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Exploring long-term building stock strategies in Switzerland in line with IPCC carbon budgets

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Abstract. Stringent limits and reduction strategies paths on greenhouse gas (GHG) emissions are being defined at different levels for long-term temperature stabilization. Given the nearly linear relationship between warming and cumulative net emissions, a carbon budget approach is required to limit global warming, as stated by the IPCC. In this setting, the built environment, as a cross-sectorial and transnational area of activity, plays a crucial role in today's carbon emissions and future reduction potentials. Previous research showed the need for effective and aligned carbon-targets to support and guide all actors in the construction sector towards these challenging global goals. In this context, previous research compared top-down derived carbon budgets for the Swiss built environment with a preliminary estimation of future cumulative emissions of the sector. Findings showed the misalignment of current best practices and the significant magnitude of effort that would be required to comply with such objectives. Nevertheless, limitations in the preliminary work emerged, such as the lack of dynamicity of the parameters included in the model restricting the representativity of its results. The current paper brings further this previous work by integrating the dynamic evolution of the energy supply, the materials' production, and the renovation rate. Results are then presented by mean of a parallel coordinate interactive graph. This interactive component allows the parametric exploration of the compliance with limited global budgets by varying the input parameters. This way the influence of macro-level strategies to decarbonize the Swiss building stock can easily be visualized with reference to the IPCC carbon budgets. Ultimately, the available interactive tool might support policy makers in decisions taken at the building stock level.

Keywords: Carbon Budgets, Building Stock, Carbon targets, Emissions, Mitigation

1. Introduction

To limit global warming and thus achieve the set long-term temperature stabilization (well below 2°C and pursuing efforts towards a 1.5°C limit) as defined by article 2 of the Paris Agreement [1], countries must take immediate action to reduce and mitigate emissions. Although reaching a set goal of net-zero emissions by midcentury (article 4 of the Paris Agreement) is essential to achieve the required balance for our environment, limiting cumulative emissions over time is not to be forgotten. As stated in the IPCC Special Report of 2018 [2]: “limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO₂ since pre-industrial period, that is, staying within a total carbon budget”. The quantification of global carbon budgets is an integral part of the work conducted by the IPCC [2–4] and the latest values (2021) are used in this work. The concept of a limited remaining carbon budget and its distribution to countries and sectors is presented in various works in the literature [5–7].



In this context, buildings and related construction activities contribute to 38% of all energy-related CO₂ emissions [8] and urgent reduction strategies are required.

The building stock is a complex dynamic system that evolves over time and needs, amongst others, to accommodate a constantly increasing population. Although new buildings are becoming increasingly energy efficient, the impact of the existing stock and the increasing impact of embodied emissions [9] are still an unsolved long-term problem. Furthermore, building stock strategies often focus on only one aspect of buildings' emissions and forget the cross-impact that, for example, increasing deep renovations can have on embodied emissions [10]. Especially, countries' initiatives and incentives to tackle renovations often lack this level of understanding and tend to focus on the reduction of operational energy without considering the impact of the materials put in place. For example, the 110% superbonus [11] in Italy requires renovations to pass at least two energy-efficiency categories but does not mention the embodied impact of the work. Similarly, in Switzerland the "Programme Batiments", regulated by the Cantons, defines a framework of incentives to increase the energy efficiency of buildings but no weight is given to the choice of materials. An urgent need to understand these relations, especially at a policy making level, is identified and thus, the present work presents a way to explore the impact of building stock strategies, enabling the possibility to set more informed long-term policies for our built environment. This contribution builds upon previous work, presented in section 2.

2. State of the art

Previous work from the same authors [12] attempted a first static estimation of future cumulative emissions of the Swiss building stock, highlighting the great misalignment of current best practices in Swiss constructions with limited budgets. The first part of the previous research established a methodology to allocate the IPCC global carbon budget to the operation and construction of Swiss buildings. This methodology is retained in the current paper but updated with most recent global carbon budgets [3]. The second part of the previous work estimated future cumulative emissions with static parameters such as a constant 1% renovation rate till 2050. The static nature of the previous model presented shortcomings in its representative value. A more realistic evolution of the parameters used in the model, such as a gradual increase of the renovation rate, is needed to fully represent the possible pathways of the building stock and its compliance with climate goals. Furthermore, the initial state of the stock, in the previous work, was assessed as a best case scenario following the SIA 2040 targets [13]. In this work, the initial impact of the stock is assessed in more depth to better represent the current level of emissions.

