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Exploring the gap between carbon-budget-compatible buildings and existing solutions – A Swiss case study

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ABSTRACT

Challenging climate goals demand immediate greenhouse gas emissions reductions for long-term temperature stabilization. Given the nearly linear relationship between warming and cumulative net emissions, the carbon budget approach is a useful tool to quantify remaining carbon allowances for countries, sectors, and even buildings. The built environment plays a crucial role in today's carbon emissions and future reduction potentials. Although much progress has been achieved towards energy efficient buildings, less attention has been given to the impact of materials put in place. Furthermore, the construction sector lacks of quantified reduction efforts and time horizon limits to clearly define a climate neutrality pathway. This article proposes a definition of yearly targets until 2050 for the operational and embodied carbon of buildings in line with a global 1.5 °C carbon budget and the Swiss climate strategy. The proposed targets are then compared with the impact of current practices and future technical developments. Gaps between targets and practices are quantified and discussed to better understand the upcoming challenges of the Swiss construction sector.

1. Introduction

Limiting global warming, and thus achieving long-term temperature stabilization, to well below 2 °C and pursuing efforts towards a 1.5 °C limit as defined by Article 2 of the Paris Agreement [1], is demanding unprecedented efforts, and immediate action to countries. Mitigating emissions is a principal goal, and although reaching a set goal of net-zero emissions by midcentury (Article 4 of the Paris Agreement) is essential to achieve the balance required for our environment, limiting cumulative emissions over time is a challenge that also needs to be addressed. As stated by the IPCC [2]: "limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since pre-industrial period, that is, staying within a total carbon budget". Global carbon budgets (GCBs) have been quantified in numerous works conducted by the IPCC [2–4]. GCBs are robustly defined at a global scale considering worldwide carbon flows and balances, but their distribution to lower territorial scales, such as countries, cities, and sectors involves a set of political boundaries, social and economic interactions, and climate justice questions that are not easily answered [5–7].

Switzerland is committed to the climate cause and abides to the international agreements on emissions reporting and reduction goals [8]. The Swiss climate strategy [9] sets a long-term net-zero goal by 2050 complying with Article 4 of the Paris agreement. In line with accounting rules (defined by the UNFCC), Switzerland reports only territorial, or production-based emissions. Therefore, the reduction pathway is set for emissions occurring inside national borders. Considering the global climate crisis, responsibility for the consumption-based footprint must also be considered by accounting for emissions on imported goods [10,11]. Furthermore, without denying the importance of achieving a balanced state by 2050, cumulative emissions over time will define the contribution to limit global temperature increase. Although Switzerland is active in the climate mitigation plan, a limited budget to limit global warming is yet to be defined, and the impact of imported goods has been hardly discussed.

Buildings and related construction activities contribute to 38 % of worldwide energy-related CO_2 emissions [12], and urgent reduction strategies in the sector are required. Although developments in the building sector have optimized the operational efficiency of new buildings, research shows that the embodied impact is yet to be mastered [13]. The operation of the existing building stock is responsible for 24 % of Swiss national emissions [14], mainly due to the high share of fossil-fuelled heating systems, accounting for circa 55 % of the installed capacity [15]. Even though renovation of existing build-

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ings is an overall compliant strategy to reduce operational emissions, recent studies have shown the importance of considering trade-offs in the life cycle analysis of such renovation works [16,17]. For example, adding layers of polystyrene insulation might not be justifiable for carbon accounting when the energy supply has been decarbonized. The impact of buildings is undeniable; much progress has been made to optimize the operation of new buildings, but the way to net-zero is still far from being solved.

The Swiss national climate strategy defines a linear reduction for the operational emissions of the building stock until 2050 without making specific statements so far about limited emissions for new or renovated buildings. At this level, they assume the stock of 2050 will emit zero carbon. On the other hand, embodied emissions are not directly mentioned in the national strategy. Emission reductions are expected in the industry sector, including materials production, but no link is made with building materials and even less with the impact of imported materials.

The overall climate goals seem to be clear, but a lack of practical coherence is evident especially in the Swiss construction sector. Currently, no normative framework and legally binding limits are in place to control and limit life cycle emissions of buildings. This leads to lack of knowledge regarding future specific sectoral goals as well as lack of understanding of our current ability to meet future climate goals. In this setting, first research questions are posed and addressed in this paper: How do we define specific building targets in line with overall climate goals? How do these targets look like compared to the current standards?

In every prospective analysis it is natural to assume that our way of doing will evolve in the next decades. Future predictions of energy supply and materials production are available in the literature, bringing us to our next questions: Are predicted technological improvements enough to meet our future targets? If not, what is the remaining gap, and do we know how to fill it?

In conclusion, the challenging climate goals ahead demand short term solutions, for long term effects, and all involved parties must do their part. The construction sector lacks specific and aligned targets and struggles to understand its way in these challenging times. This paper presents and quantifies the targets we should strive for and attempts to benchmark current and future developments of the Swiss construction sector, to finally quantify the knowledge and technical gap with our climate goals.

2. State of the art

In the literature, the overall topic of carbon targets and climate neutral buildings is being actively discussed but different results are presented depending on the methodology and definitions used [18–21]. This section presents the existing literature on using carbon budgets as a policy tool in the building sector, on existing recommendations and targets in Switzerland, and on predictions of future buildings' emissions. Finally, the frame of this article is described by highlighting the innovation and contribution of the work conducted.

2.1. Carbon budgets to guide climate policy in the construction sector

The allocation of remaining carbon budgets to nations and sectors is a widely discussed topic [5,22–27]. One of the main advantages of a budget perspective is the global nature of it; everybody has access to the same limited global budget of emissions. The same argument can turn into a major risk. As no methodology or agreement has been developed to distribute the GCB, countries and sectors can find themselves applying different allocation principles, resulting in contrasting goals. Remaining budgets range widely and the high level of uncertainties around it requires a transparent reporting of its calculation [27]. The focus of this article is on the distribution of limited budgets to buildings. The discussion on a fair distribution [25] of GCB to countries or sectors, acknowledging its high impact on the end results, is considered out of the scope of this contribution.

