

## RESEARCH

# Pathways toward a carbon-neutral Swiss residential building stock

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**Abstract**

Current policies to reduce energy consumption and CO<sub>2</sub> emissions associated with buildings focus on technological developments such as energy efficiency, renovation rates and renewable energies. While technological developments are effective at mitigating climate change, the omission of lifestyle changes such as lower floor area per capita and indoor temperatures as well as disruptive measures (e.g. replacement of highly energy-consuming buildings) leave untapped potential for further savings. A dynamic stock-driven model is presented that quantifies direct energy consumption and direct CO<sub>2</sub> emissions associated with the use phase of Swiss residential buildings. Eleven scenarios involving technological developments, lifestyle changes and disruptive measures are evaluated against relevant goals (Paris Agreement, Energy Strategy 2050 and 2000-Watt Society). Disruptive measures are modelled with a new combined lifetime-leaching approach. The scenario analysis indicates that the main leverage points for energy savings reside in lifestyle changes, whereas emission reductions can be highly levered by technological developments. Reaching all the goals is possible, but requires ambitious strategies. This study provides a basis for expanding the portfolio of climate change mitigation strategies for the residential building sector, although further research is needed to understand social, cultural and economic aspects, and indirect (embodied) emissions.

**Policy relevance**

Switzerland currently applies two policies in the building sector to reach the climate goals (Energy Strategy 2050, Paris Agreement and 2000-Watt Society). This study shows: (1) current policies (a CO<sub>2</sub> levy on fossil fuels for heating and the Buildings Program subsidising renewable energies and energy-efficient renovations) are effective at lowering energy consumption and CO<sub>2</sub> emissions, but insufficient to meet any of the goals; (2) reaching the Energy Strategy 2050 and Paris Agreement requires an extension of current policies and a complete phase-out of fossil fuels by 2050; and (3) achieving the 2000-Watt Society requires the measures described above, households heating only areas inside dwellings up to 20°C, and one of these three measures: (a) households living with 41 instead of 47 m<sup>2</sup>/cap, (b) increasing the renovation rate from 1.3% to 3.0%, and (c) replacing buildings consuming > 140 kWh/m<sup>2</sup>/yr. Further evaluations including social, cultural and economic aspects, and indirect energy consumption and embodied emissions are needed.

**Keywords:** building stock; climate change; combined lifetime-leaching approach; dynamic material flow analysis (MFA); mitigation strategies; scenario analysis; Switzerland

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## 1. Introduction

Many governments have set CO<sub>2</sub> emissions and energy-reduction goals and developed action plans to mitigate the potentially catastrophic consequences of climate change. The building sector plays an important role in these action plans due to its high CO<sub>2</sub> emissions and energy consumption. Although available and affordable low-carbon technologies make the sector attractive, the long lifetimes of buildings require long-term management strategies (Bauermann 2016; Kohler 2017). Worldwide, energy and emissions stemming from the operation of buildings are responsible for 31% of total annual energy consumption and 8% of total annual CO<sub>2</sub> emissions; when emissions associated with electricity production are included, these emissions account for 23% (IPCC 2018).

Strategies to reduce direct energy consumption and CO<sub>2</sub> emissions associated with the use phase of buildings vary widely, but can be categorised as technological developments (energy efficiency, renovation activities, energy mix) and lifestyle changes (indoor temperatures, size of dwellings). The existing literature for various countries and regions shows that future energy and emissions could be substantially reduced by the following technological developments: increasing the frequency of renovation (2–3% yearly renovation rates), increasing the use of photovoltaics and heat pumps, and improving the energy performance of existing and new buildings (Bauermann 2016; Bettgenhauser & Hidalgo 2013; Charlier & Risch 2012; Economidou *et al.* 2011; Firth *et al.* 2010; Meijer *et al.* 2010; Müller 2015; Pauliuk *et al.* 2013; Sandberg *et al.* 2017; Serrenho *et al.* 2019; Vásquez *et al.* 2016). Lifestyle changes are less prominent in the current literature; however, existing research indicates that a smaller floor area per capita (FAPC) and lower indoor temperatures could contribute considerably to meeting climate targets (Pauliuk *et al.* 2013; Sandberg *et al.* 2017; Serrenho *et al.* 2019).

Current policies for national building stocks tend to address climate change through technological developments only, which evidences the untapped savings potential of lifestyle changes. Additionally, disruptive measures such as replacing the entire building stock by 2050 have been found to reduce direct energy consumption and emissions substantially (Pauliuk *et al.* 2013; Serrenho *et al.* 2019). However, the concomitant increase in construction activity and indirect environmental impacts make these disruptive measures unreasonable. Nevertheless, an increased replacement of only the most energy-consuming buildings by highly energy-efficient ones could result in long-term energy and emissions savings, given that the environmental impacts of construction would be offset by substantial savings of direct energy and emissions. To the authors' knowledge, disruptive measures triggering the replacement of only a specific segment of the stock have not yet been considered in the literature.

In Switzerland, operating buildings accounts for 27% of total CO<sub>2</sub>e emissions and 28% of total energy consumption (FOEN 2019b; SFOE 2019). Switzerland has two central energy-related goals: (1) the Energy Strategy 2050 (ES2050) with per capita energy reduction targets for 2020, 2035 and 2050 of 16%, 43% and 54%, respectively, compared with the year 2000 (SFOE 2018b); and (2) the 2000-Watt Society envisioning 2000 W of primary energy use per person in 2050, in terms of continuous power (Stulz *et al.* 2011). Regarding emissions, the main goals are: (1) the Kyoto Protocol with a 40% reduction by 2020 compared with 1990 (FOEN 2018a); and (2) the Paris Agreement, which aims at carbon neutrality by 2050 (FOEN 2019a). To reach these goals, Switzerland applies the following policies specific to the building sector: (1) a CO<sub>2</sub> levy on heating oil, natural gas and coal; and (2) a Buildings Program (BP) subsidising the transition toward renewable energies and energy-efficient renovations (FOEN 2018b).

The literature on energy and emission reductions for the Swiss residential building stock shows that the energy goals could be reached by a 50% decrease of space heating demand in 2050 compared with 2005, and by heat pumps and solar energy supplying about 70% of the total energy demand in 2050; the reduction in space heating demand could be achieved through high energy-performance standards and high retrofitting rates (2%) (Drouilles *et al.* 2017; Heeren *et al.* 2013; Kost 2006; Pfeiffer *et al.* 2005; SFOE 2016; Siller *et al.* 2007; Wallbaum *et al.* 2009; Wang *et al.* 2018). The scarce literature on lifestyle changes indicates that a 25% reduction in FAPC could decrease energy by 10% and emissions by 25% in 2050 compared with 2005 (Drouilles *et al.* 2017). Existing studies often neglect the performance gap between the theoretical or technical energy performance of buildings and real energy consumption by households, which according to the results of Schneider *et al.* (2017) could lead to 20% higher energy demand in 2050. Much of this gap could be reduced if households used energy responsibly (lower indoor temperatures) (Khoury *et al.* 2017).

