

The impacts of future sectoral change on the greenhouse gas emissions of construction materials for Swiss residential buildings

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ABSTRACT

Life Cycle Assessment (LCA) is a comprehensive method for evaluating building sustainability. However, most studies have relied on generic or national LCA databases, overlooking the systematic consideration of future scenarios and sectoral developments due to data and tool constraints. Moreover, there's a gap in providing a standardized workflow for such evaluations and understanding their impact on the greenhouse gas (GHG) emissions of buildings on a national level. Addressing these gaps, our study incorporates scenarios from two Integrated Assessment Models (IAMs), considering the future developments of the electricity, cement, and steel sectors, to assess embodied GHG emissions of Swiss residential buildings from 2015 to 2055. Our findings reveal that incorporating these future considerations can lead up to a 25% GHG emissions reduction by 2055 compared to 2015, primarily due to GHG emission reductions in concrete and brick as a result of these considerations. This is much less than the emissions reduction potential of some specific construction materials and far from the goal of net zero. It also underscores the importance of exploring alternative strategies for net-zero GHG emissions at the building stock level. Consequently, we present reproducible workflows using open-source tools and future versions of the Swiss national building LCA databases, offering a blueprint for similar future studies in other countries.

1. Introduction

As greenhouse gas (GHG) emissions continue to rise globally, the associated climate change impacts intensify and threaten our ecosystems and society at large, making the need to cap and reduce anthropogenic GHG emissions more critical than ever. The buildings and construction industry plays a vital role in this regard because it contributes 37% of the global CO₂ emissions in 2021 [1]. In Switzerland, the GHG emissions of the building sector often refer to the GHG emissions from fuel combustion during the operation of buildings, which contributed about a quarter of national GHG emissions in 2020 [2,3]. Including both the embodied GHG emissions of buildings and the indirect GHG emissions

from electricity consumption would further raise this sector's contribution to the overall national GHG emissions.

Conventionally, the primary focus of GHG emissions of the building sector has been on the operational phase, specifically concerning energy consumption [4]. This narrow focus, however, ignores the growing contribution from GHG emissions embodied in construction materials of buildings [4]. For buildings constructed under more stringent energy standards, the embodied GHG emissions could be higher than the GHG emissions during the operation phase [4], and in some cases even up to 80% of the life cycle GHG emissions of a building [5], indicating that more emphasis should be placed on the decarbonization of building envelopes in future mitigation strategies [6]. The embodied GHG

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emissions of a building mainly consist of the GHG emissions from the product stage (A1-A3), construction stage (A4-A5), as well as the end-of-life stage (C1-C4) according to EN 15978 [7]. The contribution from the construction stage is found to be relatively insignificant based on past research [8–10], and is often neglected by many assessments [11]. Consequently, a substantial portion of embodied GHG emissions is attributed to the production and end-of-life stages of buildings.

Nonetheless, traditional building Life Cycle Assessments (LCA) relying on static databases fail to represent the evolving embodied GHG emissions of construction materials [12,13], especially considering their future development driven by the advancements in key industrial sectors [14]. While Prospective LCA offers a better approach by considering these evolving factors [15], several research gaps remain. First, its application is typically restricted to specific materials and technologies [16–18], and the systematic and reproducible analysis of future system changes on GHG emissions from construction materials, particularly considering the broader evolution of building stock [19], is lacking. Second, although energy scenarios have been incorporated in past studies [20], the difference when applying different energy system models and scenarios is not discussed. Moreover, the geographical origins of life cycle GHG emissions from construction material consumption are not well understood. These oversights present opportunities for further investigations, as systematically understanding the future development of embodied GHG emissions of buildings on a national level is crucial for developing effective decarbonization strategies.

To address these research gaps, we have conducted a case study for Switzerland to quantify the life cycle GHG emissions caused by the Swiss consumption and end-of-life treatment of construction materials for residential buildings from 2015 to 2055. The study incorporates future developments globally by including electricity, cement, and steel as exemplary sectors. The detailed assumptions for these future sector developments are based on the outputs from two Integrated Assessment Models (IAMs). Scenarios that combine different Representative Concentration Pathways (RCPs, which reflect different levels of GHGs and other radiative forcings that might occur in the future [21,22]), IAMs, and different sector updates are considered, and the influence of these various factors on future embodied GHG emissions of Swiss residential buildings is assessed at the material and national level.

The structure of this paper is as follows: first, we provide a thorough literature review, which clarifies the current state of research associated with the aforementioned research gaps, and underscores the areas that require further exploration. We then detail the methodology and assumptions underpinning our analysis. In the results section, life cycle GHG emissions and their reductions are presented at the material, national residential building stock level, as well as on a global geographical resolution to track the origins of the embodied GHG emissions for Swiss residential buildings. The discussion section starts by discussing the key data requirement for replicating the analysis for other countries, and then examines the influence of the applied background database options, discusses the limitations of the approach and points out corresponding future directions of research. Finally, we conclude with the major findings of the study, emphasizing the addressed research gaps, the implications for policymakers, and the contributions of this work to the field of building life cycle assessment.

2. Literature review

Current assessments of the production and end-of-life stages of buildings typically rely on static databases, which often reflect the current GHG emissions embodied in construction materials [12,13]. However, the production and processing of construction materials are intricately connected to the energy used in manufacturing and the use of other significant materials, such as cement and steel, which are subject to ongoing changes and anticipated future shifts. Yet, these evolving factors are seldom considered in the assessment of embodied GHG emissions at the building stock level over a multi-decade time horizon [14].

Prospective LCA has emerged as a valuable method to take into account such factors in the future [15]. However, the scope of prospective LCA studies typically exhibits a narrow focus, often centering on specific materials and technologies [16–18]. A notable exception is the study by Alaux et al. [19], which examines a variety of GHG mitigation strategies in the construction of new residential buildings in Tyrol, Austria. This study encompasses a broad range of factors, including the reduction of GHG emissions in future construction material manufacturing, energy consumption during the operational phase, and the promotion of wood constructions to varying extents. It takes into account future trends in material manufacturing, such as the increase in renewable electricity, bioenergy, and energy efficiency, as well as the application of carbon capture and storage. However, it does not integrate results from systems models to support its assumptions for energy transformation and lacks consideration of a realistic evolution of the building stock, such as building renovations and individual building considerations. Furthermore, its scope is limited to four major construction materials (wood, concrete, brick, and steel), and it does not consider the temporal storage of carbon by wood.

