whole life-cycle. They also highlight the importance of such regional investigations, considering that the built environment, the availability of the resources and the decisions taken by policy makers may vary greatly within different regions. However, no other strategies regarding material efficiency are considered in their analysis.

In terms of larger-scale studies, He et al. (2019) assessed the possibility of achieving net zero CO_2 emissions in Beijing by 2050 by using an Integrated Energy and Environment Policy Assessment Model developed for China. They focused on the transport, building and industry sectors, by analysing key technological advances, such as electrification in industry or CCS. The analysis seems to rely strongly on CCS for electricity production (an implementation in all fossil fuel and biomass power plants is presumed). However, CCS is used in fuel production but not at the material manufacturing level; it is assumed the heavy industries will gradually move out of the city, while the remaining industries are expected to shift to electrical processes and renewable heat generation. In particular, cement manufacturing inside of the current city limits is assumed to end by 2050 due to low local demand and fewer new construction projects. Cement factories are therefore assumed to move out of the city. The analysis of the building sector is, as a result, more focused on the operational phase.

In a wider geographical extent, Zhong et al. (2021) evaluated the GHG emissions reduction potential of residential and commercial buildings by 2060 in 26 global regions. Based on an integrated global assessment model linked with the ecoinvent database and using prospective life cycle assessment methods, they focused on seven key material efficiency strategies and seven construction materials (steel, concrete, brick, wood and various metals). Although the biggest reduction potential appears to be in the low- and lower-middle-income regions, they observe a 6% mitigation potential which could be achieved in Western Europe with their high material efficiency scenario. They also mention the challenges of decarbonising the cement production sector, and that the use of carbon capture technologies, which were not part of their analysis, would be necessary to increase the mitigation potential. Increasing the amount of wooden construction is also part of one scenario of the analysis. This strategy is actively discussed in the literature as an approach to reduce the embodied GHG emissions of buildings (Pomponi and Moncaster, 2016; Moschetti et al., 2019; Peñaloza et al., 2016; Saade et al., 2020; Cabeza et al., 2013).

To the knowledge of the authors, there are no identified studies which combine at the same time at the building stock level the use of renewable electricity for material production, the use of renewable electricity for operational energy in buildings, and also future trends in the manufacturing of construction materials, such as CCS.

2. Objective and research questions

The objective of this paper is to investigate the influence of an increased renewable electricity use in material production, as well as future trends in the manufacturing processes – such as an intensified use of bioenergy, improvements in energy efficiency and the introduction of carbon capture and storage (CCS) – for the minimisation of the global warming potential (GWP) of buildings. Combined in a “future materials” scenario, these strategies are analysed from a life cycle assessment (LCA) perspective on a macro scale within the Tyrol province, Austria, focusing on new residential constructions. The reduction in greenhouse gas (GHG) emissions that these measures would lead to is compared to the possible GHG reductions of two additional scenarios. The first contains a set of strategies which are politically adopted to reduce the operational emissions of buildings, including the use of renewable electricity. The second one considers an increased use of wood in buildings as a possible approach to reduce the embodied GHG emissions of buildings. The main research question is, therefore, defined as:

What is the impact of an increased renewable electricity use in material production, as well as an intensified use of bioenergy, improvements in energy efficiency and the introduction of CCS, on the GHG emissions of new residential buildings, in comparison to an increase in wooden constructions and to the projected reductions in operational GHG emissions?

The novelty of this paper stems from investigating the use of renewable electricity for material production in addition to its use for operational energy in buildings and comparing their influence at the province level. This main research question is then further divided into the following research questions:

1. What would the future embodied and operational GHG emissions of the new residential constructions be, without any mitigation measures?
2. What are the politically adopted strategies to reduce the operational GHG emissions of new residential buildings and what would their impact on these GHG emissions be?

3. What is the impact of an increased renewable electricity use in material production, as well as an intensified use of bioenergy, improvements in energy efficiency and the introduction of CCS, on the embodied GHG emissions of new residential buildings? What is the impact of an increase in wooden constructions?
4. Which GHG emissions reduction potentials can be achieved for all these strategies and how do they compare?

3. Methodology

To answer these research questions, the LCA methodology is first applied to six design variations of two building case studies (a single-family house and a multi-family house) which are used to model the regional building stock. In other terms, detailed LCA studies were performed at the building level, and these studied buildings were then chosen as representative typologies for the residential buildings that the region has planned to build within the study period (from 2020 to 2050). The functional equivalent used for the building LCAs and the overall LCA methodology are specified in section 3.1. The focus is on new residential buildings, which is why the current building stock and its possible activities (renovation, refurbishment, etc.) are out of the scope of this analysis. The selected buildings are presented in section 3.2. Next, the different scenarios are presented. A reference business-as-usual scenario is first created, which assumes no technology or energy improvements are adopted in upcoming years. Then, an estimation of the future evolution of the operational GHG emissions is realised, built upon the current political targets. No other scenarios are defined for the operational emissions, as reduction pathways for these emissions are already politically set. Since the embodied emissions are not yet entirely regulated, diverse hypothetical scenarios are developed and analysed in this paper to be able to answer the third research question. The first is a "future materials" scenario including an increased renewable electricity use in material production, as well as an intensified use of bioenergy, improvements in energy efficiency and the introduction of CCS. The other scenarios are an increase in wooden constructions, for which different increase rates are used. In addition, conservative and optimistic versions of these embodied emissions scenarios are developed, leading to a total of six investigated scenarios. The scenarios are further explained in section 3.3. Finally, the LCA results are projected to the provincial level, from 2020 to 2050, by using available data and current predictions. The data and projections used are reported in section 3.4. Based on the total embodied GHG which are emitted during the 30-year observation period, GHG reduction potentials are calculated for each scenario and compared. A summary of the steps followed is presented in Fig. 1.

3.1. Life cycle assessment methodology

The LCA calculations were performed in compliance with the European norms regulating the LCA of buildings and construction products (EN-15978, 2012 and EN-15804, 2019). The goal of this LCA is to assess the GHG emissions of two buildings, a single-family house (SFH) and a multi-family house (MFH), which will then be used to draft the scenarios for future residential constructions. The chosen functional equivalent for this study is 1 m^2 GFA (gross floor area) of a residential building, including the manufacturing of its construction materials for its structure and envelope, and its operational energy use following the Austrian low-energy standard (Austrian Standard Institute, 2011), excluding its surroundings, built with the current construction techniques in Austria, which can be used as representative typologies for the residential buildings which will be built in Tyrol from 2020 to 2050, for a reference studied period of 50 years, as is common in current LCAs of buildings (DGNB, 2018; Passer et al., 2012).