The limited consideration of lifestyle changes and the lack of scenarios portraying disruptive measures highlight the potential to expand the Swiss portfolio of climate change mitigation strategies for the building sector. An extension of the portfolio could improve decision-making processes under adverse futures. Therefore, the main goal of this contribution is to inform policy-makers in the Swiss residential building sector of alternative strategies (including technological developments, lifestyle changes and disruptive measures) to meet the energy and emissions goals. The following research questions will be addressed:

- How can disruptive measures be modelled, such as increased replacement of the most energy-consuming buildings by highly energy-efficient buildings?
- What are the main leverage points in the Swiss residential building stock to reduce energy and emissions?
- What measures are needed for the Swiss residential building sector to reach the energy and emissions goals?

To answer these questions, the authors developed a dynamic stock-driven model to quantify direct energy consumption and direct CO<sub>2</sub> emissions associated with the operational phase of Swiss residential buildings. Disruptive measures are

modelled with a new combined lifetime-leaching approach, and 11 scenarios are evaluated, including technological developments, lifestyle changes and disruptive measures, against the Swiss energy and emissions goals.

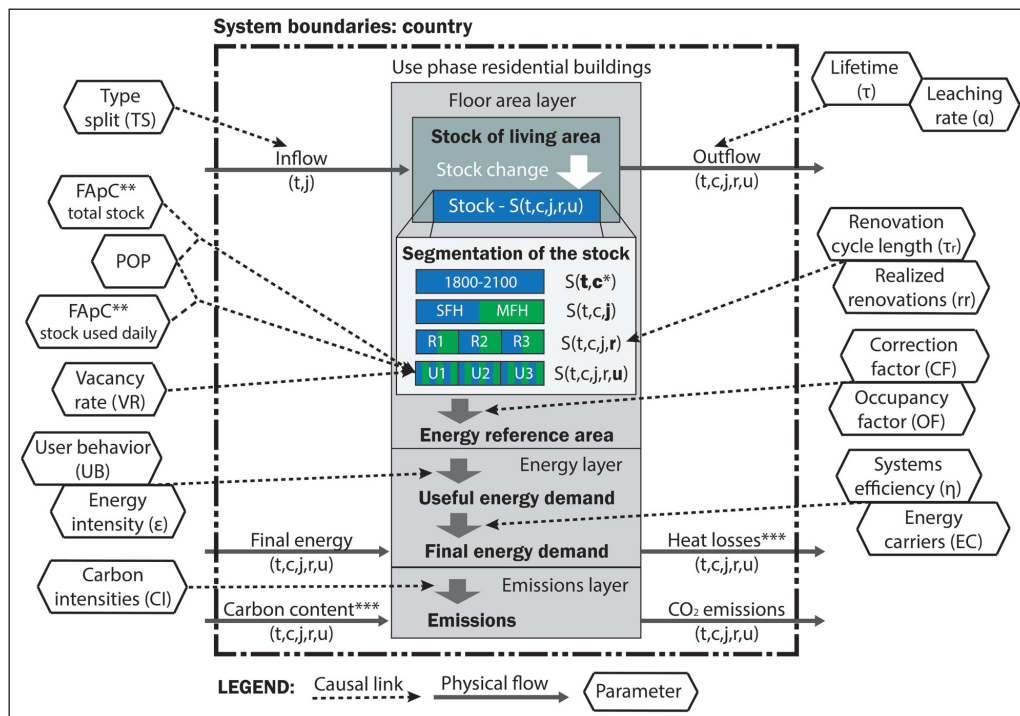
## 2. Methods

### 2.1 System definition

The system describes the use phase of residential buildings with the following aspects: floor area, direct energy consumption and direct CO<sub>2</sub> emissions (Figure 1). Given that these aspects are closely coupled with each other, the system contains one multilayered process representing the use phase of residential buildings with three layers: floor area, energy and emissions. The *floor area layer* quantifies the stock of living area and the stock of energy reference area (ERA). According to the Swiss Society of Engineers and Architects, the living area accounts for the area available for the occupant(s) inside the dwelling, and the ERA accounts for the effective heated area including areas beyond the dwelling area (e.g. staircases, attics, basements) (SIA 2007). Furthermore, the floor area layer quantifies the inflow (construction), outflow (demolition) and stock change associated with the stock of living area.

The stock is segmented by cohorts (construction years), building types, renovation states and intensity of use. Historical cohorts are defined following the official classification, and the length of future cohorts is set to 10 years, corresponding to recent historical cohorts (see Appendix A in the supplemental data online). The building types are segmented into single-family houses (SFH) and multi-family houses (MFH). Three renovation states were differentiated reflecting the improvements in energy efficiency: non-renovated (R1), renovated with the technologies available between 1971 and 2020 (R2) (1971 marked the beginning of energy-efficient renovations, and 2020 was considered as the current year), and renovated with the technologies available after 2020 (R3) (scenario specific). The use of the stock was segmented by three intensities: stock used daily (U1), stock used temporarily (U2) and vacant stock (U3).

The *energy layer* quantifies the direct demand for useful and final energy. The energy demand accounts separately for space heating (SH), domestic hot water (DHW) and other uses (lighting, electric appliances, ventilation, air-conditioning



**Figure 1:** System definition and model description for the use phase of residential buildings, including floor area stock, direct energy consumption and direct emissions. System variables: stock, stock change, inflow, outflow, energy reference area (ERA), useful energy, final energy and CO<sub>2</sub> emissions.

*Notes:* Dimensions:  $t$  = time;  $c$  = cohorts;  $j$  = building types (SFH = single-family houses; MFH = multi-family houses);  $r$  = renovation states (R1 = non-renovated; R2 = renovated during 1971–2020; R3 = renovated after 2020);  $u$  = intensity of use (U1 = used daily; U2 = used temporarily; U3 = vacant). Parameters: POP = population; FApC = floor area per capita for total stock and stock used daily; TS = type split;  $\tau_r$  = renovation cycle length;  $rr$  = realised renovations; VR = vacancy rate; CF = correction factor; OF = occupancy factor; UB = user behaviour;  $\epsilon$  = energy intensity;  $\eta$  = heating systems efficiency; EC = energy carriers; and CI = carbon intensity.

\* Cohort segmentation is not visualised.

\*\* FApC is calculated by two additional parameters: FApD = floor area per dwelling; and PpD = people per dwelling.

\*\*\* Heat losses and carbon content are not explicitly calculated in the model; they are shown for the unit consistency of each layer.