In Switzerland, Alig et al. estimated the future life cycle environmental impacts of major construction materials, taking into account changes in energy supply, transport, and manufacturing processes [20]. The assessment's time horizon spans from 2030 to 2050, with a single future scenario representing this period, combining assumptions from various sources published in different years. For instance, the study refers to the World Energy Outlook and IEA Sustainable Development scenarios from 2018 for electricity supply mixes in 2040 for selected world regions [23], potentially creating inconsistencies in the study's time horizon. Furthermore, the study investigated the influence of future changes at both the material and building levels, with the latter focusing on two Swiss buildings - an office and a residential building. However, it did not explore the implications of future production and treatment of construction materials at the national building stock level, considering the amount of material consumption. Heeren et al. quantified the GHGs of construction materials for Swiss residential buildings assuming constant GHG emissions of construction materials in the future, equivalent to their current levels [24]. Their analysis utilized a generic LCA database, ecoinvent v3.2, whereas national LCA databases for construction materials are often used in building life cycle assessments. Moreover, updates in various global sectors (e.g. electricity, cement, and steel) affect the GHG emissions of construction materials in Switzerland on a national scale, but their total and respective impacts were not analyzed. The origins of GHG emissions caused by the consumption of construction materials in Switzerland (e.g. in Swiss residential buildings) remains unclear, which is potentially valuable for enhancing Swiss sustainable procurement policies for construction materials [25].

3. Methodology

This section delineates the methodology employed to calculate the embodied GHG emissions of Swiss residential buildings, factoring in various future scenarios and sectoral developments. Initially, we start by providing an overview of the analytical workflows, then delve into the specifics of the IAMs, RCPs, scenarios and future sectors considered. Subsequent to this, we detail the assumptions for annual material flows, which facilitates the extrapolation of results from individual materials to the entire Swiss residential building stock, together with the equation applied for quantifying GHG emission reductions at the material level. In the end, the section specifies the tools employed in our analysis, with comprehensive input data accessible in the Research Data, emphasizing the transparency and reproducibility of this study.

3.1. Analytical workflows

The methodology of this analysis adheres to a step-wise procedure depicted in Fig. 1.

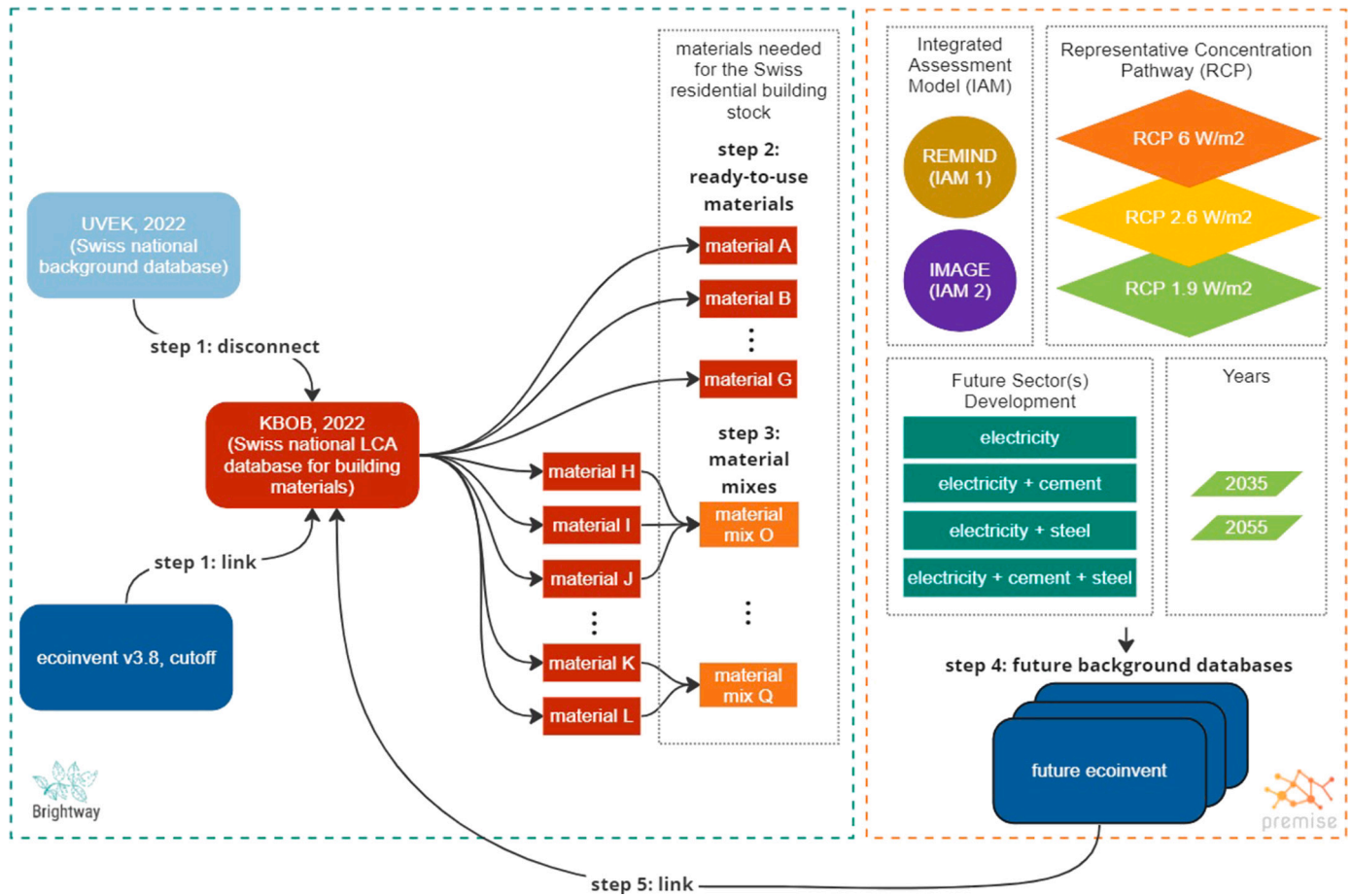


Fig. 1. Overall analytical workflows of the study.