Allocation of global carbon budgets to building level targets is discussed in a few examples in the literature [20,23,28,29]. One approach is to divide the carbon budget allocated to the area of activity related with construction by the total gross floor area of existing and newly built dwellings in the reference period of time [30]. What is missing is the alignment of global budgets with the dynamic evolution of the building stock, in order to set targets that could be more feasible as they gradually decrease to be able to reach the final goal. Clear target values for emissions per square meter of building floor area are a practical necessity for all actors involved in the building sector [23].

2.2. Climate goals and carbon targets for buildings in Switzerland

Even though, as mentioned in the introduction, no legally binding carbon targets exist in the Swiss construction sector, few recommendations, labels, and studies can be found attempting the formulation of such targets. The SIA 2040 energy efficiency path [31] sets out targets for buildings divided by typology and separated into operation, construction and mobility targets. The proposed values are based on works conducted in the 1990s and are not aligned with current climate goals [32]. The 2000-watt society [33] proposed a vision of emissions reduction for Switzerland and aligned its construction targets with the SIA 2040. In 2021, the 2000-watt concept was updated [34] to increase the level of ambition of its reduction path in line with the national net-zero goal by 2050, but no specific building targets are mentioned. More specific to the building scale, the Minergie-standard[1] is a building label defining high energy efficiency standards (Minergie / -P / -A) by outlining requirements in heating demand, insulation, and other factors. The supplementary Minergie-ECO label proposes instead, among others, targets for the embodied emissions of the construction [35], but the connection with overall climate goals is not clear. The above-mentioned existing targets are usually applied in the framework of building or neighbourhood certifications but do not yet represent a common practice and the link with overall national and international climate goals is difficult to track.

A direct link with the national reduction pathway is found in the report published by NovaEnergie and carbontech [36], where the national mid-term goal of 50 % reduction in emissions by 2030 is applied to building level embodied goals. The definition of "climate positive building" refers, in this case, to a footprint reduction equal or higher than the nationally set goal (i.e.: −50 %). Even though such targets seem to be aligned with national goals, no deeper analysis of specific building dynamics have been conducted, leaving the proposed values disconnected from the market reality.

Finally, the concept of carbon budgets for the Swiss construction sector in line with global goals has been explored in an initial attempt [32]. This approach distributes the quantified global carbon budget to countries, sectors and specifically to square meters of building activities through different allocation principles accounting for social, economic, fairness and technical development parameters.

2.3. Assessing current practices and benchmarking future developments

To assess emissions of current practices, quantifiable studies of life cycle assessments of residential buildings in Switzerland are

[1] https://www.minergie.ch/fr/.

investigated. In John's work [37], 12 mainstream multi-family Swiss buildings were evaluated over their life cycle. The buildings studied represent standard to highly energy efficient buildings and span different construction techniques (massive, light, medium). These buildings represent in this study the so-called current practices.

Predictions on future developments are also taken from the literature. A study published by treeze Ltd. [38] presents the assessment of greenhouse gas emissions of future production of common Swiss construction materials (mineral and metal materials, wood, and plastics). The assessment of future life cycle inventories focuses mostly on a general switch to renewable energy sources, and substantial changes in production processes were also considered for a few materials. Results are presented in $kgCO_{2eq}/kg$ of material. The same study also shows the improvement of the future Swiss electricity mix and can be applied to the electric consumption of buildings in 2050. The future Swiss electricity mix is estimated in accordance to the Energy Perspectives 2050 [15] that envisions an increase in the share of renewable energies (mainly solar) and the gradual phase out of nuclear power plants as decided at the federal level.

Furthermore, in the ''Klimapositives Bauen" report [36], different construction measures and combined strategies have been evaluated and compared to a reference building to estimate the embodied reduction potential. The study presents a variety of design strategies, re-use of components as well as biogenic storage potential (reported separately) and the potential embodied impact improvement with reference to a base case study is quantified. Results of the above-mentioned study are discussed in this paper in contrast to the here assessed targets and results, but direct comparison of values could not be performed as detailed data was not available (i.e.: quantities of materials and buildings information).

Finally, broader studies on predictions of future building sector carbon emissions are also available [39–41]. At building stock level, predictions are usually done with material flow and scenario analysis [40] or with advanced statistical models [41]. These studies do not consider future technological innovations and more importantly they are not confronted with environmental targets. As mentioned by Röck et al. [39]: "...environmental benchmark data for EU buildings are lacking in terms of both existing building performance (baseline) and target values.".

2.4. Research objectives

Although a framework of recommended carbon targets exists in Switzerland, the goal in this article is to specifically align building activities to a 1.5 °C carbon budget accounting for the complexity of the sector dynamics (i.e.: imported materials, relative future capabilities to reduce emissions, and relative impact of different construction activities). The methodology of allocation of GCB to nation and sectors is presented step by step and hypotheses discussed. The fairness principles related to this allocation are not discussed in this paper. To address the high sensitivity of this allocation a second budget is considered by extracting the results from the official Swiss climate strategy. This second method reduces the uncertainty on the appropriateness of the allocation method as the strategy is already adopted at the political level. Furthermore, the direct extraction of building related targets from a national climate strategy has not been discussed in the literature. The definition of targets is then approached by combining limited construction activity budgets to yearly developments of the building stock (renovations and new constructions). This allows a dynamic tracking of the targets in relation to stock parameters.

Current practices are extracted from the literature and projected to 2050 with the future predicted impacts of materials and electricity to explore the gap with the defined targets. The aim of this article is therefore to explore the gap between common practices and target values today and in 2050.

3. Methodology

Considering the contribution and outputs of previous works, this paper brings further the concepts of carbon targets and assessment of future potentials following the methodology presented in this chapter. The first section defines the framework of the study by setting the boundaries of emissions accounting. The second section investigates the definition of remaining budgets at different scales and the corresponding pathways to net-zero. The third section defines the methodology to derive building carbon targets in line with a 1.5 °C limited carbon budget as well as with the Swiss climate strategy. The last section defines how current practices are, in terms of emissions, assessed and projected into future developments. Fig. 1 presents the methodological steps and the corresponding sections.