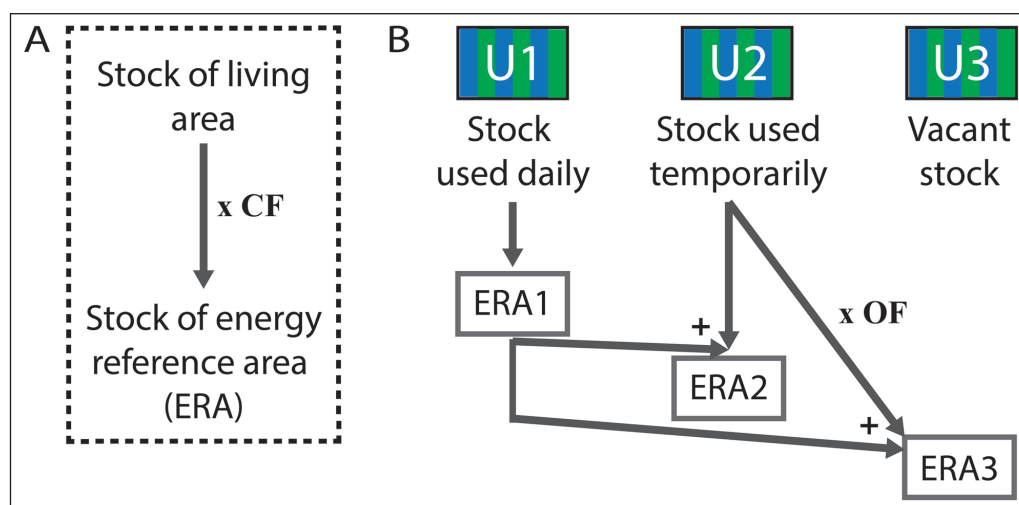
and minor uses). Cooking accounts for 3% of the total energy consumption in buildings (SFOE 2018a), and it was not included due to poor data availability. Following SFOE (2018a), the energy carriers considered were heating oil, natural gas, coal, direct electricity, electricity for heat pumps, wood, renewables (solar energy), district heating and others. The *emissions layer* provides the direct CO<sub>2</sub> emissions; therefore, other greenhouse gas emissions are not accounted given that CO<sub>2</sub> accounts for 99% of the CO<sub>2,e</sub> emissions associated with the use phase of residential buildings (FOEN 2019b).

## 2.2 Model description

The stocks and flows were calculated using a dynamic stock-driven model in which population and FApC define the stock of living area. The model formulation was based on a series of publications (Müller 2006; Sandberg *et al.* 2016, 2017; Vázquez *et al.* 2016). The entire model formulation is presented in Appendix B in the supplemental data online, and the differences between the model and those described in the existing literature are provided below, and summarised as the segmentation of the stock by intensity of use and the combined lifetime-leaching approach.

Siller *et al.* (2007) found differences between statistical data and model results, which could be explained by the omission of the intensity of use of the stock. The model tackles this by calculating two FApC: (1) that accounting for the total stock; and (2) that accounting for stock used daily. In both cases, FApC was obtained by dividing the floor area per dwelling by the people per dwelling. Each FApC was multiplied by the population to obtain the total stock and the stock used daily (both stocks in terms of living area). The vacant stock was obtained by multiplying the vacancy rate by the total stock. The stock used temporarily was determined by subtracting the vacant stock and the stock used daily from the total stock. The stock of ERA was calculated using the method described by Streicher *et al.* (2019) (Figure 2A), which resulted in ERA1 and ERA2 depending on the stock of the living area used (Figure 2B). This study additionally calculated the stock of ERA as the sum of the stock used daily and the stock used temporarily corrected by the occupancy factor (ERA3).

The combined lifetime-leaching approach was developed to explore disruptive measures by using the existing lifetime and leaching approaches. Buildings stock models assume that the demolition of the stock is either determined by a predefined building lifetime (lifetime approach) or by a demolition or leaching rate (leaching approach) (Bauermann 2016; Müller 2006; Van der Voet *et al.* 2002). While the lifetime approach considers the heterogeneity of the stock (cohort or age structure), it has limitations with respect to representing disruptions of the predefined building lifetime such as age-independent demolition. The leaching approach calculates demolition as a fraction of the stock; therefore, the stock is considered homogeneous and demolition is independent of the cohort structure, which may lead to inaccurate results. However, the leaching approach allows immediate growth of the demolition activity to be modelled by increasing demolition rates. Both approaches have their strengths, weaknesses and areas of application; therefore, a novel approach is proposed in which the strengths of the two are combined. The natural ageing process of a heterogeneous stock is accounted for by the lifetime principle, while the leaching approach captures the age-independent outflows triggered by the increased replacement (disruptive measure). The age-independent outflows are determined by multiplying a leaching rate, which is targeted at a segment of the stock, by the stock. The targeted segment of the stock was assumed to have no lifetime-related outflows during leaching. For the mathematical formulation of the combined approach, see Appendix C in the supplemental data online.



**Figure 2:** Energy reference area (ERA)-related calculations. **(A)** Generic ERA calculation from the stock of living area using a correction factor (CF) that accounts for heated areas beyond the dwelling area. **(B)** ERA approaches used in this study: ERA1 obtained from the stock used daily; ERA2 obtained from the stock used daily and temporarily considered as stock used daily; and ERA3 obtained from stock used daily and temporarily corrected by the occupancy factor (OF).



The model was implemented using Python by adapting the library Open Dynamic Material Systems Model to include types, energy, emissions and the combined lifetime-leaching approach (Pauliuk & Heeren 2020).

### 2.3 Parameter estimation and uncertainty analysis

The model description is generic; thus, it could be adapted to different system boundaries. In this study, the Swiss national borders define the spatial system boundaries and a simulation time of 301 years, 1800–2100, is applied. The overview of the input data, parameter assumptions and calibration for the most relevant parameters is provided in **Table 1** (for the complete table and specifications see Appendix D in the supplemental data online). In line with the findings of Naber *et al.* (2017) regarding predominant uncertainty analyses in building stock models, an uncertainty analysis, including two sensitivity analyses (SA) and comparative analyses, was performed. Two SA were conducted to study the effects of a one-factor-at-a-time (OFAT) parameter variation ( $\pm 10\%$ ) in either the historical input data or the future development of the parameters. Similarly, as in Sandberg *et al.* (2016), for the historical parameter variation, the parameters were classified as having either high or low uncertainty depending on the data sources used (**Table 1** and see Appendix D in the supplemental data online), the SA was performed with the parameters evaluated with high uncertainty and the results were evaluated for 2020. The parameter variation for future input data was carried out for all parameters except for the carbon intensities of heating oil, natural gas and coal, given that they are determined by the carbon content of the fuel, which is expected to remain unchanged (for details, see Appendix D in the supplemental data online). The results were analysed for 2050. For the two SA, the results were calculated as relative sensitivities (relative change in output over relative change in input) (for the equation, see Appendix D in the supplemental data online). The comparative analyses were conducted to validate model results against statistical data and similar studies.

### 2.4 Scenarios

A scenario analysis was conducted to assess the strategies for reducing direct energy and emissions stemming from the operation of Swiss residential buildings. The results were evaluated against the goals presented in section 1. The conceptual outline and description of the scenarios are presented in **Figure 3**; for a detailed description of the goals and scenarios, see Appendix E in the supplemental data online.

The scenarios were built considering a cumulative aspect and two types of scenarios. The cumulative aspect is illustrated in **Figure 3** by arrows indicating how the scenarios build on each other (*e.g.* carbon neutrality considers the premises in extend Buildings Program). The two scenario types are forecasting and backcasting.

The baseline scenario was defined with current policies in place, assuming the end of the BP in 2025 (currently planned). An extension of the programme was explored in the extend Buildings Program scenario. Given that the Swiss government has officially committed to carbon neutrality and the ES2050 goals, a backcasting scenario, carbon neutrality, was built to explore how the two goals can be reached.