The GHG emissions of materials are estimated mainly using the Swiss national LCA database for construction materials, provided by the Coordinating Conference of Construction and Property Bodies of Public Builders (Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren, KBOB) [26]. The 2022 version of the KBOB database is linked with the UVEK 2022 background database (Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation, UVEK), the latest version of the national LCA background database commissioned and published by the Swiss Federal Department of the Environment, Transport, Energy and Communications [27]. Both databases are available in exported Simapro project format [28]. However, the UVEK database's lack of parameterization necessitates manual updates for prospective LCA, potentially impacting the reproducibility of the analysis.

To enhance transparency and reproducibility, this study begins by transitioning the background database for the KBOB database from UVEK 2022 to ecoinvent v3.8 cutoff version (Fig. 1, step 1). This involves migrating any dataset in KBOB 2022 linked with an upstream process in UVEK 2022 to a corresponding dataset in ecoinvent v3.8. To ease the migration process, we also extracted a subset of materials from the KBOB 2022 database, guided by the material flows list from Heeren et al. [24]. The alignment between the UVEK 2022 database and ecoinvent v3.8 is facilitated by an automatic fuzzy lookup [29] considering the name, location, and reference product of the datasets, followed by a manual verification of the matched datasets. The list of 137 matched dataset pairs is provided in the Research Data. For materials with corresponding datasets in KBOB, datasets from the foreground KBOB database are chosen for use (step 2). For some other materials, for which only aggregate category flow amounts are tracked (e.g. insulation materials mix), we combine various material datasets from KBOB

and ecoinvent v3.8 to create new datasets representing these material categories (step 3). By combining IAM, RCP, sector developments, and future years, we create a corresponding future background database (step 4) using premise v1.3.7 [30] and link it with the foreground KBOB database (step 5). The specific RCPs, their projected temperature increases by 2100, associated global scenarios from IAMs, and corresponding Swiss national scenarios applied are listed in Table 1 and explained below. In addition, we use Brightway2 [31] for the Life Cycle Impact Assessment of materials as well as database management, including database importing, storing, and transformations.

3.2. Integrated Assessment Models (IAMs), Representative Concentration Pathways (RCPs), scenarios and future sector developments

In this analysis, we employ two IAMs, namely the Integrated Model to Assess the Global Environment (IMAGE) [32] and the Regional Model of Investment and Development (REMIND) [33]. Unlike cost-benefit IAMs such as DICE [34] and FUND [35], which lack a representation of system changes and interactions necessary for constructing future process-based Life Cycle Assessment (LCA) datasets, IMAGE and REMIND are process-based IAMs that provide extensive details on the energy sector and its end uses [36]. They have been prominently featured in the IPCC reports and study [37–39] and are among the five IAMs used to derive scenarios for the Shared Socio-Economic Pathways (SSPs) [40]. They are chosen as exemplary IAMs to demonstrate the integration of process-based IAMs into the background database of a national Life Cycle Assessment (LCA) database for construction materials. Although the selection is based on their availability in premise [30], our analysis showcases the possibility of extending this approach to include a wider variety of process-based IAMs in such LCA databases.

Table 1

List of scenarios from IAMs and Swiss Energy Perspectives incorporated in the future background databases.

| Representative Concentration Pathways (RCPs) | Temperature increase by 2100 (°C) | Global Scenarios from IAMs | | Swiss National Scenario - Energy Perspectives |
|--|-----------------------------------|----------------------------|-------------------|---|
| | | IMAGE Scenarios | REMIND Scenarios | |
| RCP 6 W/m ² | 3.5 | IMAGE Base | REMIND Base | Business-as-usual |
| RCP 2.6 W/m ² | 1.8-2 | IMAGE RCP26 | REMIND PkBudg1150 | Zero (Basis) |
| RCP 1.9 W/m ² | 1.5 | IMAGE RCP19 | REMIND PkBudg500 | |

For each IAM, we applied three RCPs. These include:

RCP 6 W/m²: a counter-factual baseline RCP, which assumes no stringent climate policy and projects a temperature rise of 3.5 °C by 2100,

RCP 2.6 W/m²: an RCP targeting a temperature increase limit of 1.8-2.0 °C, and

RCP 1.9 W/m²: an RCP aiming for a 1.5 °C increase.

Each of these RCPs corresponds to a different global scenario depending on the IAM applied (Table 1). Current global GHG emissions, as influenced by national commitments, are between the baseline RCP and the RCP limiting temperature rise to 1.8-2.0 °C [41]. Given the local production and processing of numerous construction materials in our study, incorporating specific scenarios considering Swiss energy perspectives is crucial. To this end, we integrate two scenarios from the Swiss Energy Perspectives for 2050 [42]: the Business-as-Usual scenario, which presumes the continuation of current energy and climate policies, and the ZERO (Basis) scenario, which is formulated based on anticipated technological advancements and aligns with Switzerland's goal of achieving net-zero GHG emissions by 2050 while ensuring a secured national energy supply [43].

In our study, the considered global sector developments in the future encompass various combinations: electricity alone, electricity and cement, electricity and steel, and a comprehensive case including all three sectors (Fig. 1). It is essential to consider dual-sector combinations, such as cement and electricity or steel and electricity, rather than analyzing each sector in isolation. This approach is necessitated by the fact that the decarbonization of the industrial sectors is closely linked to the decarbonization of the electricity system. For instance, strategies like carbon dioxide capture and storage (CCS) and the increased production of recycled steel in electric furnaces demand more electricity, particularly electricity with lower GHG intensity. Hence, the decarbonization strategies for the cement and steel sectors are linked with the electricity sector's decarbonization. The sector developments incorporate specific future considerations:

Electricity Sector: future developments include increased power generation efficiency and a higher proportion of low-carbon electricity, including electricity generated with CCS.