3.1. Framework of study

Current practices and limited targets in this work refer to both renovation works and new constructions. A life cycle approach is used to evaluate the environmental impact of buildings and to define targets. This approach considers in most cases emissions from the extraction of the construction materials until their disposal as well as replacement of components (embodied emissions) and energy consumed during the operation of the buildings (operational emissions) during their life cycle. In this work, only greenhouse gas emissions are assessed in $kgCO_{2eq}$, and for comparative purposes, emissions are reported per square meter of building and amortized per year of building life span, assumed to be 60 years, in line with current national recommendations [42]. The timeframe of the study is 2020 – 2050. For the scope of this work, two climate goals for defining targets for buildings are used. First, we used a top-down allocation of the global carbon budget for a 1.5 °C limit in global warming. Second, specific building targets are extracted from the official Swiss climate strategy. The building stock model assesses the evolution of surfaces from 2020 until 2050 by considering dynamic parameters such as an increasing renovation rate and an increasing population. The dynamic model can be accessed online (link in Supplementary Data) and parameters are detailed in the Supplementary Data section 4.

3.2. Definition of budgets

Remaining budgets are identified at national, sectoral, and construction activities in Switzerland from 2020. The definition of limited global budgets refers to the work conducted by the IPCC [4].

3.2.1. Budget for a 1.5 °C limit in global warming

A top-down allocation methodology is used to cascade the global 1.5 °C global carbon budget (GCB) [4] to lower territories or activities by implementing different allocation principles at each scale. The first scale refers to the national carbon budget. In this case, an equal-*per*-capita (EPC) distribution is applied, which distributes the GCB equally to the worldwide population, thus each country receives its population share of the budget [32]. At a lower scale, the national budget is allocated to the main national activity sectors, namely buildings, industry, transport, and others with a grandfathering approach. Current and future share of emissions are reported for each sector and a first budget repartition is calculated according to the cumulative share from 2020 until 2050. This step allows to consider the disparity in ability of the sectors in reducing emissions in the next three decades. A further step was performed

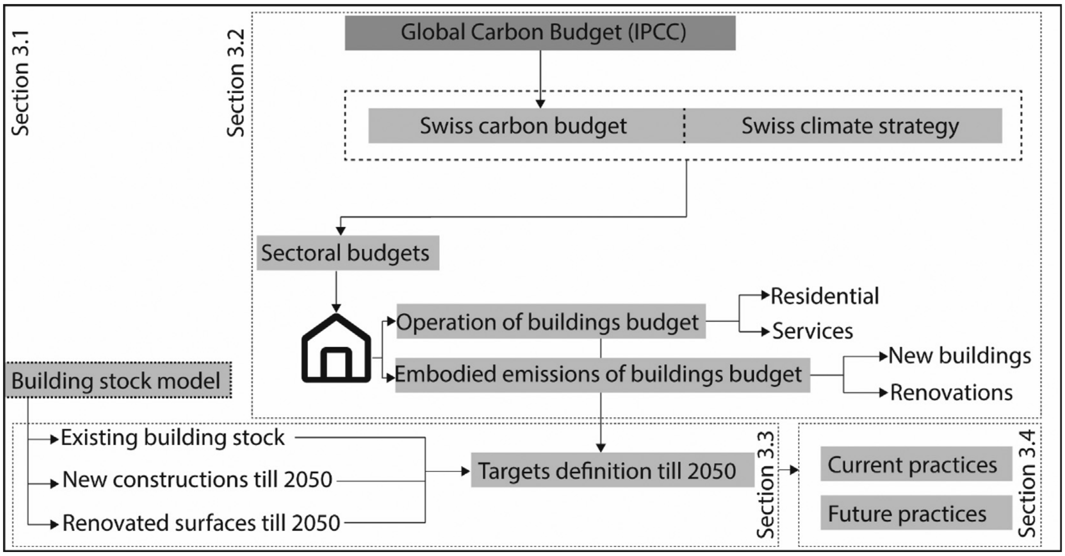


Fig. 1. Methodology of the contribution.

to include the estimated potential of negative emissions technologies (NET) [15] in the final sectoral budgets. Detailed calculation steps can be found in Supplementary Data sections 1a to 1d.

These steps defined sectoral budgets for the operation of buildings (i.e.: activity sector "buildings") and for the industry (responsible to produce construction materials among others). The industry sector was further decomposed to extract only construction related emissions and differentiate between construction of buildings and infrastructure. This procedure was possible with the National Inventory Report (NIR) [14] and a market report from cemsuisse [43]. The NIR reports detailed information on the contribution of specific branches of the industry sector towards final national GHG emissions; thus, construction related production of materials could be separated. Cemsuisse reports instead the market importance of buildings' construction versus infrastructure construction and this share was used as a hypothesis for respective share of emissions. Furthermore, since the national industry represents only locally produced materials, a 70 % percentage of imported emissions [44] was added to the embodied budget of buildings. This value is found in the study conducted by the Federal Office for the Environment where GHG impacts for residential construction are evaluated with a consumption perspective using an input–output (IO) analysis. Detailed calculation steps are presented in the Supplementary Data section 1e.

Resulting budgets are then distributed to corresponding building activities identified as surfaces of new constructions, renovations as well as existing buildings. Newly built surfaces are calculated according to the increase in population until 2050 and current average surfaces per capita. Yearly renovated surfaces are calculated with a current 1 % renovation rate [45] that gradually increases until 2050 fostering the operational emissions reduction needed in the existing building stock. Details on the estimation of surfaces are found in the Supplementary Data section 4. The construction budgets are distributed to the specific construction activities by considering the relative quantities of surfaces as well as relative current shares of impacts of the different activities. The operational budget is further differentiated between residential and other buildings. Detailed calculation steps are presented in the Supplementary Data section 1f.