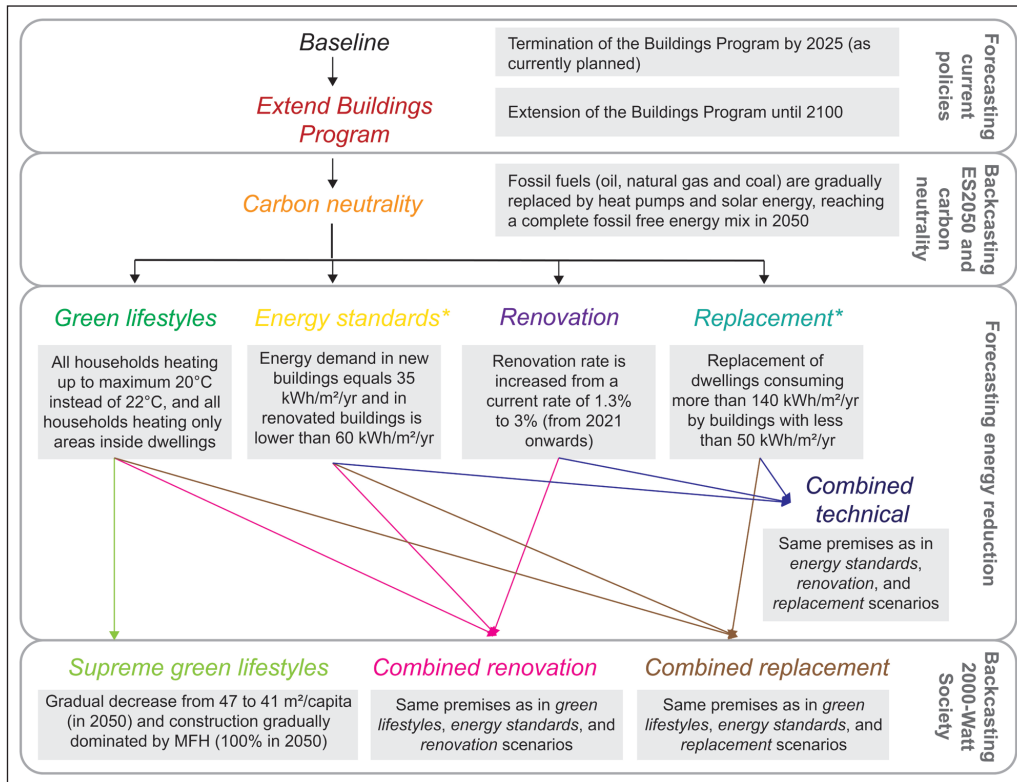
The forecasting energy-reduction scenarios explore ambitious measures to reduce energy consumption in buildings further. While the green lifestyles scenario analyses two lifestyle changes (a gradual shift from average indoor

**Table 1:** Description of the most relevant parameters. The source corresponds to the values and assumptions.

Parameter	Value	Sources	Assumptions	Evaluation of data uncertainty
Population	See Appendix D	FSO (2018b), HSSO (2012b), UN (2019)	Medium projection	Low
Floor area per dwelling <sup>a</sup>	See Appendix D	Bergsdal <i>et al.</i> (2007), FSO (2000, 2018c)	65 m <sup>2</sup> /dwelling in 1800 104 m <sup>2</sup> /dwelling in 2100	Low
People per dwelling <sup>a</sup>	See Appendix D	FSO (2017), HSSO (2012a), Müller (2006)	5 people/dwelling in 1800 2 people/dwelling in 2100	Low
Lifetime	200 years	Kornmann & Queisser (2012)	Lifetime was assumed equal for all cohorts and types, and was found through a process of calibration and validation (see Appendix D)	High
Renovation cycle length	40 years	Filchakova <i>et al.</i> (2009)	Renovation cycle length equal to the longest lifetime of energy-relevant building components	High

Notes: <sup>a</sup> Stock used daily.

For appendices, see the supplemental data online.



**Figure 3:** Conceptual outline of the scenarios.

*Note:* Arrows between scenarios indicate how the scenarios build on each other. The premises are specified in the grey boxes. The scenario typology (forecasting or backcasting) is presented on the right side. \* Energy values are given for useful energy.

temperatures of 22 to 20°C and gradual avoidance of heating up areas outside dwellings), the energy standards, renovation and replacement scenarios investigate individual technological measures: best energy standards for new (Minergie-A) and renovated buildings (Minergie-P) (Minergie 2020), increased renovation rate and gradual replacement of dwellings with the highest energy demand by energy-efficient dwellings during the period 2021–30, leading to their complete replacement by 2030. A combination of the three technological measures was analysed in the combined technical scenario. The 2000-Watt Society goal was investigated with three backcasting scenarios: supreme green lifestyles, combined renovation and combined replacement. While highly ambitious lifestyle changes (lower FApC and construction linearly dominated by MFH) were studied in supreme green lifestyles, the combined renovation and combined replacement scenarios explored combinations of technological measures together with less ambitious lifestyle changes. The scenario results beyond 2050 are highly uncertain; therefore, they are presented but not discussed.