The contribution presented in this paper builds upon this previous work and further develops a usable final interactive graph to enable the simple exploration of the results. Cumulative emissions of the Swiss building stock are calculated considering the gradual evolution of the renovation rate, the operational emissions as well as the embodied emissions of construction works. The main aim of the current work is to explore which macro strategies would allow the compliance with limited budgets until 2050. The graphical and interactive representation, by means of a parallel coordinate graph, further allows the exploration of the sensitivity of the parameters put in place, giving insight on the parameters we should focus on to reach the challenging climate goals.

In conclusion, this paper focuses on building stocks emissions and their ability to comply, or not, with a limited carbon budget allowance for the sector till 2050. Furthermore, it allows the exploration of various long-term building stock strategies in Switzerland in line with climate goals. The estimation of cumulative emissions of buildings is made possible through a building stock model. As the scope of this work was to create a simple model with easily accessible data, the level of detail of the model is limited to its purpose.

3. Methodology

This section presents the methodology used to, initially build a simplified model with few input parameters, then estimate emissions till 2050 and finally automatically explore different scenarios. The construction of the graphical final output is presented in subsection 3.3.

3.1. Model components and structure

A simplified top-down and statistical building stock model was built using the programming language Python [14]. As presented in Figure 1 the model can be separated in three main “blocks”. The first one incorporates the development of surfaces composing the stock in terms of square meters. The second one includes greenhouse gas emissions related to every square meter of the stock in kgCO_{2-eq}/m². The changes in surfaces and related emissions are calculated yearly and finally added up in the last block of the model in terms of cumulative emissions over the studied period in Mt.CO_{2-eq}. The outputs of one block feed the other block through predefined relations as shown in Figure 1. The model is further composed of two main elements with varying functions. First, input data, mainly retrieved by national statistics or literature, are mainly used to characterize the initial state of the building stock. Secondly, variable and dynamic parameters, defined as possible targets to be explored by the model. The number of possible values (limited for computational reasons) for each variable parameter is shown in Figure 1 with the value “n” under each parameter. Further details on these parameters are found in section 3.2. . All blocks are explained in more details in the following subsections, where input data, assumptions, relations, and sources are presented.