The system boundaries that distinguish the life cycle phases of a building are divided into modules according to the principles of the EN 15804 norm (EN-15804, 2019). In this study, the focus on the embodied emissions is purely on the manufacturing phase, which is why a cradle-to-gate approach is preferred. Modules A1 (raw material supply), A2 (transport of the raw materials) and A3 (product manufacturing) are included, regarding the embodied emissions. It was also not relevant to include the end-of-life modules (C1, C2, C3 and C4) as well as module D, because a building constructed after 2020 wouldn't theoretically be demolished during the time frame of the study (2020–2050). Moreover, the GHG emissions of the existing building stock (built prior to 2020) are not taken into account in this study. For the operational emissions, the operational energy use (B6) is considered. In particular, the energy used for heating as well as the electricity needed for lighting and other electrical appliances are included. A representation of the system boundaries and research focus is provided in Fig. 2.

A life cycle impact assessment (LCIA) was carried out using the generic database ecoinvent 3.6 (Wernet et al., 2016), which we accessed through SimaPro LCA simulation tool (PRé, 2019). Specific data could in particular be used for Austrian steel and concrete production. For the other materials, when no specific data was available, data representative of Europe was always favoured. The GWP, expressed in $kgCO_2eq$, is the only considered indicator in this LCA. In terms of the method used, the calculations followed the IPCC guidelines and characterisation factors (IPCC, 2021). Finally, the modelling of biogenic carbon for the wooden elements follows the 0/0 approach. Biogenic carbon refers to the carbon dioxide absorbed from the atmosphere in the photosynthesis process occurring during wood growth, which is released at the end-of-life of the product, in the form of carbon dioxide, carbon monoxide or methane depending on the end-of-life treatment (combustion, landfill, etc.). The 0/0 approach assumes that the carbon release which takes place at the end-of-life of the building is offset by the carbon intake occurring during biomass growth. Consequently, the carbon intake (0) and its release (0) are both considered to be zero (Hoxha et al., 2020). In other words, no biogenic carbon uptake is considered in this study during the A1-A3 product stage.

3.2. Description of the case studies

This section presents the two building case studies which are to be assessed using the previously described LCA methodology. The detailed inventories of the case studies used in this paper are provided in the supplementary materials. The first one is a two-storey SFH which has a GFA of 221 m^2 (Sölkner et al., 2014). This house typology is particularly relevant in the context, as SFH roughly represented 60% of the new residential constructions in Tyrol in 2019 (Statistik Austria, 2020a). This case study was designed under the low-energy standard, which is based on a heat-demand perspective, in accordance with Austrian standards (Austrian Standard Institute, 2011). The house was modelled with a considerable number of details, containing the structure (including the basement and foundation), the envelope, the internal and external finishes, as well as the plumbing works. Previous work on this case study led to the development of 45 scenarios with varying energy standards, constructions techniques, insulation materials and technical systems. This house was designed as an average representative Austrian SFH by a consortium including the Austrian research institutes and associations for construction materials (Sölkner et al., 2014; Passer et al., 2016). The construction technique (brick, concrete, wood, etc.) mainly refers to the structural materials used for the building design. The external dimensions, the basement and the roof designs were kept identical between all variants. For this analysis, the four most representative versions of the studied Austrian region were picked:

- The brick version with expanded polystyrene (EPS) insulation;
- The concrete version with EPS insulation;
- The frame wood version with rock wool insulation;
- The massive wood version with rock wool insulation.

The second case study is a theoretical seven-storey MFH with a GFA

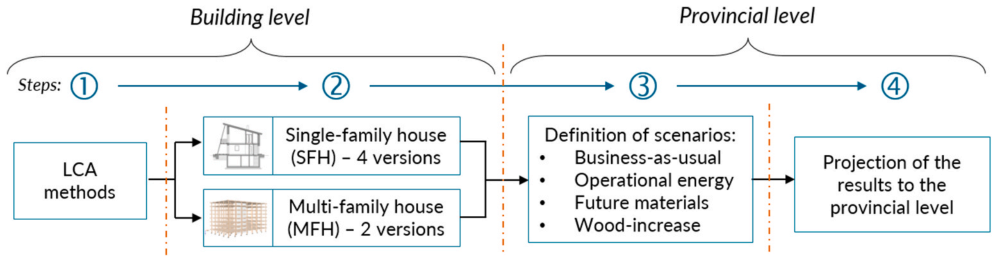

Fig. 1. Overall methodology.

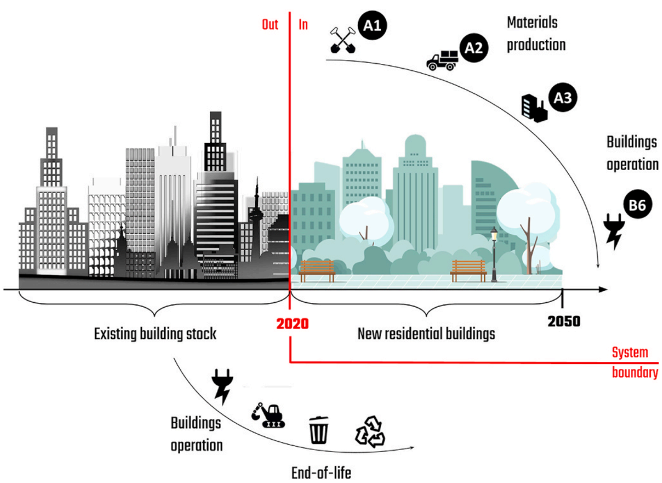

Fig. 2. Representation of the system boundaries of this study. The existing building stock (prior to 2020), including its possible operation and end-of-life, is outside the scope of this analysis. The focus is on new residential constructions which will be built between 2020 and 2050. In particular, the production of the construction materials and the energy use of these buildings are considered in the LCA.[11].

of 9792 m^2. The building is based on a previously designed structure, including the foundations, floors, roof, supporting columns, beams and central core. Two versions of this structure were created to fit the same mechanical requirements and are voluntarily open-designed in order to fit different possible uses (Gierlinger, 2020). One is built with reinforced concrete, and the other one with mainly wooden elements (glued- and cross-laminated timber). The building span, that is to say the distance between two load-bearing elements (in this case, the columns), is 5.5 m long, which is an average span for residential buildings in Austria. In addition, for this study, an envelope was designed for this building, following the low-energy standard requirements (Austrian Standard Institute, 2011). This envelope almost exclusively contains wooden elements and incorporates a 30 cm rock wool insulation.

