



## Potential for biogenic carbon storage towards a net-zero built environment in Switzerland

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### ARTICLE INFO

Editor: Dr. Vinicius Picanco Rodrigues

#### Keywords:

GHG emissions  
Biogenic carbon storage  
Biobased materials  
Building Stock  
Carbon targets

### ABSTRACT

The built environment is a major contributor to global greenhouse gas (GHG) emissions, posing challenges for achieving net-zero targets by 2050. This study examines the potential of an increased use of biobased materials in the Swiss residential building stock to mitigate emissions while increasing biogenic carbon storage. Using a Python-based building stock model, the study evaluates the effectiveness of increasing the share of biobased materials in both renovations and new constructions under different scenarios compared to climate goals. Results indicate that renovations will become the dominant driver of building stock emissions and biogenic carbon storage potential by 2050. While new construction activities will decline due to demographic trends, renovations will contribute nearly four times more to GHG emissions than new buildings. Nevertheless, new constructions are more effective at storing biogenic carbon, achieving a biogenic-to-emissions ratio of 300 % by 2050, compared to 176 % for renovations. By mid-century, the yearly biogenic carbon storage in buildings could reach 2.5 Mt. CO<sub>2</sub>, approaching a balance with yearly GHG embodied emissions. However, even in the most optimistic scenario, increasing biobased material use alone reduces cumulative emissions by only 5–8 % compared to business as usual, underscoring the need for additional emission reduction strategies, including decarbonizing material production and reducing construction activities. The long-term analysis reveals that biogenic carbon storage potential is constrained by demolition rates (assuming full re-emission at the end of life), with a higher demolition rate accelerating carbon turnover and limiting storage capacity. A cumulative maximum biogenic carbon stock of 300–400 Mt. CO<sub>2</sub> is projected in the long-term, surpassing Switzerland's expected cumulative net emissions removals by 2050 by 6 times. This study highlights the built environment's potential as a long-term carbon reservoir and emphasizes the necessity of targeted renovation strategies, regulatory policies, and material production improvements to achieve climate goals effectively.

### 1. Introduction

The signing of the Paris Agreement in 2016 introduced two widely recognized climate goals: net-zero by mid-century and limit average global temperature to well below 2 °C and aim for 1.5 °C (United Nations / Framework Convention on Climate Change, 2015). Nearly a decade later, the sentiment for achieving these goals is not very positive. Achieving net-zero by mid-century is still in the political agenda of most signing parties but limiting global temperature to well below 2 °C starts

becoming a far to reach goal. In 2024, the 1.5 °C target has been exceeded for the first time, which doesn't yet mean that the goal is not attainable (World Meteorological Organization, 2024) but surely makes it ever more challenging (United Nations Environment Programme, 2023). As global temperature increase presents an almost linear relation to cumulative greenhouse gas (GHG) emissions in the atmosphere (Cline, 2020), the remaining carbon budgets are often used as quantifiable metrics to define maximum allowances of GHG emissions to stay within temperature limit targets (Alcaraz et al., 2019). Furthermore,

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<https://doi.org/10.1016/j.spc.2025.08.019>

Received 9 April 2025; Received in revised form 13 August 2025; Accepted 23 August 2025

Available online 25 August 2025

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more and more we come to the conclusion that negative emissions technologies (NET) and durable storage will have to play an important role in stabilizing global temperatures, not only to effectively achieve the net-zero balance but also to counteract probable overshoots (Shukla et al., 2022).

Switzerland is a signing party of the Paris Agreement and has therefore published a national climate strategy (Federal Council, 2021) and approved national laws enforcing sectoral reduction targets (Federal Act on Climate Protection Targets, Innovation and Strengthening Energy Security, 2025). In this setting, the Federal Office of Energy published a detailed pathway to reach net-zero in 2050 in its energy perspective 2050 (Swiss Federal Office of Energy, 2020). In line, with international agreements on emissions' accounting stemming from the Kyoto Protocol (United Nations Framework Convention on Climate Change, 1998), national emissions reporting includes only territorial based emissions and imports are excluded. The Swiss strategy does not directly account for a distributed global carbon budget but could be aligned with a “below 2 °C” target under certain effort-sharing assumptions (Priore et al., 2021). A 1.5 °C target seems, on the other hand, out of reach based on current national commitments. The strategy also relies on a relatively high deployment of NET within national borders and beyond (The Federal Council, 2022). The energy perspectives 2050 (Swiss Federal Office of Energy, 2020) include circa 70 Mt. CO<sub>2</sub> of NET cumulatively from around 2033 until 2050. Within Swiss borders, circa 75 % of these NET will rely on oxyfuel CO<sub>2</sub> capture from biomass facilities and cement clinker production, as well as post-combustion CO<sub>2</sub> capture from waste incineration plants. However, the availability of long-term storage sites within national borders remains a well-recognized constraint (The Federal Council, 2022).

The built environment is a known major contributor to global GHG emissions (Cabeza et al., 2022). Reduction targets are not easily set in this environment as multiple sectors and trade exchanges are involved making it difficult to assign a common target for buildings. Nevertheless, it is clear that current practices, in Switzerland, are not aligned with challenging climate goals (Priore et al., 2023) and urgent strategies need to be applied to reduce GHG emissions. An attempt to define specific targets for the Swiss built environment is presented in a previous study (Priore et al., 2023), with operational emissions dropping linearly to an absolute zero and embodied emissions following a non-linear curve to –67 % GHG emissions in 2050 compared to 2020. The remaining “hard to abate” emissions from the national industry are estimated to be covered by the NET national estimated deployment, thus complying with the net-zero goal.

## 2. Literature review

In the literature, different studies have estimated Swiss building stock material flows and associated emissions over time, aiming to highlight reduction potential and critical parameters. Heeren et al. (Heeren and Hellweg, 2018a) developed a bottom-up building stock model that integrated geo-referenced and three-dimensional data to track material stocks and flows in Swiss residential buildings. The main findings of the study highlight the role of construction materials in building's environmental impact and especially the expected increased usage of thermal insulation as well as the major structural changes that the stock will undergo (from a growth phase to a maintenance phase). The project Mat-CH (Gauch et al., 2016) modelled material and energy flows in Switzerland's construction sector to assess resource efficiency, environmental impacts, and hotspots for circular economy potential. The conclusions highlighted that while concrete and aggregates dominate material stocks, energy use contributes most to CO<sub>2</sub> emissions. A gap was identified in these studies, with none of the literature systematically comparing emissions to reduction targets in the sector nor discussing in detail the potential of storing biogenic carbon in the Swiss built environment.

At the building stock level, the treatment of biogenic carbon storage

remains poorly defined and largely untracked. While national LULUCF (Land Use, Land-Use Change and Forestry) inventories account for stock changes in harvested wood products (HWPs), they exclude imported materials and do not establish a direct link to the built environment. Consequently, the storage potential of national building stocks remains underexplored and is not integrated into climate planning or mitigation strategies. Recent work by Arehart et al. (Arehart et al., 2021) reviewed over 180 studies and identified a growing body of literature assessing carbon storage potential at the scale of building stocks. For example, Churkina et al. (Churkina et al., 2020) estimate that a global shift to mid-rise timber buildings could store up to 0.68 Gt C annually by 2050 (equivalent to nearly 6 % of current CO<sub>2</sub> emissions) and up to 20 Gt C cumulatively over three decades. The study highlights that such storage is particularly promising because it leverages construction that would happen regardless and replaces emissions-intensive materials. Region-specific studies also demonstrate the potential of bio-based materials in large-scale applications. Pittau et al. (Pittau et al., 2019) examined straw, hemp, and timber-based façade retrofits for the EU building stock using a dynamic life cycle assessment (LCA) over 200 years. Results showed that fast-growing materials like straw could sequester up to 100 Mt. CO<sub>2</sub> by 2050 due to their short regrowth cycles, whereas timber offered more limited short- to medium-term benefits due to slower forest regeneration. Across the literature, however, the effectiveness of biogenic storage strategies is consistently shown to depend on broader context. As Arehart et al. (Arehart et al., 2021) emphasize, increasing bio-based material use alone is insufficient for meaningful climate mitigation unless embedded within a rapid global decarbonization pathway. Storage currently offsets less than 6 % of fossil-fuel-related emissions, and substitution effects remain the primary benefit of timber use in buildings. Nonetheless, in scenarios with aggressive decarbonization, the share of stored carbon relative to remaining emissions would become increasingly significant.