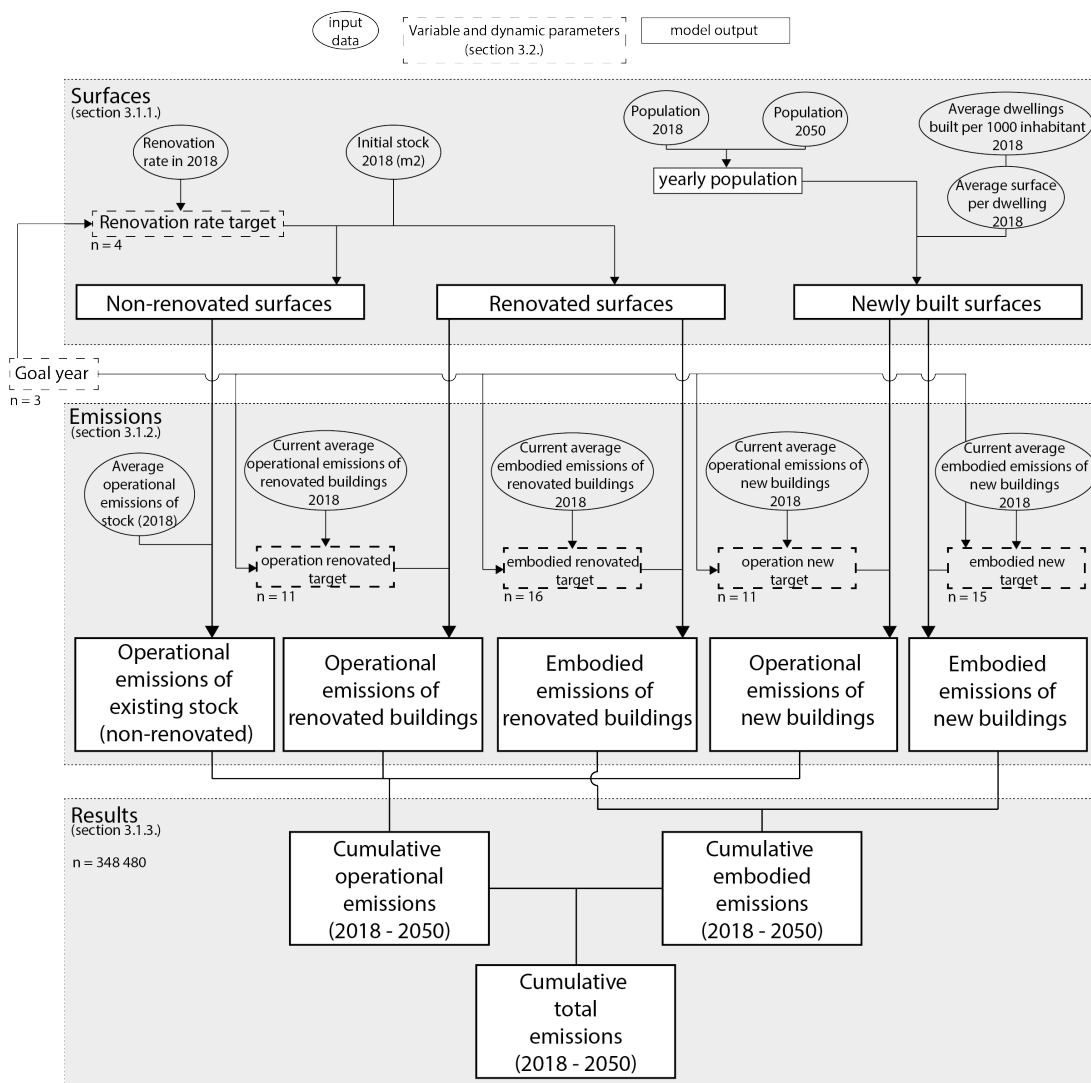


Figure 1. Graphical representation of the model (“n” represents the number of possible values).

3.1.1. Surfaces. The Swiss building stock in this work is represented in terms of existing (non-renovated), renovated, and newly built surfaces. Considering surfaces instead of buildings makes the model easier to manage as no distinction is made between different typologies but is limited in terms of level of detail. The main assumptions behind these surfaces and their evolution are shown in the previous research [12] and are here summarized in Table 1. Table 1 further presents the dependency on variable and dynamic parameters used in this contribution. In summary, every year of the studied period, a part of the existing stock is renovated while a part stays untouched and new surfaces are added. Renovated and non-renovated surfaces are calculated with a renovation rate that varies every year depending on the renovation rate target and goal year chosen for the scenario. Newly built surfaces are, instead, independent of variable parameters and calculated based on the increasing population over the studied period.

Table 1. Definition of surfaces in the model, input data, sources, and variable relations.

	Input data	Sources	Dependency on variable and dynamic parameter
Non-renovated surfaces	Initial stock 2018 = 392 945 800 m ²	[15]	<ul style="list-style-type: none"> ▪ Renovation rate target ▪ Goal year
Renovated surfaces	Initial stock 2018 = 392 945 800 m ²		<ul style="list-style-type: none"> ▪ Renovation rate target ▪ Goal year
Newly built surfaces	Population 2018 = 8 525 611 Population 2050 = 10 440 600 Average new dwellings per 1000 inhabitant = 6 Average surface per dwelling = 99m ²	[15]	/

3.1.2. Emissions. Emissions from the building stock are subdivided into operational emissions and embodied emissions. Each set of surfaces, outputted from the previous block, is related to each type of emissions according to the methodology presented in previous work [12] and updated values that are summarized in Table 2. Input data in this case represent the current emissions of buildings and construction works in Switzerland. Most values are derived with a top-down approach from total national territorial emissions and imported emissions for materials in construction in relation to surfaces affected from it. Consequently, the average values presented do not refer to a specific new or renovated construction. Operational emissions of new buildings are instead estimated analysing consumption levels and energy carriers for buildings built in the last year in the cantonal energy certification scheme database [16]. Operational emissions of renovated buildings are adapted by using the same ratio used by the SIA 2040 [13]. Although the operational emissions of renovated buildings do not directly refer to a specific strategy, they do refer to a representative average renovation work as presented in the literature [17]. Average operational emissions of the existing stock remain unchanged and are not affected by a variable parameter. It was here assumed that, although buildings are being renovated, no order is defined (ex: renovating first buildings with highest impact), therefore the average emissions of the stock will not be affected. The initial inputs estimate a current share of embodied and operational emissions of 77%/23% and 56%/44% for new and renovated buildings respectively. These shares are very close to the current targets proposed by the SIA 2040 [13] in Switzerland as well as shares found in the literature [17].