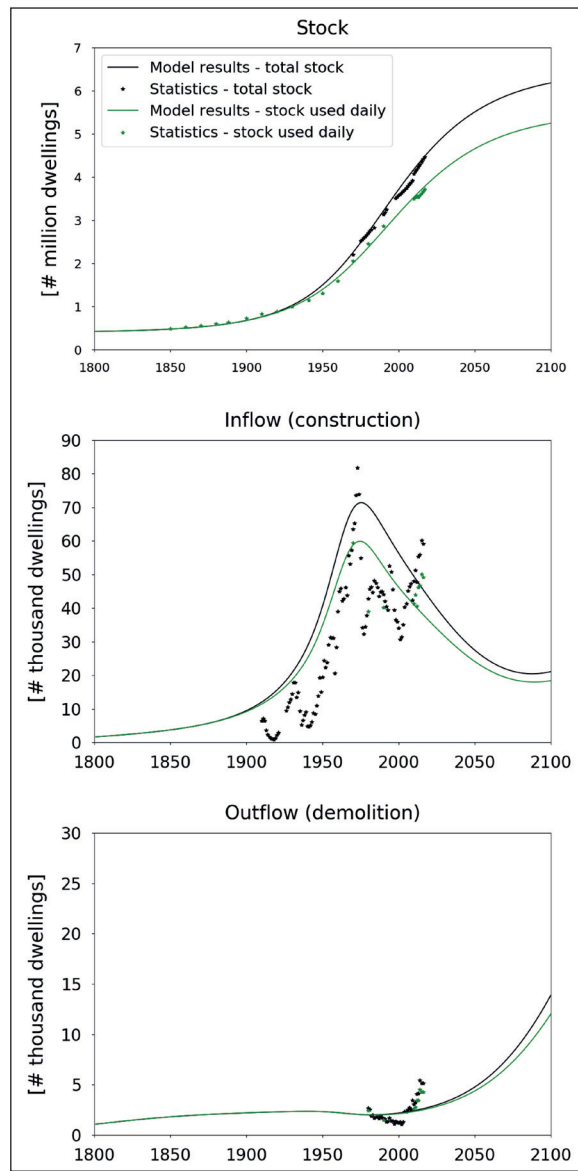
### 3. Results

#### 3.1 Baseline scenario and uncertainty analysis

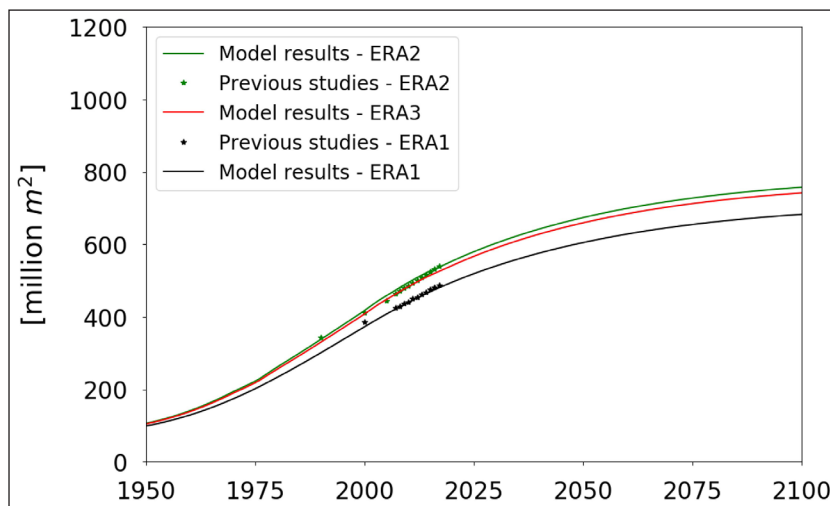
According to the baseline scenario, the Swiss residential building stock is expected to grow until 2100; however, the growth toward the second half of the 21st century will slow down (**Figure 4**). The expected stock growth is driven by a projected increase in population, given that FApC was assumed to stagnate at current levels. Simulation results for construction show an increase until 1975 with strong growth after the Second World War, a decrease in 1975–2075, and a small increase for the last 25 years simulated. The results for demolition present a flat trend until 2025 and a subsequent increase. The decrease in construction after 1975 and the low demolition activity are driven by the long lifetime of dwellings. The historical results of the stock, inflow and outflow fit the overall trends of the statistical data well; however, they fail to capture the short-term fluctuations of construction and demolition activities.

The results of the stock segmented by renovation states were equivalent to a renovation rate of 1.3%, which was validated by the rate reported by Rey and Brenner (2016). The trend presented by the results of the stock of ERA using the three approaches described in **Figure 2** reveals an increase in the first half of the 21st century and a flattening in the second half (**Figure 5**). The comparison of ERA results with previous studies shows a good fit.

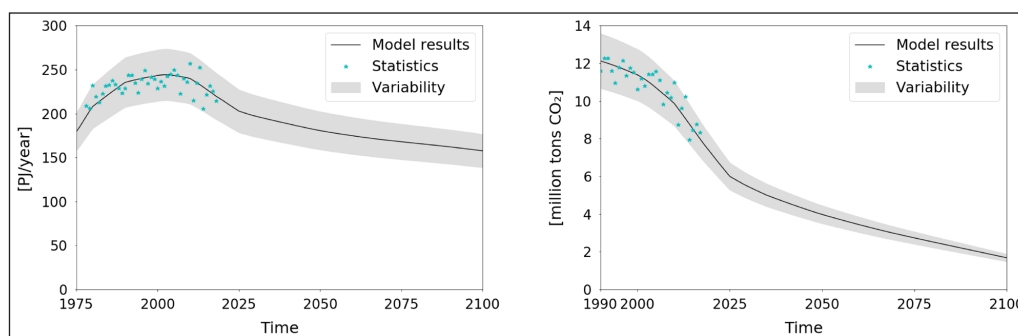
The evolution of direct final energy consumption according to the baseline scenario shows a trend with three phases: (1) an increase until 1990, (2) stagnation for the period 1990–2010 and (3) a decrease from 2010 onward (**Figure 6**). Emissions results depict a rapid decrease until 2025, and a slower decrease until 2100. Historical energy and emissions results fit well with the overall trend presented by the statistical data; however, they fail to capture the annual data fluctuations, which might be caused by annual climatic variability. These fluctuations were quantified to differ from model results by  $\pm 12\%$  for historical years; therefore, future energy consumption and emissions are expected to lie



**Figure 4:** Evolution of the stock, inflow and outflow for the total stock and stock used daily for the period 1800–2100, for the baseline scenario. The model results are compared with statistical data.  
 Sources: FSO (2018a, 2019a, 2019b).



**Figure 5:** Stock of energy reference area (ERA) using three calculation approaches (described in Figure 2). Historical results are compared with previous studies (SFOE 2018a, Siller *et al.* 2007; Wallbaum *et al.* 2009). Future results correspond to the baseline scenario.



**Figure 6:** Evolution of direct final energy consumption and direct CO<sub>2</sub> emissions associated with the use phase of Swiss residential buildings for the baseline scenario, including the variability range due to annual fluctuations. The model results are compared with statistical data (FOEN 2019b; SFOE 2019).

**Table 2:** Relative sensitivities in 2020 with +10% of input parameter.

Parameters	Energy results	Emissions results
Lifetime	-0.02	-0.02
Renovation cycle length	0.33	0.39
Realised renovations	-0.21	-0.25
Occupancy factor	0.09	0.09
Energy intensity SH R1	0.39	0.47
Energy intensity DHW R1	0.09	0.11
Energy intensity Others R1, R2	0.18	0
Energy intensity SH R2	0.27	0.32
Energy intensity DHW R2	0.02	0.03

*Note:* Negative values indicate that the parameter increase leads to an output decrease.

within this range. Similarly, energy consumption segmented by energy carrier presents a good fit with the overall statistical trends (see Appendix F in the supplemental data online).

The results in **Figure 6** were obtained using ERA3 and accounting for user behaviour (real energy). Energy results using ERA1–2 and not accounting for user behaviour (technical energy) were computed to study potential discrepancies and to compare the results with previous studies (see Appendix F in the supplemental data online). Energy results using different ERA approaches lead to differences of 10% in 2050. Historical results obtained using the same ERA approach are comparable among studies (Siller *et al.* 2007; Wallbaum *et al.* 2009). The results obtained accounting for user behaviour present about 20% higher real energy consumption in 2050 compared with technical energy, which is in line with the results of Schneider *et al.* (2017). The scenario analysis was conducted using ERA3 and real energy consumption because they account for user behaviour, occupancy in holiday houses and provided the best fit to statistical data.