Several methodological approaches are used in the literature to quantify biogenic carbon, each with different implications:

- Static LCA approaches apply fixed global warming potentials, typically over 100 years. They differ in how they treat biogenic carbon:
  - The 0/0 approach excludes both uptake and release.
  - The –1/+1 approach accounts for carbon sequestration at the beginning of life and re-emissions at end of life.
  - The –1/0 approach counts sequestration as a benefit but omits future release, potentially overstating net climate benefits.
- Dynamic LCA uses time-dependent carbon flows and impact metrics to capture the timing of both sequestration and re-emissions. This is particularly relevant for materials with short carbon cycles like straw and hemp. Studies show that early sequestration and delayed release can provide near-term climate benefits, though these are temporary unless emissions are permanently avoided (Cherubini et al., 2011; Levasseur et al., 2013).
- Material flow analysis (MFA) accounts for the quantity and permanence of carbon embedded in materials over time. When coupled with assumptions about material lifespan and end of life treatment, MFA provides a more systemic view of stock-level carbon dynamics.

The idea of buildings as carbon reservoirs, similar to forests, by storing carbon and reducing atmospheric CO<sub>2</sub> (Arehart et al., 2021) is an effective strategy if carbon inflow from biobased materials exceeds outflow from demolition and material replacement (Mishra et al., 2022). Maintaining a net-positive carbon balance in the built environment can help delay CO<sub>2</sub> emissions, mitigating temperature rise and climate tipping points (Matthews et al., 2023). This delay also provides more time to develop carbon capture technologies (Minx et al., 2017).

Nevertheless, the potential climate benefits of temporary storage of biogenic carbon are effective only if coupled with strong mitigation efforts and should only be framed as a complementary, transitional measure, not a substitute for fossil CO<sub>2</sub> emissions reductions.

Within the context and research gaps outlined, this paper explores the potential of an increased use of biobased materials in the Swiss residential building stock with regards to 2050 carbon targets and budgets and long-term storage of biogenic carbon. The study considers both structural (timber) and non-structural (straw, grass, hemp, wood fibre insulation as well as wood-based finishings) biobased materials. The following sub-questions are posed: how much can an increased use of biobased materials reduce GHG construction-related emissions until 2050, and is it enough to meet set carbon budgets for this timeframe? In the same lines, how much biogenic carbon could be stored in the Swiss stock following this strategy and for how long? And finally, which construction activities (new constructions, full energy renovations, and replacements along the life cycle) are expected to be the most effective at reducing GHG emissions and storing biogenic carbon?

### 3. Methods

#### 3.1. Residential building stock model

The building stock model developed in the frame of this work aims to assess GHG embodied emissions and biogenic CO<sub>2</sub> storage associated with residential construction activities in Switzerland until 2050 and specifically to evaluate the potential of an increased use of biobased materials in these activities. Construction activities are defined, in the frame of this work, as new constructions, complete energy renovations, and replacements of elements within the lifespan of the building. The scope of a complete energy renovation includes the increased performance of the thermal envelope by adding insulation and replacing windows to match the U-value limits reported in the Swiss standards, the update of technical systems (heating, ventilation, sanitary), and the replacement of external finishings. The model is built in a Python environment and operates with a set of initial input parameters, variable parameters, and predefined evolution algorithms and is available in the supplementary information S1. The model uses statistical data available in the Swiss context to ensure the robustness of the starting point (see Table 1) and the structural evolution of the stock is validated with other studies in the literature (Gauch et al., 2016; Heeren and Hellweg, 2018b). While the model was, in the frame of this work, calibrated for the Swiss context, its modular structure allows for adaptation to other geographic contexts by adjusting input parameters (see Table 1) as well as building level and building stock scenarios (see section 3.3.) to reflect local characteristics and policy directions.

##### 3.1.1. Structure

The model is structured using three interconnected levels. The first level defines the residential surfaces divided into typologies (multi-family houses and single-family houses) and periods of construction and is based on the Federal Register of Buildings and Dwellings (RegBL) (Federal Statistical Office, 2024a). The second level defines so-called archetypes for building components' dimensions per typology of building and period of construction based on (Pongelli et al., 2023). Lastly, material quantities per component are extracted from specific case studies of multi-family houses (MFH) and single-family house (SFH) for both renovations and new constructions. Yearly construction activities are modelled using rates of renovation and demolition of residential surfaces and a demand for new construction surfaces tied to the population growth and an average surface per inhabitant.

##### 3.1.2. Input data

Table 1 presents all the initial input parameters necessary for the model to define and characterize the initial stock and run the basic structural evolution of surfaces and construction activities over time.

**Table 1**

Input parameters used by the residential building stock model, initial input value used for the case of Switzerland, and associated reference.

Input	Input value (Switzerland)	Reference
Swiss population 2024	8,960,800	(Federal Statistical Office, 2024)
Swiss population 2050 and evolution over time	10,400,000 (non-linear evolution, with a strong decline of yearly growth after 2030)	(Swiss Federal Office of Energy, 2020)
Evolution of population beyond 2050	The rate of decline modelled until 2050 is continued until a stop in growth is reached at around 2080.	Hypotheses based on: (United Nations, Department of Economic and Social Affairs (Population Division), 2024)
Initial residential stock	479,664,812 m <sup>2</sup>	RegBL surface of dwellings (Federal Statistical Office, 2024a)
Subdivision of residential stock by typology (Multi-family/single-family) and period	Circa 30 % of surfaces: single-family 70 % of multi-family Period clusters: before 1919; –1945; –1960; –1970; –1980; –1990; –2000; –2010; –2024	(Federal Statistical Office, 2024a)
Initial renovation rate (total energy efficiency renovation)	1 %	(International Energy Agency, 2018)
Initial demolition rate	1 ‰	Demolition permits (Federal Statistical Office, 2024a)
Definition of archetypes composition	Archetypes per period of construction and typology and median size of components.	(Pongelli et al., 2023)

For each parameter the input data used for the case of Switzerland in the frame of this work and associated sources are reported. Additional information on the population growth, evolution of surfaces, and archetypes characterization is available in the supplementary information S1.1, S1.2, and S1.3 respectively.

##### 3.1.3. Evolution of the residential stock over time

The main timeframe of the study is from 2025 until 2050 as mid-century is the main timeline for most climate commitments. In this timeline, parameters evolve following predefined algorithms. The population growth is taken from the Federal Statistical Office reference scenario which assumes an increase in the permanent resident population up until 2050 to approximately 10.4 million people in a non-linear way (see Table 1 and supplementary information S1.1). The structural parameters in the model (renovation rate, demolition rate, and square meters per inhabitant) are defined as variable parameters over the timeframe to allow the testing of different evolution scenarios. This means that these parameters can evolve over time in a linear manner from the initial point reported in Table 1 to a goal value in 2050. The subdivision of the new residential stock by typology (MFH/SFH) is kept constant at the share reported in the input parameters in Table 1.