3.2.2. Swiss climate strategy

Specific building targets can also be extracted from the Swiss climate strategy [15]. Although the strategy does not specifically attribute neither a limited carbon budget nor specific carbon targets for buildings [9,15], an interpolation is possible by cumulating emissions until 2050 following the defined linear reduction path and treating the resulting value as a limited budget. The same methodology discussed in the previous section can then be applied and budgets for each construction activity can be defined. Detailed calculation steps are presented in the Supplementary Data sections 1c to f.

3.2.3. National pathways to net-zero

The cumulative budgets for operation and embodied carbon of the Swiss stock are then transformed into national pathways to net-zero. Two scenarios are here analysed. The first takes the operational and the embodied budgets separately and defines a linear and non-linear reduction pathway for the operation and the embodied yearly impacts respectively. The linear pathway of the operational emissions follows the one defined by the Swiss climate strategy, but is dependent on the cumulative emissions defined by the chosen budget. The non-linearity of the embodied emissions accounts for the predicted non-ability of the industry sector to reach absolute zero emissions by 2050. The second scenario combines the operational and embodied budgets in one budget for the overall development of the stock. This allows one impact (ex: embodied) to compensate for the other (ex: operational) over the studied period. For this scenario, it is assumed that embodied targets could reach negative values while operational targets are assumed to reach absolute zero only in 2050. Negative net-values for the embodied impact of buildings are assumed to be possible as presented by Carcassi et al. [46]. The study presents the material GHG neutralization by using herbaceous biobased insulation materials to compensate for building elements that release GHGs. They show that timber- and bamboo-based construction with biobased insulation could reach net-negative values. This scenario was analysed to give an alternative scenario to the otherwise very challenging pathway for the operational impact. Detailed calculation steps are presented in the Supplementary Data section 2.

3.3. Definition of building targets

Finally, specific yearly construction activity budgets are transformed into yearly targets until 2050 for each activity. For this purpose, yearly budgets are divided by the expected surfaces for the activity. The results are yearly targets for each activity in $kgCO_{2eq}/m^2$. Embodied targets refer to newly and renovated surfaces each year. These surfaces are calculated through a previously developed building stock model [47]. The model can be accessed online (link in Supplementary Data) and the background assumptions for this study are mentioned in the Supplementary Data section 4. Embodied targets in this paper are directly derived from the industry's production of materials at national scale; thus, the impact of disposal at the end of life is not accounted in the same sectoral budget and should be reported in the waste management sector. Furthermore, end of life is assumed to happen outside the timeframe of this study and targets are, therefore, not accounted in the yearly construction targets until 2050. For comparative reasons with existing targets and standards life cycle assessment of buildings, the targets derived from the industry's budget are assumed to represent only 85 % of total life cycle emissions, in line with the report of Röck et al. [48]. The remaining 15 %, representing the end-of-life impact, is added to the target and final values are amortized over the 60 years life-cycle of the building to be comparable with other sources.

Operational targets refer instead to existing, new and renovated buildings. In order to fairly distribute the yearly budgets between these three typologies a weighting procedure is undertaken. The weighting considers the difference in size of the stock typologies (surfaces) and the difference in impact level. For example, the existing stock holds by far the biggest share of surfaces as well as the highest average impact per square meter; thus, this category of building is given a higher share of the budget every year. Details of this calculation are given in the supplementary data section 3.

3.4. Assessing current practices and future developments

To quantify a current gap with defined goals and targets in a 2050 timeframe, current practices must be assessed and projected to the future environment. The impacts of mainstream buildings found in the literature, mentioned in section 2.3., are adapted with own life cycle calculations using the KBOB inventory [49]. This adaptation is necessary to allow consistency with other examples as well as with future predictions. Impacts are reported for both embodied and operational impact in $kgCO_{2eq}/m^2$.year.

3.4.1. Projection into future impacts and solutions

Future trends are identified to be able to quantify the future remaining gap between practices and future goals and targets. Mainstream buildings are reevaluated accounting for known trends, taken from the literature, in materials production improvement as well as energy supply of 2050 [38]. The KBOB inventory used to assess current practices is replaced by a "future KBOB" with the impact values found in the literature and the life cycle assessment is performed again for the same buildings.

4. Results

This section presents the results of the steps described in the previous section divided into the definition of budgets for the building sector, quantification of targets for buildings, and mapping of current and future practices.

4.1. Building sector 1.5 °C carbon budget

Fig. 2 shows the remaining carbon budgets at national and sectoral scales directly derived from a GCB of 400 Gt. CO_2 from 2020, corresponding to a 67 % chance of limiting global warming to 1.5 °C. Switzerland receives a 0.11 % share of it, thus 447Mt. CO_2, corresponding to its share of population. The distribution of the Swiss budget to its four main activity sectors applies the grandfathering approach with future capabilities. The "others" sector includes agriculture and waste management processes and is assumed to have little potential to drastically reduce emissions until 2050. For this reason, the allocated budget is proportionally larger than the other activities. The final building sector is divided into "operational budget" and "embodied budget". The first refers directly to the "buildings" while the second comprises national materials production from "industry" activity sector, and imported materials, not accounted for in the national budget. The total budget for the sector amounts to 173 Mt. CO_2 to be spent from 2020 onwards. This budget is further distributed into new constructions and renovation activities for the embodied side and into residential and others for the operational side.

The limited budgets are transformed into pathways to net-zero as described in section 3.2.3 and in the Supplementary Data section 2. By considering the two budgets (embodied and operation) separately, the operation of the building stock will have to reach zero by 2035 (Fig. 3 (a)) in order to comply with a maximum budget of 88 Mt. CO_{2eq}. This drastic reduction corresponds to a yearly reduction rate of circa 6 %, such an important rate would require a rapid decarbonization of existing buildings far from the current 1 % renovation rate. If we instead consider the two budgets together and a more gradual rate (linear increase from 1 % to 5 % in 2050) of decarbonization of the existing stock (Fig. 3 (b)), the embodied part of the building activities would have to fulfill a compensating role (i.e.: carbon sequestration) in order to comply with the total 173 $MtCO_{2eq}$ budget. This approach clearly demonstrates, first, the important consequence that a limited 1.5 °C budget would have in the building sector demanding a decarbonization rate of the stock of more than 6 % every year and reaching zero more than a decade before the official commitment. Secondly, it shows the potential contribution that the construction industry should have, in order to limit global warming, by transforming itself into a carbon sink to compensate a slower and more probable decarbonization rate of the operation of the stock.