Table 2. Definition of emissions in the model, input data, sources, and variable relations.

	Input data	Sources	Dependency on variable and dynamic parameter
Operation of non-renovated surfaces	Average operational emissions of existing stock = 28 kgCO _{2eq} /m ² .year	[12]	▪ /

Operation of renovated surfaces	Current average operational emissions of renovated buildings = 5.8 kgCO _{2eq} /m ² .year	[13,16]	<ul style="list-style-type: none"> ▪ Operation renovated target ▪ Goal year
Embodied of renovated surfaces	Current average embodied emissions of renovated buildings = 440 kgCO _{2eq} /m ²	[12]	<ul style="list-style-type: none"> ▪ Embodied renovated target ▪ Goal year
Operation of new surfaces	Current average operational emissions of new buildings = 3.5 kgCO _{2eq} /m ² .year	[16]	<ul style="list-style-type: none"> ▪ Operation new target ▪ Goal year
Embodied of new surfaces	Current average embodied emissions of new buildings = 696 kgCO _{2eq} /m ²	[12]	<ul style="list-style-type: none"> ▪ Embodied new target ▪ Goal year

3.1.3. *Results.* The final block, as illustrated in Figure 1, produces the results by cumulating, over each year, emissions stemming from the stock for each possible combination of the variable parameters (348 480 combinations in total). Results are subdivided into operational cumulative emissions, embodied cumulative emissions, and total cumulative emissions. This subdivision gives a better understanding of the influence of each parameter on final emissions over time. The final output of the Python model is a csv file compiling all combinations of variable parameters and respective results.

3.2. *Variable and dynamic parameters*

Variable parameters are characterized in this work as the clue elements defining long-term strategies at the stock level. Their variability stands in the possible “target” value to be achieved in the chosen goal year. Each variable parameter in the model has predefined sets of values it can reach in the goal year as well as initial values as presented in Table 3 and graphically shown in Figure 2. The list of possible values was limited for computational reasons but can easily be changed, increased, or decreased in the Python model to generate different scenarios. The goal year definition was kept separate as it has a different level of relation compared to the other parameters. The choice of the goal year complements the other target choices by defining the length of the x-axis and not the y-axis in Figure 2. For all parameters, the choice of minimal, maximal, and steps of possible values was chosen to represent both acceptable and extreme scenarios. The renovation rate was assumed to remain constant or increase according to Swiss and European commitments [18,19] and 10% is considered a drastic value.

Table 3. Variable parameters definition.

	Initial value (2018)	List of possible values
Renovation rate	1% [20]	[1%, 3%, 5%, 10%]
Operational emissions of new buildings (in kgCO_{2-eq}/m².year)	3.5	[0 to 10]
Operational emissions of renovated buildings (in kgCO_{2-eq}/m².year)	5.8	[0 to 10]
Embodied emissions of new buildings (in kgCO_{2-eq}/m²)	696	[-540 to 1140] steps of 120
Embodied emissions of renovations (in kgCO_{2-eq}/m²)	440	[-300 to - 600] steps of 60
Goal year	/	[2040, 2045, 2050]

3.2.1. *Dynamic evolution over time of parameters.* The dynamic aspect applied in this work refers to the non-static behaviour of the parameters in the model. The variable parameters presented in the previous chapter are characterized by an initial value and a possible target (variable) to be reached in a certain year (goal year). The assumption is here made that each parameter evolves linearly from its starting point till its target value in the time frame defined by the goal year chosen as presented in Figure 2.

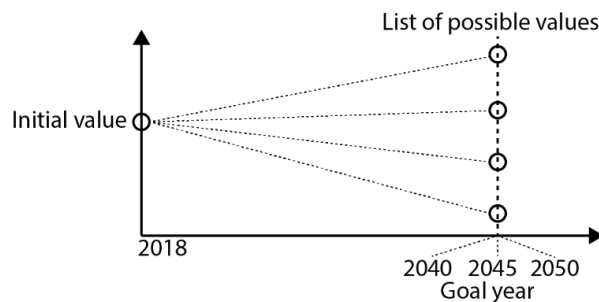


Figure 2. Linear evolution of variable parameters.

