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Doctoral thesis

Marta Roca Puigròs

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"Imagine you have the ability to travel through time and hear voicemail recordings from 100 years into the future. If present trends in sea-level rise or atmospheric warming continue, what kinds of story would be told regarding everyday life in these voicemail messages?"[1]

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[1] Wu, Jason S., and Joey J. Lee. "Climate change games as tools for education and engagement." *Nature Climate Change* 5.5 (2015): 413-418.

Abstract

Humanity is facing a global climate crisis induced by a growing population, carbon-intensive lifestyles, and highly polluting production systems. Solving the climate crisis requires a profound transformation of our socio-economic metabolism (SEM), i.e. the physical system of anthropogenic stocks and flows of materials, energy, and greenhouse gas (GHG) emissions. The transformation of the SEM towards a carbon-neutral system requires climate change mitigation (CCM) measures.

The implementation of CCM measures is driven by a constellation of different actors, i.e. the social system. Most research on CCM focuses on studying either the transformation of the physical or the social system. However, the two systems are highly interdependent and connected to each other. Therefore, the solutions need to address both systems. Most existing approaches to integrating the two systems focus on exploring the actors as objects, for example through agents in agent-based models. Such approaches are useful to include different actors' rationale; however, they are limited in (1) including participatory exercises and (2) triggering personal experiences. This limitation can be addressed by considering the actors as acting subjects. In this thesis, we propose the use of SEM-based simulation games (SGs) in order to integrate the two systems and to explore the actors' perspectives through acting subjects.

Furthermore, SEM-based SGs allow us to tackle another challenge of CCM research, namely its limited accessibility to wider audiences. Studies on CCM are typically targeted at policy-makers, industry representatives, and researchers, by means of scientific articles, reports, and oral presentations. By using SGs, we can use more playful and interactive means to address target groups such as the general public. In this thesis, we exemplify the link between SGs and SEM models with a case study, the postfossilCities SG, which contains a SEM model of the Swiss economy. The postfossilCities SG was developed in the frame of the Post-Fossil cities project.

In SEM models, the physical system is typically modeled through technology- and lifestyle-based parameters. Examples of technology-based parameters are energy intensity, energy carriers, and systems efficiency, whereas lifestyle-based parameters include stocks per capita, user behavior, and intensity of use. Despite the use of these two types of parameters, SEM studies on CCM have largely focused on exploring technology-driven measures, and thus on refining the modeling of such measures through technology-based parameters. This leaves (i) untapped potential for further CCM

through lifestyle-driven measures and (ii) unexplored synergies across technological developments and lifestyle changes. In this thesis, we explore and refine the modeling of both types of measures by developing two sectoral SEM models for the Swiss residential building stock and the Swiss passenger car stock. The sectoral models served as the basis for modeling and refining the Swiss economy-wide SEM model used in the postfossilCities SG.

The results of the sectoral models show that technology-driven measures are highly effective in lowering emissions and can transform the physical system into a carbon-neutral system. In particular, we found that the Swiss residential building sector can reach carbon neutrality in 2050 by (i) an extension of the current buildings program (i.e. lower energy intensity of buildings and increase use of renewable energies) and (ii) a complete replacement of fossil fuel heaters with heat pumps and solar energy by 2050. For the passenger car sector, the results show that carbon-neutrality can be achieved in 2050 through a full and rapid electrification of the car fleet, i.e. phase out sales of gasoline- and diesel-cars by 2025 and hybrid and plug-in hybrid cars by 2030.

While technology-driven measures are highly effective at reducing emissions, they are limited in lowering energy consumption, and thus CCM strategies solely based on technology-driven measures can result in missing some of the energy-related goals. For example, in the residential building sector, we found that the 2000-Watt Society target can only be achieved by combining technology- and lifestyle-driven measures, which include (i) lower average indoor temperatures, i.e. from 22°C to 20°C, (ii) a reduction in heated surface areas, and (iii) a reduction in floor area per capita. For passenger cars, the results show that the lowest energy consumption is provided by a combination of technology- and lifestyle-driven measures, which includes a widespread use of ride-sharing and autonomous cars (ACs). In contrast, the penetration of ACs without ride-sharing is expected to trigger the highest energy consumption in 2050. Consequently, lifestyle-driven measures are highly effective in reducing energy consumption and in preventing an increase in energy demand from emerging technologies, such as ACs.

Additionally, the results of the sectoral models indicate that the full mitigation effect of technology-driven measures can be severely delayed by the time it takes to replace the existing (technology) stock, while lifestyle-driven measure have an immediate impact on the entire stock. As a consequence, a longer delay in the implementation of technology-driven measures would require more drastic lifestyle-driven measures based on "old" technologies to reach the climate goals by 2050.

Through the development of the postfossilCities SG, we found that SEM-based SGs can be used to integrate physical and social systems in a novel manner. In this integration, the physical system is described through a SEM model and the social system through (1) a role-play, (2) role-strengths models to quantify the success of each role, and (3) other game mechanics. Furthermore, we identified several benefits of linking SEM models and SGs: (1) the communication and understanding of complex systems through experiential and emotional learning, (2) the use of oral, written, non-verbal, and visual communication through activities and processes such as reading, writing, discussing, and doing, which are usually more appealing and intuitive for the general public, and (3) the increased robustness of SGs through mass- and energy-balance consistent representations of physical systems. However, we also found challenges in linking SEM models and SGs: (1) the integration of approaches from different disciplines, (2) the highly resource-intensive nature of the game development process, and (3) the identification of the right balance between simplification and complexity. Some of these challenges can be addressed by considering them early in the planning process of the project.

Further research can support the refinement of SEM models and SEM-based SGs. For SEM models, future efforts should focus on refining the link between sectors through material, energy, and GHG emissions flows, which requires a better understanding of the dependencies and dynamics across sectors. An example of such dependencies is observed between stocks (e.g. building stock or car fleet) and material industries, as the stock size and the stock dynamics drive material demand. Therefore, the refinement of the links across sectors will allow for a more comprehensive evaluation of the direct and indirect emissions associated with CCM measures. This refinement can also provide a solid basis for improving the modeling of lifestyle-driven measures, and thus for understanding the (systemic) effects of behavioral change.

For the SEM-based SG, further developments can exploit the rapid evolution of the SGs field through the use of new technologies, such as virtual reality, augmented reality, or real location-based features. By doing so, SGs can make the game experience highly engaging and motivating, and increase the outreach of CCM strategies to wide audiences with no prior knowledge of the topic.

Acknowledgements

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Table of content

List of Appended Papers and Author's Contributions

Primary publications:

	Title and authors	**Contribution by Roca-Puigròs, M.**
I	*Pathways toward a carbon-neutral Swiss residential building stock* Roca-Puigròs, M., Billy, R. G., Gerber, A., Wäger, P., & Müller, D. B., in *Buildings and Cities*, 2020, DOI: http://doi.org/10.5334/bc.61	Research design, data collection, modeling, analysis, visualizations, and writing
II	*Modeling the transition toward a carbon-neutral car fleet: Integrating electrification, shared mobility, and automation* Roca-Puigròs, M., Marmy, C., Wäger, P., & Müller, D. B., in review by *Transportation Research Part D: Transport and Environment*, 2022.	Research design, data collection, modeling, analysis, visualizations, and writing
III	*Linking Socio-Economic Metabolism models and Simulation Games: Reflections on benefits and challenges* Roca-Puigròs, M., Gerber, A., Ulrich, M., Reich, M. Y., Müller, D. B., & Wäger, P., in review by *Journal of Industrial Ecology*, 2022.	Research design, analysis, visualizations, and writing

Additional publications:

	Title and authors	**Contribution by Roca-Puigròs, M**
IV	*Games on Climate Change: Identifying Development Potentials through Advanced Classification and Game Characteristics Mapping* Gerber, A., Ulrich, M., Wäger, F. X., Roca-Puigròs, M., Gonçalves, J. S. V., & Wäger, P., in *Sustainability*, 2021, DOI: https://doi.org/10.3390/su13041997	Co-design of research and writing

1. Introduction

1.1. Coordinated and systemic strategies for climate change mitigation

Global warming induced by human activities has been increasing at an unprecedented rate since the start of the industrial revolution. The global mean surface temperature has increased by 1.09°C between the pre-industrial period 1850-1900 and the recent decade of 2011-2020 (**Figure 1**) [1]. Similarly, the greenhouse gases (GHG) causing global warming have been increasing at staggering rates over the past century, reaching average concentrations of 410 ppm for CO_2, 1866 ppb for CH_4, and 332 ppb for N_2O in 2019 [1].

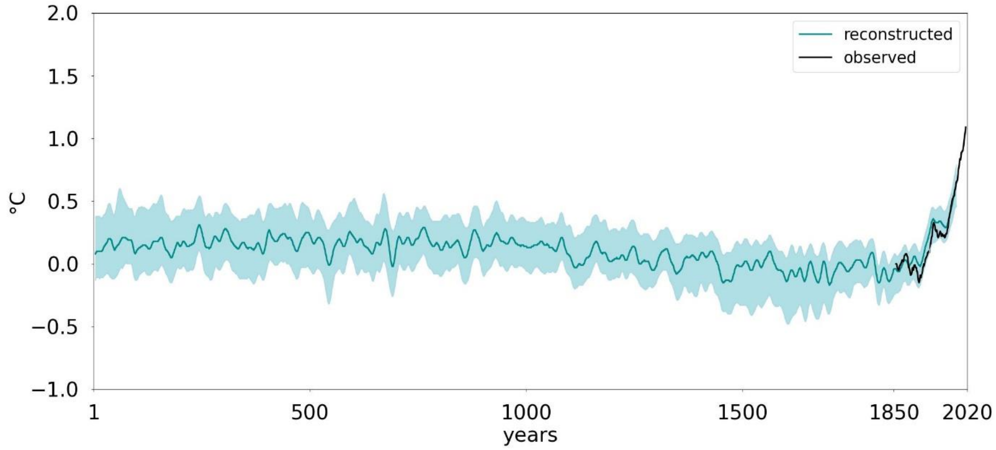

Figure 1 Changes in global surface temperature reconstructed from paleoclimate archives and observed for the period 1850-2020, relative to the period 1850-1900. The blue shading shows the ranges for the temperature reconstructions with 5-95% likelihood [1].

Over the past decades, a large body of scientific research has focused on the causes, effects, and evolution of global warming and climate change. Since 1988, the Intergovernmental Panel on Climate Change (IPCC) has used scientific research to compile highly comprehensive assessment reports (AR) on the state of knowledge on climate change, including impacts, future risks, and mitigation options [2]. In 2014, the AR5 exposed that climate change had already contributed to problems such as flooding, food supply disruption, and species migration and extinction [3]. The AR5 also highlighted the need to reduce GHG emissions to avoid the worst consequences of climate change, and it strongly centered the challenge of reducing GHG emissions on the transformation of the energy sector. The transformation of the energy sector was found to require an almost total stop of fossil fuel burning by 2100 and a tripling of the share of low-carbon energy by 2050 if global warming is to be limited to 2°C [3].

In 2018, the IPCC published a special report on global warming of 1.5°C [4]. This report builds on the Paris Agreement, which includes the goal of "holding the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit temperature increase to 1.5°C above pre-industrial levels". The special report concluded that limiting global warming to 1.5°C, with no or limited overshoot, requires reducing global CO_2 emissions by about 45% from 2010 levels by 2030 and achieving net zero by 2050 [4]. In addition, the special report highlighted the need for fast transformations not only in the energy sector, but also in agriculture, land use, food supply chains, transport systems, buildings, material manufacturing and consumption, among others. For example, it was exposed that recycling and substituting materials, together with developing circular economy strategies, could play an important role in reducing emissions [4].