3.3. Definition of the scenarios

3.3.1. The business-as-usual (BAU) scenario

The business-as-usual (BAU) serves as a reference scenario, from which the GHG emission reduction potentials are calculated. It represents the common practice for new residential constructions in the studied Austrian province, without specific improvements during the time frame of the study. In particular, the operational GHG emissions are assumed to follow the historical reduction trends, without additional improvements measures. A 2.5% yearly reduction of the emissions is applied for the electricity mix, and a 1.9% reduction of the emissions is applied for the heating mix (European Environment Agency, 2021). The energy demand of all newly built houses is assumed not to reduce over time. Concerning the embodied GHG emissions, the construction materials are assumed to be produced with the current manufacturing technologies, without improvements. The percentage of new residential buildings being built with wood is considered likely to stay at 24% (Federal Ministry for Sustainability and Tourism, 2019). A wooden building is usually defined as a building in which more than 50% of the load-bearing structures are created with wood-based materials (Federal Ministry for Sustainability and Tourism, 2019). In this paper, the wooden buildings refer to those defined in the case studies, which also correspond to this definition. In terms of proportion of buildings, for this scenario, 24% of the MFH are wooden and 76% are concrete. Regarding the SFH, the number of frame and massive wood versions are equally distributed, such as the number of brick and concrete versions. This means that 12% are frame-wood, 12% are massive-wood, 38% are concrete and 38% are brick.

3.3.2. Main scenario regarding the operational GHG emissions

The province of Tyrol aims to completely phase out fossil fuels by 2050 (Energie Tirol, 2018). To achieve this political goal, the development of potential scenarios was previously commissioned and investigated by the Austrian province (Ebenbichler et al., 2018). As a result, on an operational energy level, the need for the following measures to be implemented in new residential constructions were specifically pointed out (Ebenbichler et al., 2018):

1. All new residential buildings which are built after 2023 must comply with the passivhaus standard.
2. Fossil fuels (in particular oil, gas and coal) must not be used as direct heating sources for new constructions from 2021 on.
3. Electricity generation must be gradually shifted to renewable energy to reach 100% of the electricity coming from renewable sources in 2050.

However, these three mitigation measures are used in this study to create a main scenario for the operational GHG emissions, to be able to compare the expected GHG reduction potentials with those that can be obtained for the embodied emissions. For this operational emissions scenario, the heating demand, the heating energy mix of new residential constructions and the conversion factors for the end energy use are directly taken from Ebenbichler et al. (2018). The electricity demand for the SFH is based on Sölkner et al. (2014). For the MFH, average values from Ebenbichler et al. (2018) are used. The electricity mix of the province and its evolution was determined by expert guesses. A large part of this electricity mix was assumed to come from imports (from 30 to 60%, depending on the decade). These imports were presumed to come from an average European electricity mix. The values for 2020 came directly from the ecoinvent database (Ecoinvent, 2019). For 2050, an electricity mix was designed based on the projections from Alig et al. (2020), and was adapted after consulting experts, to achieve a 100% renewable electricity mix in 2050. The values were then fitted from 2020 to 2050 to have a gradual decrease in GHG emissions. The GHG emissions of the European and Tirolean electricity mixes considered in this scenario are provided in Fig. 3. The differences between the BAU and the main operational emissions scenario are summarised in Table 1.

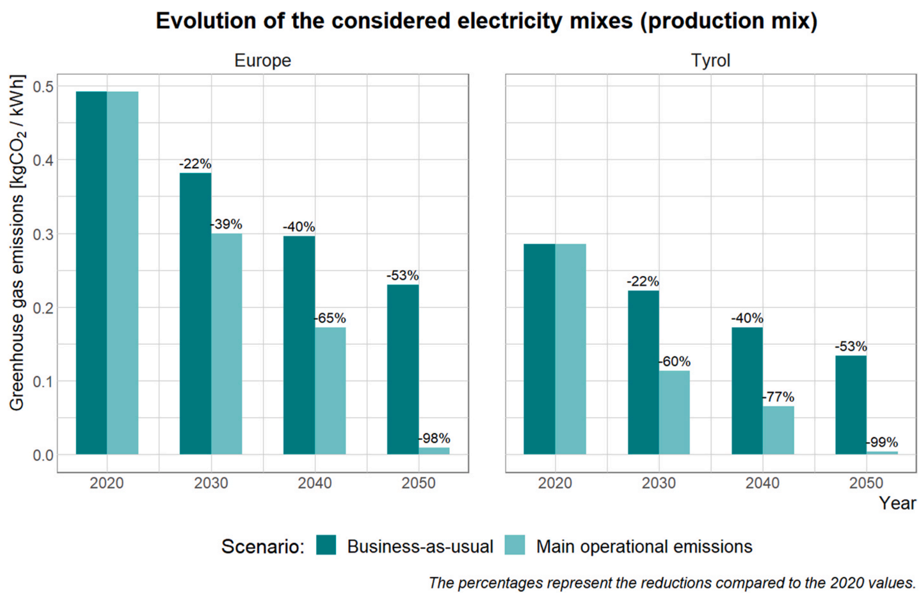

Fig. 3. The bars represent the GHG emissions of the European and regional electricity mixes while the percentages indicate the reduction percentages compared to the 2020 value.

Table 1
Differences between the BAU and the main operational emissions scenario.

Scenario	BAU	Main operational emissions
Electricity mix	Yearly 2.5% decrease of the GHG emissions	60, 77 and 99% decrease of the GHG emissions in 2030, 2040 and 2050 respectively
Heating mix	Yearly 1.9% decrease of the GHG emissions	65, 85 and 91% decrease of the GHG emissions in 2030, 2040 and 2050 respectively
Heating demand	Identical to current demand (23 kWh/m^2/year for the MFH and 29 kWh/m^2/year for the SFH)	From 2023, 10 kWh/m^2/year for the MFH and 9 kWh/m^2/year for the SFH

3.3.3. Scenarios regarding the embodied GHG emissions

As opposed to the operational GHG emissions, specific political goals and regulations aimed at decreasing the embodied GHG emissions of new residential constructions were not yet fixed until this research was finalised. Diverse hypothetical scenarios were, therefore, developed and analysed in this paper.

- The first one is a **future material production technology scenario (future materials)**, which is the main research focus of this paper. In this scenario, the percentage of new residential buildings being built with wood is assumed to stay at 24%, as in the BAU scenario. In contrast, in the future materials scenario, improvements in the production of wood, concrete, brick and steel (which represent the main structural components used in the case studies) are considered. In addition to their current production technology (2020), these materials were modelled for 2030, 2040 and 2050. Between each decade, the values were fitted to have a gradual decrease of emissions.