3.3. Graphical representation

Finally, the model output feeds a parallel coordinate graph [21], outlining all variable parameters and related outcomes in terms of cumulative emissions in Mt.CO_{2eq}. The graph is also created in python, using the pandas and plotly libraries [22,23]. The graph is interactive, and strategies can be explored to compare results with defined limited carbon budgets. The same graph can be used as well to test the sensitivity of the different parameters by choosing the cumulative emissions goal and visualizing instead the span of possible combinations.

3.3.1. Climate goals reference. The final graphical tool makes a reference to temperature limit targets as seen in Figure 3 (coloured scale bar on the right). Those are derived by calculating the limited carbon budgets (to be spent during the time frame of the study) for the operation and construction of buildings in Switzerland. The methodology used to derive a 1.5°C and a 2°C budget is presented in previous work [12], where global carbon budgets are first allocated to Switzerland with an equal per capita method and then further distributed to the relevant sectors with a grandfathering method, considering future estimations of negative emissions technologies. Furthermore, the Swiss climate strategy goal was added as reference, taken from the Energy Perspective 2050+ [24].

4. Results

This section presents the main outcomes of this work by showing first, results in a business-as-usual scenario, secondly a commonly accepted strategy of increased renovation rate and finally the sensitivity of parameters to achieve specific climate goals. The final output of this research, the interactive graph, is meant to be used to explore different solutions and this can be done only by actively using the said graph on <https://github.com/YasminePriore/Exploring-long-term-building-stock-strategies>. The results presented here are just part of the possible conclusions and outcomes of this output.

4.1. Business as usual

The business-as-usual scenario represents a path till 2050 that keeps current targets and practices unchanged in this time span. In this case the renovation rate stays constant at 1% until 2050 and operation of new and renovated buildings as well as their embodied emissions keep current values, as presented in Table 3. As shown in Figure 3 this scenario exceeds the 2°C budget reaching a 2.1°C temperature limit. Total cumulative emissions are here clearly driven by cumulative operational emissions. These results are explained by the relatively low renovation rate, resulting in a high number of existing buildings that keep a high operational impact until 2050.

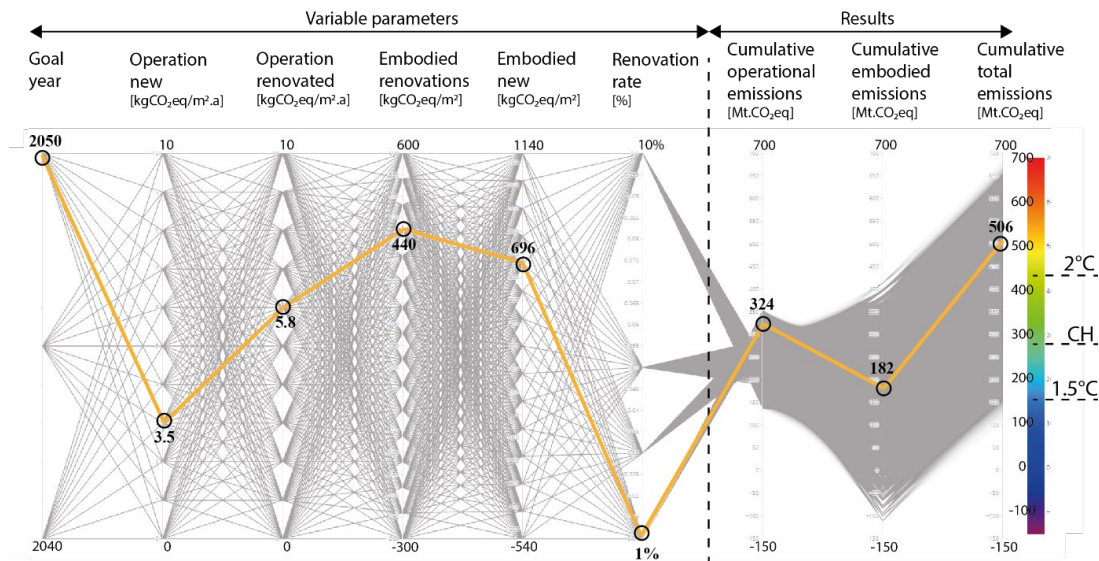


Figure 3. Illustration of cumulative emissions results for the Business-as-usual scenario.