In 2021-2022, the AR6[2] expanded the findings of previous reports by (1) highlighting the unequivocal evidence that humans have warmed the planet and (2) warning that further delays in climate action will make us miss the window of opportunity to ensure a "liveable and sustainable future for all" [5]. Furthermore, the AR6 reported that in 2019, humans contributed to climate change globally by releasing about 59 Gt of GHG emissions, of which 38 Gt were CO_2 emissions from fossil fuel combustion and industrial processes [6]. The list of sectors contributing to GHG emissions in terms of direct emissions in 2019 was as follows, from highest to lowest contributor: (1) energy production, (2) industry, (3) agriculture, forestry, and other land use (AFOLU), (4) transport, and (5) buildings (**Figure 2**) [6]. If indirect emissions are allocated to the final consumer sectors, the ranking is: (1) industry, (2) agriculture, forestry, and other land use (AFOLU), (3) buildings, (4) transport, and (5) energy production[3] (**Figure 2**) [6].

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[2] In the course of writing this thesis, the synthesis report of the 6th AR had not been published.

[3] Energy production includes the entire energy sector except for electricity and heat production. This categorization follows the scope 2 reporting for indirect emissions.

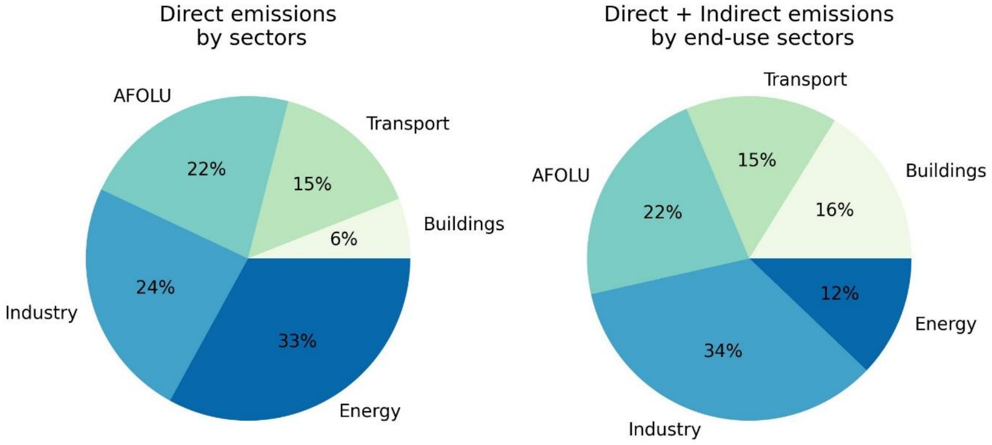

Figure 2 Total direct and indirect greenhouse gas emissions related to human activities in 2019, based on [6]. Percentages may not sum up to 100 due to rounding. The categorization under "Direct + Indirect emissions by end-use sectors" follows the scope 2 reporting for indirect emissions, which allocates the emissions related to electricity and heat production to the end-use sectors but not material-related emissions or other energy-related emissions [6].

Based on the AR6, the global carbon project [7] and Friedlingstein et al. 2021 [8] reported a remaining carbon budget[4] of 420 Gt CO_2 in 2021 to limit global warming to 1.5°C with a 50% likelihood. This budget will be depleted in 11 years if no further reductions occur.

The remaining carbon budget supports the findings of the latest ARs by showing that the time window for climate action is small. However, drastically and quickly reducing emissions is a complex task. Recent research has underlined such complexity by describing (1) the systemic nature of the climate problem, i.e. climate change is caused by multiple interrelated sources and (2) the importance of focusing climate change mitigation (CCM) strategies beyond an energy transition, for example by transforming materials industries and the building and vehicle stocks [9, 10]. The climate problem requires therefore a transformation of the entire physical system of our society, i.e. flows and stocks of goods, materials, energy, and emissions.

The transformation of the physical system is realized by a large number of actors who together form a multi-actor network or constellation, i.e. the social system. The multi-actor constellation together with the systemic nature of the climate problem requires

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[4] The remaining carbon budget is the total net amount of CO_2 that can be emitted in the future by human activities while keeping global warming to a specific global warming level.

coordinated and systemic CCM strategies. The difficulty of coordinating systemic strategies with multi-actor constellations confronts humanity with a global and wicked crisis, the climate crisis. Next, we describe the physical and the social systems of our society in the context of the climate crisis.

1.2. The physical system

Human activities aim at satisfying human needs and wants, such as shelter, food, clean water, mobility services, education, and health care [11-13]. In order to satisfy such needs and wants, we harvest, extract, transform, and use natural resources from the environment, and we built large stocks, such as buildings, vehicles, products, factories, or infrastructure [10]. The resources used to build, maintain, and operate stocks are eventually returned (in one way or another) to the environment. Consequently, the fulfillment of human needs and wants leads to exchanges between the anthroposphere (humans) and the environment, which, in the field of industrial ecology, has been named socio-economic metabolism (SEM)[5] [14-19].

In particular, SEM refers to the set of goods, materials, energy, and emissions flows and stocks associated with human activities [13, 14, 16, 17, 20, 21]. **Figure 3** presents an example of the global SEM and its quantification for 2008. The stocks and flows in SEM systems can be traced for goods (e.g. battery electric cars), materials (e.g. steel), and/or individual chemical elements (e.g. lithium) [22], depending on the scope of the study. The different goods, materials, and elements can be described in different layers of a SEM system, creating a multi-layer framework [23]. SEM studies are also defined in terms of geographical space and time.

In SEM studies, the material flow analysis (MFA) methodology is commonly used to assess and quantify the stocks and flows based on the mass and energy balance conservation principle [10, 19, 22, 24]. Furthermore, the MFA methodology also allows for the segmentation of the stocks into different types according to common characteristics. For example, a stock of cars can be segmented according to the fuel type or energy technology, i.e. internal combustion engine cars, battery electric cars, hydrogen cars, hybrid and plug-in hybrid cars, among others.

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[5] In this thesis, SEM is used as a synonym for anthropogenic metabolism, industrial metabolism, and social metabolism.

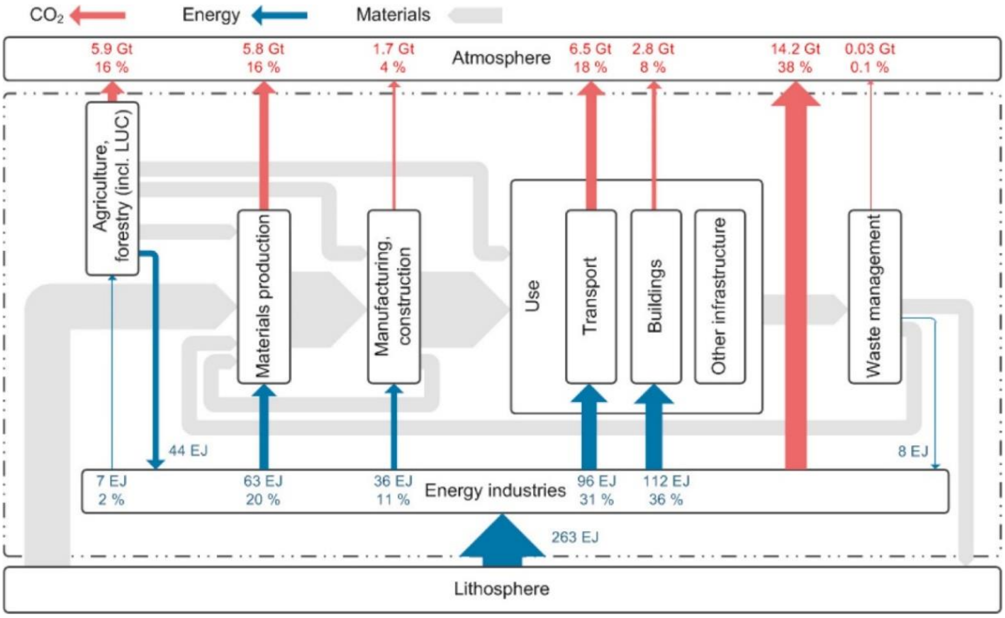

Figure 3 Global socio-economic metabolism system in 2008 [25]. The system definition includes the links between the major sectors (boxes inside the system boundaries) and the environment (boxes outside the system boundaries) through materials, energy, and CO_2 emissions. LUC stands for land use change. Further details about the quantification are provided in Müller et al. 2013 [25].

SEM studies often focus on exploring systemic problems related to human activities, such as climate change. For the case of climate change, SEM systems can link the flows of GHG emissions with the stocks and flows of different goods and materials, as well as with flows of energy in different sectors (see an example in **Figure 3**). In this way, we can identify hotspots for CCM and reflect on the drivers and the dynamics related to climate change. Furthermore, SEM studies can include scenario analyses to quantitatively assess alternative CCM strategies.

1.3. The social system

The physical system is constantly shaped and transformed by multiple actors. The actors realize such transformation mainly through the production and consumption of goods and services. In the literature, the key actors and their interactions have been described and analyzed using different frameworks.

A well-known framework is the triple helix, which defines the interactions between academia (university), industry, and government, to foster innovation and societal development [26] (**Figure 4**). These interactions can be highly complex, but in simple terms, academia is considered the provider of education and basic research, which serves as groundwork for the development of commercial goods and services by industry [26]. The government is responsible for implementing regulations and policies that determine the boundary conditions for academic and industrial activities [26]. The triple helix has been expanded by the so-called quadruple helix, which adds the civil society to the framework [27] (**Figure 4**). The civil society interacts with academia, industry, and government by determining the needs and demands of society [27].

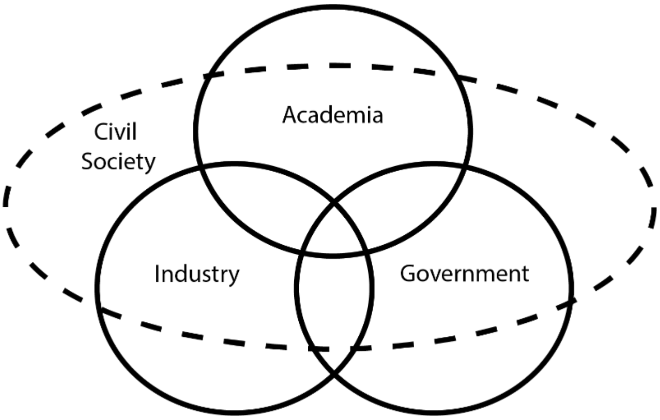

Figure 4 Triple and quadrupole helix visualization [26, 27].

Another well-known framework is the multi-level perspective on (sustainability) transitions by Geels [28] (**Figure 5**). The framework describes three dimensions of transitions: niche innovations, socio-technical regime, and socio-technical landscape [28]. The niche innovations act as "incubation rooms" for radical and new ideas [28]. The socio-technical regime refers to the established practices and rules that constrain human activities [29, 30]. The regime is defined by (1) technology, (2) user preferences and markets, (3) industry, (4) policy, (5) science, and (6) culture [29, 30]. These aspects are defined by practices and rules such as cognitive routines and shared believes, capabilities and competences, lifestyles and user practices, and legally binding contracts [30]. During a transition process, all the aspects of the socio-technical regime undergo changes [28]. The last dimension of the framework, the socio-technical landscape, refers to the exogenous environment, global trends, and cultural changes, which cannot be changed at will by the actors [28].

The two presented frameworks can support the identification of relevant actors, as well as their perspectives, goals, and motivations.

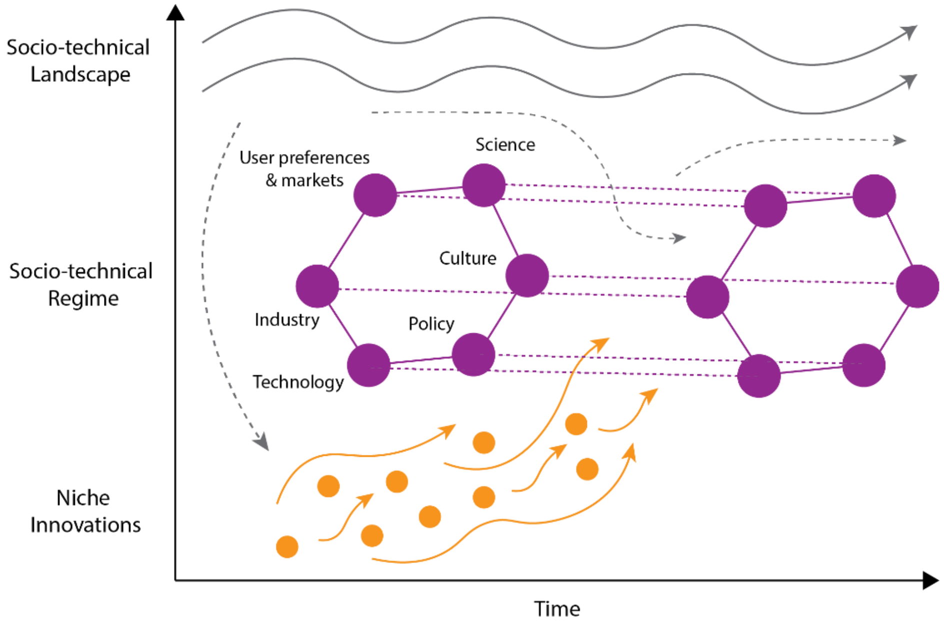

Figure 5 Multi-level perspective on transitions, based on [28-30].