The future materials scenario is based on the study conducted by Alig et al. (2020) for Europe and was regionalised to the specific situation of Austria. In particular, the previously described evolution of the electricity grid, incorporating more renewable electricity over the years, was used for the future production of these materials. Future transportation modes, such as lorries running on electricity and biofuels, were also considered for all four materials. Additionally, each material had its specificities concerning the improvement of their manufacturing process (Alig et al., 2020). For wooden materials, an increased use of biofuels was assumed from 2030 and the use of heat produced from production residues was additionally implemented. A 53% GHG emissions reduction per cubic metre of wood is reached in 2050, compared to 2020. For concrete, an energy reduction in clinker production was enforced from 2030 onwards and CCS was implemented from 2040 onwards. An 86% GHG emissions reduction per cubic metre of concrete is achieved in 2050, compared to 2020. Concerning brick production, energy optimisation, waste heat utilisation and substitution of natural gas with biogas begin in 2030. From 2040 onwards, the use of CCS was also generalised, as was a new production technique called microwave-assisted gas firing. The reduction in the GHG emissions in 2050 amounts to 75% per kg of brick, compared to 2020. Finally, steel production in Austria (reinforcing and low-alloyed steel) mostly stems from electric arc furnaces and is considered quite advanced compared to average European standards; it already has relatively low GHG emissions. Therefore, no additional technology was implemented for the future production of steel. Only the electricity mix and transportation needs were adapted, as previously described. This led to a 45% reduction of GHG emissions per kg of steel.

Increasing the number of wooden constructions is an oft-cited strategy for reducing the embodied GHG emissions of buildings in the literature (Pomponi and Moncaster, 2016; Moschetti et al., 2019; Peñaloza et al., 2016; Saade et al., 2020; Cabeza et al., 2013). For that reason, it seemed relevant to include wood-increase scenarios in this analysis to be able to compare the influence of the future materials scenario to this popular concept. The designed wood-increase scenarios are the following:

- **A slow increase in wood scenario (Wood +5%)**, in which the percentage of new residential buildings being built with wood is assumed to start at 24% (Federal Ministry for Sustainability and Tourism, 2019), but to slowly increase at a rate of 5% per year, reaching 100% of new residential constructions being built with wood in 2050. The materials are assumed to be produced with the current manufacturing technologies without any improvements over the next 30 years.
- **A high increase in wood scenario (Wood +10%)**, in which the percentage of new residential buildings being built with wood is

[1] The icons and images used to create this picture are provided by Pixabay (https://pixabay.com/).

assumed to start at 24% (Federal Ministry for Sustainability and Tourism, 2019), but to increase at a rate of 10% per year, reaching 100% of new residential constructions being built with wood in 2035. The materials are also assumed to be produced with the current manufacturing technologies without any improvements over the next 30 years.

One should keep in mind that these scenarios are theoretical. It is, for example, highly unlikely for all buildings from 2035 onwards to be built with wood. The availability of wood, as well as imports and exports, were not taken into account in the elaboration of these scenarios.

Each one of these embodied GHG emissions scenarios was additionally subdivided into conservative and optimistic versions. Regarding the wood-increase scenarios, the conservative version assumes the use of the most common construction technique for the wooden MFH. Concerning the SFH, the number of wood-frame and massive-wood houses are considered to be equally distributed. For the optimistic version, an optimised construction technique is adopted for the design of the wooden MFH (Gierlinger, 2020). This optimised construction technique is, in practice, not frequently used, as it requires a more complex design phase. Regarding the SFH, it is assumed that all the wooden SFH are frame-wood houses, which achieve lower embodied GHG emissions than the massive wood houses (Passer et al., 2016). Finally, for the future materials scenario, the optimistic version presumes that all cement plants will have implemented CCS from 2040 onwards, and that biofuels will be fully implemented wherever possible from 2020 onwards. In the conservative scenario, it is assumed that only a maximum of 25% of the cement plants have implemented CCS. This value is based on the estimations of the International Energy Agency, which states in its international cement roadmap that 25% of the direct CO_2 emissions will be captured and stored by 2050 (IEA, 2018). The use of biofuels is also fixed at a limit of 35%, from 2020 and until 2050. This value is based on the projections for biogas availability in Switzerland, discussed in Alig et al. (2020). According to these predictions, if the demand in gas does not decline, biogas could cover approximately one third of the demand, about 35%. A summary of all the embodied emissions scenarios is provided in Table 2.

3.4. Modelling of the future building stock

In this section, an explanation of the procedure used to model the regional building stock and its future evolution is provided. Precisions are also given on the inclusion of the presented case studies in this model. To estimate the number of new constructions by 2050, two data sources were combined. The projected area used for new residential constructions in 2019 was first obtained from the Austrian National Statistical Institute (Statistik Austria, 2020a). In this statistical data, two typologies were considered for residential constructions: the buildings containing one or two dwellings, and the buildings containing three or more dwellings. This data was then combined with the yearly increase in building floor area, expressed as a percentage of the previously built area, which was based on Ebenbichler et al. (2018). However, it was recalculated to smoothen the dataset. This adaptation did not change the total amount of area built within the time frame but allowed for an improved visual rendering. This yearly percentage was originally derived from the population forecast, regularly updated by the Austrian National Statistical Institute (Statistik Austria, 2020b).

The combination of these two data sources led to the calculation of the yearly built surface (projected area) per typology. This yearly built area was then adapted to the two specific case studies presented in this paper by using their GFA and their number of floors, to be able to convert the GFA to the projected built area. Regarding the typologies, it was assumed that the buildings containing one or two dwellings correspond to the SFH and that the buildings containing three or more dwellings correspond to the MFH. The share of each typology was estimated not to change during the time frame. This led to the calculation of the number of buildings being built from 2020 to 2050, as presented in Fig. 4. The line in this figure represents the yearly built surface (projected area). The columns represent the number of buildings being built after 2020. Each year, the dark green part is added to the existing light blue one. That means that, in 2050 for example, the light blue part corresponds to the total number of residential buildings which will have been built between 2020 and 2049. As previously mentioned, the buildings which were built before 2020 are beyond the scope of this analysis.

To conclude the explanation of the methods, a compilation of all the data interactions, allowing for the creation of this model, is provided in Fig. 5. An additional summary table containing the data sources is also provided in the supplementary materials.

