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Embodied net-zero compatible buildings? They already exist!

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Embodied net-zero compatible buildings? They already exist!

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Abstract. This paper identifies buildings on pathway to meet carbon targets for embodied emissions aligned with global carbon budgets and mitigation pathways. A simplified bottom-up model is used, assessing multiple variations of a new construction archetype to identify the main strategies to achieve the targets. The model estimates the quantities of the main components with a few input geometry parameters. Life cycle emissions are then computed based on predefined building components. The reference building is representative of a typical new construction with standard operational values and massive construction. Strategies evaluate design optimization measures, construction techniques, and materials variations. Results show that (1) characteristics and volume of the building play a determining role. The existence and size of underground floors can determine the achievement of todays and future targets. (2) Construction choices can half emissions just by switching from concrete to wood and using natural insulation. (3) Future improvements in the supply chain of materials do not follow the required reduction pathway determined by the Swiss climate strategy. Net-zero compatible buildings are already possible, it is just a matter of making the right choices.

1. Introduction

As clearly stated in the last report of the IPCC [1], the climate is changing at an unprecedented rate and is already affecting societies in multiple ways. Efforts to reduce emissions and limit further global warming need to be strengthened and urgent actions are required to rapidly transition to a climate resilient development. The built environment is central to the climate question. The operation and the construction of our buildings account for about 40% of the annual anthropogenic greenhouse gases (GHG) emissions [2]. Moreover, buildings need to accommodate rapid urbanization while also providing increasing levels of comfort. Most studies and improvements in the building sector have focused on reducing operational emissions by evaluating the potential of energy-efficient or passive buildings [3]. Although an important decrease of GHG in the operation of new dwellings can be observed, no trends of reduction are found for the embodied impact of buildings [4]. Multiple life cycle analysis of buildings can be found in the literature [5,6] but the urgency and exceptional situation humanity is currently in urges us to reconsider commonly accepted conclusions. Existing and new buildings need to be energy efficient today and in 100 years while also drastically reducing their embodied impact and possibly contributing to delaying emissions in the atmosphere by acting as a carbon stock. The definition of a “climate neutral” or “net-zero” building is often unclear and confusing [7]. This work focuses on designing buildings that follow the decarbonization pathway and meet specific yearly carbon targets for embodied emissions aligned with global carbon budgets to reduce the release of GHGs emissions in the atmosphere and thus limit global warming. A recent study [8] defined operational and embodied targets until 2050 for new constructions and renovations in Switzerland to align with carbon budgets and thus limit global warming to 2°C or better 1.5°C as defined by the Paris Agreement [9]. Results showed that drastic improvements are needed compared to current practices and the sector needs to urgently reconsider the way we build and renovate. What is clear is that emissions both for embodied and operational must decrease progressively and drastically from now until 2050. Due to the unique nature of each building, the construction industry is characterized by its diversity. As a result, there already exist numerous examples of buildings with lower carbon footprints, and a variety of strategies, both conceptual and technical, are available to mitigate the environmental impact of construction activities. The aim of this study is to demonstrate that already available strategies can bring buildings on pathway to net-zero. The following research question is therefore formulated: are the existing solutions enough to reach the net-zero embodied targets? The strategies are chosen based on common recommendations without, in this study, assessing their generalization to the whole building stock nor the overall availability of materials.

2. Methodology

This study employs a simplified model of a building archetype to determine whether net-zero buildings are currently possible. The main components of the archetype are quantified, construction techniques assigned to it, and the environmental impact is calculated to evaluate various strategies and compare them with net-zero targets.

2.1. Simplified building model – quantities and environmental impacts

To evaluate the environmental impact of the building in exam, the model operates in two main steps. Firstly, using five main geometry inputs (number of floors above and below ground, energy reference area, envelope factor, and window-to-wall ratio), it establishes the bill of quantities of the building by determining the quantities of construction elements in accordance with the SIA2032 classification. Various assumptions and calculation rules are used to obtain a complete but simplified bill of quantities, such as assuming that all floors have the same area, a fixed floor height of 3m, and fixed ratios for the quantity of internal walls and balconies. In the second step, predefined construction details are assigned to each construction element of the bill of quantity.

The construction elements in the model are defined per functional unit of the element in question (ex.: surface of internal walls in m^2). The different materials are listed in layers and the specific quantities calculated per functional unit. The dimensioning and choice of the components comes from data available in the Swiss standards (SIA 2032) and has been validated with practical examples and practitioners. The environmental impacts are then calculated per component and further scaled up with the bill of quantities to the building scale.