For the case of transforming the SEM to mitigate climate change, many actors play an important role. The description of some of these actors and their goals are presented in **Table 1**. The table is illustrative and by no means complete in terms of the actors, the descriptions, and the goals.

As exposed in **Table 1**, the actors have diverse and often conflicting goals and perspectives. For example, industry has a major interest to be profitable through the production of services and goods even if they pollute the environment, while the population wants to live a happy and healthy life in a pollution-free environment. The conflicting interests lead to major challenges in transforming our society, especially towards a carbon-neutral future, because the transformation requires negotiations, coordination, and agreements in large networks of actors.

Table 1 Illustrative descriptions of actors and their goals in socio-economic metabolism systems.

Actors	Description	Primary goals
Politicians	Design and create regulations and laws to organize society.	Be re-elected. Develop policies on behalf of their constituents.
Investors	Lend money to the economy, e.g. industry leaders.	Make profit.
Researchers	Understand the world. Generate knowledge.	Provide a robust understanding of problems and potential solutions.
Citizens	Live a happy and healthy life.	Satisfy human needs and wants.
Journalists	Find and present information through different media.	Inform the public about problems, solutions, and events.
Industry leaders	Produce and manufacture materials, energy, and goods. Operate services. Manage infrastructure.	Make profit.
City planners	Desing urban spaces and systems.	Provide solutions to organizational societal challenges.
Non-governmental organization representatives	Lobbying and campaigning for a social mission. Educate and raise awareness.	Hold power in decision-making processes. Influence society.

The complexity of both physical and social systems and the strong interdependence of the two systems, make the integration of the systems and the combined assessment crucial for the design and implementation of CCM strategies. Next, we describe how such integration can be done.

1.4. Integrating the physical and the social systems

The combination of physical and social systems can be done by integrating SEM models, i.e. the physical system, with the following models and frameworks representing the social system:

- *Structural agent analysis (SAA) models*. The SAA models provide a framework to analyze how social structures (e.g. social norms, traditions, and cultures) and stakeholder's decisions affect material flow management [31, 32].
- *Action-in-context (AiC) frameworks*. The AiC framework allows the modeler to explicitly connect the physical system and their social driving forces, such as chains of actors, actions, and decision-making mechanisms to identify pivotal actors and relevant policies to control the system [33].

- *Multi-attribute utility theory (MAUT)*. MAUT is an assessment method used to measure the attractiveness of different scenarios based on a set of environmental, economic, and social attributes, or criteria [34, 35].
- *Agent-based models (ABMs).* ABMs represent decision-making processes via agents, who, restricted by certain attributes and behavior rules, make decisions and interact with the system and/or other agents [36].

All of these approaches integrate physical and social systems by considering actors as objects. This implies that the integration of the two systems is performed by a modeler who considers the expected behavior of the actors. Therefore, these approaches are highly useful to include different actors' rationale and perspectives, in particular, when the different perspectives in multi-actor constellations are sufficiently understood. However, these approaches are limited in (1) including participatory exercises and (2) triggering personal experiences. This limitation can be addressed by considering the actors as subjects, e.g. subjects in negotiation processes. By considering the actors as subjects, we can enable the development of personal exploration through active participation in addressing societal problems. An example of an approach in which actors are explored as acting subjects is participatory modeling.

Participatory modeling is a model development method characterized by the involvement of the stakeholders or actors in the actual modeling process [37]. The use of participatory processes provides actors the opportunity to design and describe the model from an early stage of development, thereby increasing transparency and trust in models [38].

A third group of approaches to integrating physical and social systems is formed by simulation games (SGs). Similar to participatory modeling, SGs also allow for the exploration of actors as acting subjects, e.g. through a role-play [39-41]. SGs are defined as games specifically applied to reproduce dynamic real-world-phenomena in an experimental workshop setting [42, 43]. Typically, the workshops are composed of three phases: the introduction, the simulation, and the debriefing [44]. In the introduction, players are familiarized with the topic, the game scenario, the roles, and the rules of the game. The simulation phase consists of the activity of "playing the game", and the debriefing is about reflecting on the insights gained from the game.

1.5. Problem statement, goals, and research questions

In the literature, the environmental impacts of human activities and the effectiveness of CCM measures have been extensively assessed by using life-cycle assessment (LCA), environmental extended input-output (EE-IO) models, integrated assessment models (IAMs), and MFA or stock and flow models. While LCA and EE-IO are robust and exhaustive in providing static/comparative assessments of the environmental impacts of certain products or services, they are rather constrained in assessing future CCM strategies due to a limited consideration of the time dimension [45].

In contrast, IAMs consider the time dimension, and thus they have been extensively used in IPCC reports to assess CCM scenarios [3, 4, 6]. However, IAMs have been rather limited in assessing lifestyle-driven CCM measures (e.g. smaller stock for the same service demand, transport mode shift, or lower energy demand) because the stocks and the stock dynamics have traditionally not been included in such models [45-48]. Stocks are crucial for assessing CCM measures, and in particular lifestyle-driven measures, because (i) they link end-use service demand (e.g. demand of m^2 for housing), energy demand (e.g. space heating per m^2), and GHG emissions, (ii) they determine long-term dynamics of physical systems due to the long lifetime of goods (e.g. buildings or cars), (iii) they can serve as proxies to determine the state of the metabolic transition to sustainability [10]. In addition, most lifestyle-driven measures affect the existing stock, for example by changing the intensity of use of the stock, which means that a representation of the stocks and their development is crucial to model lifestyle-driven measures.

Due to the reasons explained above, IAMs are typically used to assess technology-driven measures (e.g. higher use of renewable energies or higher energy system efficiencies), thus omitting the CCM potential of lifestyle-driven measures. However, in recent years, more efforts have been put into including lifestyle-driven measures in IAMs. For example, Grubler et al. 2018 used an IAM to find that lifestyle changes such as (1) a reduction of the floor area per capita in the global North, (2) an increase in service-based business models, and (3) transport mode shifts away from private cars, can lead to a 20% decline in material production and consumption by 2050 [49]. This decline, combined with decarbonization and afforestation, can result in a scenario that complies with the 1.5°C temperature increase threshold without using negative emissions technologies [49].

In this thesis, we use stock and flow models[6] to assess technology- and lifestyle-driven CCM strategies because these models provide an explicit representation of the time dimension and the stocks. Furthermore, the model dynamics in stock and flow models are based on parameters that represent both technological development and lifestyle-related aspects [24, 50].

In the literature, stock and flow models have been used sparsely to explore lifestyle-driven measures for CCM. For example, Pauliuk et al. 2013 developed a dynamic stock and flow model for residential buildings, and found that smaller flats combined with lower heated floor areas can considerable contribute to meeting climate targets [51]. Another example is the RECC framework that expands the quantification of the stocks by including the "intensity of use and operation", which is defined by either "more intense use of buildings" or "ride and car-sharing" [52, 53]. Although these studies provide first assessments of lifestyle-driven measures using stock and flow models, the nexus between stocks and lifestyle changes remains highly underexploited. This leaves (i) untapped potential for further CCM through lifestyle-driven measures and (ii) unexplored synergies across technological developments and lifestyle changes. In this thesis, we contribute to the solid definition of the nexus between stocks and lifestyle changes by assessing a large set of technology- and lifestyle-driven measures in the Swiss residential building sector (paper I) and the Swiss passenger car sector (paper II) (**Figure 6**). These two sectors were chosen due to their high share (in 2020 both sector together represented 38%) of total Swiss GHG emissions [54].

Most research on CCM focuses on studying either the transformation of the physical or the social system. Approaches that integrate the physical and the social systems are seldom used. However, in reality, the two systems are highly interdependent. While actors in the social system can implement measures to change the physical systems, the physical systems provide the physical boundary conditions for the actors. Thus, climate change requires solutions that assess and integrate both systems. As specified in **section 1.4**, most approaches that integrate the two systems consider the actors as objects and are therefore limited in triggering personal exploration of societal problems. In this thesis, we use SEM-based simulation games (SGs) in order to integrate the two systems and to explore the actors' perspectives through acting subjects.

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[6] The term "stock and flow models" includes the terms "stock dynamics models" and "dynamic stock-driven model" used in the appended papers.

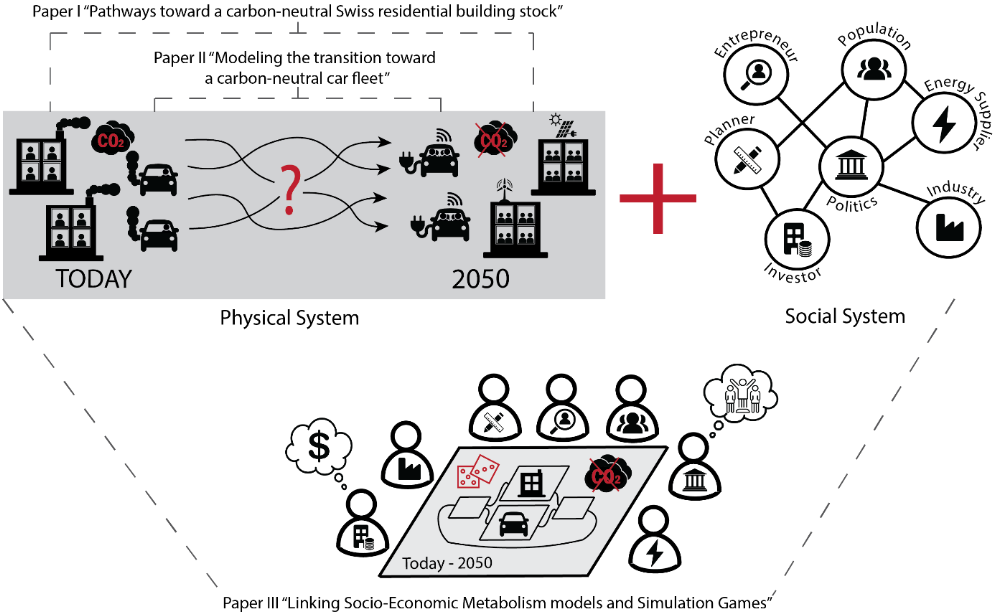

Figure 6 Framework of the thesis with the conceptual connections between the three main papers.

SEM-based SGs allow us to tackle another challenge of CCM research, namely the limited accessibility of CCM research to wider audiences, including the general public. Studies on CCM are typically targeted at policy-makers, industry representatives, and researchers, by means of scientific articles, reports, and oral presentations. Nevertheless, the general public plays an important role in CCM through their lifestyle, daily choices, and political engagement.

The expansion of the accessibility of SEM studies is therefore critical for the success of CCM strategies. SGs address the audience by means of interaction tools, which have been found to be more effective than lecture-driven learning processes [55]. In this thesis, we propose the use of SEM-based SGs to expand the outreach of CCM research. We illustrate this proposal by developing a SEM-based SG, namely the postfossilCities SG, which was developed in the frame of the "Post-Fossil cities" project. In paper III, we present the postfossilCities SG (**Figure 6**), and we reflect on the potential benefits and challenges of linking SGs and SEM models.

The goals of the work conducted in this thesis are:

- To inform the general public, industry representatives, policy-makers, and researchers about different mass-balance consistent transition pathways towards a carbon-free future, including both technology- and lifestyle-driven measures.
- To provide a set-up, where the general public, industry representatives, policy-makers, and researchers can explore and experience alternative transitions towards carbon-neutrality, including the physical and social systems of our society.