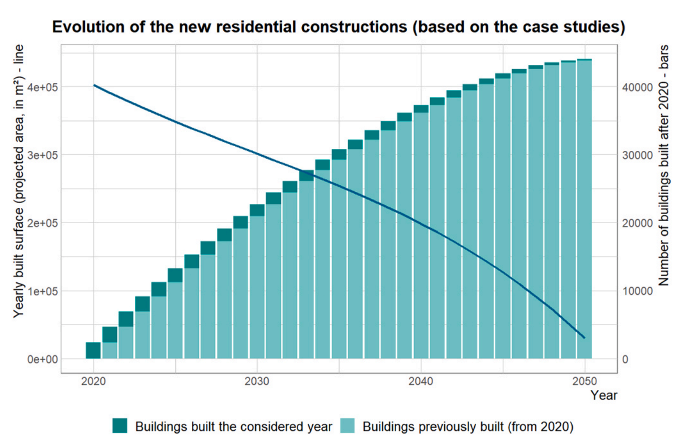

Fig. 4. Estimated future number of new residential constructions in Tyrol. The line in this figure represents the yearly built surface (projected area). The columns represent the number of buildings being built after 2020.

Table 2
Differences between the embodied emissions scenarios. The BAU scenario is not added for readability of the table. The BAU scenario uses the current technologies, current construction techniques and current shares of buildings.

Material production	Wood +5%		Wood +10%		Future materials	
	Conservative	Optimistic	Conservative	Optimistic	Conservative	Optimistic
	Current technology	Current technology	Current technology	Current technology	Future technology	Future technology
Use of CCS	No	No	No	No	In 25% of the cases	In 100% of the cases
Use of biofuels	No	No	No	No	In 35% of the cases	In 100% of the cases
Share of wooden buildings	+5%/year, 100% in 2050	+5%/year, 100% in 2050	+10%/year, 100% in 2050	+10%/year, 100% in 2050	Current share (24%)	Current share (24%)
Construction technique for wooden buildings	Current technique	Optimised technique	Current technique	Optimised technique	Current technique	Current technique

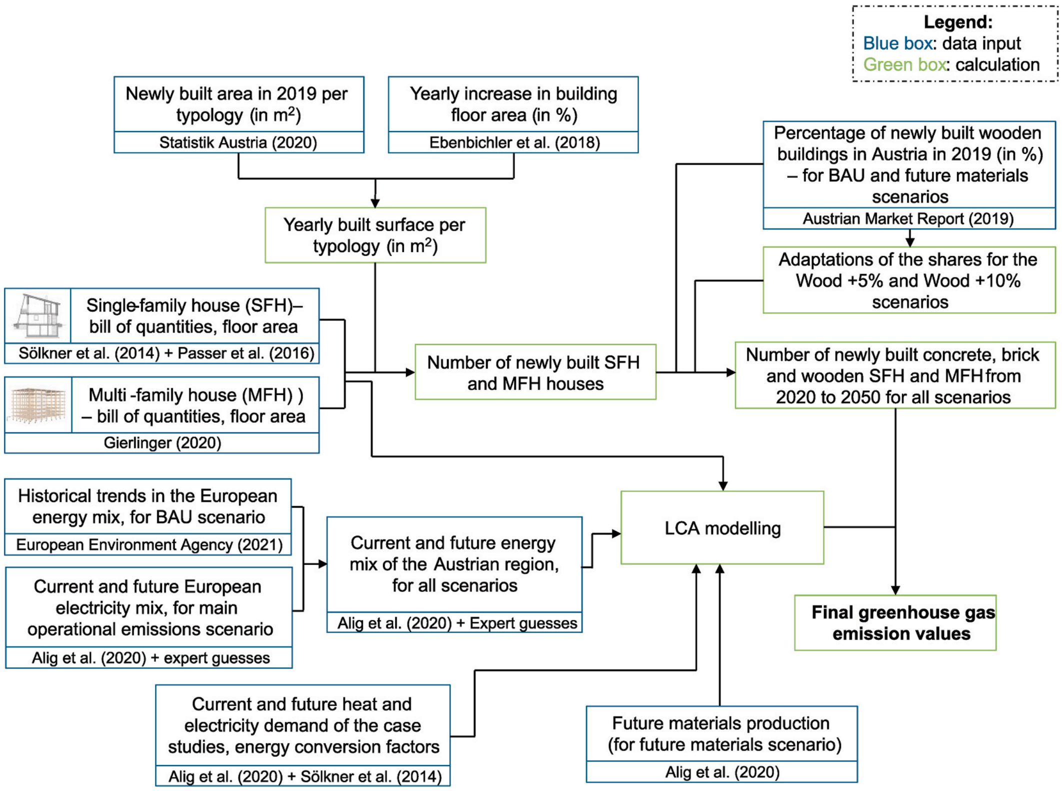

Fig. 5. Summary of the different data sources and their interaction, allowing for the creation of the calculation of the GHG emissions for new constructions in Tyrol, from 2020 to 2050.

4. Results and discussion

4.1. The business-as-usual (BAU) scenario

The yearlyGHG emissions of the BAU scenario are provided in Fig. 6, per type of emissions. The green line represents the embodied GHG emissions. Every year, these emissions decrease, which is a direct result of the decline in the number of new residential constructions, as it could be observed in Fig. 4. These emissions are only emitted once, during the manufacturing of the building's materials and components, which is assumed, in this analysis, to happen at the construction year of the building. On the contrary, the operational emissions (represented in light blue) occur repeatedly every year; therefore, the buildings are presumed to consume the same amount of energy every year after their construction. This means that, each year, the operational emissions from the new buildings are added to the emissions of the buildings which were built previously. Since only a conservative decrease of the energy mix is applied in the BAU scenario (following historical trends), the operational GHG emissions are consequently mostly increasing, as long as new residential buildings are being constructed. A small decrease can be observed in the last decade, due to the relatively low number of new constructions. Cumulatively, i.e., taking into account all the GHG emitted during the 30 years, the operational emissions account for 56% of the total GHG emissions, while the embodied emissions only account for 44% of the total.

4.2. The operational GHG emissions scenario

Similar to the BAU scenario, the yearly GHG emissions of the main operational emissions scenario are provided in Fig. 7, per type of

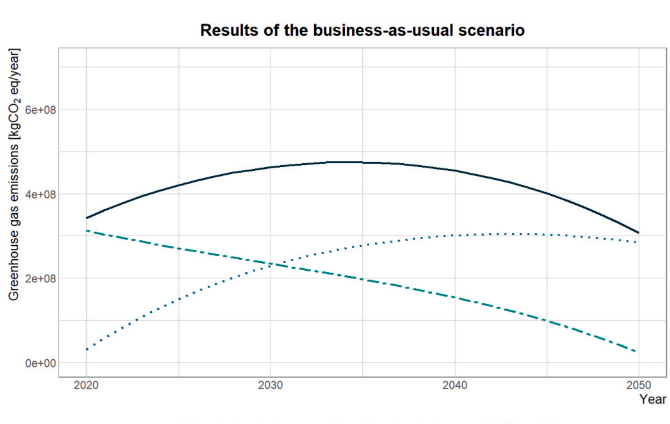

Fig. 6. Yearly GHG emissions of the BAU scenario.