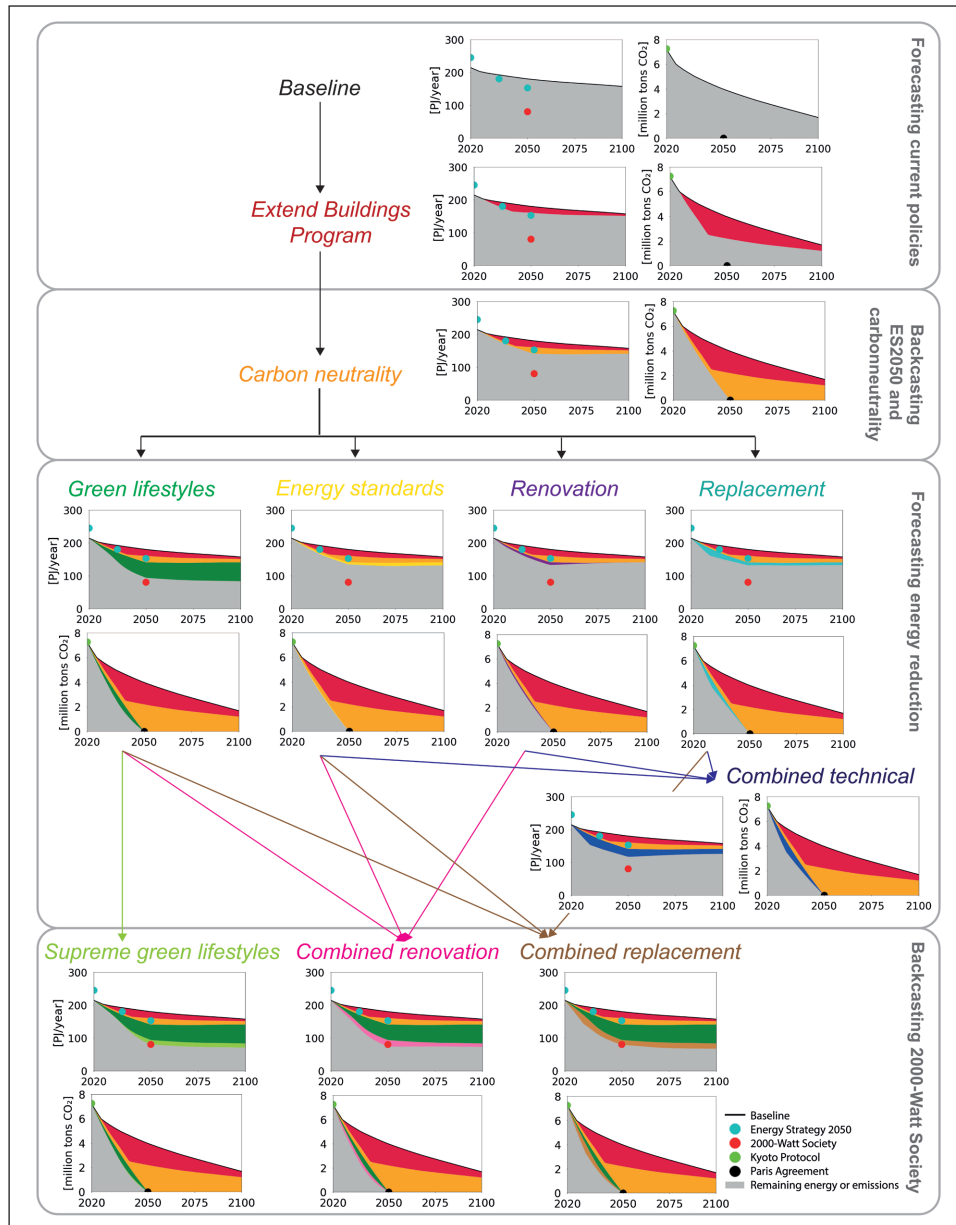
The results of the SA for 2020 reveal relative sensitivities < 0.5 (**Table 2**), which highlights that the historical energy and emissions results are not very sensitive to changes in highly uncertain parameters. The SA results for 2050 show large differences in the impacts of parameters; however, most relative sensitivities are < 0.5, which indicates that the model is not very sensitive to changes in the future input data of parameters. The parameters with relative sensitivities > 0.5 are population, people per dwelling, correction factor and user behaviour (see Appendix F in the supplemental data online). The impacts of population, FApC (determined by people per dwelling and floor area per dwelling) and correction factor are expected to be high given that they determine the stock (living area and ERA), which is the driver of the model. The user behaviour shows a coefficient for energy results of about 0.57, which is similar to that reported by Sandberg *et al.* (2017) using a similar model formulation. The parameters with sensitivities > 0.5 are included in the scenario analysis, except for population, for which the medium projection for all scenarios was assumed. The future evolution of population is highly dependent on economic developments as well as migration and fertility policies, which are outside the scope of this study.

Given the results of the uncertainty analysis, the model was regarded as robust and suitable for scenario analysis.

### 3.2 Scenario analysis

The scenario analysis for both direct final energy consumption and direct CO<sub>2</sub> emissions shows that all scenarios comply with the Kyoto Protocol and the first intermediate goal of the ES2050, given that these goals are defined for 2020, which is considered as the current year (**Figure 7**).



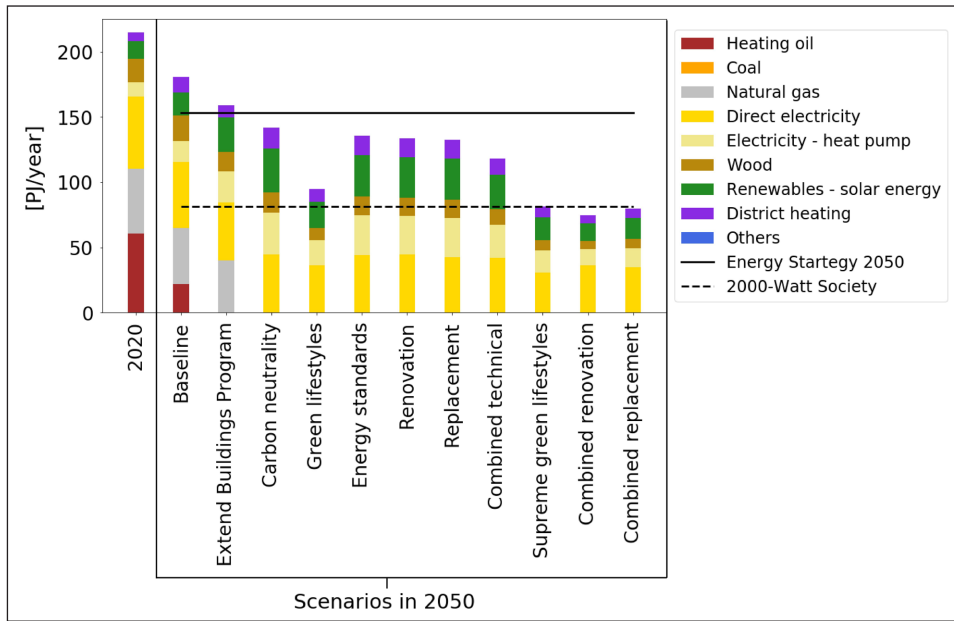


**Figure 7:** Direct final energy consumption and direct CO<sub>2</sub> emissions pathways associated with the use phase of Swiss residential buildings for 11 scenarios and compared with the Kyoto Protocol, Paris Agreement, ES2050 and 2000-Watt Society goals. The energy and emissions savings are segmented according to the premises of the scenarios.