The environmental impact of the components and of the building is calculated according to the SIA 2032 (phases A1 to A3, B4 and C1 to C4). Construction phase (A4 and A5) is neglected. In the use stage (B) only B4 (replacements) are accounted for. The operational phase (B6) is assumed to remain constant and therefore not included in the calculations. Impact assessment method is IPCC 2013 and climate change is the impact category chosen with GWP100 as indicator and kgCO2eq as unit. Impact factors for production and end-of-life of construction materials are taken from the KBOB 2009/1: 2022 database [10]. The carbon storage content of materials in kgC is also extracted from the KBOB and transformed into carbon dioxide sequestered according to the SIA265.576. The time frame for the assessment is 60 years and replacements periods are taken from the annex C of the SIA standard 2032.

2.2. Strategies applied to the reference buildings

The strategies applied to the reference building are based on the recommendations found in the annex B of the SIA 2032, the Minergie EN-101b simplified tool, and the technical reports published by the conference of cantonal directors of energy (EnDK) and are clustered in three main groups:

- Design options: densification, compactness/volume, lower window-to-wall ratio, reduction of underground floors, reduced balconies, simple load-bearing concept, and flexibility of use;

- Material and construction method choices: Type of construction (massive vs light), low embodied materials for same function, low carbon materials for internal walls, light insulation materials, reduced technical installations;
- Future supply chain: estimated reductions in materials' production impacts.

Further strategies are mentioned in the literature but not included in this work. Simple structural load concepts and thickness of elements can highly vary the embodied impact, but this research compares variations of structurally comparable archetype, and no further improvements were analyzed. Reuse of resources, reusability of components/materials, and increased lifetime can play a crucial role in the impact of the building but is considered out of scope of this work. Shorter transport distances of materials is also an impact factor but is excluded from the life-cycle assessment in this contribution. Finally, the variations of the reference building are kept comparable in terms of structural loads and energetic performance, thus adjusting thicknesses of materials if needed.

2.3. Comparison with targets

The main objective of this research is to identify buildings that comply with embodied targets to reach net-zero. To this purpose the targets presented in a recent study [8] are used. The study defines targets for new constructions in Switzerland in line with a limited 1.5°C budget or the Swiss climate strategy (corresponding to a budget for ca. 1.8°C increase in temperature) until 2050. Life-cycle embodied targets for 2025, 2030, 2040, and 2050 are extracted from the previous study and presented in $kgCO_{2eq}/m^2$.year. The target of 2025 is used for today's design as it is considered that the design process takes at least 2 years before beginning of construction. Targets follow a descending pathway to reach net-zero and comply with a cumulative budget until 2050. This means that, in the frame of this work, a building built today has a larger budget than the same building built in 2050.

3. Reference archetype and specific strategies

A base, or reference, geometry is used to define the initial archetype to which improvements' strategies are applied to. This base case is taken from a study from Pongelli et al. [11] that identified archetypes of the Swiss building stock by construction year and typology from the Swiss cantonal energy certificate of buildings (CECB) database. As this paper refers to a new construction, the most recent archetype (2011-2019) of a multi-family house is taken. The geometry is a straightforward rectangle defined by the following characteristics: 4 above-ground floors, an Energy reference area (ERA): 1 456m^2, an envelope factor of 1.5, a window to wall ratio of 30%, a Photovoltaic installation of 15kWp, a heavy construction type (representing the level of thermal inertia according to the SIA380-1), and a heat pump installation. Furthermore, two underground floors directly in line with the building are added to the archetype. This corresponds to ca. 0.9 parking slots per inhabitant by considering an average surface per inhabitant of 50m^2 and 28m^2 of parking surface. The construction elements for the base archetype are based on a standard concrete massive construction (heavy construction type) and the detailed quantities are taken from the elements proposed by the SIA 2032, annex D. The whole structure is in concrete elements (20 to 30cm depending on the element), EPS insulation is used with thicknesses that comply with standard regulations, non-load-bearing walls are made of 15cm bricks, and a 70%/30% proportion is used for floor finishing in parquet/ceramics.

3.1. Strategies applied to the reference archetype

The strategies identified in section 2.2 are quantified and applied to the reference archetype as presented in **Table 1**. The variations to the reference are presented in a specific order (number in table) for readability reasons, the contribution to the embodied impact is cumulated in the same order in the results. Finally, the whole construction type of the reference archetype is switched to a wooden typology where mainly the above ground structure is switched to compact wood elements and the external finishing of the envelope is also built with wood. This strategy is kept separate to allow the evaluation of these two representative typologies independent.