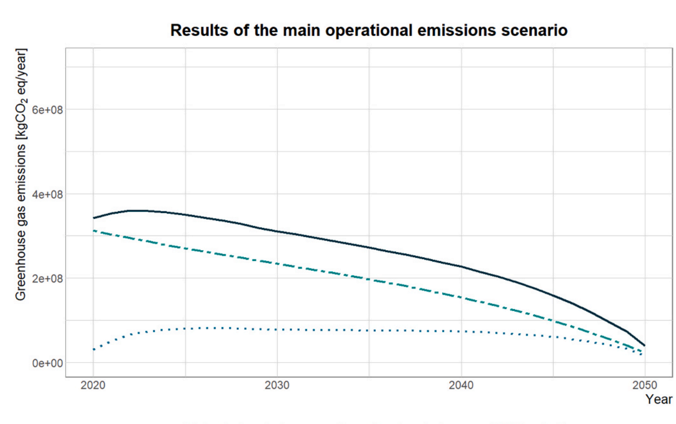

Fig. 7. Yearly GHG emissions of the main operational emissions scenario.

emissions. The embodied emissions, which are still in green, are the same as in the BAU scenario, since they are not affected by any specific measures in this scenario. The operational emissions, on the contrary, display a significantly different profile than in the BAU scenario. Although they increase in the early years, the rate of this increase slightly declines around 2023 when all newly built residential buildings start to comply with the passivhaus standard. The operational emissions then start to be reduced from around 2027, as the integration of renewables in the energy grid increases and keeps on slightly decreasing until 2050. Even though the improvements in efficiency standards, which are taken into account in this model, only apply to new constructions (no renovation or refurbishment are included in the scope of this study), the decarbonisation of the electricity grid applies to all buildings; no specific operation is necessary at the building level for this measure to be implemented. This explains why the increase of renewable energy leads to such a decline in the operational GHG emissions; from 2027 onwards, the reduction in the GHG emissions coming from the energy grid is significant enough to counter-effect the additional operational emissions from the number of newly built buildings.

In this scenario, the operational emissions cumulatively account for 26% of the total GHG emissions, while the embodied emissions cumulatively account for 74% of the total emissions. The ratios highly differ compared to the BAU scenario, leaving the embodied GHG emissions as the main source of emissions in the next 30 years. When comparing the total (embodied + operational) 30-year cumulative GHG emissions of this scenario with the BAU scenario, a 40% reduction is obtained. This reduction potential even rises to 72% when the embodied emissions are discarded (i.e., by only comparing the operational emissions of these two scenarios).

4.3. The embodied GHG emissions scenarios

The obtained results for the scenarios focusing on the embodied GHG emissions are provided in Fig. 8. For better clarity of comparison, only the embodied GHG emissions from these scenarios are displayed. The black line represents the embodied GHG emissions from the BAU scenario; it is identical to the green line which was presented in Fig. 6. This overall decrease in the GHG emissions over the years is once again to be attributed to the declining number of new residential constructions. The results of the other embodied emissions scenarios are illustrated in the form of a range of values. For the future materials scenario, the conservative and optimistic versions are used to create the range. All the wood-increase scenarios (Wood +5% and Wood +10%) have been combined in one range for this graph. The highest values correspond to the most conservative scenario (Wood +5%, conservative) while the lowest corresponds to the most optimistic scenario (Wood +10%, optimistic). The coloured points illustrate the GHG reduction percentages which are reached for the best-case versions of each range, i.e., the lowest values of the range, in comparison with the BAU scenario. Not to overload the graph, these percentages are only displayed each decade. These reduction percentages are not cumulative, meaning that, for example, for 2030, the reduction percentage is calculated only based on the 2030 values, without taking into account the GHG emitted in the previous years.

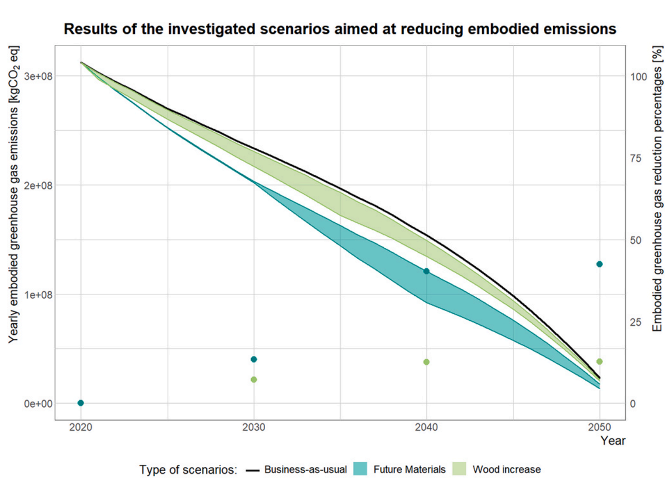

Fig. 8. Yearly embodied GHG emissions and decadal reduction percentages of the embodied emissions scenarios.

When looking closely into the different scenarios, it can be seen that the future materials scenario (the blue range) rapidly reaches lower GHG emissions than the wood-increase scenarios. This is mainly due to the decarbonisation of the electricity grid, which is the main driver of this decline in the early years (before 2030). After 2030, the range expands quite widely depending on the introduction rates of biofuels and CCS. However, the whole range always stays below the wood-increase values (the green range), and therefore achieves lower emissions than any other scenario from 2030 on, up until 2050. The most considerable difference between the conservative and optimistic versions of the future materials scenario occurs in 2040, when CCS is introduced. The most conservative wood-increase scenario (Wood +5%, conservative), which corresponds to the upper green line on the graph, is hardly different from the BAU scenario. The reduction of the embodied GHG emissions is, therefore, quite modest. On the other hand, the optimistic version of the Wood +10% scenario (the lower green line), emits considerably less GHG than any other scenario in the first years of the model (until 2022–2023). The GHG emissions then remain significantly lower than the BAU scenario until 2040, although higher than the future materials scenarios. From 2040 onwards, the difference in the GHG emissions reduces with time and by 2045, is less significant.