4.2. Building targets in line with climate goals

The definition of targets, as presented in the previous section, can be seen in Fig. 4 (embodied targets) and Fig. 6 (operational targets) for both a 1.5 °C GCB and the Swiss climate strategy. These are defined as maximum yearly values that can be reached in new and renovated projects in order to stay within the boundaries of the selected national budget. In this section, the operational and the embodied budgets are considered separately, and no compensating effect is expected by the embodied side at building stock level as mentioned in section 4.1.. Targets found in the existing labels and standards presented in section 2.2. are added as reference to position the proposed values in an existing framework in Fig. 5 and Fig. 6. Existing targets are represented as constant values until 2050 although updates could happen in the meantime. The most evident property of the proposed targets is the gradual reduction until 2050 allowing for a progressive implementation and adaptation also in line with other sectors' improvements. Considering a planning delay of three years, 2025 is used as reference for today's targets, meaning that when planning a building today (2022) the construction is assumed to finish in 2025 thus, targets of that year must be used. Operational emissions are recurrent yearly emissions (i.e.: once the building is built emissions occur every year), thus targets are reported as reduction pathways. Even though buildings today can aim for operational emissions up to 2.4 $kgCO_{2eq}/m^2$.year, this value must gradually decrease and reach zero in order to achieve the set goals. On the contrary, embodied emissions are mainly punctual (i.e.: upfront carbon for initial construction, maintenance or end of life) and targets are, in this case,

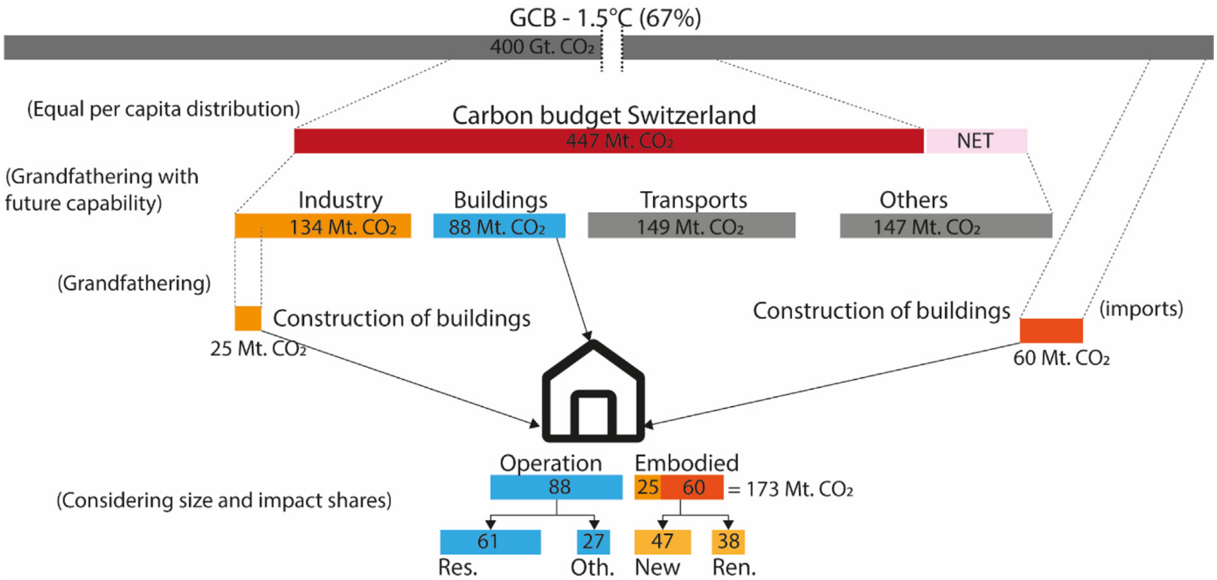


Fig. 2. 1.5 °C budget definition from global scale to national, sectoral, and construction activities of the Swiss building stock.

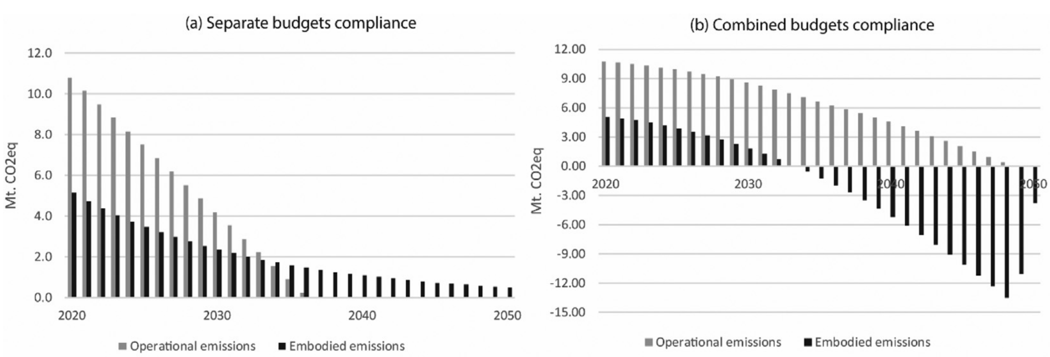


Fig. 3. Reduction pathways of national operational and embodied emissions in line with a 1.5 °C budget considering operational and embodied budgets separately (a) or combined (b) from 2020 until 2050.