The renovation and demolition rates represent the proportion of building surfaces in the stock that will undergo a full energy renovation or a demolition, respectively. A life expectancy constraint is applied, allowing these actions only for buildings older than 30 years, representing half the amortization time suggested in SIA2032 Swiss standard (SIA, 2020). Furthermore, no bias was introduced towards a specific cluster, so demolitions and renovations are distributed across building age clusters solely in proportion to their share of surface in the stock. This means that the share of older building age clusters reduces over time but does not reach zero, reflecting the practice of keeping older buildings for their historical value or to maintain existing structures within dense urban areas.

The model is able to run beyond the timeframe of 2050, but parameters are not set to evolve further and remain constant within plausible constraints. The purpose of extending the model far into the future (i.e.: 2500) is solely to test the sensitivity and analyse the dynamics of carbon flows in relation to building stock parameters and to gain insights into factors influencing the potential for long term storage of biogenic CO<sub>2</sub>. It is not intended to represent potential future scenarios or predict the evolution of the building stock beyond 2050.

### 3.2. Carbon flows accounting

The model integrates the accounting of embodied GHG emissions and biogenic CO<sub>2</sub> flows and stocks associated with construction activities happening each year. Fossil emissions and biogenic flows are modelled at the time of the activity happening, thus the year a new building is built or renovated, fossil GHG emissions will be released for its construction (corresponding to phases A1 to A3 in the Life Cycle Assessment – LCA – framework outlined in (European Standard, 2011)) and biogenic CO<sub>2</sub> will be stored that year if present (indicated as a negative flow). The year a building is demolished, fossil GHG emissions for end of life are released (phase C in the LCA framework) and biogenic CO<sub>2</sub> will be released if present. Similarly, within the lifespan of existing buildings in the stock, replacements of elements (phase B4 in the LCA framework) are modelled at fixed intervals as in the SIA2032 Swiss guidelines (SIA, 2020). Replacements assume the disposal (end of life GHG emissions and release of biogenic CO<sub>2</sub> if present) of the existing element and the integration of a new element (construction GHG emissions and storage of biogenic CO<sub>2</sub> if present). The end of life of buildings or elements always assumes full reemission of biogenic carbon when present, and end of life scenarios that could further prolong the stock are not included in the model. Operational emissions (phase B6 in the LCA framework) are assumed to not be affected by the biobased scenarios (constant thermal transmittance performance) and are therefore excluded from this analysis.

GHG emissions and biogenic storage of construction materials are calculated with the Swiss database (KBOB) version 5 (KBOB, 2022). In the KBOB database, biogenic carbon content of materials is indicated in kg of carbon per functional unit, this content is converted into biogenic CO<sub>2</sub> content following the EN 16449:2014 standard. As the model evolves over time and is used to do a prospective scenario analysis of the Swiss building stock, estimation on future GHG emissions associated with materials' production and end of life are also integrated. The study from treeze (Alig et al., 2020) is used to this purpose to associate 2050 emissions' factors to the materials modelled (referred as “materials production improvements” in this article). A linear interpolation from 2025 to 2050 is included to assume a gradual reduction in supply processes. After 2050 no further improvements are modelled as it is assumed that a net-zero balance has been reached at national level.

Results are presented either as yearly flows (positive values represent emissions being released in the atmosphere and negative values represent the net biogenic CO<sub>2</sub> amount being stored that year) or as a cumulative progression of emissions and storage over the timeframe.

Finally, the ratio between biogenic CO<sub>2</sub> storage and embodied GHG emissions is calculated throughout the results to express the effectiveness of the strategy towards climate goals. Where a ratio of 100 % would indicate that an equal amount of GHG emissions and net biogenic CO<sub>2</sub> is being released and stored respectively thus resulting in a neutral state for the climate. A ratio above 100 % indicates that more biogenic CO<sub>2</sub> is being stored than GHG emissions being released thus having a positive impact on the climate. While a ratio below 100 % indicates that more GHG emissions are being released than biogenic CO<sub>2</sub> stored thus having a negative impact on the climate.

### 3.3. Scenarios

#### 3.3.1. Building level biobased scenarios (standard – middle – advanced)

Three scenarios are implemented at the building scale of the model to express three levels of biobased implementation in both new constructions and renovations of MFH and SFH calculated in a previous work (Priore et al., 2024). The standard scenario reflects current common practices with little to no biobased materials, the middle scenario assumes a middle level of biobased materials based on current common practices, while the advanced scenario stretches the amount of biobased materials implemented within the limits of what is possible to do in current practices. The three scenarios for each case study have been designed to maintain comparable thermal envelope transmittance properties (u-values of 0.1 W/m<sup>2</sup>K in new constructions and 0.17 W/m<sup>2</sup>K in renovations), thus assuming constant operational impact throughout the scenarios. Further material properties, such as thermal inertia or hygrothermal behaviours were not included in this study. Table 2 presents an overview of the life-cycle embodied GHG emissions and biogenic CO<sub>2</sub> storage of the three scenarios (standard, middle, advanced) applied to the four case studies (two renovations and two new constructions), a detailed overview is available in the supplementary information S2. The overview of Table 2 is meant to only give the reader a feeling of the building-level scenarios that are used in the model. Compared to other case studies using biobased materials in the literature (Galimshina et al., 2021; Ouellet-Plamondon et al., 2023; Petrović et al., 2023), the range of biogenic CO<sub>2</sub> content is confirmed to be high in the advanced scenario. The scenarios are based on specific case studies and do not aim to be the sole representatives of building practices in Switzerland but rather to support the explorative nature of this study and quantify the potential of biobased materials in construction practices.

#### 3.3.2. Building stock scenarios (Business as usual – Realistic – Optimistic)

The building level scenarios, described in section 3.3.1. are implemented in the building stock model as a share of yearly practices. The starting point assumes a 90 % share of standard scenario and a 10 % of middle scenario based on (Federal Office for the Environment FOEN, 2018). This means that 90 % of new constructions and renovations happening at year 0 are assumed to apply standard construction compositions and 10 % apply middle construction compositions. Details on

**Table 2**

Overview of greenhouse gas (GHG) embodied emissions and biogenic CO<sub>2</sub> storage of building scale scenarios used in the model to feed the composition of building components in the residential stock based on (Priore et al., 2024).