Cement Sector: future improvements focus on better fuel efficiency and fuel mix. Future strategies also involve lowering clinker-to-cement ratios and reducing emissions of non-CO₂ air pollutants. CCS is integrated into cement production, coupled with a reduction in electricity consumption for future cement production.

Steel Sector: future updates include increased production efficiencies and the integration of CCS. Additionally, the proportion of secondary steel in global supplies is set to increase.

Each of these future considerations is underpinned by detailed assumptions, the specifics of which are available in the Research Data (scenario_report.xlsx) as well as documentation in Sacchi et al. [30]. Noting that the considered future sector developments are limited in our study, we exclude the consideration of other sectors that might be relevant (e.g. industrial heat), mainly due to the lack of high-quality and systematic data on a global scale to support the creation of future background databases. On the other hand, although including other sectors might provide more insights, their inclusion could dilute our focus and introduce more uncertainties to the study. More details on this are discussed in section 4 and section 5.

Using the KBOB database linked with these diverse future background databases, we calculate life cycle GHG emissions at the material level for the years 2015, 2035 and 2055, with GHG emissions for intervening years determined through interpolation.

3.3. Annual material flows

The annual material flows are multiplied by the material-level life cycle GHG emissions. Subsequently, the annual GHG emissions associated with the production, end-of-life disposal and treatment of construction materials used in Swiss residential buildings are determined by summing these products' totals. The annual material flows for residential buildings in Switzerland, encompassing both inputs (consumption) and outputs (materials requiring disposal and treatment), are obtained from Heeren et al. at a 20-year time interval from 2015 to 2055 [24], and the detailed data can be found in the Research Data. From the six scenarios presented by Heeren et al. [24], we select the wood scenario that promotes new constructions using wood. This choice was made because the differences among the scenarios were not substantial enough to affect the outcomes of this study. Additionally, this scenario allows us to account for the carbon sequestration potential of wood buildings, a factor not quantified in the previous study [24]. To factor this in, our analysis extends beyond the conventional global warming potentials (GWPs) defined by the IPCC 2013 GWP 100a [44], which are typically used in LCIA of climate change but do not consider the GWPs of biogenic carbon dioxide (the "0/0 approach", [45]). We have incorporated the GWPs of biogenic CO₂ into our assessment, adopting a "+/-1 approach" to account each kilogram of CO₂ absorbed from or released to the atmosphere [45]. The implementation details of this impact assessment method are documented online in premise-gwp [46].

To understand the GHG emission reduction potentials at the material level, we calculate the percentage of emission reductions for the year 2055, incorporating global scenario IMAGE RCP19 (as shown in Table 1) and future developments in electricity, cement, and steel sectors in the background database. The percentages of GHG emission reductions by material (R_m) for production and the end-of-life treatment are calculated using equation (1).

$$R_m = \left| \frac{G_{2015,m} - G_{2055,m}}{G_{2015,m}} \right| * 100\% \quad (1)$$

In this equation, R_m is the percentage of GHG emission reductions for each material m, G_{2015,m} is the GHG emissions for each material production/end-of-life disposal and treatment in the year 2015, G_{2055,m} is the GHG emissions for each material production/end-of-life disposal and treatment in the year 2055.

We also examine the origins of GHG emissions in 2015. To represent GHG emissions at the same geographical resolution by country, we divide emissions from broader regions and global datasets into their constituent countries based on each country's share of regional GDP in 2015, as per data from the World Bank in 2015 [47]. For datasets labeled "global" (GLO) or representing regions larger than a single country (e.g. "Eastern Asia" or "UN-EASIA"), GHG emissions were allocated to individual countries within these regions proportionally to their GDPs. Emissions from areas smaller than a country (e.g. a Chinese province) were attributed to their respective countries (e.g. China). However, some datasets use a unique ecoinvent region called "Rest-of-the-World" (RoW). This location is used when data for certain countries

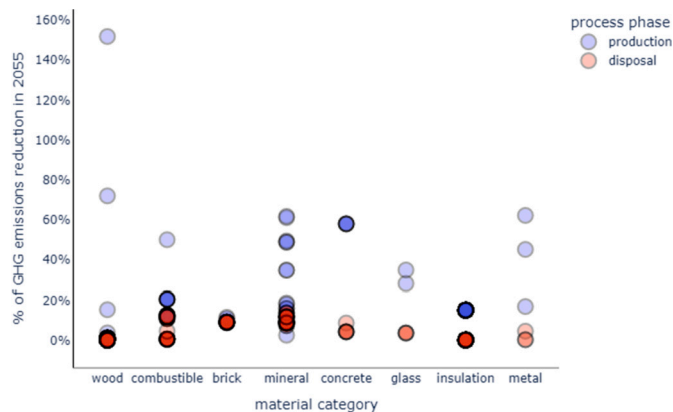


Fig. 2. Emission reduction potentials by construction material in 2055 compared to 2015 incorporating IMAGE RCP19 and all sector updates (i.e. electricity, cement, steel). An interactive version of this figure in HTML format, which displays specific material names upon hovering over data points is available in the Research Data.

is not available, and represents regions with only generic data. The definition of RoW varies across datasets, depending on data availability. While RoW can be geographically defined for each dataset, visualizing GHG emissions for RoW is not practical, as it is a construct for database completeness rather than a real-world region. Therefore, in our maps tracking the origin of GHG emissions on a global resolution, RoW contributions are omitted. Nonetheless, we calculate and report the total GHG emissions attributed to RoW datasets, as well as to GLO datasets. These figures, displayed above the map, indicate the proportion of GHG emissions without a specific geographic origin, highlighting areas for future data improvement.