As mentioned earlier in this section, the consideration of lifestyle-driven measures in CCM scenarios is rather sparse. Thus, in order to achieve the first goal, i.e. the inclusion of lifestyle changes in CCM strategies; we had to refine the modelling of behavioral change through lifestyle-based parameters in stock and flow models.

The goals of this thesis were addressed by considering the following research questions:

1. How can the Swiss physical system be transformed into a low-energy and carbon-neutral system through technology- and lifestyle-driven measures?
2. How can the physical and social systems be integrated through simulation games (SGs)? What are the benefits and challenges of such integration?

2. Methodology

In this thesis, the Swiss physical system is described in three SEM models, two of which have a sectoral focus and one of which has an economy-wide scope. The sectoral models have a twin purpose: (1) build a robust scientific understanding of CCM strategies and (2) inform the development of the Swiss economy-wide model. The economy-wide SEM model was developed for the postfossilCities SG. **Figure 7** presents an illustrative and aggregated system definition of all three models and a visualization of the parts covered by each paper.

Next, we briefly explain the two sectoral SEM models (detailed explanations can be found in the appended papers I and II) and the economy-wide SEM model. We then describe the modeling of disruptive CCM measures considered in the Swiss residential building stock model and the postfossilCities SG. Subsequently, we introduce the social system associated with the economy-wide SEM model, and finally, we present the integration of the economy-wide SEM model and its social system through a SG.

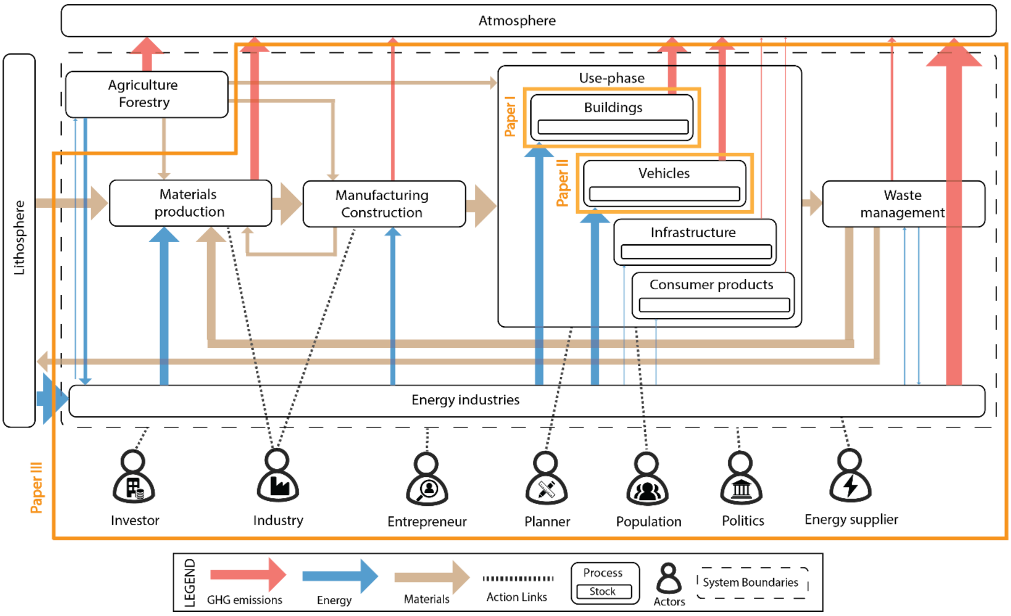

Figure 7 Illustrative scheme of a socio-economic metabolism system, including the physical flows and stocks of materials, energy, and greenhouse gas emissions associated with the major economic sectors, and the social actors steering the socio-economic metabolism system (adapted from [25]). The orange squares determine the parts of the system covered in each paper of this thesis.

Physical system: sectoral models

The sectoral models represent the Swiss residential building stock and the Swiss passenger car stock. The system definition for the sectoral models describes the use-phase of the sectors by including the stock, the direct energy consumption, and the direct emissions.

In the sectoral models, the stock was defined together with the corresponding stock change between two consecutive years, the inflow, and the outflow. These variables were described in terms of floor area (m^2) and number of dwellings for the residential building sector, and in terms of number of passenger cars for the passenger car sector.

For both sectors, the stock was defined for several dimensions, including time, cohorts, and types. In the residential building stock model, the types included building types (single-family and multi-family houses), renovation states (non-renovated, renovated during 1971-2020, and renovated after 2020), and intensity of use (dwellings used daily, dwellings used temporarily, and vacant dwellings). In the passenger car stock, the types included the ownership category (non-shared cars and shared cars through car- or ride-sharing services)[7], the energy carriers (internal combustion engine vehicles (ICEVs), hybrid and plug-in hybrid electric vehicles (P/HEVs), and battery electric vehicles (BEVs)), and the autonomous level (level 0 or non-autonomous cars and level 5 or fully autonomous cars (ACs)) [56].

From the segmented stock of residential buildings and passenger cars, we calculated the direct energy use and direct GHG emissions, i.e. flows of energy and GHG emissions. This calculation chain is based on Kalt et al. 2019 [57].

The stocks and flows were quantified using a dynamic stock-lifetime-driven approach [10, 24, 50, 58-63] and a set of technology- and lifestyle-based parameters. These parameters were used to model CCM measures. Technology-driven CCM measures were modeled by using technology-based parameters such as energy carriers, energy intensity, heating system efficiency, fuel efficiency, and renovation rates. These parameters were defined and calibrated using a wide range of literature [24, 50, 51, 59-61, 64] and are therefore not further specified here. Detailed descriptions of these parameters and the assumptions can be found in the appended papers I and II.

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[7] Non-shared cars are owned by households, while shared cars are owned by the companies providing car- and ride-sharing services.

Similarly, lifestyle-driven CCM measures were modeled through lifestyle-based parameters. For the residential building sector, the lifestyle-based parameters included: (1) user behavior that translates the technical energy intensity to the real energy consumption[8], (2) floor area per capita in terms of daily used dwellings and temporarily used dwellings (holiday houses), and (3) correction factor from stock of living area to stock of energy reference area (ERA). For the passenger car model, the lifestyle-based parameters included: (1) cars per capita (car ownership), (2) car occupancy defined as the average number of people in a driving car, and (3) transport performance indicator, which represents the average annual distance driven by a person using a car.

The data used for the model parameters was mainly sourced from the Swiss Federal Office of Statistics [65], the Swiss Federal Office of Environment [66], scientific articles, and reports. The uncertainty of the sectoral models was assessed through sensitivity and comparative analyses, which included validating the historical results of the models against statistical data. The efficiency of alternative CCM measures was assessed using scenario analyses. An overview of the CCM measures included in the scenarios for both Swiss residential buildings and Swiss passenger cars is provided in **Figure 8**.

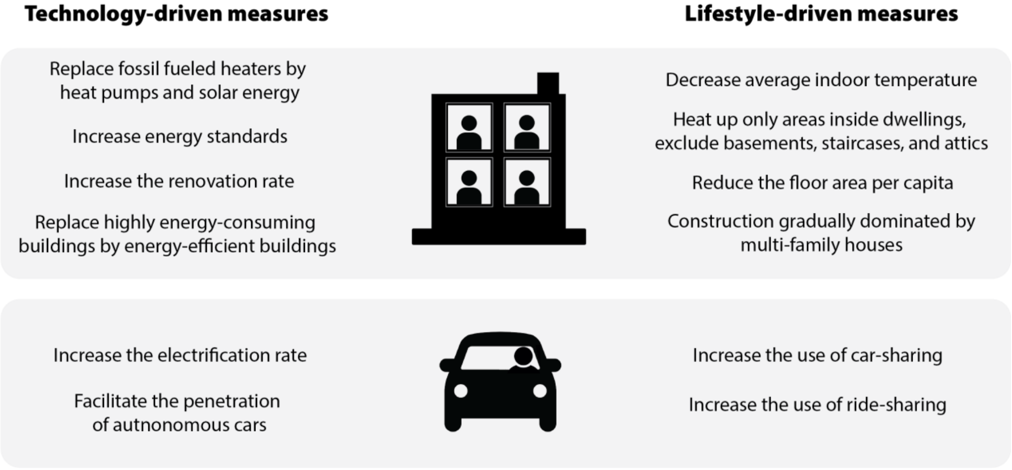

Figure 8 Overview of the technology- and lifestyle-driven measures assessed in the Swiss residential building stock model and the Swiss passenger car stock model.

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[8] Technical energy refers to the calculated (theoretical) energy demand of a building, whereas real energy corresponds to the energy demand by the households living in the building.

The scenario analyses included forecasting and backcasting scenarios. Forecasting scenarios start with the current situation and possible future paths, and then derive the end state. Backcasting scenarios start with the current situation and an end state, and then derive the possible pathways to reach the pre-defined end state.

According to the twin purpose of the sectoral models, the physical system represented in the sectoral models was described in a highly detailed and comprehensive manner, e.g. through a high segmentation of the stock. Such detailed model descriptions provide a solid basis to develop robust scientific understanding of CCM strategies.

The sectoral models were applied for the case of Switzerland; however, they were built using generic model descriptions, and thus they can be used for other countries or regions. The two models were implemented using Python and the library Open Dynamic Material System Model (ODYM) [67], with a highly modular framework, which facilitates a potential expansion of the system definition.

Physical system: economy-wide model

The sectoral models and the MatCH model [68-71] were used as a basis for designing and building the economy-wide SEM model. The economy-wide model was developed for the postfossilCities SG. An illustrative system definition of the economy-wide model is presented in **Figure 7**, inside the orange square for paper **III**.

The economy-wide model represents the Swiss physical system with the following sectors: (1) industry, (2) energy industry, (3) buildings, (4) vehicles, (5) infrastructure, (6) consumer products, and (7) waste management. The agriculture and forestry sector was modeled using results from the MatCH model and is therefore not fully integrated with the main economy-wide SEM model [68-72]. This implies that cross-sectoral synergies and trade-offs between the agriculture and forestry sector and the other sectors were not included.

The industry sector is defined by two industries: (1) steel and (2) cement and concrete. These two industries were used as a proxy for the entire industrial sector due to their high contribution (40%) to the total Swiss GHG emissions from industry [54, 66]. While this approach simplifies the modeling efforts, especially due to the high heterogeneity of the industry sector, it also brings some limitations, including the underrepresentation of synergies and competition between different industries, e.g. the substitution of steel by wood in construction.

The energy sector includes both energy produced locally, e.g. through nuclear power plants, hydro power plants, and renewable energies, as well as imported energy, e.g. petroleum, coal, and natural gas.

The buildings and the vehicles sectors are composed of commercial and residential buildings, and private and public vehicles, respectively. Infrastructure includes roads, bridges, streets, railways, and water, gas, and electricity networks. Consumer products comprise all goods related to clothing, accessories, offices, apartments, communication, education, leisure and entertainment, and health, among others. In other words, consumer products consist of all goods not covered by the other processes in the use-phase. The waste management sector includes landfill, incineration, recycle, and re-use.

The quantification of the economy-wide model was conducted using the same methodology and parameter types as for the sectoral models. The use of a dynamic stock-lifetime-driven approach in the Swiss economy-wide model implies that the stock of buildings, vehicles, infrastructure, and consumer goods are the drivers of the system dynamics. This means that these stocks and their dynamics determine the demand for materials (e.g. steel, concrete, and cement), as well as the amount of available scrap material. Furthermore, the size of the stocks and their energy intensities determine the energy demand. In this way, we modeled a system with high dependencies and connections across sectors.

The economy-wide model was developed as a multi-layer system, with the following layers: (1) goods, (2) steel, (3) cement and concrete, (4) energy, and (5) emissions. The goods layer defines the system using units such as the number of vehicles, m^2 of buildings, or tones of all materials in vehicles or buildings. For the case of the steel and concrete and cement layers, the system is defined by tones of the specific material. The energy and emissions layers include the energy and emissions flows associated with each process and stock of the system. The energy layer is quantified in terms of TJ and the emissions layers in terms of tons of CO_2-eq.