	GHG embodied emissions [kg CO <sub>2eq</sub> /m <sup>2</sup> .year]	Biogenic CO <sub>2</sub> content [kg CO <sub>2eq</sub> /m <sup>2</sup> .year]
Renovation SFH		
■ Standard	5.5	-0.3
■ Middle	5.3	-1.0
■ Advanced	4.3	-2.8
Renovation MFH		
■ Standard	5.9	-0.1
■ Middle	5.6	-0.7
■ Advanced	4.8	-1.0
New construction MFH low density		
■ Standard	13.9	-0.2
■ Middle	11.1	-5.4
■ Advanced	8.4	-7.5
New construction MFH medium density		
■ Standard	14	-0.2
■ Middle	12.8	-3.5
■ Advanced	10.3	-8.3

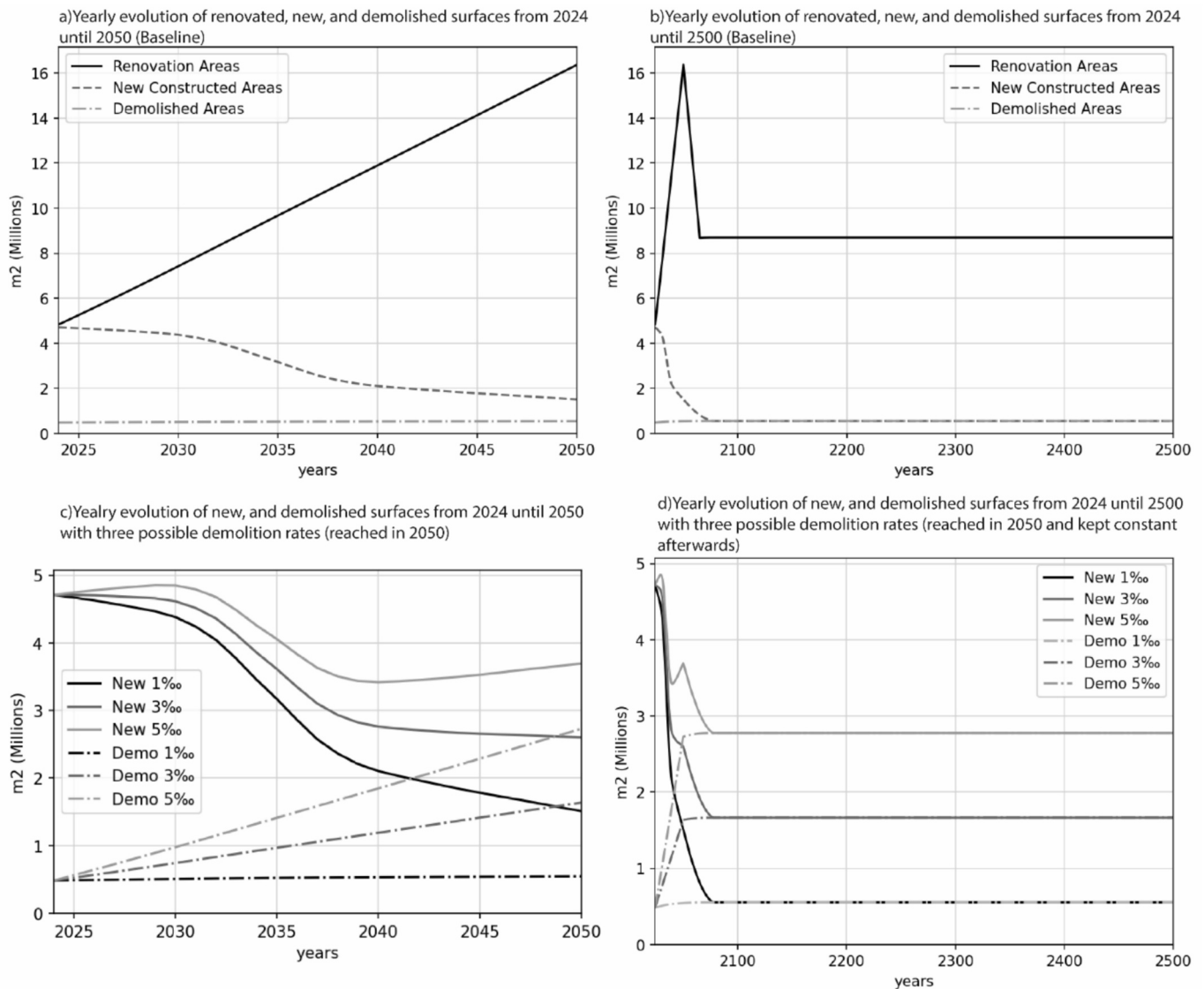
construction typologies can be found in the supplementary material S2.1. From there (starting point in the model), three scenarios of implementation are used in this work. The business as usual (BAU) keeps this share (90/10 %) constant throughout the analysis. The realistic scenario assumes that by 2050 practices will be shared equally between the three building level scenarios (1/3 standard, 1/3 middle, and 1/3 advanced). Finally, an optimistic scenario is modelled to fully showcase the potential of biobased materials with 100 % of advanced practices in 2050. In the realistic and optimistic scenarios, the shares of building level practices evolve linearly during the timeframe to reach the final target in 2050.

Construction activities are also following multiple scenarios in the frame of this work. A baseline scenario is defined to reflect commonly expected practices. This includes a 3 % renovation rate goal in 2050 (in line with Swiss and European commitments (European Commission, 2021; The Federal Council, 2016)), a constant demolition rate, and a constant surface per inhabitant throughout the timeframe as per input parameters in Table 1. To be able to depict a bigger range of the possible evolutions, two other scenarios are implemented reflecting an upper and

a lower bound of activity levels. The upper bound assumes an increase in demolition rate and surface per inhabitant, resulting in a higher volume of new constructions in the timeframe. The lower bound instead, assumes a constant rate of demolition and of renovation and a decrease in surface per inhabitant, resulting in a lower volume of both renovations and new constructions in the timeframe. These scenarios do not aim to fully represent a realistic future but rather to span a bright range of the possible futures to explore the potential of biobased practices within this range.

### 3.4. Carbon budgets and negative emissions technologies targets

Carbon budgets for the Swiss built environment are taken from (Priore et al., 2023). The budget was extracted from the national climate strategy (Swiss Federal Office of Energy, 2020) with a top-down allocation approach from sectoral pathways to construction of buildings including a share for imports. In the frame of this work only the embodied carbon budget is used as benchmark to evaluate the effectiveness of building stock scenarios to align with the national strategy.



**Fig. 1.** Building stock evolution in the model developed in the context of this work in terms of yearly surfaces (million square meters) of new constructions, renovations, and demolitions. a) baseline evolution in the 2024–2050 timeframe. b) baseline evolution in the 2024–2500 timeframe. c) Impact of variation of demolition (Demo) rate (1 ‰, 3 ‰, 5 ‰) on new constructions (New) and demolition surfaces in the 2024–2050 timeframe. d) Impact of variation of demolition rate (1 ‰, 3 ‰, 5 ‰) on new constructions and demolition surfaces in the 2024–2500 timeframe.

The embodied carbon budget is further subdivided into a budget for new constructions and a budget for renovations by accounting for their dynamic evolution over time.

Additionally, the NET deployment within Swiss borders (circa 50 Mt. CO<sub>2</sub>) outlined in (Swiss Federal Office of Energy, 2020) is used as a reference in this work to assess the relevance of biogenic carbon storage in the built environment.

#### 4. Results and discussion

Results are structured in three main sections. The first section presents the underlying evolution of the building stock in the model in terms of residential surfaces. The second section discusses the GHG embodied emissions and biogenic carbon storage until 2050 while the last section tests the sensitivity of biogenic storage over time.

##### 4.1. Building stock baseline evolution

In this first section, a brief overview of the evolution of construction activities in terms of residential surfaces (Fig. 1) is presented to better understand the underlying causes behind GHG embodied emissions and biogenic storage evolution described in the following sections. The principal timeframe of the model is 2025 until 2050 (Fig. 1 a and c). Within this timeframe, most parameters evolve in a gradual manner to reflect the gradual shift of construction related practices. Beyond 2050 (Fig. 1 b and d), building stock parameters are kept constant as assumptions are harder to predict and to avoid speculative assumptions.