The analysis is transparently carried out through Python script in Jupyter notebooks with raw inputs included in the Research Data. This ensures the complete reproducibility of this study and the application of the approach to other similar analyses in the future.

4. Results

The results section is organized as follows: first, we explore the potential for reducing GHG emissions at the material level by 2055. This investigation utilizes the most ambitious scenario considered in our study and incorporates future developments across all three sectors considered. Following this, we examine the embodied GHG emissions from residential buildings in Switzerland on a national scale. This includes a breakdown of GHG emissions by material categories, highlighting which materials offer the most significant potentials for embodied GHG emission reductions and contributions in the residential building sector. Within this, we assess the impact of different IAMs and future sector developments, focusing on their influence on total embodied GHG emissions and carbon stored. Lastly, we analyze the geographical origins of life cycle GHG emissions caused by the consumption, disposal and end-of-life treatment of construction materials used in Swiss residential buildings, extending the national GHG emissions result to a global context.

4.1. GHG emissions reduction by materials

Considering future sector developments, the life cycle GHG emissions of various materials demonstrate diverse emission reduction potentials. Fig. 2 illustrates these potentials for 2055, considering the IMAGE RCP19 scenario with anticipated changes in the global electricity, cement, and steel sectors. The data is segregated into production and disposal categories.

The analysis reveals that, with the sector developments considered, a significantly higher potential for GHG emission reduction is consis-

tently observed in the production phase compared to the disposal phase of materials. Among the materials, wood exhibits the broadest range of emission reduction potential. Notably, the production of wood window frames shows the most substantial potential, with an estimated GHG emission reduction of approximately 150%. This is followed by selected materials in the mineral and metal categories, and one each in the combustible and concrete categories, each capable of achieving around a 50% to 60% GHG emission reduction.

Conversely, insulation materials display the least potential for emission reduction. This category primarily includes mineral-based insulation materials like stone wool (47%) and glass wool (15%). The production of these materials is energy-intensive, involving melting and fiberization processes that predominantly rely on fuel combustion, such as coke. Future developments in this area, such as enhanced efficiency or alternative fuels, are not considered in this analysis. This omission is due to the complexity of modeling the decarbonization of heat, which depends not only on technological advancements and heat requirements, but also on regional variations in available heat sources, including fuel types and heat quality (i.e. temperature of heat). This complexity renders such modeling beyond the scope of this study.

4.2. Embodied GHG emissions of Swiss residential buildings

Fig. 3 presents the net life cycle GHG emissions from the production and disposal of construction materials, accounting for the total biogenic carbon stored in material stocks, which reduces the net GHG emissions. This figure categorizes emissions by material type for residential buildings in Switzerland. It compares the base scenarios with the most climate-ambitious scenarios, specifically PkBudget500 and RCP19, from REMIND and IMAGE respectively. In the base scenarios, the figure includes results that consider prospective developments in the electricity sector (subfigure a and d). For the most climate-ambitious scenarios, the figure examines two conditions: one where all sector updates are included (subfigure c and f), and another where only future development in the electricity sector are factored in (subfigure b and e).

Depending on the scenario, IAM, and sector updates considered, total GHG emissions may initially increase until 2035 and then align with the 2015 level by 2055 (Fig. 3a). Alternatively, a reduction of approximately 25% is achievable by 2055 under the most ambitious climate scenarios with all future sector developments considered (Fig. 3c), mostly driven by the GHG emission reductions of concrete and brick, as a result of these future considerations, followed by the storage of carbon by wood materials in buildings. Concrete significantly contributes to lowering the GHG emissions, with an estimated 60% reduction in its production stage at the material level (Fig. 2). Conversely, brick's GHG emission reduction potential is markedly less, at less than 20% by 2055 (Fig. 2). The anticipated GHG emission reductions for concrete and brick can be also attributed to their reduced consumption (i.e. by around 70% in mass) by 2055. However, the reduced GHG emissions for concrete and brick counterbalances with the concurrent increase of GHG emissions associated with combustibles and insulation materials, resulting in less percentage of GHG emissions reduction achieved at the building stock level. IMAGE also has a more conservative base scenario compared to REMIND, with total GHG emissions in 2055 being comparable to those of 2015. (Fig. 3a). In contrast, the REMIND base scenario (Fig. 3d) forecasts a 10% reduction by 2055. However, IMAGE's most stringent climate scenario is marginally more ambitious than REMIND's, yielding slightly lower total GHG emissions.

When IMAGE is applied, both the introduction of the most ambitious climate scenario with updates solely in the electricity sector (Fig. 3b) and the inclusion of cement and steel sector updates (Fig. 3c) appear to contribute equally to the GHG emission reductions, each accounting for 50% of the total reduction. Conversely, with REMIND, the most stringent climate scenario considering only electricity sector update (Fig. 3e) has less impact on GHG emission reduction compared to the inclusion of cement and steel updates (Fig. 3f), with the former reducing emis-