The input data for the Swiss economy-wide model was based on the Swiss Federal Office of Statistics [65], the Swiss Federal Office of Environment [66], the MatCH model, scientific articles, and reports. Similarly as in the sectoral models, the model uncertainty was analyzed through sensitivity and comparative analyses, which also included validating the historical results of the models against statistical data.

In contrast to the sectoral models, the economy-wide model represents the physical system in a crude manner, e.g. through using the steel industry and the cement and concrete industry as proxies for the entire industry sector. However, the economy-wide model was developed using the same modular framework as the sectoral models, which implies that the system definition of the economy-wide model could be easily expanded to include other industries, i.e. other material cycles.

Disruptive measures

The assessment of disruptive and radical CCM transition pathways is crucial for expanding and diversifying the portfolio of climate strategies, in particular under adverse futures. Thus, we included disruptive measures in the scenario analysis conducted for the Swiss residential building stock, as well as in the postfossilCities SG.

In this context, disruptive measures are defined as interventions that alter the lifetime profile of the stock by generating outflows, which are not determined by the age structure of the stock. An example of such interventions is the replacement of the buildings with the highest energy consumption in the existing stock by highly energy-efficient buildings, before the buildings reach end of life. Another example is the ban on driving gasoline and diesel cars and their consequent replacement before they reach end of life by for example battery electric cars.

In stock and flow models, the outflows from the stock are quantified either by predefined lifetimes (lifetime approach) or by leaching rates (leaching approach) [73]. The lifetime approach considers the heterogeneity of the stock (cohort or age structure) but it has limitations with respect to representing disruptions/alterations of the predefined lifetime. In contrast, the leaching approach calculates the outflows as a fraction of the stock, which, by increasing the fraction, allows the modeling of a sudden and substantial growth of the outflows. Thus, in the leaching approach, the cohort distribution of the stock is considered to be homogeneous and the outflows are independent of the cohort structure, which may lead to inaccurate results.

Both approaches have their strengths, weaknesses, and areas of application; therefore, we developed a novel approach in which the strengths of the two are combined. The new method uses both existing approaches in combination, which is why it was called the "combined lifetime-leaching approach". In the combined approach, the natural ageing process of a heterogeneous stock is accounted for by the lifetime approach, while the leaching approach captures the age-independent outflows triggered by the disruptive measure. Further details on the combined approach are presented in the appended paper I.

Social system

The social system associated with the Swiss economy-wide model in the context of the postfossilCities SG is composed of the actors shown in **Figure 7**. Each actor has specific motivations and goals, which in the postfossilCities SG were defined as follows:

- Investor: achieve highest possible return with the investments.
- Industry: achieve the highest possible profit.
- Entrepreneur: implement as many ideas as possible.
- Planner: develop and maintain public infrastructures and spaces.
- Population: maximize wellbeing and thereby live a good and happy life.
- Politics: maximize popularity.
- Energy supplier: guarantee the security of energy supply and achieve the highest possible return with the investments.

Integrating the social and the physical system through a SG

In this thesis, the social and the physical systems are integrated through the postfossilCities SG. The postfossilCities SG was developed in the context of a research project by a team including game developers, software developers, and SEM researchers. The game provides an experimental space where players can explore the transformation to a post-fossil future in Switzerland, i.e. a future that is not relying on fossil resources.

The game is applied in workshops, which last 3-6 hours and are facilitated by 1-2 trained facilitators. It features seven roles, each of which is played by 1-4 players. Each role has its own, role-specific goal, and at the same time works towards the common goal of reducing the GHG emissions to net zero without exceeding the available carbon budget. To pursue their goals, players are given a set of action cards that represent measures they can implement. If an action card is played, the measure is implemented and the consequences are evaluated in different models (including the Swiss economy-wide SEM model) that provide immediate feedback regarding GHG emissions, the carbon budget, and the role-specific goal. The game is played in rounds. Each round represents a third of a decade and includes strategy formation, negotiations, and evaluation of the decisions. Further details on the game development process are provided in the appended paper III.

The integration of the physical system (SEM model) and the actors or social system was done through the so-called connection models. The connection models link the actions in the game with the parameters of the SEM model. In particular, the connection models establish which actors affect which parts of the SEM system, and especially, through which actions. The actions links in **Figure 7** provide an illustrative example of such connections. Furthermore, the connection models also include the quantification of the new values for the model parameters upon actions in the game. Further details on the integration of physical and social systems through SGs are presented in the appended paper III.

3. Discussion, conclusions, and outlook

3.1. Research question 1: How can the Swiss physical system be transformed into a low-energy and carbon-neutral system through technology- and lifestyle-driven measures?

In this section, we first discuss the transformation of the Swiss residential building stock and the Swiss passenger car stock in sequential order. Then we describe the differences in the implementation or deployment of technology- and lifestyle-driven measures, and finally we reflect on the potential systemic perspective of the transformation of the two stocks.

Transforming the Swiss residential building stock

In paper I, technology-driven measures were found to be highly effective at lowering direct emissions associated with the Swiss residential building stock. In particular, we found that direct emissions can be reduced to zero in 2050 by (i) an extension of the current buildings program[9] (i.e. lower energy intensity of buildings and higher use of renewable energies) [74] and (ii) a complete replacement of fossil fuel heaters with heat pumps and solar energy by 2050. The results for the first measure are shown in **Figure 9** under the scenario *Extend Buildings Program* and the results for the first and second measures are presented under the scenario *Carbon neutrality*. The descriptions of all the scenarios developed for the Swiss residential building stock are provided in **Table 2**, further details are presented in the appended paper I.

The previous findings imply that meeting the Paris Agreement, i.e. carbon neutrality in 2050, in the residential building stock can be achieved through technology-driven measures alone. Unsurprisingly, current climate policies for the Swiss residential building stock focus solely on technological solutions [75]. These policies include the buildings program mentioned before and a CO_2 levy on fossils fuels for heating [74]. As shown in the results for the *Baseline* scenario (**Figure 9**), current policies are effective at lowering direct emissions, but they are insufficient to meet the Paris Agreement. In order to meet the Paris Agreement, the transformation of the residential building sector needs to be faster than the current speed. A faster transformation could be stimulated

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[9] The buildings program subsidizes energy-efficient renovations and renewable energies. The program timeline is 2010-2025.

by higher subsidies for energy-efficient buildings and renewable energies, i.e. a buildings program with higher subsidies.

Table 2 Descriptions of the scenarios developed for the Swiss residential building stock.

Scenario Name	**Scenario Descriptions**
Baseline	Past trends continue into the future, i.e. current policies are extended until 2100, except the buildings program that is assumed to terminate in 2025, as currently planned.
Extend Buildings Program	Extension of the buildings program until 2100, i.e. lower energy intensity of buildings and higher use of solar energy and heat pumps.
Carbon neutrality	Fossils fuels are gradually replaced by heat pumps and solar energy, reaching a complete fossil free energy mix in 2050. The premises in the scenario *Extend Buildings Program* are also assumed.
Green lifestyles	All households heat their dwellings to a maximum of 20°C instead of 22°C, and all households heat only areas inside dwellings. The premises in the scenario *Carbon neutrality* are also assumed.
Energy standards	The energy demand in new buildings is equal to 35 kWh/m^2/yr and in renovated buildings is lower than 60 kWh/m^2/yr. The premises in the scenario *Carbon neutrality* are also assumed.
Renovation	The renovation rate is increased from a current rate of 1.3% to a 3%. The premises in the scenario *Carbon neutrality* are also assumed.
Replacement	Buildings consuming more than 140 kWh/m^2/yr are replaced by buildings consuming less than 50 kWh/m^2/yr. The premises in the scenario *Carbon neutrality* are also assumed.
Combined technical	The combination of the premises defined in the scenarios *Energy standards, Renovation*, and *Replacement* are assumed.
Supreme green lifestyle	Gradual decrease from 47 to 41 m^2/capita (in 2050) and construction gradually dominated by multi-family houses (MFH) (100% in 2050), as opposed to MFH and single-family houses (SFH). The premises in the scenario *Green lifestyles* are also assumed.
Combined renovation	The combination of the premises defined in the scenarios *Green lifestyles*, *Energy standards*, and *Renovation* are assumed.
Combined replacement	The combination of the premises defined in the scenarios *Green lifestyles*, *Energy standards*, and *Replacement* are assumed.

Technology-driven measures were also found to reduce direct energy consumption; however, with a much lower potential than for emissions. An example of such energy decrease is presented in **Figure 9** under the scenarios *Extend Buildings Program*, *Carbon neutrality*, and *Combined technical.* The decrease in energy consumption caused by technology-driven measures is mainly driven by an increase in energy efficiency.

Such improvement in energy efficiency is restricted by technical limitations, and thus has a limited potential. Although most technology-driven measures lead to a decrease in overall direct energy demand, they also cause an increase in direct electricity consumption, since low-carbon solutions typically use electricity, e.g. heat pumps.

By contrast, we found that lifestyle-driven measures have a high leverage to reduce direct energy consumption, including electricity demand. For example, the 2000-Watt Society target[10] (2000 watts of primary energy per capita in 2050 in terms of continuous power [76]), which is the most ambitious target in terms of reducing the energy use per person by 2050, can only be achieved by a combination of technology- and lifestyle-driven measures. The combination is defined by the above-mentioned measures for the *Extend Buildings Program* and *Carbon neutrality* scenarios, together with (1) lower average indoor temperatures, i.e. from 22°C to 20°C, (2) heated surface areas only inside apartments, and (3) one of the following alternatives: (3.1) reduce floor area per capita from 47 to 41 m^2/cap and construction gradually dominated by multi-family houses (MFH), (3.2) increase renovation rate from 1.3 to 3% and implement high energy standards for new and renovated buildings, or (3.3.) replace buildings consuming more than 140 kWh/m^2/yr by buildings consuming less than 50 kWh/m^2/yr. The results of the three alternatives are presented respectively under the *Supreme green lifestyles*, *Combined renovations*, and *Combined replacement* scenarios in **Figure 9**.

The findings of paper I in relation to lifestyle-driven measures indicate that their consideration in policy designs will be crucial to reaching energy-related goals. The formulation of climate policies and regulations to incentivize lifestyle and behavioral change is not trivial; however, there are preliminary examples around the world and conceptual ideas that can lead the way. For example, a reduction in floor area per capita could be achieved through co-living initiatives (i.e. unrelated adults share a flat), cooperative houses (e.g. buildings with shared spaces for the kitchen or laundry room), or high taxes for purchasing holiday houses [77].

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[10] Switzerland has not legally committed to the 2000-Watt Society target, instead, it is regarded as a future vision.