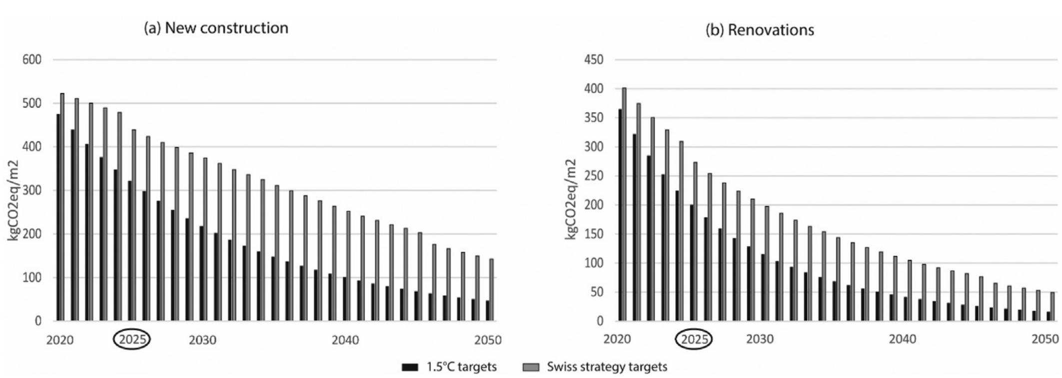


Fig. 4. Embodied upfront carbon targets for new constructions (a) and renovations (b) of residential buildings in Switzerland from 2020 until 2050 in line with both a 1.5 °C budget and the Swiss climate strategy.

yearly fixed values. Fig. 5 shows the total embodied life-cycle targets amortized over the life-cycle time in $kgCO_{2eq}/m^2$.year only to compare the targets with the existing standards. Targets for the construction and renovation of buildings at year of construction in $kgCO_{2eq}/m^2$ are listed in the Supplementary Data section 3 and presented in Fig. 4.

4.3. Practices and future potential

Fig. 7 maps current practices as well as future potentials in 2050 in contrast to the defined targets for new residential buildings in terms of embodied emissions. The 12 buildings assessed int the work of John [37] result in an average impact of 12.7 $kgCO_{2eq}/$

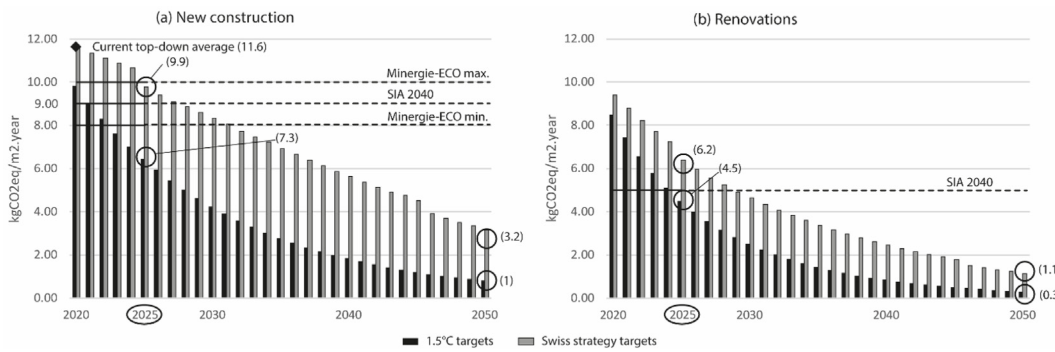


Fig. 5. Embodied carbon yearly targets for new constructions (a) and renovations (b) of residential buildings in Switzerland from 2020 until 2050 in line with both a 1.5 °C budget and the Swiss climate strategy. Values are compared with existing recommendations (SIA2040, Minergie-ECO (minimal and maximal values)).

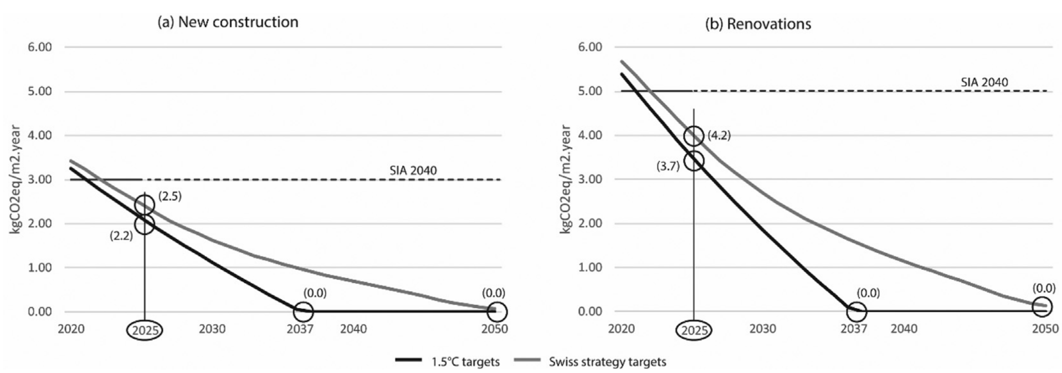
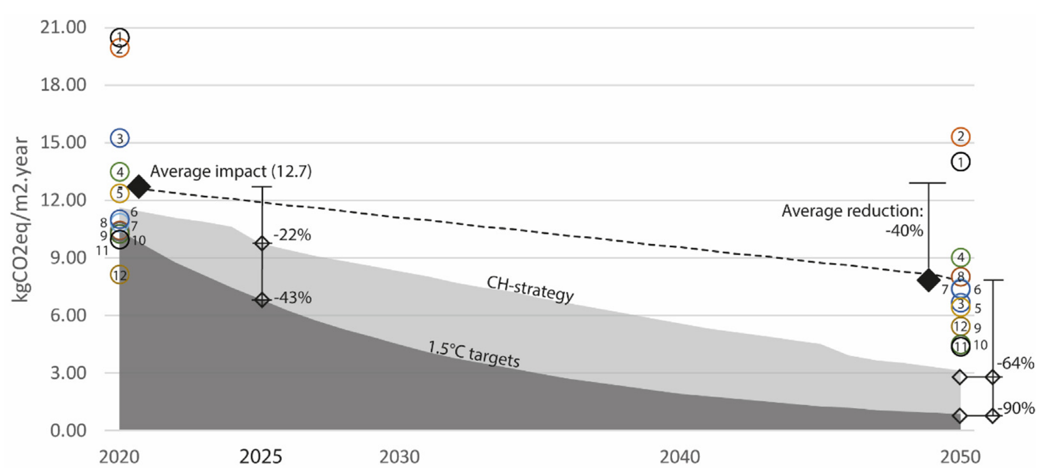


Fig. 6. Operational carbon targets for new constructions (a) and renovations (b) of residential buildings in Switzerland from 2020 until 2050 in line with both a 1.5 °C budget and the Swiss climate strategy. Values are compared with existing recommendations (SIA2040).