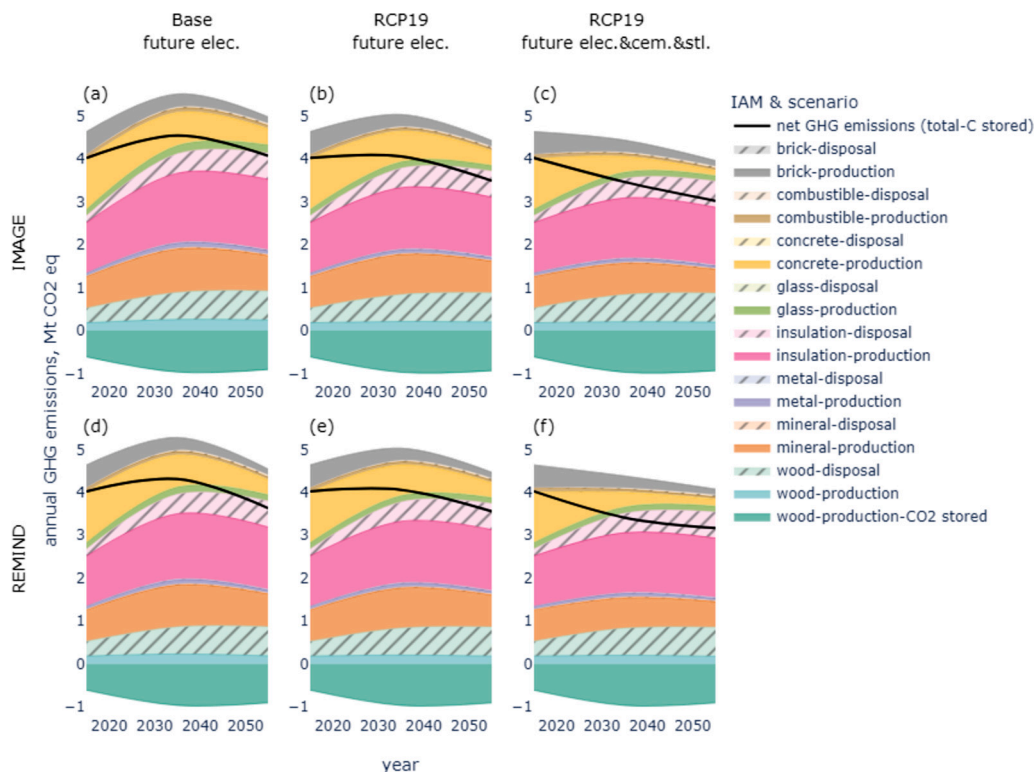


Fig. 3. Total annual GHG emissions for residential buildings in Switzerland, including breakdowns of GHG emissions by material category and contributions from production and end-of-life disposal and treatment, incorporating global scenarios different IAMs and sector developments. Carbon dioxide emissions stored in wood materials are negative and shown by the green shaded area at the bottom. The net GHG emissions throughout the years (i.e. total GHG emissions minus the carbon dioxide stored in wood materials) are shown by the black lines. An interactive version of this figure in HTML format is available in the Research Data. (For interpretation of the colors in all the figures in this article, the reader is referred to the web version of this article.)

sions by less than 0.1 million tons (Mts) of CO₂ eq and the latter by an additional 0.4 Mts annually.

Regardless of the IAM, scenario and future sector updates considered, a consistent trend emerges in the ranking of material categories by their contribution to total embodied GHG emissions for Swiss residential buildings. In 2015, concrete and insulation materials each contributed approximately 1.2 Mts of CO₂ eq annually. Over time by 2055, insulation materials’ contribution increases to between 1.4 and 1.6 Mts annually, while concrete’s contribution declines to 0.1-0.4 Mts. This shift is attributed to a future focus on renovations over new constructions in Switzerland and the exclusion of heat decarbonization from this study, which is significant for manufacturing certain materials, such as insulation. According to Alig et al. [20], the contribution of fuel supply, which is primarily for heat generation, can contribute to about 40% and over 60% of the life cycle GHG emissions for glass wool and rock wool, respectively. Mineral materials maintain a relatively stable contribution of 0.6 to 0.8 Mts annually. Wood materials demonstrate a net negative GHG emissions contribution. The carbon they store is equivalent to 0.6 to 0.9 Mts of CO₂ annually, which slightly outweighs the GHG emissions from wood treatment. However, this net negative impact is relatively minor in the overall GHG emissions context. Overall, material production dominates the total embodied GHG emissions of Swiss residential buildings, with only insulation and wood materials showing relatively significant contributions from disposal and treatment phases, primarily due to the CO₂ release from incineration.

Fig. 4 presents the annual greenhouse gas (GHG) emissions associated with the production and end-of-life disposal and treatment of materials, alongside the carbon stored in Swiss residential buildings in CO₂ eq. This representation encompasses all combinations of scenarios and future sector developments considered. A notable observation is that integrating future development in the cement sector globally leads to a more pronounced reduction in embodied GHG emissions of Swiss

residential buildings compared to the steel sector (as evident from subfigure b and c).

When comparing the IAMs, IMAGE results in a broader range of total GHG emissions across all scenarios than REMIND. The “middle” scenarios of both IAMs exhibit a gradual increase until approximately 2035, followed by an accelerated reduction in emissions between 2035 and 2055, aligning closer to the most ambitious climate scenarios. This pattern is particularly evident when considering future development solely in the electricity sector: except for IMAGE’s base scenario, all other scenarios show a convergence in total GHG emissions over time.

Furthermore, when future developments in the cement sector are also factored in (subfigure b and d), employing the most ambitious climate scenarios in both IAMs appears to induce a nearly linear decline in total GHG emissions. This suggests that considering the future development of both the electricity and cement sectors together could have a significant impact on reducing GHG emissions, potentially attributed to the application of CCS.

4.3. Embodied GHG emissions of Swiss residential buildings - global origins

Fig. 5 traces the global origins of GHG emissions from the production and end-of-life treatment of construction materials used in Swiss residential buildings. In 2015, 36% of these emissions were emitted within the territory of Switzerland, followed by Germany with 10%. Other notable contributors include the UK (6%), France (5%), Italy (4%), Russia (4%), and China (3%). Most EU countries and the US each contributed approximately 1%, with the Netherlands and Poland each at 2%. Notably, 22% of emissions originated from unspecified regions, with RoW areas accounting for 19% and global contributions at 3%. This highlights the need to improve data on the geographical origins of upstream supply chain processes involved in manufacturing construction materials used in Switzerland.