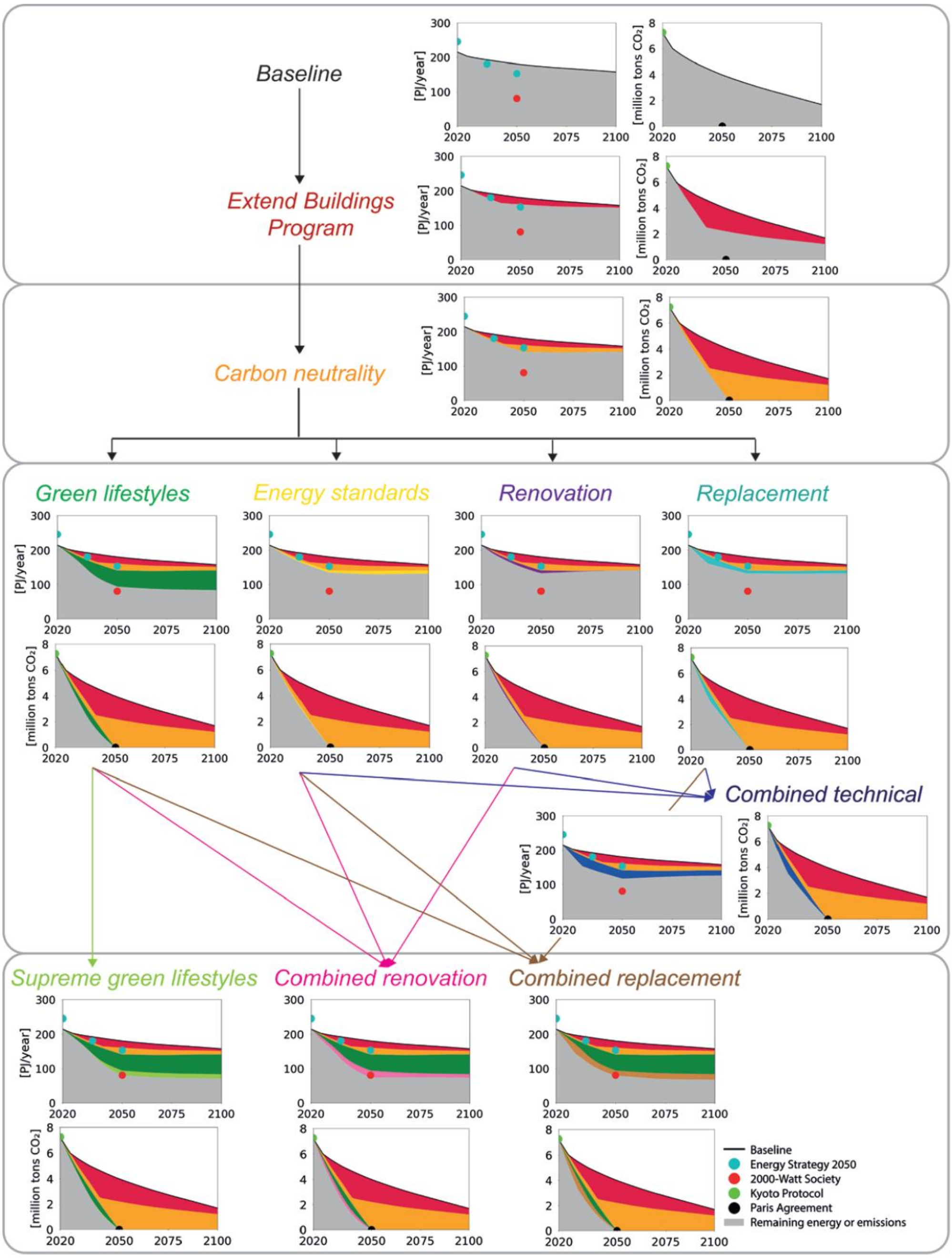

Figure 9 Direct final energy consumption and direct CO_2 emissions associated with the Swiss residential building stock for 11 scenarios compared with the Kyoto Protocol, Paris Agreement, Swiss Energy Strategy 2050, and the 2000-Watt Society goals. The energy and emissions savings are segmented according to the premises of the scenarios.[11]

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[11] Discussions on the Kyoto protocol and the Swiss Energy Strategy 2050 goals for the residential building sector are not provided here, but they can be found in the appended paper I.

Transforming the Swiss passenger car stock

In paper II, we found that technology-driven measures are highly effective in reducing direct emissions associated with the Swiss passenger car stock. Similarly as in the residential building stock, the results of the passenger car stock show that carbon neutrality in 2050 can be reached by technology-driven measures alone.

In particular, we found that carbon neutrality in 2050 can be reached by a full car fleet electrification that follows either a rapid or a medium electrification speed. The rapid electrification was defined by a phase out of new ICEVs by 2025 and P/HEVs by 2030, and the medium electrification was based on the same premise but with the year 2030 for ICEVs and 2035 for P/HEVs. **Figure 10** presents the descriptions of the scenarios for the Swiss passenger car stock, further details are specified in the appended paper II. The results for the rapid and medium electrification scenarios are presented under *Non-ACs w/o shared mobility* in **Figure 11**. While these two scenarios lead to carbon neutrality in 2050 (Paris Agreement goal in 2050), only the rapid electrification will result in meeting the interim goal of the Paris Agreement, i.e. 50% GHG emissions reduction by 2030 compared to 1990 [78].

Similarly as for residential buildings, the previous results imply that the Paris Agreement in the passenger car fleet can be met by technology-driven measures alone. The current climate policies for passenger cars focus solely on technology-driven measures, which include a CO_2 emissions regulations policy for new cars with a target of 118gr CO_2/km in 2020 [79].

In order to achieve the 2030 and 2050 goals of the Paris Agreement, the CO_2 emissions regulations target would have to be set at 0gr CO_2/km in 2030. This definition corresponds therefore to the rapid car fleet electrification scenario, and it implies a highly ambitious penetration of battery electric cars, with approximately 90% of all new cars being battery electric cars in 2025, when in 2020 the value was 8% [65]. If this highly ambitious penetration of battery electric cars fails, the medium electrification scenario could be supported by a CO_2 emissions regulations target of 10gr CO_2/km in 2030.

In terms of energy consumption, we found that the electrification of the car fleet has a considerable potential to reduce direct energy use, as shown by the scenarios under *Non-ACs w/o shared mobility* in **Figure 11A**. This reduction was found to be sufficient to meet all the energy goals, i.e. the 2000-Watt Society target (defined in the Swiss residential building sub-section) and the Swiss energy strategy. The Swiss energy strategy is defined by reduction targets of energy consumption per capita for 2020, 2035, and 2050 of 16 %, 43 %, and 54 % compared to 2000, respectively [80]. Despite such decrease in direct energy use, the electrification of the car fleet was also found to substantially increase direct electricity consumption.

The lifestyle-driven measure of car-sharing was found to generate the same direct environmental impacts as the baseline scenario (see results under *non-ACs w/car-sharing* in **Figure 11**). In car-sharing, the cars are shared, but the rides are not shared. This results in a smaller car fleet that drives the same total distance as in the baseline scenario, because the demand for car transport remains unchanged. By driving the same distance, the direct environmental impacts associated with a widespread use of car-sharing are the same as in the baseline scenario.

By contrast, a widespread use of ride-sharing was found to reduce direct environmental impacts (see results under *non-ACs w/ride-sharing* and *ACs w/ride-sharing* in **Figure 11**), including electricity consumption. This reduction can be explained by an increase in car occupancy, which leads to a decrease in the total distance driven by the car fleet. In addition, ride-sharing is expected to cause an increase in car transport demand, as ride-sharing allows previously underserved population groups (unlicensed individuals, children, and disabled and elderly people) to use cars because they do not have to drive the car themselves (rebound effect) [81, 82]. Consequently, ride-sharing allows to satisfy a higher car transport demand with a smaller car fleet which drives less kilometers compared to the baseline scenario.

The potential of ride-sharing to reduce environmental impacts is greater for the cases in which the speed of fleet electrification is slower. This can be explained by the fact that in the scenarios with slower electrification rates, non-shared ICEVs and P/HEVs are replaced by shared BEVs. This replacement leads to lower impacts because more distance is driven by shared BEVs, which consume less energy than ICEVs and P/HEVs, and do no emit direct GHG emissions. In the scenarios with a rapid electrification rate, shared BEVs are replaced by non-shared BEVs, and thus direct energy use and GHG emissions remain unchanged.

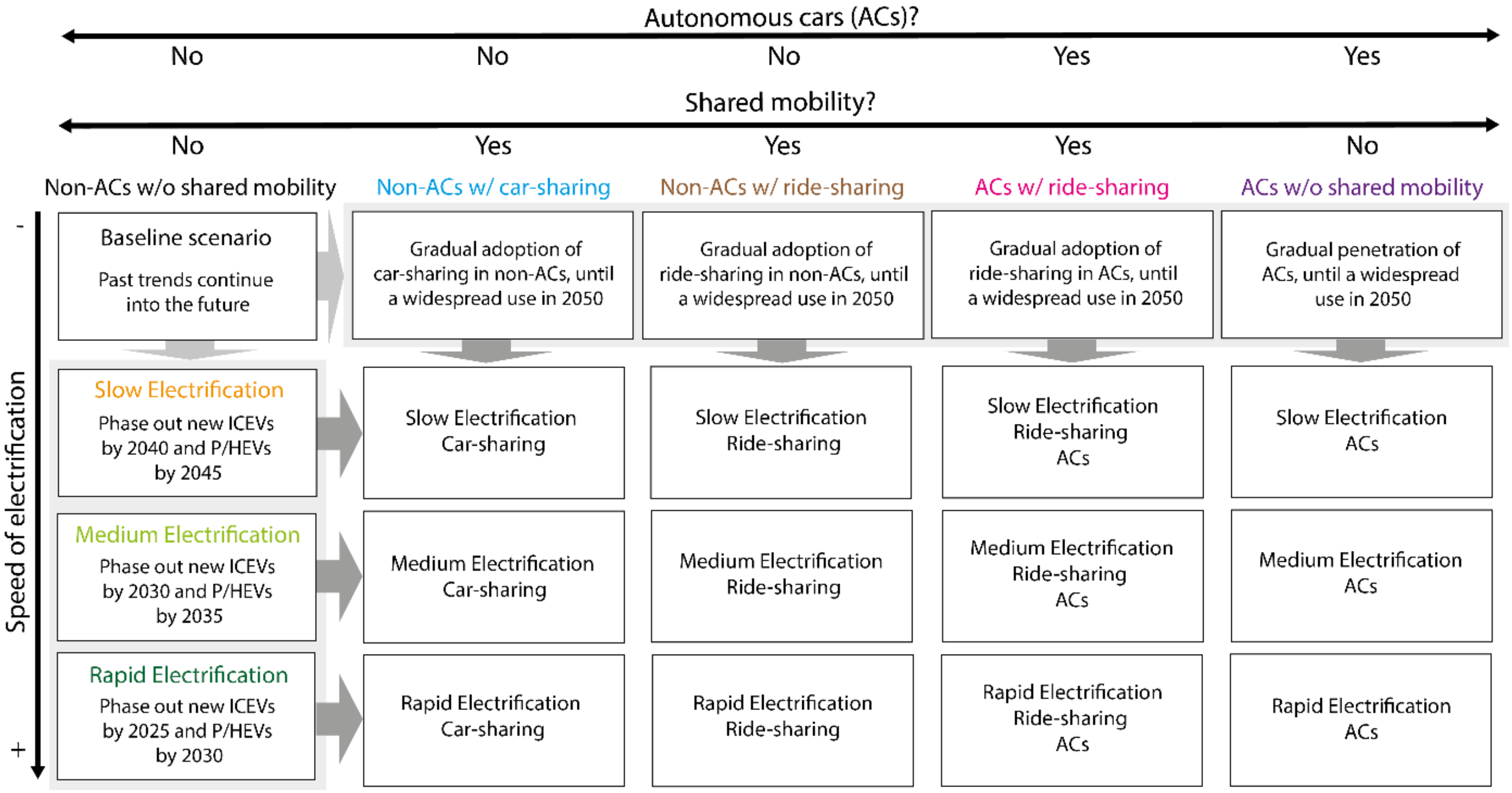

Figure 10 Descriptions of the scenarios developed for the Swiss passenger car stock. The scenarios were developed around the three car transport revolutions of (1) car fleet electrification, (2) widespread adoption of shared mobility, through car- or ride-sharing, and (3) penetration of autonomous cars (ACs). Each square represents a scenario and the arrows show how the scenarios build on each other.