2020				2050			
①	20.45	⑦	10.84	①	14.00	⑦	7.42
②	19.91	⑧	10.42	②	15.29	⑧	8.00
③	15.23	⑨	10.38	③	6.64	⑨	5.40
④	13.47	⑩	10.23	④	8.99	⑩	4.46
⑤	12.35	⑪	9.95	⑤	6.43	⑪	4.34
⑥	11.02	⑫	8.10	⑥	7.36	⑫	5.41

Fig. 7. Embodied emissions of current practices and potential reduction with 2050 impact of materials production.

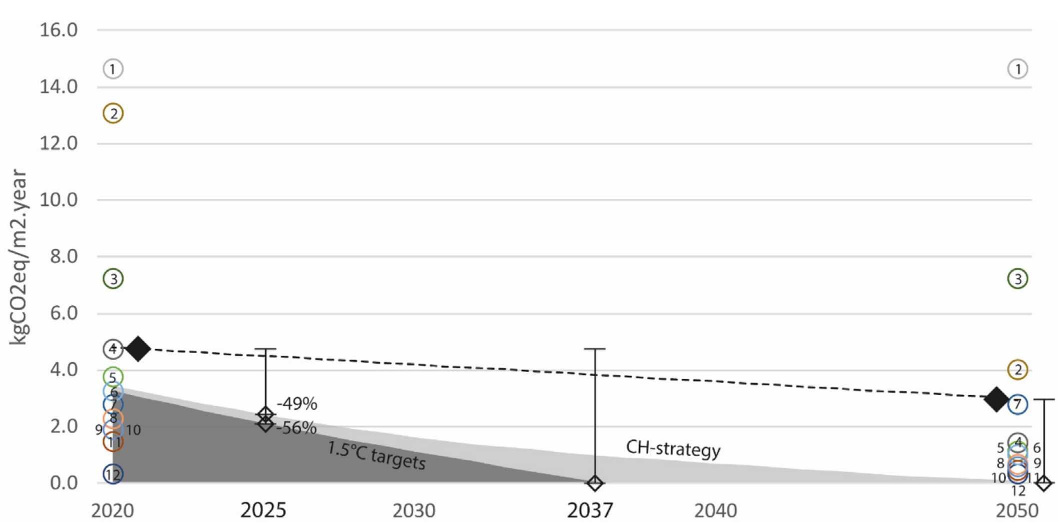
m^2.year in 2020 with a highest of 20.45 $kgCO_{2eq}/m^2$.year and a lowest of 8.10 $kgCO_{2eq}/m^2$.year. Considering the targets of 2025, the average impact must fall by 22 % and 43 % to align with the Swiss strategy and the 1.5 °C targets, respectively. By applying the predicted improvements in materials production in 2050, an average reduction of ca. 40 % is achieved for the 12 studied buildings, with a maximum of 15.29 $kgCO_{2eq}/m^2$.year, a minimum of 4.34 $kgCO_{2eq}/m^2$.year, and an average of 7.62 $kgCO_{2eq}/m^2$.year. This average should be reduced by 64 % and 90 % to align with the Swiss strategy and the 1.5 °C targets, respectively. It must be noted that the potential improvements in 2050 are here only based on technical improvements in materials production and no further strategy (i.e.: changing materials, sufficiency measures, compact design, etc…) is considered.

Fig. 8 represents current operational emissions of the 12 studied buildings as well as potential improvement achieved in 2050 with the impact reduction of the electricity mix. In 2020, an average of 4.80 $kgCO_{2eq}/m^2$.year is reported with a majority of systems dependent on electricity. Considering the targets of 2025, the average impact must fall by 49 % and 56 % to align with the Swiss strategy and the 1.5 °C targets, respectively. In 2050 an average reduction of 39 % is achieved by considering the improvement of the electricity mix. Values for natural gas heating supply remain unchanged in 2050, reinforcing the fact that fossil-fueled based energy supplies should not be an option today. In line with the proposed targets, the operational impact of buildings should fall to zero by 2037 or by 2050 for a 1.5 °C scenario or the Swiss strategy, respectively. As already mentioned, operational targets are presented as reduction pathways, meaning that a building built today with the 2025 targets must have a vision to reach zero during the time frame either by relying on the Swiss electricity mix impact decrease or by implementing local measures of carbon emissions reductions. Another possible use of the operational target is to consider a 20-year life span of the installation and use the average target over this timeframe.

5. Discussion

The proposed target definitions show that an important reduction effort in buildings is required in the next three decades and current standards (SIA2040, Minergie-ECO) need to follow the important reduction pathway. Currently, the timeframe for the update of such targets is long, up to circa 5 years, and not aligned with the challenges ahead. Furthermore, no regulatory framework exists to impose limits for the embodied impact of buildings, and the current business as usual is generally far from achieving any target if assessed. As no mandatory rule is in place to track the impact of buildings in Switzerland, having access to enough data to fully assess current practices is difficult. The few sources used in this paper only partially represent the current activities in the construction sector, but no further detailed data was easily accessible. The data needed to coherently assess and compare multiple buildings require a high level of detail (ex: quantities of materials) and a standardized methodology to conduct life cycle assessments. Even though results of impact assessments can be found in the literature, the methodology, the inventory, the system boundaries, and the time frame used are often unclear, making a direct comparison of studies difficult.