Every decade, the GHG reduction percentages increase for the most optimistic versions of both scenarios. These percentages are calculated in comparison to the BAU scenario. They almost reach 15% in 2050 for the wood-increase scenarios and 43% for the future materials scenarios. It is also useful to compare the total GHG of the two scenarios which were emitted over the 30 years. By doing so, the cumulative GHG emissions reductions can be calculated and are provided in Table 3. Firstly, in A, the cumulative embodied emissions of each scenario were compared to those in the BAU scenario, without including the operational emissions. Then, in B, the operational emissions of the BAU scenario were included in the calculation for all scenarios. In other words, for each scenario, operational emissions which were calculated for the BAU scenario were added to the embodied emissions. These total sums of emissions were then compared to those of the BAU scenario. Finally, in C, the same procedure was performed, but with the operational emissions of the main operational emissions scenario. The total emissions of each scenario were then compared to those of the main operational emissions scenario.

In every case, the optimistic version of the future materials scenario achieves the highest GHG reductions of up to 19%, followed by the Wood +10% scenario (optimistic), reaching at best a 7.6% reduction. The conservative future materials scenario still reaches a high reduction of up to 12%. The most realistic increase in wood scenario (Wood +5% - conservative) leads to relatively low GHG emissions reductions, with a maximum of 1.6% when only the embodied GHG emissions are considered. If the operational emissions stay as high as in the BAU scenario, these percentages reduce drastically, with a maximum of 8.2% for the optimistic future materials scenario.

5. Discussion

In the main operational emissions scenario, it was ambitiously assumed that 100% of electricity would be coming from renewable sources in 2050. The possibility of achieving this goal is widely discussed in the literature. At the European level, most studies point towards the

Table 3
Cumulative greenhouse gas emissions reductions achieved for each scenario.

Scenarios		A – Embodied emissions only	B – Total emissions, operational from BAU	C – Total emissions, operational from main operational scenario
Wood +5%	Conservative	1.6%	0.7%	1.2%
	Optimistic	4.6%	2.0%	3.4%
Wood +10%	Conservative	3.3%	1.4%	2.4%
	Optimistic	7.6%	3.4%	5.6%
Future materials	Conservative	12%	5.5%	9.1%
	Optimistic	19%	8.2%	14%

fact that, even in an optimistic approach, the electricity mix would still utilise fossil fuels in 2050 (Alig et al., 2020; Parisi et al., 2020; Spiecker and Weber, 2014). Berrill et al. (2016) also highlights that nuclear energy will very likely be part of the future European electricity mix and advises its inclusion in future scenarios. Ramon and Allacker (2021) similarly describe the phasing out of nuclear power in the Belgian electricity mix as a major future challenge. However, achieving 100% renewable energy seems more feasible in smaller countries or regions. Kwon and Østergaard (2012) discuss the possibility of achieving this objective in Denmark in 2050. Measures for achieving this include the expansion of biomass and wind power capacity and the integration of the transport sector into the energy sectors. As such, they found that all scenarios are likely to achieve a fossil fuel free future in Denmark by 2050. On the contrary, doubts are raised about a fossil fuel free future in bigger countries such as France (Krakowski et al., 2016) or Germany (Cordroch et al., 2022). Krakowski et al. (2016) show that a significant transformation of the power system would be needed with high renewable energy penetration. In particular, a huge amount of biomass capacity would have to be installed to cover just 70% of the demand during harsh winter weeks, which would only minimally be used the rest of the year. This raises the question of the economic profitability and feasibility of such power plants. Cordroch et al. (2022) also warn against the potential instability of the grid infrastructure and argue that, to achieve a fossil fuel free future, it is not enough to rely on efficiency measures as well as renewable energy.

Some authors argue that the decarbonisation of the energy grid, as well as ensuring the construction of new residential buildings under the passivhaus standard, remaining strong political goals, will not sufficiently reduce GHG emissions and call for the urgent consideration of sufficiency measures (Cordroch et al., 2022; Samadi et al., 2017). Energy sufficiency actions, such as a reduction in living area or a reduction in room temperature, reduce energy demand by usually requiring behaviour changes. Such measures were found to have largely been ignored in global energy scenarios (Samadi et al., 2017). However, they provide the advantage of being rapidly implementable at very low cost. Energy sufficiency measures could also be an opportunity to quickly decrease GHG emissions, allowing for more time to develop future low-carbon technologies (Dietz et al., 2009; Bierwirth and Thomas, 2019). In terms of reduction potential, Dietz et al. (2009) estimate that 20% of household direct emissions or 7.4% of US national emissions could be saved in 10 years with a set of sufficiency measures. Focusing on space reduction, Bierwirth and Thomas (2019) quantify an energy reduction potential for space heating in the EU of 17.1–28.8%. van Sluisveld et al. (2016) additionally found that lifestyle changes lead to a reduction in 2030 of about 13% of the global emissions in the residential sector. Although it was noted in the BAU scenario of our study that the GHG emissions are highly related to the evolution of the number of new constructions, no sufficiency measures were considered in our scenarios because they are extremely difficult to estimate. Delzendeh et al. (2017) show the impact of occupants' behaviours on building energy analysis, which can lead to a performance gap between the predicted and actual energy consumption of buildings of up to 300%. Further research could include sufficiency measures, such as a reduction in floor area per person, or other energy-saving measures from residents, and their potential contribution to a reduction in emissions.

The future materials scenario, adapted from Alig et al. (2020) to the specific Austrian conditions, leads to the highest GHG emissions reductions of all embodied emissions scenarios, between 12% (conservative) and 19% (optimistic), if the focus is only on the cumulated embodied emissions. This is slightly higher than the 6% reduction which was obtained by Zhong et al. (2021) in their model for Western Europe. This discrepancy may have arisen from the fact that they did not consider the extended use of CCS in the manufacturing of the construction materials, a technology which highly contributed to the emissions reductions in this analysis, as can be observed in Fig. 8. Besides, as Ayagapin et al. (2021) pointed out, the results are highly dependent on the state or countries which produce the construction materials. In their case, considering that the majority of the materials were imported, the change of the local electricity mix towards more renewables merely had an impact on the product stage of the building, reducing the emissions by about 1% at the building level; the electricity mix is only used for semi-finished items that must be assembled before being transported to the construction site. On the other hand, Karlsson et al. (2021) achieved more than an 80% reduction of the embodied emissions of multi-family buildings by 2045. However, the comparison with the analysis conducted in this paper is not straightforward, as they included more construction materials (plastics, gypsum and glass) and some additional strategies (such as circularity approaches) but calculated the reductions at the building level as compared to this study's use of the regional level. The time-implementation of CCS is another main difference that can be observed between the two studies. They seem to adopt a more optimistic view by expecting a larger and earlier application of CCS, with the technology widely implemented in 2030, which is the year from which CCS slowly emerges in this study.