4.2. Renovation+ scenario

Following up on the previous results, the renovation+ scenario follows a commonly agreed pathway where renovation rate is gradually increased to reduce the operational impact of the existing stock. In this case, presented in Figure 4, renovation rate linearly reaches 10% in 2050. However, it must be noted that this rate influences only the existing stock of 2018 and by circa 2040 all buildings are renovated; thus, renovation works stop. All other parameters are kept the same as in the BAU scenario. As shown in Figure 4, although cumulative operational emissions are strongly reduced by this measure, embodied emissions increase due to the strong renovation activities, resulting in the same total cumulative emissions in 2050 as in the BAU scenario. This result clearly demonstrates that just renovating more, without considering the carbon content of the materials, will not help the end result for our climate change goals.

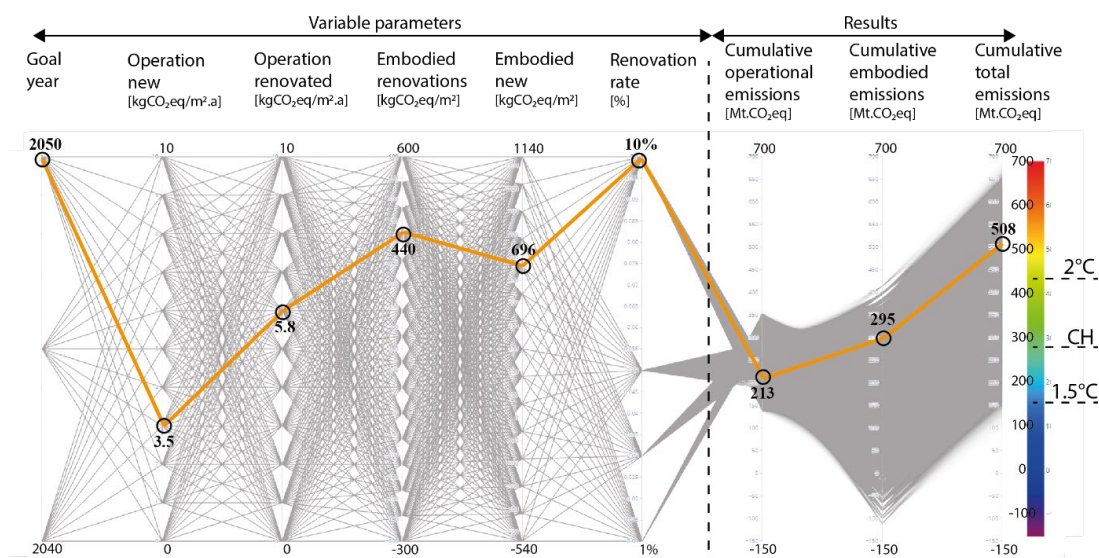


Figure 4. Illustration of cumulative emissions results for the Renovation+ scenario.

4.3. Sensitivity to reach climate goals

As mentioned before, the interactive graph can also be used to test the sensitivity of the parameters in reaching specific climate goals. Previously presented scenarios were constraining the variable parameters to explicit values in order to get results. In the following sections, instead, results are constrained to a precise goal to visualize the range of possible parameters.

4.3.1. 1.5°C limited budget. Figure 5 represents the possible range of values to achieve a 1.5°C limited budget and in Table 4 the minimal and maximum values possible to achieve this goal are listed. It must be noted that each line of the graph represents a specific scenario and that not every combination of values in the range will reach the 1.5°C goal.