The baseline scenario (Fig. 1 a) integrates a tripling in renovation rate by 2050 (i.e.: linear increase from current 1 % to 3 % in 2050 of the initial stock), a constant average surface per inhabitant, as well as a constant demolition rate (1 ‰) over the main timeframe. Average surface per inhabitant has been increasing in the past decades (Federal Statistical Office, 2023) but recent observations show a slowing down in this growth (The Swiss Parliament, 2023). The assumptions made here of a constant surface from now until 2050 is speculative but as with the renovation rate, the baseline scenario partially includes the commitments being discussed in the sector. Similarly, the assumption of an increasing rate of renovations is also speculative. According to a recent study (Jakob et al., 2024) and the latest report from the institution giving economic incentives for renovations (Federal Office of Energy, 2024), renovations are increasing in Switzerland in the last years. Nevertheless, often renovations are not carried out on the whole building but rather on specific elements or installations and varying replacement rates are reported. Clearly, the 3 % stock wise renovation rate is a challenging goal compared to current reported advancements, but the challenge is aligned with the ambitious national decarbonization targets. Moreover, the demolition rate applied proportionally to all building age clusters does not delve into the topic of service lives of buildings, resulting in the assumption of buildings remaining in service long after the proposed 60 year span proposed by Swiss standards (SIA, 2020). A study by Kornmann and Queisser (Kornmann and Queisser, 2012) already highlighted that 60 years might not be representative of the Swiss building stock, with service life of dwellings estimated to reach even 180 years. The 60-year span is therefore more of a methodological convention rather than direct reflection of practice. In the model developed in this work, the building stock gradually ages (i.e., share of older buildings increases) over time, partially also justifying the need to increase the renovation rate. Nevertheless, future studies could integrate more accurate probabilistic service life per age cluster and adapt the demolition rate accordingly to better account for this highly relevant parameter.

Beyond 2050 (Fig. 1 b), the renovation rate falls as most of the initial building stock has undergone a deep energy renovation and the rate stabilizes to circa 1.3 % of the total stock to keep up with renovation of buildings getting older. Since new constructions are closely linked to population growth, the evolution of this activity directly reflects

demographic trends and is expected to drastically slow down after 2030. Additionally, new constructions depend on the rate of demolition (Fig. 1 c and d), as this rate is increased new constructions increase proportionally to respond to the fixed demand for residential surface dictated by the resident population and the average surface per inhabitant. As seen in Fig. 1 d, around 2080 new constructions activity stabilizes as population growth stops and new buildings are needed only to replace demolished surfaces, hence the match with the two corresponding curves.

##### 4.2. Carbon flows until 2050

This section presents the carbon flows until 2050 and is further subdivided into two subsections. The first gives the overall picture of cumulative emissions and storage of the Swiss building stock. The second section delves into more details of the single activities contributing to this potential.

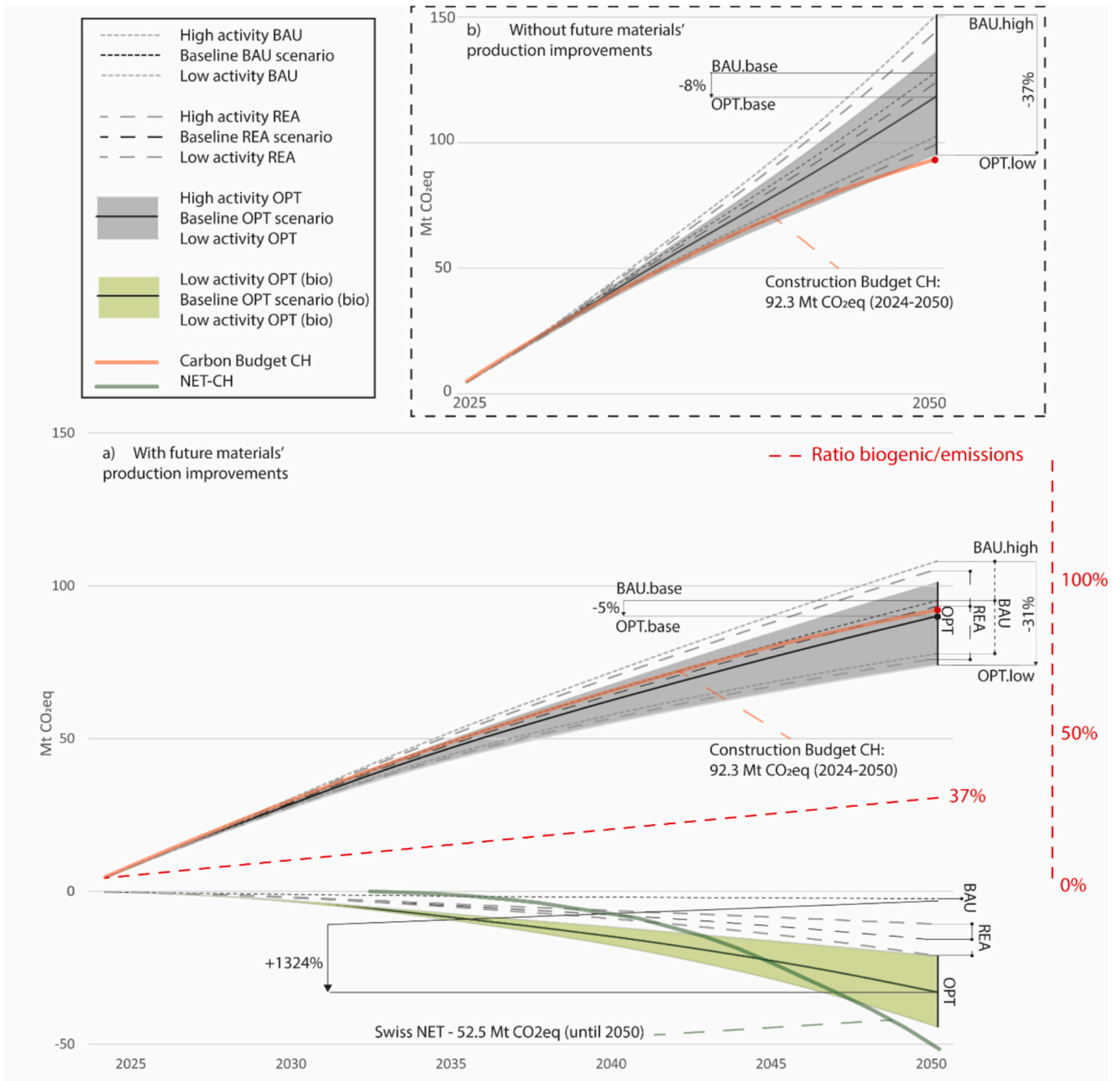
###### 4.2.1. Building stock cumulative emissions – impact of biobased scenarios

Fig. 2 displays the cumulative evolution of GHG embodied emissions and biogenic carbon storage of the Swiss housing stock over the timeframe 2025–2050 considering different scenarios of biobased material shares and construction activity levels. Fig. 2a reports the results including a linear reduction of GHG emissions tied to the production of building materials while Fig. 2b does not include this linear progression into the calculation. The first evident result based on these two scenarios is that if the industry of materials production is not improved in the timeframe, cumulative emissions will be circa 31 % higher by 2050 (baseline optimistic scenario) and no scenario would be able to respect the carbon budget (up to 63 % above the target).

The decarbonization of the industry does not affect the evolution of biogenic carbon storage as the quantity of materials and the share of biobased materials is not concerned by improvements in material production. The main conclusion from this result is that if the industry is not able to decarbonize as expected, drastic measures will have to be taken to limit construction activities and implement large amounts of low carbon materials to stay within carbon budgets.