Table 1: Specific strategies applied to the reference archetype

Strategy	Variations
Design options	(1) Compactness: the envelope factor is reduced to the minimal value (1.5 to 1.1)
	(2) WWR is reduced to 20%
	(3) Underground floors reduced to 1
	(4) Underground floors are completely avoided
	(5) Surface of balconies is halved (from 0.2m^2/ERA to 0.1m^2/ERA)
	(6) Load-bearing internal walls are reduced – assuming a simpler structural concept (from 0.4m^2/ERA to 0.3m^2/ERA)
	(7) Non-load-bearing internal walls are reduced – assuming a more flexible internal arrangement (from 0.4m^2/ERA to 0.3m^2/ERA)
	(8) Densification: 1 extra floor is added, impacting the compactness
Construction and materials	(9) Insulation materials are changed with a lower carbon option (blow-in straw)
	(10) Materials for internal non-load-bearing walls are changed (wood and earth)
	(11) Technical installations are reduced (no active heating and ventilation)
Supply chain	(12) Estimated impacts of materials' production in 2050 are extracted from the literature [12]. Values for 2030 and 2040 are extrapolated assuming a linear reduction

4. Results

Figure 1 shows the potential embodied impact reduction from the reference concrete building and the wood reference. The margin lines at each step represent the possible accounting of carbon storage in the materials of the building. Carbon targets are represented with a range area spanning from the targets of the Swiss climate strategy (upper bound) and a 1.5°C budget (lower bound). The initial concrete reference is ca. 30% above the upper bound target and does require a certain number of strategies (ex: avoiding underground floors) to reach today's target but is also capable of going beyond that if attentive design and optimizations are implemented. Switching to a wood construction, immediately enables it to fall into the target range without further improvements. Further strategies applied to the wood reference allow to reach all the targets until 2050 and even reach a net-zero state in 2050 if carbon content of the materials is accounted for. Adding bio-based materials as insulation (9) doesn't drastically reduce the impact but increases the carbon storage content of the construction.

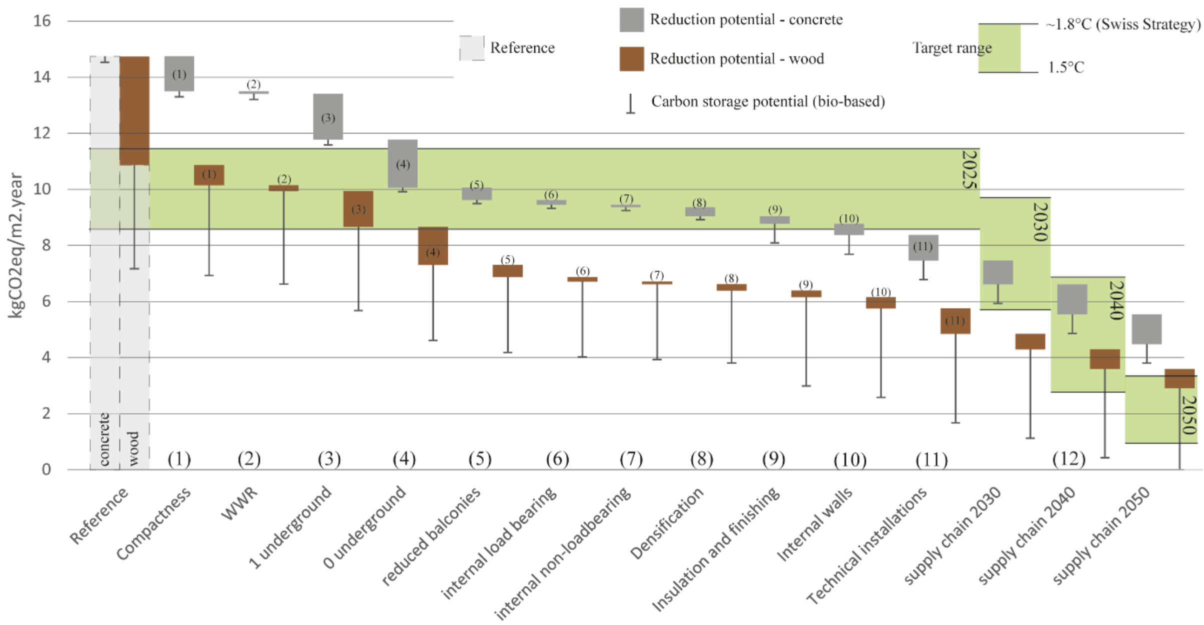

Figure 1: Reduction potential of strategies applied to reference building (concrete and wood) in contrast to embodied targets until 2050.

Figure 2 shows the detailed impact repartition for the two reference cases and the groups of strategies applicable today. Underground construction has a major impact on the total (17% in concrete and up to 23% for the wood reference) and represents an important lever in the mitigation potential. Completely avoiding underground floors assumes that parking slots are available above ground (not included in the boundaries of the building LCA) or that a no-car policy is in place. Envelope and internal elements hold the majority of the embodied impact in a building and the biggest improvement can be achieved by changing the structural material (ex: from concrete to wood). Technical installations play an important role, especially once the building has been optimized in its design and are difficult to eradicate. Variation 11 (technical installations) reduces the needs for active ventilation because vapor permeable materials have been added in variation 10 (materials of internal walls) and assumes no heating installation if the thermal properties of the building allow it. Finally, results show that 2025 targets are met with a concrete building by only applying design strategies without changing the materials in place. As expected, it is easier to reach the targets with wood construction rather than concrete. The wood reference meets the Swiss strategy targets without any further optimization and can remain compatible with a 1.5°C budget until 2030 if all strategies are applied. The concrete building is instead able to reach the 1.5°C target of 2025 only if strategies are applied and becomes incompatible in 2030 even if materials production improves as expected.