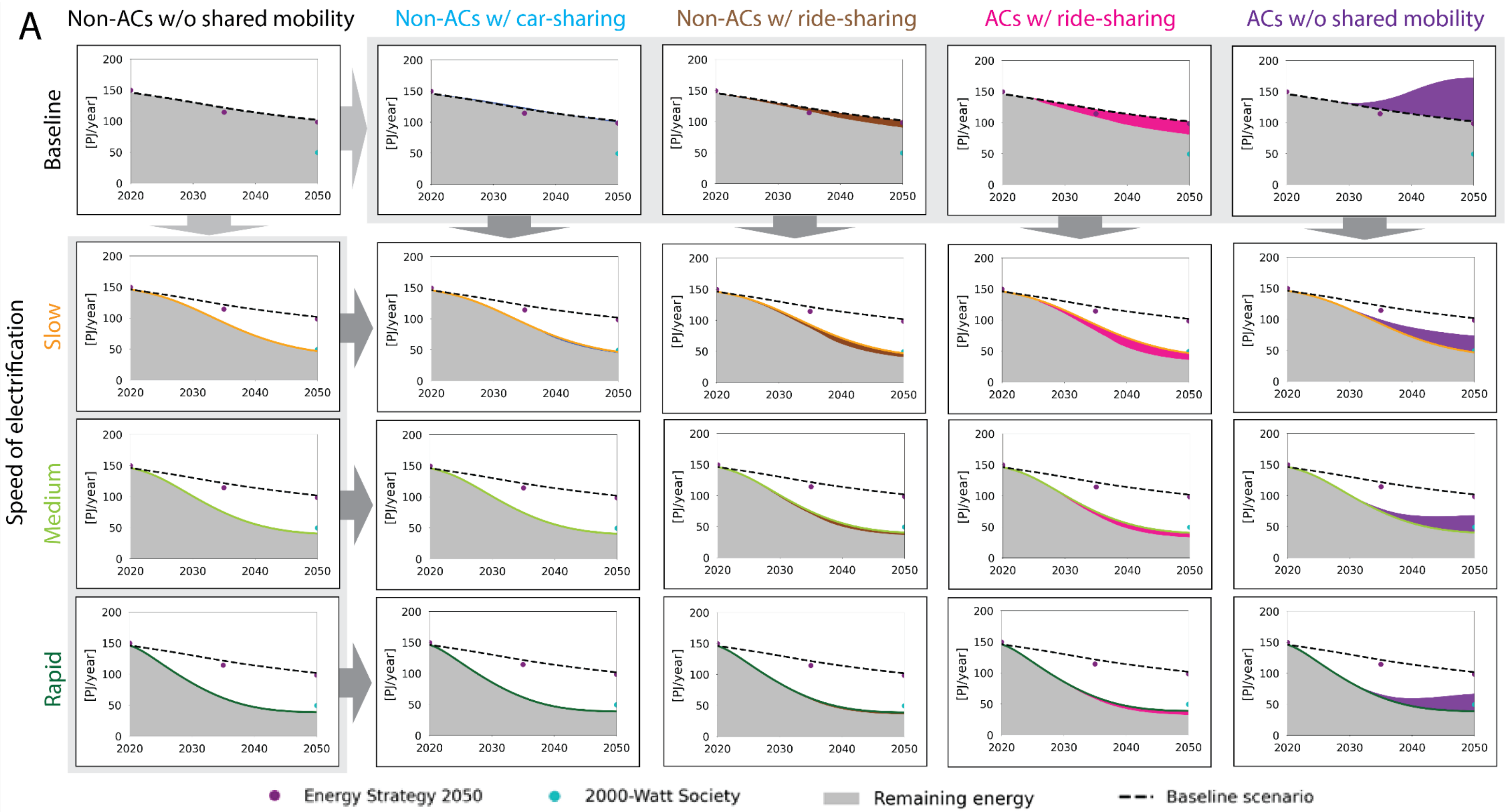

Figure 11A Direct energy consumption associated with the use phase of Swiss passenger cars for the scenarios presented in Figure 10 and compared with the Swiss Energy Strategy 2050 and the 2000-Watt Society goal.

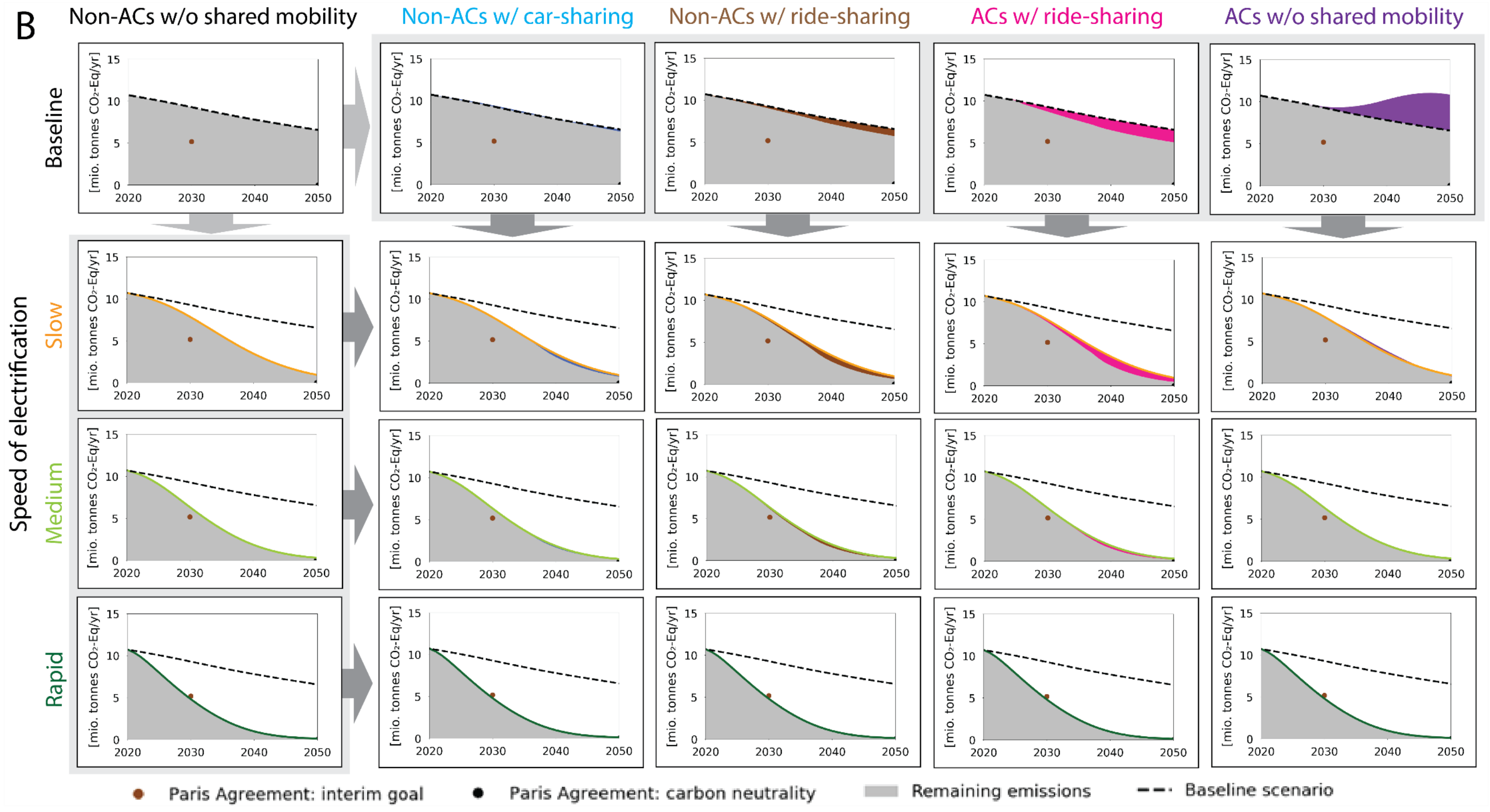

Figure 11B Direct greenhouse gas emissions associated with the use phase of Swiss passenger cars for the scenarios presented in Figure 10 and compared with the Paris Agreement goal. Note: the interim goal of the Paris Agreement has not been officially approved in Switzerland.

In the literature, ACs have been regarded as a double-edged sword, with great potential to either increase or reduce environmental impacts [83-85]. Our results confirmed this notion. On one side, we found that a penetration of AC without shared mobility will lead to a substantial increase of environmental impacts (see results under *ACs w/o shared mobility* in **Figure 11**), and on the other side, AC with ride-sharing will reduce these impacts (see results under *ACs w/ ride-sharing* in **Figure 11**).

Furthermore, our results showed that the largest CCM potential in the Swiss passenger car stock is provided by a combination of the three revolutions, i.e. a rapid fleet electrification and a widespread use of ride-sharing in ACs.

The findings of the appended paper II in relation to lifestyle-driven measures (ride-sharing) indicate that their consideration in scenarios with a late stock transformation (i.e. slow car fleet electrification) will be crucial to reduce direct environmental impacts. In addition, lifestyle-driven measures (ride-sharing) will be crucial to preventing a potential increase of environmental impacts by emerging technologies, i.e. ACs. Similarly as for residential buildings, the formulation of climate policies to stimulate lifestyle changes in the passenger car sector is not easy. However, examples around the globe show that a higher car occupancy could be incentivized through road toll prices based on the number of people inside the car or lower parking fees for shared cars [77].

Deployment differences between technology- and lifestyle-driven measures

Technology- and lifestyle-driven measures are fundamentally different with regards to their implementation or deployment in the physical system.

For the case of technology-driven measures, its deployment is generally highly time-restricted. This is because the penetration of new technologies (e.g. BEVs, ACs, or highly energy-efficient buildings) occurs through the inflow of new buildings or passenger cars. The speed at which a new technology can be introduced through the inflow depends on the stock dynamics. This means that the complete deployment of a new technology in the stock (i.e. the stock is composed only by the new technology) requires a time span equivalent to the lifetime of the "old" technology, starting from the moment when the new technology has reached 100% of the inflow. Therefore, the deployment of technology-driven measures in the residential building stock and passenger car fleet is highly dependent on the lifetime of buildings and cars. For both cases, the average lifetime is long. In paper I and II, we estimated a lifetime of approximately 200 years for Swiss residential buildings and of approximately 16 years for Swiss passenger cars. These long lifetimes and the stock dynamics imply that technology-driven measures can only penetrate into the physical system slowly, and thus these measures will have a small impact on CCM at the beginning of their implementation. However, on the long-term, their impact can be profound. Consequently, technology-driven measures are generally characterized by a slow deployment, and thus a slow development of CCM potential.

In the residential building stock model, we defined the stock in terms of m^2 of residential buildings, which means that the technology-driven measures of replacing heating systems and renovating buildings are not restricted by the above-mentioned stock dynamics, as they are not implemented through the inflow of new m^2. Nevertheless, the deployment of these two measures is also highly dependent on time. For example, heating systems have lifetimes in the range of 20-40 years, and thus they are typically exchanged at end of life [86], or buildings tend to follow renovations cycles of 30-40 years, which means that buildings undergo deep renovations at the end of each cycle [50, 87].

By contrast, lifestyle-driven measures can be deployed immediately as they are independent of time, stock dynamics, and lifetime of residential buildings and passenger cars. Examples of such lifestyle-driven measures are: (1) reducing the average indoor temperature of dwellings, (2) heating only areas inside dwellings, excluding thus areas such as attics, basements, or staircases, (3) reducing the floor area per capita by increasing the number of people per dwelling, and (4) increasing the occupancy of cars through shared-mobility options. Lifestyle-driven measures are therefore characterized by a fast deployment profile, as they are implemented through the existing stock. This fast implementation means that lifestyle-driven measures can have a large impact on CCM in both the short- and long-term. Therefore, lifestyle-driven measures are expected to gain significance in climate scenarios with late (technology) stock transformation, which implies a late decline in GHG emissions.

Despite the tendency of lifestyle-driven measures of being less time dependent, there are exceptions. For example, in paper I, we included the measure of a gradual shift of a construction activity composed of SFH and MFH to an activity fully dominated by MFH. The speed at which the shift can be implemented is fully dependent on the inflow and thus on the stock dynamics and the lifetime of buildings. Since buildings have long lifetimes and the demand for new buildings is expected to decrease in the next 50 years in Switzerland, the construction measure can only be implemented at a rather slow speed. Thus, the impacts of the construction measure tend to be small initially, but grow overtime.

In overall, the consideration of the implementation characteristics of each measure is critical for building up effective CCM strategies that reach all the climate goals.

Systemic perspective of the transformation

The two sectors are assessed in isolation, which means that only direct environmental impacts are considered. However, as shown in **Figure 7**, the two sectors are part of a bigger system, and thus the CCM measures have also indirect impacts, i.e. impacts related to activities such as material production, manufacturing of goods, construction, and energy production. Next, we reflect on the potential indirect impacts associated to the technology- and lifestyle-driven measures for the Swiss residential building stock and the Swiss passenger car stock.