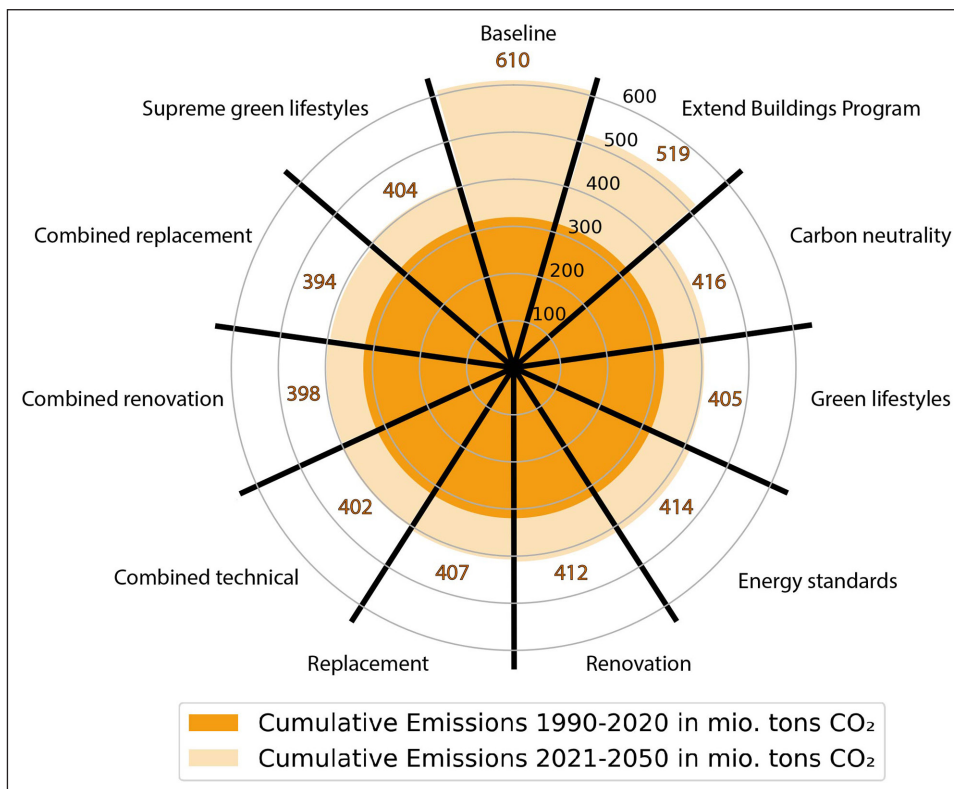
The future evolution of energy consumption and emissions triggered by assuming that current policies are in place (baseline) is insufficient to fulfil any of the goals beyond 2020. The trend shift observed in 2025 corresponds to the termination of the BP. An extension of current policies (extend Buildings Program) leads to 11% and 45% reductions in 2050 for energy and emissions, respectively, compared with baseline, which are insufficient to satisfy the goals for 2050. The shift observed in the emission trend in 2040 is triggered by the complete disappearance of oil heaters.

Extending the BP together with a rapid and gradual phase-out of fossil fuels until 2050 (carbon neutrality) results in a stock consuming about 22% less energy compared with baseline and emitting zero emissions in 2050. The carbon-neutrality scenario complies with the ES2050 and Paris Agreement goals, but not with the 2000-Watt Society goal. This scenario requires a twofold increase of energy supplied by renewable energies and heat pumps in 2050 compared with the baseline (Figure 8), and it leads to a 30% reduction of cumulative CO<sub>2</sub> emissions by 2050 compared with the baseline (Figure 9).

Compared with the baseline, the green lifestyles, energy standards, renovation, replacement and combined technical scenarios lead to energy savings of 48%, 25%, 26%, 27% and 35%, respectively. Despite the energy reductions mentioned, none of the scenarios reaches the 2000-Watt Society goal. The replacement and combined technical scenarios trigger a 34 times higher demolition and a 3.4 times higher construction during the leaching phase compared with the baseline, in order to preserve the stock (see Appendix G in the supplemental data online). After the leaching phase, the demolition and construction activities are lower compared with the baseline, given that the stock is younger.



**Figure 8:** Direct final energy consumption for the use phase of Swiss residential buildings segmented by energy carriers in 2020, and in 2050 for the 11 scenarios compared with the ES2050 and the 2000-Watt Society goals.



**Figure 9:** Cumulative CO<sub>2</sub> emitted during the periods 1990–2020 and 2021–50 for all scenarios. The exact value for the entire time period is provided for each scenario.

The 2000-Watt Society goal can be met by three alternative scenarios: supreme green lifestyles, combined renovation and combined replacement. The three scenarios lead to energy pathways with a reduction of about 55% in 2050 compared with the baseline. The energy supplied by renewable energies and heat pumps is reduced by 54% and 55%, respectively, in 2050 compared with the carbon-neutrality scenario. For the three scenarios, a substantial reduction in SH demand is observed, which makes other uses (electric appliances, ventilation, air-conditioning and minor uses) a dominant energy use in 2050 (see Appendix G in the supplemental data online). The combined replacement scenario triggers the same construction and demolition results as in the replacement and combined technical scenarios. The supreme green lifestyles scenario leads to a reduction in construction of about 75% in 2050 compared with the

baseline. The combined replacement scenario provides the lowest cumulative CO<sub>2</sub> emissions, followed by the combined renovation and supreme green lifestyles scenarios; however, the differences are small.

## 4. Discussion

### 4.1 Uncertainties and limitations

While building stock models have been used extensively to study building stock dynamics (Bergsdal *et al.* 2007; Müller 2006; Stengel 2014), they are limited by input data, model assumptions and scope. The two SA found that the model is not very sensitive to changes in the historical input data of highly uncertain parameters and to changes in the future input data of parameters. However, the highest sensitivities for 2020 were found for parameters related to renovation activities and technical energy consumption in buildings, which reveals that higher data quality for these parameters could improve the model. The highest sensitivities for 2050 were found for lifestyle-related parameters, which highlights the importance of including them in long-term scenario analyses. The limitations related to model assumptions and scope are summarised as follows and explained in detailed below: (1) a constant lifetime for cohorts and types, (2) average energy intensities define cohorts and types, (3) user behaviour depends on technical energy consumption in buildings, (4) the outdoor climate remains constant, (5) unclear boundaries between residential and non-residential stock and (6) energy consumption and emissions associated with construction, demolition, energy and material production activities are disregarded.

Lifetimes of buildings and demolition activities are still poorly understood. Following previous research (Vásquez *et al.* 2016), demolition activity was modelled as a function of a normally distributed constant lifetime for all cohorts and types; however, drivers such as land price, rents, cultural heritage and households' preferences influence demolition activities, and these drivers were considered to be outside the scope of this study. The non-inclusion of such drivers might explain the short-term fluctuations in construction and demolition not captured by the model results. While this behaviour is typical of stock-driven models, these models are robust in portraying long-term dynamics (Müller 2006).

The model formulation considers cohorts and types which are defined by average energy intensities. This approach captures the heterogeneity of the stock; however, it fails to capture the variability within a specific cohort and typology. Considering normally distributed averages could reflect the variability, but would be conditioned to the availability of disaggregated data.