Each baseline of biobased scenario (business as usual BAU, realistic REA, and optimistic OPT) is affected by assumptions in construction activities (renovation rate, amount and size of new constructions, and demolition rate). This uncertainty is represented in Fig. 2 by a high activity bound and a low activity bound deviating from the baseline. Important to notice is that high and low activity bounds have opposite effects towards GHG emissions and biogenic storage goals. High activity results in an increased level of GHG emissions (not desirable) but also of biogenic storage (desirable) while low activity can drastically reduce GHG emissions but will also reduce the potential of biogenic storage. Clearly, the uncertainty on the level of activity has the biggest impact on cumulative emissions in this timeframe with a total variability of 31 % by 2050 from a high activity BAU (BAU.high in Fig. 2a) and a low activity OPT (OPT.low in Fig. 2a). Also, all low activity bounds manage to keep cumulative emissions well below the carbon budget when improvements in the industry are included. The sole gradual increase in biobased shares in construction activities over the timeframe has relatively low impact on cumulative GHG emissions (–5 % from baseline BAU to baseline OPT, corresponding to 5 Mt. CO<sub>2eq</sub> saved over the studied timeframe) but a high impact on potential biogenic storage (+1381 % from baseline BAU to baseline OPT, circa 30 Mt. CO<sub>2</sub>). The potential reduction is slightly higher (–8 %) in the case of no improvements in the industry indicating that in a carbon-intensive context, material choices weight more. Nevertheless, the baseline OPT is the only baseline that falls just below the carbon budget thus still demonstrating the potential of biobased materials to meet carbon budgets.

The potential biogenic storage in the optimistic baseline scenario reaches circa 30 Mt. CO<sub>2</sub> which correspond to circa 63 % of the NET cumulative goal within the Swiss climate strategy. In the BAU the



**Fig. 2.** Cumulative embodied emissions and biogenic carbon storage of Swiss building stock from 2025 until 2050 following the three main baseline scenarios: BAU: Business as usual; REA: realistic; OPT: optimistic. Each baseline scenario is tied to a lower and upper bound of uncertainty related to different rates of activities in the construction and renovation of buildings. Ratio of biogenic to emissions is also presented. The main graph a) shows the evolution while considering improvements in emissions related to materials' production over time. b) shows the same evolution without considering any improvements in materials' production. NET = negative emissions technologies; CH=Swiss.

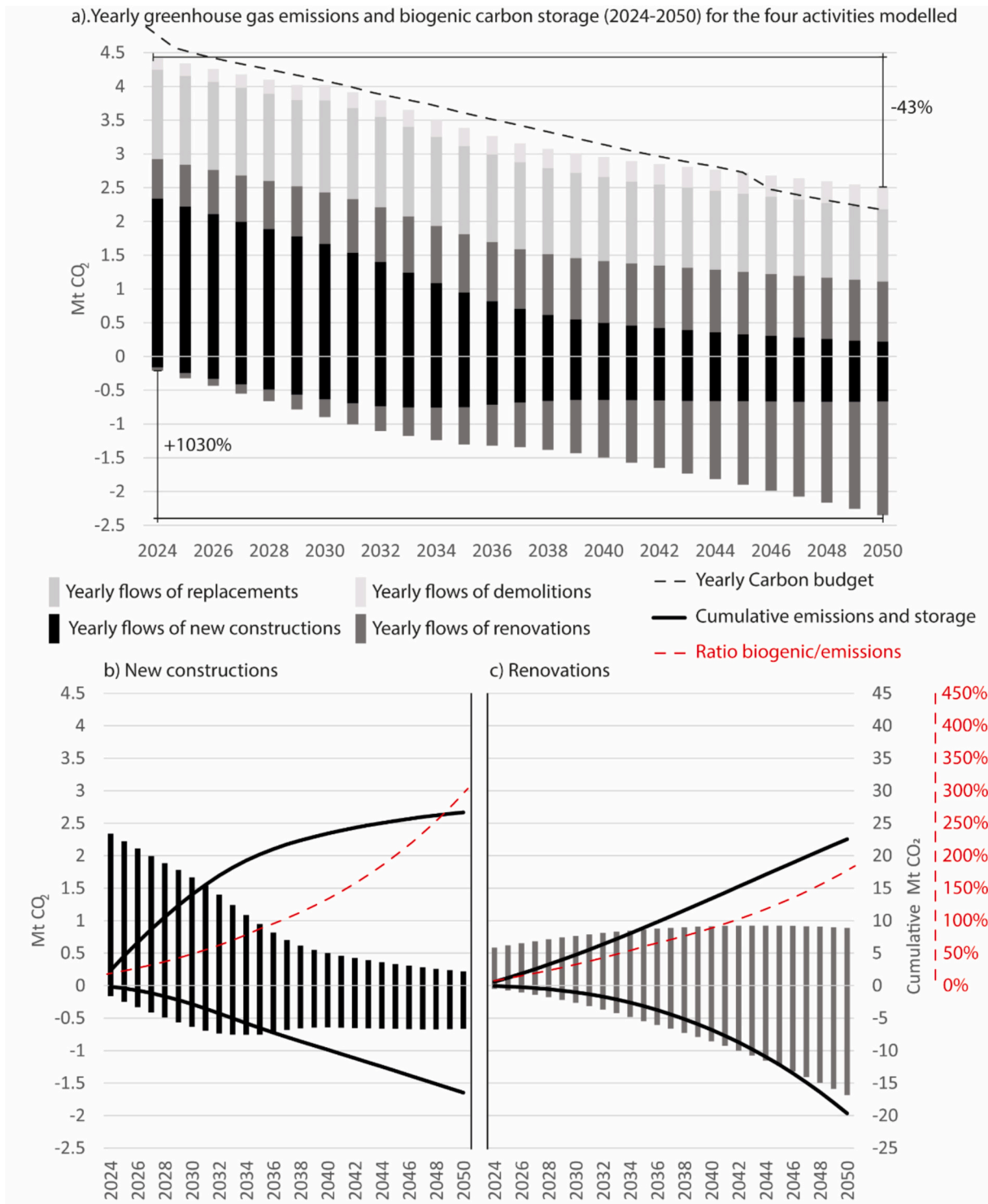
potential is effectively non-existent. The biogenic storage to emissions ratio increases linearly as more biobased materials are implemented and reaches 37 % in 2050 for the baseline OPT with future materials' improvements. This ratio is reduced to 28 % in 2050 in the case of no improvements in materials production.

**4.2.2. Impact of activities on building stock emissions and biogenic storage**

In the following section, the baseline optimistic scenario (including improvements in the industry) is analysed in further details to better understand the contribution of different activities to GHG emissions and biogenic storage along the studied timeframe. Fig. 3a shows the yearly

carbon flows (fossil embodied GHG emissions in positive flows and net-biogenic storage in negative flows) of all activities. As seen in the figure, overall building stock yearly emissions are reduced by 43 % in 2050 and yearly budgets derived from the Swiss climate strategy are met up until circa 2045. With a similar curve pattern, net biogenic storage is increased in the building stock by 1030 % in 2050 reaching an overall biogenic to emissions yearly ratio of 94 % in 2050.