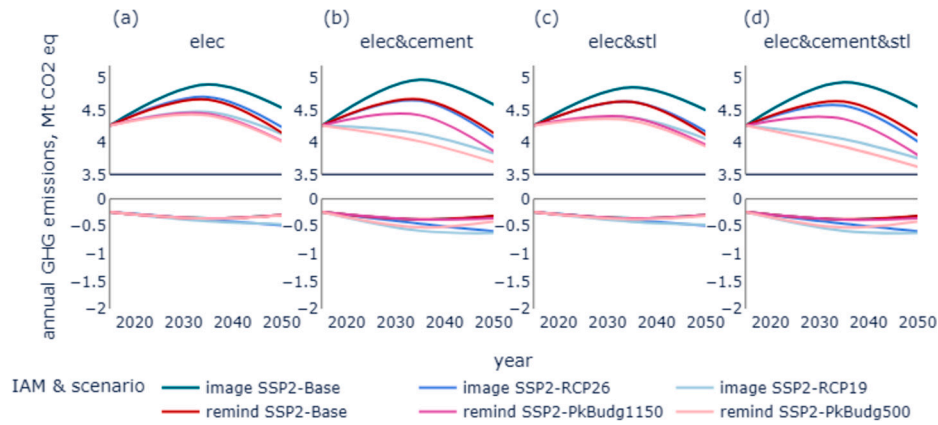


Fig. 4. Total GHG emissions of materials production and end-of-life treatment for Swiss residential buildings (positive values) and carbon dioxide temporally stored in residential buildings (negative values) considering different future sector updates and IAMs. An interactive version of this figure in HTML format is available in the Research Data.

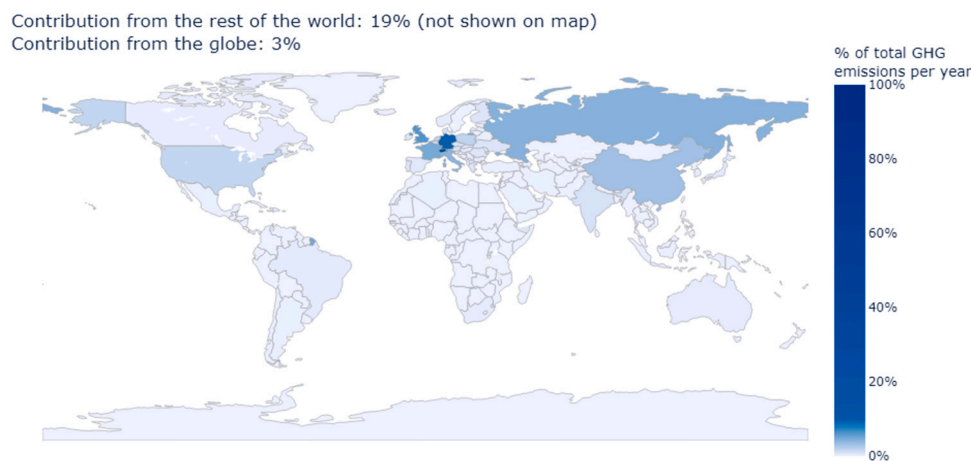


Fig. 5. Net GHG emissions of materials production and end-of-life disposal and treatment of construction materials for Swiss residential buildings in 2015. The contribution in the percentage of total GHG emissions from RoW is calculated and shown on top of the figure but excluded from the map, and the contribution from GLO and regions greater than a country are evenly distributed throughout all the countries they contain based on the share of a country's GDP in 2015. An interactive version of this figure in HTML format is available in the Research Data.

5. Discussion

Our study identified construction materials with high GHG emission reduction potential, considering the future decarbonization of the electricity, cement, and steel sectors globally. By integrating IAMs, we quantified the total GHG emissions from the production and end-of-life treatment of construction materials in Swiss residential buildings. This study serves as a practical example of applying a national construction material LCA database for prospective LCA of national building stock, offering reproducible datasets for similar analyses in Switzerland. The methodology is also adaptable to other national LCA databases for creating their prospective versions.

5.1. Data prerequisites for cross-country replicability

However, similar analysis for other countries requires access to non-aggregated unit process datasets in national building LCA databases, which may pose challenges for some countries (e.g. ökobaudat in Germany [50]) due to data confidentiality issues. To improve reproducibility, it is essential to have unit process datasets featuring parameterized Life Cycle Inventory (LCI) data. This would facilitate the integration of scenarios and future sector developments via programming scripts, ensuring transparency and reusability.

5.2. Influence of background database

Regarding the methodology, the initial step involves migrating the original KBOB background database, specifically from UVEK 2022 to the ecoinvent v3.8 cutoff version. A comparative analysis of the GHG emissions is conducted for the migrated datasets (Supplementary Information, SI). Generally, the GHG emissions for the corresponding datasets in UVEK are about the same as those in ecoinvent v3.8, indicating the insignificant effect this migration has brought to the results and conclusions. There is an exception for a few datasets related to end-of-life disposal and treatment, where a more pronounced discrepancy can be observed because the UVEK 2022 database accounts for additional inventory flows associated with transportation, dismantling, and other realistic factors in various disposal activities of construction materials [51]. However, these datasets contribute minimally to the overall GHG emissions (Fig. 3). The same applies to a few other materials and processing datasets that are insignificant to affect the results. Furthermore, when compared with the findings of Heeren et al. [24] (SI), using the generic ecoinvent database typically results in higher GHG emissions than using the national construction materials database as in this analysis, even though the majority of datasets chosen in ecoinvent represent processes in Switzerland (i.e. with the location "CH"). Differences of more than 100% are seen in all materials for end-of-life treatment

and disposal stage. Considering future sector developments in material manufacturing and end-of-life treatment results in an additional 23% of GHG emissions reduction, mostly driven by the GHG emission reductions of concrete and brick as a result of future considerations included in this study. Considering constant GHG emissions at the material level, the GHG emissions reduction as a result of the reduced consumption of concrete and brick is only about enough to balance out the increased GHG emissions from insulation materials and combustibles, achieving only about 2% of GHG emissions reduction at the building stock level [24].

5.3. Limitations and future research

This analysis demonstrates how to quantify embodied GHG emissions for Swiss residential buildings incorporating various scenarios and prospective sector developments, yet it has several limitations.