This article proposes targets for buildings and construction activities that gradually follow the reduction pathway imposed by either a limited global budget or the Swiss pathway to net-zero. As already mentioned in previous sections, the allocation of a global carbon budget to lower scales is subject to a variety of uncertainties. Firstly, a fair distribution to nations has not yet been defined and national budgets could result in very different values. Secondly, the allocation principle used in this paper to distribute the national budgets to sectors uses the cumulative share of emissions until 2050 proposed by the Swiss strategy. This share could vary and unpredicted changes in some sectors would affect the resulting budgets. Thirdly, the repartition to construction activities assumes a certain share of imported emissions. Variations in this share can highly affect the remaining embodied budget. Finally, distribution to activities (new buildings and renovations) is highly dependent on the future evolution of these activities. The amount of new constructions in relation to population growth is here assumed constant until 2050 (6 new dwellings per 1000 inhabitant with an average surface of 99 m^2). Both quantity of dwellings and size of new dwellings can vary, affecting the allocation of the budget. Though, the main factor affecting the distribution of the embodied budget is the share between new and renovations, dependent on the evolution of the renovation rate, as presented in Table 7 of the Supplementary Data. For all these reasons, the



2020				2050			
①	14.68	⑦	2.80	①	14.68	⑦	2.80
②	13.11	⑧	2.29	②	4.02	⑧	0.70
③	7.26	⑨	1.93	③	7.26	⑨	0.59
④	4.76	⑩	1.91	④	1.46	⑩	0.58
⑤	3.78	⑪	1.49	⑤	1.16	⑪	0.46
⑥	3.28	⑫	0.36	⑥	1.00	⑫	0.36

Fig. 8. Operational emissions of current practices and potential reduction with 2050 impact of electricity mix.

final targets rely on a certain number of background hypothesis that need to be considered when using them and more importantly they should be updated every year to be able to track the real evolution of emissions, surfaces, population, and technical improvements.

In contrast to the operational impact, the embodied impact is not expected to fall linearly to absolute zero because the industry sector will face technological obstacles to completely eradicate carbon emissions. Nevertheless, at national level, negative emissions technologies are predicted to compensate the remaining emissions. Instead, the operational targets for new and renovated buildings follow a linear pathway to absolute zero. The majority of operational emissions at national level is due to existing buildings, and its reduction is dependent on the renovation rate and especially on the rate at which the energy supply of these buildings is decarbonized. Staying within a limited 1.5 °C budget for the operation of the existing stock is a difficult challenge, reaching a yearly immediate rate of decarbonization of 6 %, and excess emissions will have to be compensated. Achieving a sink effect (i.e., negative embodied targets) of the building stock is a discussed topic. Although it is agreed that biobased materials sequester CO_2 during their growth and subsequently store it during their life time as building materials, deeper dynamics of forests or plantations ability to respond to the demand and still act as sinks need to be further investigated. Further negative emissions technologies could also play a role in the future such as BEECCS or DAC at production plants, but emissions must be controlled in the next three decades and existing strategies must be prioritized.

The role of the temporarily stored carbon in buildings is debated in Switzerland [36], and no official consensus on how it should be accounted for has been accepted. A very recent new version of the Swiss construction impact inventory (KBOB, 2022) has been published, and carbon content in kgC of materials is reported separately. Implementing biosourced materials can, firstly, reduce the GHG impact of buildings as they usually require less carbon-intensive processes to be manufactured and, secondly, delay biogenic carbon emissions by storing this carbon during the life time of the buildings. At the end of life, biogenic emissions might be released again in the atmosphere, depending on the end-of-life strategy of each material. This delay might be essential while waiting for further reductions or negative emission technologies.

The definition of budgets and targets is a useful tool both at building stock level and at building design scale. Budgets at national scale for the construction industry can drive the strategic planning and the required control of construction activities from a policy making perspective. A limited yearly budget imposes, at this level, not only a simple reduction of specific emissions but also a control in the renovation activities, the number of new constructions as well as the decarbonization of the energy sector. The budget perspective could be seen as an analogy to an economical budget; policies and incentives should be designed to respect the yearly budget available and if one sector is not performing well one year the others should compensate for it. At the building scale, specific targets per square meter of building can help to guide practitioners in the sustainable design. This could translate in less quantity, use of low carbon and implementation of biobased materials but also in reusing available stocks or in designing more compact buildings. An important aspect of the proposed definition of budgets is the changing targets over time. Both for policy makers and practitioners it is important to integrate the long planning timeframe of this industry. This timeframe requires to plan ahead and not with current values, the same way an architect is asked to think about the future use of the building, the environmental impact must be in line with the targets at the year it would be delivered. The reduction of emissions that our climate is requiring is a steep slope, no matter how you look at it, and what is ok today will not be in 5 years, consequently building design must also start following a pathway to net-zero.

An evident next step of this research will be to integrate a bottom-up approach to better assign budgets to more specific contributors (ex: heating, cooling, structure, finishing, etc.) and to assess the feasibility of these targets in the design and construction realities. A variety of different strategies can be applied at building scale to reduce emissions including, but not limited to, sufficiency measures (ex: reduced construction activities or reduced surfaces per capita or even reduced consumption of materials), implementation of low-carbon materials, reduction of materials production impact, renewable energies, and negative emissions technologies at different scales.

6. Conclusions

In this work, a top-down methodology was used to define building carbon targets in line with global and national climate goals considering limited cumulative emissions over time, imported goods, potential of negative emissions technologies, and future developments of building stock. The targets are quantified and presented in this work as yearly values in $kgCO_{2eq}/m^2$ of embodied and operational emissions until 2050 for new and renovated buildings.

In a second step current practices as well as future impact reductions of materials and energy supply are identified in the literature and their current impact or potential of reduction was assessed and mapped against the targets. Results show that an important gap exists today and remains in 2050. This gap cannot be filled by only relying on the future improvement of materials and electricity production. Furthermore, the potential of storing carbon in the materials put in place in our building stock is much needed to face the urgent short-term need to reduce CO_2 from the atmosphere and thus limit global warming in the medium term.

This work sets out a quantified and aligned pathway for building activities. An urgent need exists for practitioners in the construction industry to better understand the implications of the climate crisis in their professions. This need must be matched by policy makers to impose the reduction limits and the methodological framework to achieve it. Finally, the gap presented creates a clear picture of the current state of building emissions and the effort needed towards climate neutrality.

CRediT authorship contribution statement

Y.D. Priore: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **G. Habert:** Conceptualization, Supervision, Validation. Writing – review & editing. **T. Jusselme:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

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