Whiting these emissions, it is important to understand which activities contribute the most to the potential. The yearly shares of the 4 main activities included in the model (new constructions, renovations, demolitions, and replacements) are depicted in Fig. 3a. As clearly visible in



**Fig. 3.** Yearly greenhouse gas embodied emissions and biogenic carbon storage in the period 2024–2050 for a) the four activities modelled (the carbon budget derived from the Swiss climate strategy is used as benchmark in the figure) b) new constructions c) renovations. Cumulative sum and yearly ratio biogenic to emissions are included in b) and c).

the figure, replacements of building elements in the existing stock represent almost 50 % of embodied GHG emissions in 2050. It must be noted that this activity is hard to model at building stock level as no clear information is available to robustly say how many and which building elements are being replaced every year in Switzerland. Nevertheless, these results show that this activity should be studied further as its impact becomes increasingly relevant. Also evident from Fig. 3a is the drastic reduction of new construction contribution to GHG embodied

emissions. This reduction is mainly driven by the hypothesis on population evolution which dictates the need for housing and slightly affected by a stable low demolition rate in the baseline scenario.

Contrarily, emissions tied to renovations slightly increase even though the impact of materials decreases, mainly due to the hypothesis of an increased renovation rate until 2050. Finally, emissions tied to demolition activities remain quite low throughout the timeframe.

When comparing the two main activities (renovations Fig. 3c and

new construction Fig. 3b), significant differences become evident throughout the timeframe. Currently, new constructions are estimated to contribute to building stock GHG embodied emissions four times more than renovations. Though this disparity is expected to turn around completely by 2050 with renovations contributing circa four times more to GHG embodied emissions than new constructions. This finding is in contrast with current standards and regulations (e.g.: European energy performance of buildings directive) which hardly mention renovations in GHG emissions targets. Though, it is important to keep in mind that full energy renovations are mainly directed towards the goal of reducing

energy consumption which is not included in this analysis. The increase in renovation rate is necessary to achieve meaningful reductions in operational emissions but embodied emissions need to be constrained (Priore et al., 2022). It must be noted that, even though thermal transmittance properties of thermal envelopes were kept constant in the studied scenarios to ensure a certain level of operational comparability, other factors could influence operational emissions when switching materials. Thermal inertia and hygrothermal properties of the materials implemented can affect operational needs and comfort ranges, especially in future warmer climates and increasing cooling needs (de Serres-

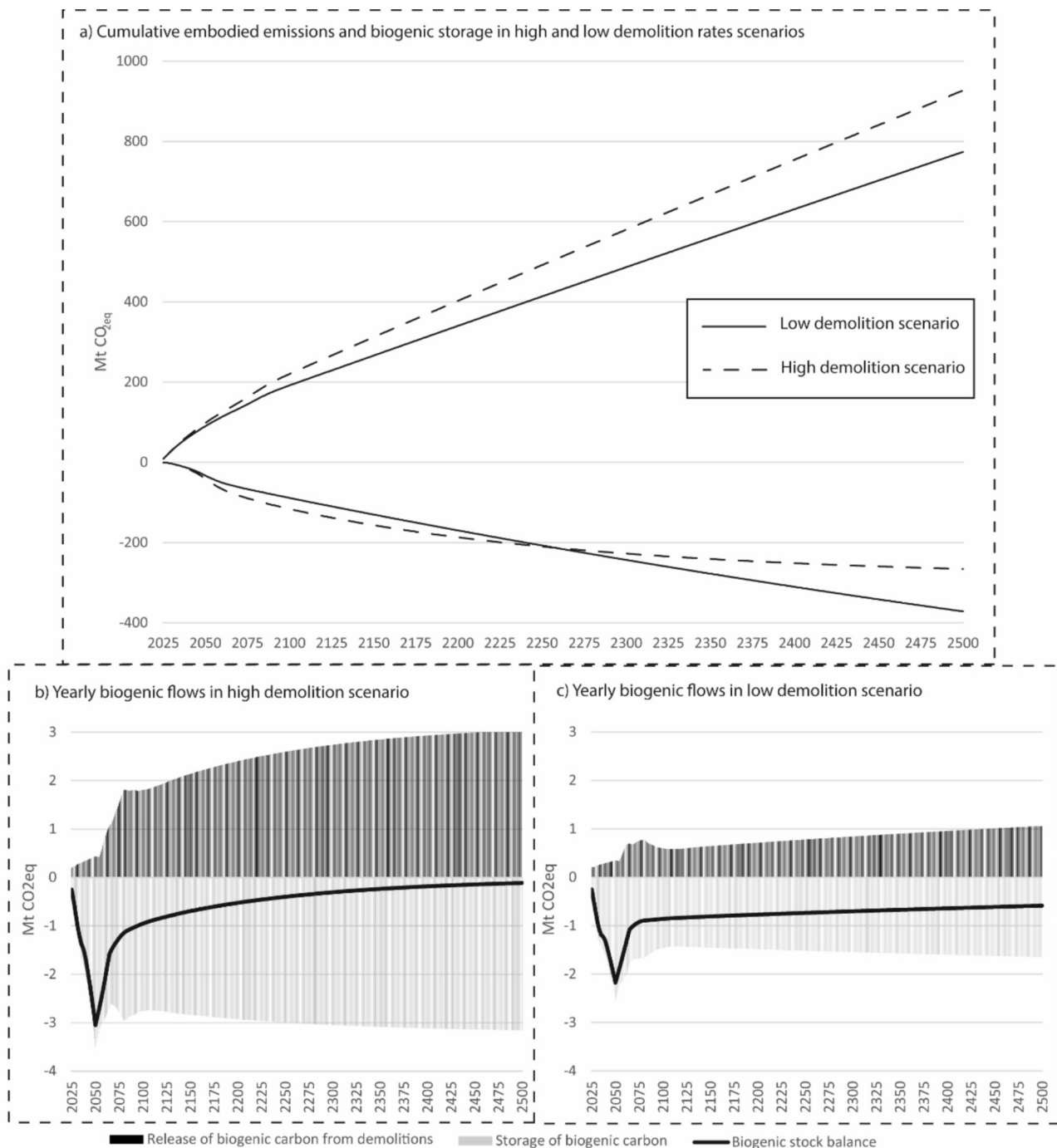


Fig. 4. a) Cumulative embodied emissions and biogenic carbon storage of Swiss building stock from 2025 until 2500 following two scenarios of demolition rates (low corresponds to a constant demolition rate of 1% of the stock and high corresponds to a linear increase to 5% in 2050 and constant from that point). The two graphs below present the corresponding yearly flows of biogenic carbon (release in the atmosphere during demolition, storage during construction and renovation, and net balance) for the high demolition scenario b) and the low demolition scenario c).

Lafontaine et al., 2024; Mnasri et al., 2020; Posani et al., 2024, 2023a, 2023b). Further studies should include the operational aspect of building stock activities to avoid transfers of impacts from one activity to another.

Similarly, in the short term, new constructions are expected to potentially store more carbon per year (with a peak around 2033 at almost double the biogenic storage in renovations in that year) but the trend is then reversed as the new construction activity is reduced (thus storing less biogenic carbon) but renovations keep increasing. In 2050 renovations could potentially store three times more biogenic carbon than new constructions. Nevertheless, results show that new constructions are more effective in terms of biogenic storage to emissions ratio reaching a 300 % ratio in 2050 while renovations reach a 176 % ratio. This to reinforce the fact that new constructions are more effective to store biogenic carbon compared to their emissions but this potential as well as their contribution to embodied GHG emissions are reduced at building stock level as the activity is decreased due to a lower demand compared to renovations. Along the time period, renovations are expected to surpass new constructions in terms of total embodied GHG emissions contribution at stock level around 2030, while the potential to store biogenic CO<sub>2</sub> will become more relevant in renovations around 2040.