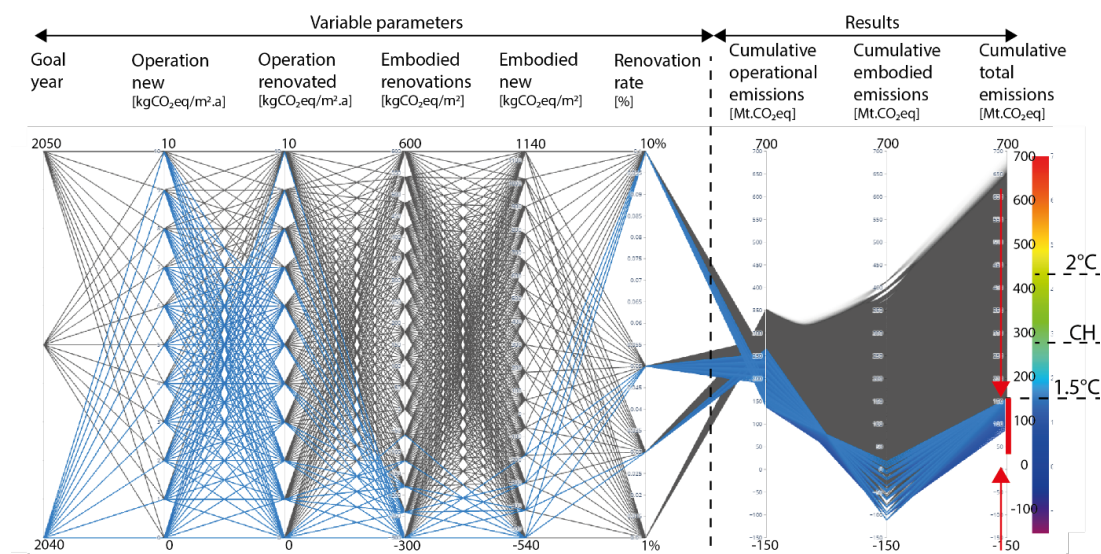


Figure 5. Illustration of variable parameters' range to comply with a 1.5°C budget.

Although operation of new and renovated buildings can span through all possible values, they are not compatible with all possible values of embodied targets and renovation rate. What is most evident in Figure 5 are the excluded values such as 2050 as a goal year or 1% renovation rate and the very limited embodied targets. These values are, in no scenario, a possibility to achieve a 1.5°C target. One can also immediately visualize the high sensitivity of the embodied targets, where the only possible values are negative targets to be achieved to compensate emissions.

Table 4. Range of possible values for a 1.5°C goal.

	Goal year	Operation new	Operation ren	Embodied ren	Embodied new	Renovation rate
Max	2040	10	10	-120	-180	10%
Min	2040	0	0	-300	-540	3%

4.3.2. Swiss climate strategy. Achieving the goals set by the Swiss climate strategy will leave more freedom in terms of long-term strategies. Important to notice in Figure 6 is the high sensitivity of the embodied targets. Although relatively high embodied targets are possible, they are only compatible if all other parameters are drastically decreased (grey lines starting from high embodied targets). From the result part of the graph one can also notice how the reduction of cumulative embodied emissions is effectively essential in achieving the goal.

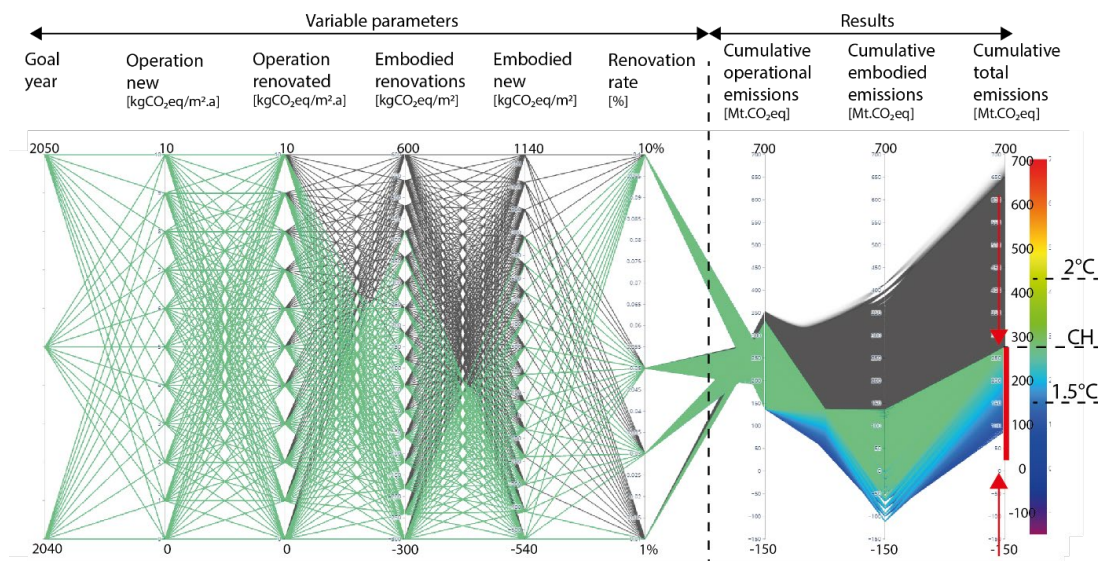


Figure 6. Illustration of variable parameters' range to comply with the Swiss climate strategy.