User behaviour was considered to depend on the technical energy intensity of buildings. While this approach has been used in previous publications (Sandberg *et al.* 2017) and offers a first attempt to account for user behaviour, it simplifies the drivers by excluding the purchasing power and lifestyle preferences of households, and it might include uncertainties associated with the technical energy intensity in user behaviour. This highlights the need for more comprehensive approaches to model user behaviour, which is especially important in long-term analyses.

The outdoor climate was assumed constant at today's climate; however, previous research for Switzerland showed that global warming could cause a 10–40% decrease in SH and a 250–1300% increase in cooling by the end of the century compared with 1980 (Berger & Worlitschek 2019; Christenson *et al.* 2006). Given that about 60% of SH demand was supplied by fossil fuels in 2017, a decrease in SH could assist the transition toward carbon neutrality. The increase in cooling could substantially increase electricity demand, and thus condition the supply of a carbon-free electricity mix.

The boundaries between residential and non-residential stock are subject to national definitions and reporting procedures. Accordingly, FApC was calculated and used to obtain the residential stock; however, the boundary between residential and non-residential floor areas in buildings sharing different functionalities or in buildings undergoing functionality conversions are often not clearly reflected in the statistical data. More systematic statistical reporting procedures could help to refine the modelling exercise.

Energy consumption and emissions associated with construction, demolition, energy and material production activities (embodied emissions) are disregarded; however, the potential indirect environmental impacts of the scenarios are discussed in section 4.3. These activities could be accounted for by expanding the system definition to include them as processes. A simple approach to include indirect emissions associated with the production of electricity and district heating is to account for their carbon intensities. When such accounting is conducted using the values from Mavromatidis *et al.* (2016), the emissions results for 2010 are 3% higher than shown in **Figure 6**.

While the limitations highlight possible further developments, the results of the uncertainty analysis show that the model is robust.

### 4.2 Modelling disruptive measures

As part of the scenario analysis, the authors modelled a disruptive measure triggering an increased replacement of the most energy-consuming buildings by highly energy-efficient buildings with a combined lifetime-leaching approach. The results obtained using the combined approach show that the method captures both the heterogeneity of the stock and the complete demolition and replacement of the targeted segment of the stock (see Appendix G in the supplemental data online).

This study considered a leaching rate leading to the complete demolition of the non-renovated buildings built before 1990 during the leaching period 2021–30. Such a definition was set on purpose as a radical intervention in order to study the effects of disruptive measures. However, the definition of the leaching is flexible and thus it could be defined

using other rates, segments of the stock and leaching periods. Despite the flexibility of the combined approach, it is subject to the limitations exposed in section 4.1. The combined approach has the potential to model other disruptive phenomena in building stocks such as wars and natural disasters (*e.g.* flooding, earthquakes, fire events), and it could be applied in other sectors such as transportation to model car accidents in the vehicle fleet.

### 4.3 Policy implications

The scenario analysis indicates that the main leverage points for energy savings during the use phase of Swiss residential buildings reside in lifestyle changes, whereas emission reductions can be highly levered by technological developments.

In terms of emissions goals, the Paris Agreement can be achieved by extending current policies together with a rapid replacement of fossil-fuel heaters by heat pumps and renewable energies, leading to their complete replacement by 2050 (carbon neutrality). These measures require high economic investments to extend current policies (BP beyond 2025) and to promote the rapid replacement of fossil fuel heaters. The carbon neutrality scenario triggers an increase in electricity and renewable energy demand, which could condition the feasibility of reaching carbon neutrality in all sectors by shifting the burden to the energy supply sector. This burden could be eased by reducing energy demand, which could also lower cumulative CO<sub>2</sub> emissions and thereby expedite efforts to remain within the carbon budget.

In terms of energy goals, while the ES2050 can be met by the technological developments presented above, the 2000-Watt Society target can only be reached if lifestyle changes are considered, as shown by the combined technical scenario, where a set of ambitious technological developments is insufficient to reach the target. The highest leverage of lifestyle changes lies in lower indoor temperatures and heating only dwelling areas, which, combined with high energy standards and either higher renovation rates or replacement measures, could provide energy savings sufficient to reach the 2000-Watt Society target, as shown by the combined renovation and combined replacement scenarios. These two scenarios require high economic incentives to promote Minergie-A and Minergie-P standards for new and renovated buildings, respectively, and either a renovation rate of 3% or the replacement of buildings consuming > 140 kWh/m<sup>2</sup>/yr. The replacement measure might induce social reluctance in households living in the targeted buildings because they need to move to other dwellings temporarily. Both scenarios require lifestyle changes toward optimisation and the responsible use of SH to minimise the performance gap of buildings and thus reduce the rebound effect of overheating due to energy-efficiency gains. Such optimisation could be assisted by temperature-controlling systems (Khoury *et al.* 2017), which could be promoted via economic subsidies.

Complementing the above-mentioned lifestyle changes with a 15% lower FApC and construction gradually dominated by MFH could be an alternative lifestyle-based strategy to meet the 2000-Watt Society target (supreme green lifestyles). As suggested by Drouilles *et al.* (2017), policies supporting such scenario are difficult; however, the promotion of densification in new buildings or extensions and reorganisations in SFH could help. The scenarios meeting the 2000-Watt Society target re-emphasise the findings of the SA for 2050 regarding the importance of including lifestyle aspects in long-term scenario modelling and policy discussions.

The strategies for meeting the 2000-Watt Society target have substantial impacts on construction and demolition activities. The combined replacement scenario leads to an increase in construction and thus a potential increase in material production activities, which might result in an increase of indirect energy and emissions. Similar effects are expected in the combined renovation scenario due to a substantial increase in renovation activity. Müller *et al.* (2013) found that greenhouse gas emissions associated with material production for construction can be critical for reaching the global climate targets. The supreme green lifestyles scenario leads to lower construction activity and thus a potential decrease in indirect environmental impacts.

## 5. Conclusions

This study presented 11 scenarios triggering different pathways for direct energy consumption and direct CO<sub>2</sub> emissions associated with the use phase of Swiss residential buildings. The scenario analysis indicates that the main leverage points for reducing energy reside in lifestyle changes, such as lower indoor temperatures, whereas emission reductions can be highly levered by technological developments. Reaching the Paris Agreement, ES2050 and 2000-Watt Society goals is possible, but ambitious strategies are needed. This study provides a first assessment of disruptive measures and expands the analysis of lifestyle changes, thereby setting the grounds for enlarging the current portfolio of Swiss climate change mitigation strategies for the residential building sector. Given that the strategies are highly ambitious, more research is needed to evaluate economic and social aspects. Further research is also needed to quantify the effects of the strategies on indirect energy and emissions associated with buildings, and to study the options for reducing carbon emissions in materials production through material choice, production technologies, reuse of components and recycling. The model presented can be used as a backbone for such system expansion, eventually enabling a simultaneous evaluation of climate change mitigation and circular economy strategies.

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## Competing interests

The authors have no competing interests to declare.

## Data accessibility

The model developed within this work and the input data are available at <https://zenodo.org/record/3984758#.XzZBsegzZaQ>.

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## Supplemental data

Supplemental data containing Appendices A–F, the model description, a detailed description of the parameter estimation and uncertainty analysis, and additional model results can be accessed at DOI: <https://doi.org/10.5334/bc.61.s1>

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