Finally, it is worth noting that the potential to decrease emissions by increasing biobased materials in the optimistic scenario compared to BAU is higher when looking at the two main activities of renovations and new constructions than the one reported in the previous section. Renovations in the optimistic scenario reduce emissions by 11 % in 2050 compared to the BAU scenario. Even more, new constructions decrease by 24 % compared to the BAU scenario in 2050. And both activities could potentially stay below the calculated carbon budgets.

#### 4.3. Sensitivity of long-term biogenic storage

In Fig. 4a, cumulative GHG emissions and biogenic net-storage are represented for the period 2025–2500. The aim of prolonging the timeframe was only to better understand the inflow/outflow theoretical dynamics of biogenic carbon and their potential to ensure a storage benefit over a long time period. The yearly inflows of biogenic carbon (grey negative bars in Fig. 4 b and c) are driven by the construction activities of the building stock and specifically by the implementation of biobased materials in those activities. As the model assumes a gradual shift to biobased practices until 2050, a peak in biogenic carbon inflow is detected that year (100 % of activities use biobased practices).

After 2050, biogenic carbon inflows are reduced and further stabilized as the volume of construction activities is slowed down and stabilized (see stock evolution in section 3.1.3.). On the other hand, biogenic carbon yearly outflows (black positive bars in Fig. 4 b and c) are driven by the demolition of existing buildings and specifically by the amount of biobased materials in these demolitions. In this case, the amount of biogenic carbon coming out from the existing stock is very limited until circa 2050 as a low share of our current stock is composed of biobased materials. After that, biogenic carbon outflows start rapidly increasing following the increasing amount of biobased materials implemented in the period 2025–2050 and reaching replacement or demolition phases. The curve then tends towards a stable amount as demographics and activities stabilize in the model. The difference between inflows and outflows represents the net yearly storage of the building stock (black line in Fig. 4 b and c) with negative values indicating a positive storage (more carbon is being stored than what is being released), positive values indicating a negative storage (more carbon released than stored), and a null value indicating that same amount of carbon is released and stored.

The demolition rate used in the model is here the main parameter influencing this balance between inflows and outflows of biogenic carbon. Therefore, two demolition scenarios are represented in Fig. 4. High demolition assumes an increase of current demolition rate five folds

until 2050 and then stable at 5 ‰. In the low demolition scenario, the rate is kept fixed at current estimates of 1 ‰. These demolition rates, and their linear evolution do not account for any deeper analysis on the typology of buildings reaching their end of life and possible peaks or lows in yearly demolition patterns. The goal of this analysis is purely to understand the influence of such parameters on the potential long-term storage of biogenic CO<sub>2</sub>.

Clearly, in both scenarios the net-balance of yearly inflows and outflows tends towards zero as implemented biobased materials start matching demolished biobased materials. But, as seen in Fig. 4 b, this tendency towards zero is accelerated by an increased demolition rate. Nevertheless, even by prolonging the analysis over a long period (i.e., 2500) the net-balance remains negative highlighting the fact that biogenic carbon can be stored in the built environment durably for a long period of time.

In a cumulative perspective (Fig. 4 a), this net-balance of inflows and outflows of biogenic carbon results in a plateau of possible biogenic carbon stored in the built environment. This plateau reaches almost 300 Mt. CO<sub>2</sub> in 2500 in the high demolition scenario while it is projected to surpass 400 Mt. CO<sub>2</sub> after 2500 in the low demolition scenario. In the high demolition scenario, more biogenic carbon enters the system in the short-medium term as more biobased constructions are built to compensate for the high demolition, nevertheless as more biobased materials start being demolished compared to the low demolition scenario, this effect is reduced fast and in the long term the low demolition scenario is able to store more carbon overall. Furthermore, a high demolition scenario is tied to higher GHG embodied emissions as seen in the cumulative positive curve in Fig. 4 a. Highlighting that cumulative emissions will keep increasing over time as construction activities are not stopping and material's production remains tied to emissions.

This study was explorative of the overall potential of an increased use of biobased materials at stock level and limitations are recognized. The consequential impacts of an increased use of biobased materials in constructions to forest, agricultural, waste, or energy systems has not been explored and is relevant to assess the feasibility of supply but also to avoid burden shifts (Hansen et al., 2024; Maierhofer et al., 2024). As highlighted by Maierhofer et al. (Maierhofer et al., 2024), harvesting wood for construction creates an opportunity cost: carbon that could have remained stored in standing forests is instead transferred to the built environment and may eventually return to the atmosphere. The authors introduced the climate optimum concept, demonstrating that in some contexts, the unrealized forest carbon storage due to wood harvest can exceed the life cycle GHG substitution benefits of wooden buildings. These insights underline that climate benefits of increasing wood use are highly sensitive to forest management practices, local forest conditions, and climate risks. In the context of Switzerland, forests are sustainably managed and studies show a potential for future sustainable harvest for construction (Federal Office for the Environment FOEN, 2011), nevertheless, future work could extend the present model by explicitly incorporating forest carbon opportunity costs and scenario-dependent material sourcing assumptions.

Finally, dynamic methods including biomass rotation periods (Guest et al., 2013b, 2013a) were not included in the model but could enhance the discussion on climate benefits related to biogenic carbon storage.

## 5. Conclusions

This study identifies the significant potential of increasing biogenic carbon storage in the Swiss housing stock through expanded use of biobased materials. Key findings indicate that by 2050, annual biogenic carbon storage could reach approximately 2.5 Mt. CO<sub>2eq</sub>, nearly matching yearly emissions and moving towards a net-zero balance. However, effectiveness varies by building activity: new constructions demonstrate a higher biogenic-to-emissions ratio (300 %) compared to renovations (176 %), yet renovations will dominate overall due to declining rates of new construction.

The long-term potential for carbon storage in buildings is substantial, potentially surpassing 300 Mt. CO<sub>2</sub>eq, suggesting the built environment could serve as a large-scale carbon reservoir. Importantly, the rate of demolition significantly influences long-term storage capacity, with lower demolition rates allowing potential carbon storage to exceed 400 Mt. CO<sub>2</sub>eq in the long-term. Consequently, regulating demolition activities emerges as a critical policy measure.

Despite these benefits, increased use of biobased materials alone provides only a modest cumulative emissions reduction (5–8 %) compared to business-as-usual scenarios. Thus, biogenic carbon storage should be considered a complementary strategy rather than a standalone solution.

To effectively harness this potential, stakeholders should:

- Prioritize renovation activities for enhanced biogenic carbon storage and emissions reduction. Deep energy renovations at building stock are needed to ensure significant reductions in operational emissions and to support a sustainable demand for renewable energy at the national level. The increasing demand for renovations will likely make this activity the main driver of both annual emissions and potential biogenic carbon storage, as seen in Fig. 3. This trend highlights the need for timely policy interventions, such as setting limits on embodied emissions, providing incentives for the use of biobased insulation materials, and promoting the reuse of existing materials.
- Implement policies regulating demolition rates and end of life scenarios to maximize long-term carbon retention.

Future research should focus on optimizing embodied GHG emissions of renovation strategies, examining effective demolition management practices focused on biobased materials, and further study replacement rates and related impacts in the housing stock.

#### CRediT authorship contribution statement

**Yasmine Dominique Priore:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lucile Schulthess:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Sarah Delmenico:** Data curation. **Lionel Rinquet:** Writing – review & editing, Supervision, Resources, Conceptualization. **Guillaume Habert:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Thomas Jusselme:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

#### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI, ChatGPT in order to improve readability and language of parts of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

#### 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.

#### Acknowledgements

Financial support from the HES-SO University of Applied Sciences and Arts Western Switzerland (engineering and architecture domain) research program is gratefully acknowledged.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.08.019>.

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