Table 5. Range of possible values for the Swiss climate strategy.

	Goal year	Operation new	Operation ren	Embodied ren	Embodied new	Renovation rate
Max	2050	10	10	420	780	10%
Min	2040	0	0	-300	-540	1%

5. Discussion

The model used in this paper was simplified, to reduce the level of complexity, to six main variables and dynamic parameters, defined as the most impactful long-term strategies on cumulative emissions. Further parameters could be implemented to increase the level of detail such as a more precise renovation rate of heating systems or the operational-embodied trade-off of renewable production on site or, again, the dynamic emission factors for electricity production. The top-down approach applied to the whole Swiss building stock used in this work has a main limitation of feasibility/representability of the strategies on single building solutions. The building stock is here generalized, and strategies are applied to every square meter without distinction of real design feasibility. This low level of detail is useful to understand overall dynamics in the stock but fails to propose concrete design solutions. Nevertheless, results can help policy makers to set high ranked national strategies to decarbonize the building sector without compromising the design intelligence required at a higher level of detail.

Furthermore, the range in which each parameter was allowed to be explored was defined and limited for computational reasons. Minimal and maximal values are meant to represent a realistic span in which each parameter could fall in the design of buildings but do not claim to be exhaustive. The limits chosen have an influence, not on the overall final result but mainly on the amplitude of possible results, especially in the comparison between the amplitude of cumulative operational emissions and cumulative embodied emissions. This contrast in the presented range of results should not be considered as an absolute reality but is dependent on the values the model is exploring. The flexibility to change these limits in the model is open and further investigations are possible.

Important to discuss is the fact that operational emissions, both for new and renovated buildings, were limited to $0\text{kgCO}_{2\text{eq}}/\text{m}^2$ as a best solution in contrast to embodied emissions that reach negative values. This choice was made by considering negative emissions as a true sequestration effect and not a balance in limited system boundaries. It could be argued that producing more energy on site than the building's demand would result in negative operational emissions for that specific building, but should this effect be accounted for on cumulative building stock emissions? On the other hand, the implementation of materials with a carbon capture potential (ex: fast growing biobased materials) was deemed as a possible contribution to reduce cumulative stock's emissions. Current building calculation

methods in Switzerland [25] do not consider biogenic materials as potential negative emissions, so there are no possibilities of producing a carbon negative building, although other methods would allow it [26].

The model and the tool are built on easily accessible building stock data and can, in a way, be adapted to different building stocks (in other countries for instance). The simplistic nature of the model and the relatively few inputs make it a very adaptable tool.

The next step would be to make the tool available in an online format, allowing its access to the responsible entities for long-term strategies of decarbonization of buildings. Future works are envisioned to investigate the feasibility of single strategies on detailed archetypes of buildings to prove the viability of the targets.

6. Conclusions

The main objective of this contribution was to investigate and visually represent the influence of building stock parameters on cumulative greenhouse gas emissions until 2050. An initial static model, presented in previous work, was enhanced by the dynamic evolution of the parameters over time allowing a gradual improvement of the building stock based on set long-term goals. Six parameters have been identified and scenarios for each one of them are defined to explore multiple combinations of them. The initial business-as-usual state of the building stock is identified with average current values.

Results highlight the urgent need to change the way we build and operate buildings, demonstrating that by continuing with a business-as-usual scenario we would surpass a 2°C budget, far from the goals set nationally and internationally. Another important result presented in this paper is the importance of accounting for interactions between different strategies as, for example, increased renovation rate without decreasing embodied impact of said renovations. Cumulative emissions until 2050 in such a scenario would result in the same 2.1°C budget as in the BAU scenario. Although renovating the existing stock remains essential to reach challenging goals, the link with the materials' impact we put into these renovations plays an essential role. Furthermore, 2050 seems already a very challenging target but it is not enough to reach a 1.5°C limit in temperature.

Finally, the visually attractive final visualization is a promising solution to easily explore different scenarios and combinations of targets and strategies. The graph further allows a simple way to test the sensitivity of each parameter in achieving set goals. At the policy making level there is a need to easily understand interactions of parameters without analysing complex construction details and high-level exploration tools can fill this gap.

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