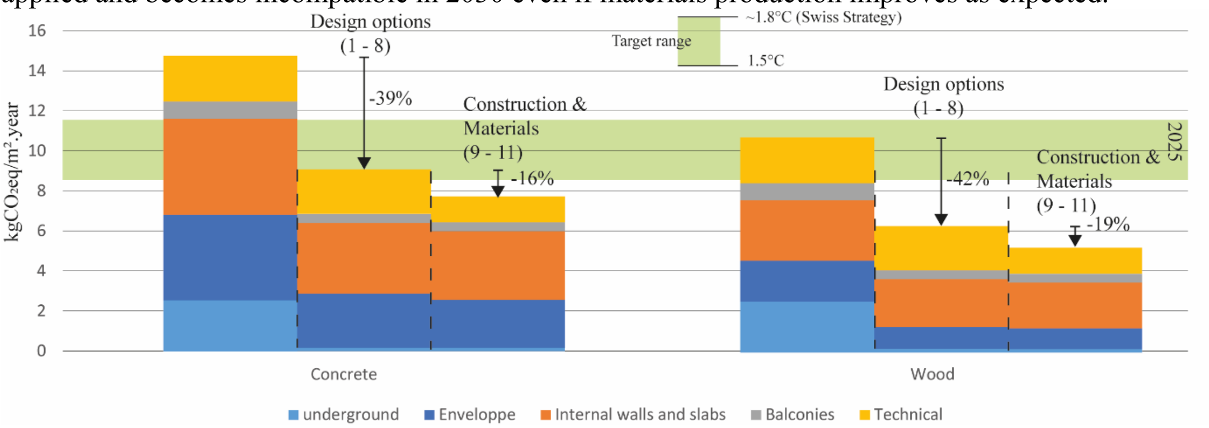

Figure 2: Embodied impact reduction of the two reference cases (concrete and wood) detailed by main building component

5. Discussion and conclusion

This paper evaluates building level design strategies to reduce embodied impact and comply with targets pathway to net-zero. A net-zero compatible building is defined as a building that, at the day of construction, meets the embodied target of the corresponding year as presented in Priore et al. 2023 [8]. The dynamic nature of a reduction pathway concept opens the question of which targets the replacement phase of today's building should follow. Current methods of static LCA account for phase B4 and C with the same impacts of today but the long time-frame of a building life-time could imply that if we change a window in 30 years (ca. 2050) its production will not have the same impact of today, especially considering the net-zero goals we have as a society by that time. To explore this question in more depth a dynamic or semi-dynamic LCA should be conducted including future scenarios of materials production footprint. The goal of this work was to demonstrate that today's embodied targets can be met with "conventional" construction methods, and we do not need to wait for future technologies to take action. For this reason, the reference building is a concrete massive building as this material represents the vast majority (more than 80%) of the Swiss market [13]. Wood constructions are central to the discussion of sustainable buildings and this material sees a slow increase in the market share and is therefore used as a second standard construction in contrast to the concrete reference. The authors are aware of the vast diversity of construction methods, materials, and elements available in the market and future works will include more options. The contribution of design choices to the operational phase is not included in this work but would give an interesting addition to the environmental analysis of buildings in future works. In general, applying the design options can reduce the initial embodied impact up to ca. 40%, further improving the materiality and reducing technical installations can reduce an extra 15% to 20%. Furthermore, only switching the reference concrete to a wood construction reduces the impact by almost 30%. This means that from the initial concrete reference to an optimized wood construction a total of 65% of emissions can be saved. It must be noted that only a limited list of strategies has been evaluated in this study and further reduction potentials are possible (reuse, structure, transport, etc.). For example, the structural optimization of concrete can use up to 40% less concrete [14,15] and the maximization of natural materials can increase the carbon stock and achieve climate neutrality [16]. The question of storing carbon and further avoiding its release in the atmosphere in the next 30 years also becomes relevant. As seen in **Figure 1**, valorizing the carbon content of materials can greatly impact the results and bring us closer to a net-zero impact building by 2050. Finally, an important and fast reduction is required to respond to the climate crisis and stay within planetary boundaries; the solutions exist but the design of buildings needs to make the environmental impact a priority.

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