First, it presumes that the structure of upstream supply chains for construction materials will remain unchanged in future background databases. This is not likely in the future, especially given that the recent shock events (such as geopolitical conflicts like the Russia-Ukraine war or public health outbreaks like Covid-19) have dramatically shaped global supply chains and might have long-term implications [52,53], as well as the observed shift of production bases from China to south-east Asian countries due to increasing labor costs [54]. Therefore, different scenarios with potential future supply chain change and their influence on the results should be explored in the future.

Secondly, only one scenario for the consumption and end-of-life treatment of construction materials is applied in this analysis, which is acceptable given the similarity of material flows in available scenarios from Heeren et al. [24]. However, the assumption that wood-based constructions constitute 10% of new residential buildings in Switzerland is rather conservative for the next decades. This is evident when considering the data in 2021 shows that wood buildings have already contributed 12% to new constructions [48,49].

Thirdly, other factors such as the decarbonization of industrial heat, material-specific GHG emissions mitigation strategies other than the ones for cement and steel, the mass deployment of alternative materials (e.g. bio-based insulation materials) and alternative end-of-life treatment and disposal pathways (e.g. increased reuse and recycling) are overlooked in the scenarios. This limits the analysis to insights on the influence of future sector developments and modeling approaches (e.g. choice of RCPs and IAMs) considered in this study on the embodied GHG emissions for Swiss residential buildings, rather than covering a complete set of factors that will influence their embodied emissions in the future, or comparing different types of interventions. For example, scenarios with a higher recycling rate for certain materials can be compared with scenarios considering the mass deployment of compact building designs. Such quantitative cross-sector comparisons would be valuable for policymaking, considering the variety of mitigation strategies, the involvement of multiple stakeholders, and limited resources for achieving climate goals. In addition, considering other factors, such as the decarbonization of heat, might lead to a change in our understanding of the GHG emission contributions by materials at the building stock level in the future, as heat has a major contribution to the GHG emissions of some specific insulation materials [20].

Additionally, the analysis is also limited to the production and end-of-life treatment and disposal of construction materials, without considering the operational phase of buildings. Although the share of GHG emissions caused by materials' consumption and disposal will become increasingly essential in the future until 2050, its share might still be less than that of energy consumption during the operational phase of residential buildings [24], so including the operational phase is important for future research.

Finally, the origins of life cycle GHG emissions are visualized on a country-level geographical resolution globally. However, because some of the datasets are for a region rather than a country, future exploration

is needed to investigate visualizing and overlaying results with multiple geographical resolutions (i.e. visualizing LCIA results with both countries and regions, even when they intersect with each other), which reflects the actual LCI data applied.

6. Conclusions

This analysis has established future versions of the Swiss national construction materials LCA database, by incorporating different IAMs, scenarios, and future sector developments. The databases are then used in estimating the embodied GHG emissions for Swiss residential buildings from 2015 to 2055.

The results show that, by combining future sector developments in electricity, cement, and steel, a 25% annual reduction of GHG emissions could be achieved in 2055, mostly driven by the GHG emission reductions of concrete followed by brick, as a result of future considerations included in this study. Meanwhile, the increasing dominance of insulation materials can be observed in the total GHG emissions. This indicates that to reach the goal of net-zero GHG emissions in the construction and building sector, other measures such as changing construction practices by using fewer materials, encouraging higher recycling rates of materials, and the use of alternative construction materials have to be explored. The influence of future developments in the electricity and cement sectors is comparably important in driving GHG emission reductions, while the contribution from the future steel sector is insignificant. The choice of IAMs, scenarios and sector updates influence the total GHG emissions as well as the extent to which different sector developments contribute to GHG emission reductions. The resulting range of GHG emission reductions due to the application of different analytical or modeling choices should be taken into account in policy-making. In 2015, about one-third of total GHG emissions for material production and end-of-life treatment are domestic emissions. Outside of Switzerland, except Germany, the UK, and France, GHG emissions originated from China and Russia are higher than those of other European countries.

In terms of methodology, in order to migrate the background database needed for this analysis, fuzzy lookup is applied, which allows the automatic mapping of datasets based on their names, reference products, and locations. This is especially useful when migrating datasets from one database to another in cases where the names of the datasets are not exactly the same and the mapping has to be carried out manually. The analysis also develops a framework for developing future versions of national LCA databases for construction materials, which is valuable for long-term LCA of building stocks of any scale (e.g. district, city, national), considering future turnover of building stocks with consumptions and disposals of construction materials. In addition, the analysis demonstrates the extraction of relevant datasets and their upstream processes from a larger database, which is commonly needed for further development of any existing LCA project in Brightway2. The analysis also explores LCA result visualization by tracing the processes' geographical origins on a global map in Brightway2. It has proposed an approach that brings LCA results to the same geographical resolution by country, which provides a better understanding on the geographical origins of life cycle GHG emissions and can serve as a reference for sustainable procurement overseas.

Future research should explore the integration of other sector developments, such as heat, potential upstream supply chain transformations, and scenarios considering other construction practices and alternative materials. Including the operational phase and alternative ways of understanding the upstream GHG emissions of buildings geographically (e.g. by combining different geographical resolutions in accordance with the original geographical resolution of the LCI datasets) would support the formation of mitigation strategies in the building and construction sector from a life cycle perspective.

CRedit authorship contribution statement

Xiaojin Zhang: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Niko Heeren:** Data curation, Methodology, Writing – review & editing. **Christian Bauer:** Funding acquisition, Methodology, Writing – review & editing. **Peter Burgherr:** Funding acquisition, Methodology, Project administration, Writing – review & editing. **Russell McKenna:** Writing – review & editing. **Guillaume Habert:** Methodology, Supervision, 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

The sharable research data is on Mendeley Data under <https://doi.org/10.17632/ptby9525tj.2>

Research Data for "The impacts of future sectoral change on the greenhouse gas emissions of construction materials for Swiss residential buildings" (Original Data) (Mendeley Data)

Declaration of generative AI and AI-assisted technologies in the writing process

During the revision of this work, the corresponding author used GPT-4 in order to enhance the English and clarity of this manuscript. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Appendix A. Supplementary Information

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