Yet, the high potential of CCS in the reduction of the GHG emissions comes with challenges to its implementation. He et al. (2019) raised the issue of political barriers by highlighting the apparent lack of policies to support CCS. Salas et al. (2016) identified technical and economic barriers, such as its significant cost compared to the other technologies. Another ongoing controversy is that CCS may have a tendency to shift the environmental impacts. The most common CCS process, post-combustion capture, which while actively reducing the GHG emissions, can also deeply increase other impact categories such as human toxicity or freshwater ecotoxicity (Singh et al., 2011; Koornneef et al., 2008). Additional CCS technologies could be explored in future studies to determine if some of these observed trade-offs could be avoided. In any case, taking into account these barriers, the use of CCS may not be as widespread as expected in 2030 and 2040. This could also be true for other strategies such as the use of biofuels. Zhong et al. (2021) warns about the significant investment required for infrastructure and technology development. In other words, high uncertainties remain for this future materials scenario and even its conservative version could be judged to be too optimistic. Despite such uncertainties, early investments in more efficient production technologies would be needed to achieve these positive long-term effects on the overall GHG emissions, as the mitigation effects could become particularly significant in 2040.

Increasing the number of wooden buildings would reduce the embodied GHG emissions in the first decades covered in this study, especially if a significant raise in the number of newly built wooden buildings is observed. This increase is meant as a replacement of buildings built with other types of materials, not as an absolute increase in new constructions. The role that this strategy would play is, nonetheless, expected to decline, as little difference between the wood-increase and BAU scenarios can be observed in the last decades covered by the model. Wood could therefore be seen as a bridging strategy, allowing for the short-term transition that is needed in the construction sector. These findings are consistent with the ones from Navarro et al. (2021), mentioning the 'expiry date' of using wood products for climate mitigation. Even so, to efficiently be able to reduce the embodied GHG emissions, the construction technique used for the wooden buildings is of great importance; the GHG emission reductions more than doubled between the conservative (Wood +5% scenario) and optimistic (Wood +10% scenario) versions. Lightwood constructions incorporating wooden elements which can be manufactured with a light process should actually be encouraged. On the contrary, the sole use of heavily engineered wooden products, such as glued- or cross-laminated timber, may not as effectively contribute to the GHG emissions reduction. The use of wood should not be seen as a universal method and should be thoroughly investigated for each construction project to ensure a wise use of wood.

Importantly, these results regarding wooden buildings should be critically interpreted in light of the biogenic carbon model used. In this analysis, the 0/0 approach, a static method, was used. With this method, the biogenic carbon balance of wood is considered to be neutral. The approach is the most commonly used method in the literature, but it is worth noting that no clear consensus on the methods exists today. In particular, these static methods have been criticised because they don't consider the temporality of the carbon emissions, nor forest management practices (Hoxha et al., 2020). The relevance of timing the carbon-uptake, in terms of temporarily storing carbon or delaying emissions, was particularly demonstrated by Levasseur et al. (2013). The use of dynamic methods, which include temporality, has then been shown to affect the LCA results at the building scale; deviations of 16% were for example reached in Hoxha et al. (2020). Fouquet et al. (2015) additionally discuss the importance of considering dynamic modelling of biogenic carbon, especially in cases when the whole life cycle carbon balance is not neutral. This could for instance happen if the biogenic carbon is permanently sequestered at the end of life of the building. Properly including the forest ecosystem could also affect the carbon balance, as discussed by Head et al. (2019), and avoid undesirable effects. For example, in cases when trees are felled and not replaced, Pomponi et al. (2021, p.160) warns against such an "inefficient form of displacing carbon". Future studies could include dynamic biogenic carbon modelling in their prospective analysis.

Finally, the representativeness of the case studies used to model the future building stock can also be discussed. Even though the construction techniques of the case studies were varied to enrich the model, the sole use of two buildings to represent a whole region is a significant limitation. Looking more closely into the possibilities of creating an average representative building stock, for example by building on the work of European projects, as suggested by Röck et al. (2021) and extending the concept of "reference buildings" which is described in the TABULA project (Amtmann, 2011), would highly improve the results from this analysis, and would be an imperative step if this methodology was to be extended from the regional to the national level.

6. Conclusion

This paper presented a first explorative LCA study regarding future residential constructions in Austria, with a specific focus on the region of Tyrol. Assuming that the current building situation remains unchanged until 2050 and that no mitigation measures are established, the embodied GHG emissions are expected to decline because of the projected decrease in new constructions. Contrarily, the operational emissions would mostly increase, and would represent 56% of the total GHG emissions over the 30 years, raising once again the importance of first tackling these emissions. When implementing the politically adopted strategies to reduce the operational GHG emissions, which are mainly based on the decarbonisation of the energy grid, as well as enforcing the passivhaus standard for new residential buildings, high reductions in GHG emissions could be achieved, up to 40% considering all emissions, and up to 72% when only considering the operational emissions. The embodied GHG emissions would then become the largest share of the emissions in the next 40 years, representing about 74% of the total. Yet, achieving 100% renewable energy remains a challenge which would require strong political support.

The predicted penetration of renewables in the electricity grid will also influence the emissions originating from the manufacturing of the construction materials. Additional technological developments are also assumed to take place, such as an improvement of energy efficiency, the establishment of CCS or an intensified use of bioenergy. Taking into account these expected changes in material manufacturing, the effect on future residential constructions would lead to a decrease of the embodied emissions by 19% at best. The mitigation effects would rather be visible in the long-term, from 2040 on, when key technologies such as CCS start to be actively implemented, which is why reaching these goals would require long-term investment. The achieved GHG reduction potential would surpass the effect of an increase in wooden-constructions, reaching a maximum of a 7.6% reduction of the embodied emissions over the 30 years. Increasing the number of wooden constructions would, on the contrary, have larger positive effects in the earlier decades, but these effects would be reduced after 2040. It could, therefore, be qualified as a bridging strategy, which is not incompatible with investment in technological developments.

Even if these reduction percentages are far lower than the ones which could be attained at the operational energy level, they remain indicative of a promising reduction in the embodied GHG emissions which can be reached for new residential constructions. In future work, increasing the modelling details of these technological developments, by, for example, applying them to further construction materials as well as increasing the number of case studies for representativeness, would strengthen the precision of the calculated reduction potentials. The inclusion of sufficiency measures, such as a reduction in floor area per person, could also complement these reduction strategies and lead to higher reduction potentials.

CRediT authorship contribution statement

Nicolas Alaux: Investigation, Writing – original draft, preparation, Writing – review & editing, Visualization. **Marcella Ruschi Mendes Saade:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Endrit Hoxha:** Validation, Writing – review & editing. **Barbara Truger:** Writing – review & editing. **Alexander Passer:** Methodology, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135278.

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