In general, technology-driven measures tend to reduce direct energy consumption and emissions at the expenses of indirect energy consumption and emissions. For example, in the building sector, we found that an increase in the renovation rate leads to a decrease in direct energy consumption and emissions (see the *Renovation* scenario in **Figure 9**). However, indirect energy consumption and emissions associated with a higher renovation rate are expected to increase due to higher material production and construction activities.

Another example in the building sector is the disruptive measure of replacing highly energy-consuming buildings by energy-efficient buildings, before end-of-life is reached. For such disruptive measure, we observed a decrease in direct energy consumption and emissions (see the *Replacement* scenario in **Figure 9**), as highly energy-efficient buildings are newly built. However, indirect energy consumption and emissions are expected to increase because part of the stock needs to be rebuilt. This leads to an increase in demolition and construction activities, and thus in material production activities.

Technology-driven measures that reduce direct impacts at the expense of an increase in indirect impacts can also be found in the passenger car sector. For example, we found that an electrification of the car fleet leads to a decrease in direct energy consumption and emissions (see scenarios under *non-ACs w/o shared mobility* in **Figure 11**). However, indirect impacts are expected to increase due to an increase in highly energy-consuming and carbon-intensive material production activities, such as the production of batteries. In addition, car fleet electrification is expected to trigger indirect impacts related to an increase in electricity demand. The future electricity supply is expected to be a critical aspect in the systemic transition towards a carbon-neutral SEM system as many low-carbon solutions use electricity as the energy carrier. Thus, an increase in electricity demand challenges the provision of a low-carbon electricity mix. The provision of a low-carbon electricity mix is an enormous challenge for Switzerland, as the country aims to phase out nuclear power plants by 2030 and the contribution of nuclear power plants was 35% of Switzerland's electricity generation in 2019 [88].

In contrast, lifestyle-driven measures tend to decrease both direct and indirect energy consumption and emissions. Lifestyle-driven measures are likely to decrease indirect impacts due to a lower demand for energy and/or new stock. For example, we found that a decrease in (i) average indoor temperatures and (ii) heated areas in residential buildings, leads to a decrease in direct energy consumption and emissions (see the *Green lifestyles* scenario in **Figure 9**). In addition, the indirect impacts of these two measures are expected to decrease, as the demand for electricity and energy decreases. A decrease in electricity demand can lead to a decrease in electricity production, which is likely to ease the challenge in the electricity sector of providing a low-carbon electricity mix.

Another example of a lifestyle-driven measure that reduces both direct and indirect impacts is the decrease in floor area per capita. For this measure, the decrease in direct energy consumption and emissions is presented under the *Supreme green lifestyles* scenario in **Figure 9**. The indirect impacts associated with a lower floor area per capita are expected to decrease due to a lower demand for new buildings, which leads to a decrease in construction, material production, and manufacturing activities.

Lifestyle-driven measures that reduce both direct and indirect impacts can also be found in the passenger car sector. For example, we found that a widespread use of ride-sharing leads to a reduction of direct energy consumption and emissions (see scenarios under *non-ACs w/ride-sharing* and *ACs w/ride-sharing* in **Figure 11**). The indirect impacts of ride-sharing are expected to decrease as the demand for new cars decreases, and thus less car manufacturing activities are needed.

The demand for new cars is likely to decrease because ride-sharing can satisfy a certain demand for car transport with a smaller car fleet compared to a fleet without ride-sharing. However, a smaller car fleet implies a reduction in the demand for new cars only if the lifetime of cars remains the same. The lifetime of cars with ride-sharing is normally shorter than non-shared cars because cars with ride-sharing have a larger utilization rate, i.e. kilometers driven per year. A shorter lifetime implies a higher turnover of the stock, which means that the inflow (demand for new cars) increases. Nevertheless, our results show that a widespread use of ride-sharing leads to a decrease in the total stock (car fleet) and the inflow, despite the shorter lifetimes of cars with ride-sharing. The reason for these findings is that we considered a widespread use of ride-sharing in a system where non-shared cars are still extensively in use. As the lifetime of non-shared cars increases over time (from 16.2 years in 2020 to 17.8 years in 2050) and the percentage of non-shared cars in the stock is high (90-95 % depending on the scenario), the shorter lifetime of shared cars has a small effect in the overall stock dynamics. Therefore, a widespread use of ride-sharing is found to decrease the inflow (demand of new cars), and thus indirect impacts are expected to decrease.

Furthermore, indirect impacts associated with ride-sharing are also expected to decrease due to a lower demand for electricity because the total distance driven by the car fleet is reduced.

For the case of a widespread use of car-sharing, direct environmental impacts were found to remain unchanged (see scenarios under *non-ACs w/car-sharing* in **Figure 11**); however, indirect impacts are expected to decrease. Similar as the stock dynamics explained above for ride-sharing, the decrease of indirect impacts is due to a lower demand for new cars as car-sharing reduces car ownership. A reduced demand for new cars is expected to lead to lower car manufacturing activities, and thus lower indirect impacts.

The relevant indirect impacts associated to ACs are likely to be related to the manufacturing of ACs. In particular, the indirect impacts of ACs are expected to be higher than those of non-ACs, mostly due to a large computing power requirement of ACs, and thus a high demand for electrical and electronic devices [89, 90]. The production of these devices is generally highly energy intensive and uses critical metals [91]. In the literature, it remains unclear whether the indirect impacts of ACs can be compensated by energy savings during the use-phase of ACs (direct impacts). For example, Gawron et al. 2018 [89] and Kemp et al. 2020 [90] found that ACs can trigger a change in overall impacts in the range of +3% to -9% compared to non-ACs. The overall life cycle impacts of ACs are expected to be more robust in the coming years as the technology matures.

Furthermore, a potential positive indirect impact of electric ACs lies on the integration of cars in the smart grid, i.e. vehicle-to-grid technology [92]. This means that electric ACs can contribute towards a more stable, efficient, and reliable electricity smart grid because they can function as batteries that can supply electricity into the grid [93].

The indirect impacts associated to a fleet fully composed of non-shared ACs (scenarios under *ACs w/o shared mobility* in **Figure 11**) are expected to increase due to a higher demand for new cars. This higher demand is mostly triggered by a shorter lifetime of ACs compared to non-ACs. The shorter lifetime is caused by a higher utilization rate, which is due to empty trips, ACs used for longer commutes, and ACs used by a previously underserved population [84, 85].

The systemic assessment of CCM strategies indicate that the sectoral models, which only quantify direct impacts, underestimate the impacts of lifestyle-driven measures, as these measures tend to reduce indirect energy use and emissions. However, the sectoral models also overestimate the impacts of technology-driven measures, as these measures tend to increase indirect energy use and emissions.

Consequently, the design of CCM strategies for a specific sector needs to consider the indirect impacts in order to facilitate the transformation of other sectors, and thus the systemic transformation of the SEM towards a low-energy and climate-neutral system.

3.2. Research question 2: How can the physical and social systems be integrated through simulation games (SGs)? What are the benefits and challenges of such integration?

In this section, we first describe how the physical and the social systems can be integrated through SGs, and later we enumerate and discuss the main benefits and challenges of such integration. A more extensive list and discussion of the benefits and challenges can be found in the appended paper III.

Integration of physical and social systems through SGs

SGs usually draw from different methodological sources, such as simulations, role-plays, games (e.g. goals, rules, and scores), and case studies (e.g. scene of the SG) [42]. The simulation aspect in SGs can be carried out using models that simulate the consequences of players' decisions. In paper III, several SGs with different types of models were found, but none using a SEM model. Thus, the postfossilCities SG constitutes a novel game, as it uses a Swiss economy-wide SEM model. This SEM model is used to simulate the physical system and thereby enables the quantification of the effects of game actions in terms of GHG emissions. The social system is integrated through several elements, namely: (1) a role-play composed of seven actors with specific goals (see **section 2** for the description of the actors and goals), (2) role-strength models to quantify the success of each actor in fulfilling their actor-specific goal, and (3) other game mechanics. An example of other game mechanisms are the so-called deblockers, which represent the concept of cooperation between actors, i.e. CCM measures supported by several actors have a stronger effect than measures implemented by one actor.

As explained in **section 2**, the integration of SEM models and SGs requires an additional aspect that connects the actions in the game and the parameters of SEM models. In the postfossilCities SG, we realized such integration through connection models. In theory, the integration of SEM models and SGs could be established with simpler approaches, such as players directly manipulating model parameters. However, in the development of the postfossilCities SG, we refrained from using this approach because (1) most model parameters in SEM models represent concepts that might not be known by the general public, and (2) the relationship between actions in the game and SEM model parameters is not always one-to-one (i.e. one action in the game can affect several model parameters). Therefore, the connections models in the postfossilCities SG also had the purpose of (1) translating the simulated concepts to the everyday life language of the players and (2) establishing the manifold relationships between game actions and SEM model parameters.

The use of SGs to integrate physical and social systems allows the players to deal simultaneously with the challenges of the social (e.g. negotiations with other actors) and the physical system (e.g. time constraints or mass-balanced processes). Through such integration, each system provides boundary conditions to the other. While the physical system sets the boundary conditions based on physical laws, the social system sets the boundary conditions based on values, interests, and social norms. For example, the interests and values of different actors can establish the minimum acceptable floor area per capita, although from a technical perspective, the value could be smaller. Therefore, the integration of the two systems through SGs allows players to explore, experience, and feel the intended and unintended impacts as well as the side effects of their decisions and actions in both the physical and social systems. Consequently, the postfossilCities SG shows that SEM-based SGs can be developed to integrate both systems, and thus use such integration to explore different CCM strategies.

Benefits of developing SEM-based SGs

Increased robustness of SGs by using mass- and energy-balance consistent representations of physical systems. In SEM models, the physical principle of mass- and energy-balance conservation is maintained over time, space, and layers of the system, which ensures that results are coherent, realistic, and robust, in a physical sense.

Support the communication and understanding of complex SEM systems. SGs can draw the attention of players to certain elements or parts of the SEM system, which, along with the right stimuli, can facilitate the comprehension of systemic connections and complex dynamics. For example, a SG can draw the players' attention to the building stock, which, for example, undergoes changes due to a sharp decline in construction activity (stimuli). By analyzing and experiencing these changes, players can learn about systemic connections and dynamics such as stock accumulation, feedback loops, and non-linear behavior. Furthermore, SGs can integrate the social system through, among other elements, role-plays, which allows players to explore the actors of the social system as acting subjects, i.e. players take on the role of actors. By taking on the role of an actor, a player can (1) gain new perspectives on problems, potential solutions, and interactions, (2) experience different and often conflicting interests, and (3) acquire new insights into actors' rationale and objectives. In addition, by exploring the actors as acting subjects, players go through experiential and emotional learning processes that usually trigger long-lasting memories and critical reflections of one's own attitudes [55, 94-97].

Safe and protected environments. SGs provide safe and protected environments where players can test uncommon and radical interventions without the usual sanctions or consequences of the world outside the game.

Re-scaled timelines. SGs can compress long time periods to manageable scales. In this way, players can experience the temporal aspect of CCM strategies, such as the time delays associated with certain measures.

Expand the outreach of SEM studies to a wider audience. SEM studies are usually published in journals and presented in conferences, both of which have a targeted, but narrow audience. SGs can expand the audience to the general public and thereby stimulate a broader learning process in society. SGs can realize this expansion because they use communication forms that are highly appealing and intuitive for the general public. In particular, SGs use communication forms such as oral, written, non-verbal, and visual through activities and processes that include reading, writing, discussing, and doing. In addition, SGs can expand the outreach of SEM studies because SGs translate the simulated concepts in SEM studies to the everyday life language of the players, creating an environment with familiar terms and concepts.

Challenges of developing SEM-based SGs

Integrating approaches from different disciplines. The development of SGs and SEM models requires the use and integration of approaches from different disciplines such as simulation and gaming, mathematical modeling, social science, and computer science. This integration requires a precise definition of the interfaces between different disciplines, so that the tasks within the different disciplines are clear. The integration of different disciplines can be facilitated by developing a shared understanding across all disciplines, and thus all team members. This shared understanding can avoid misunderstandings among different team members. The prevention of misunderstandings can be also supported by developing a "common" language within the game development team [98].

Resource intensity. The development of SGs is a highly resource-consuming process, in particular in terms of time, effort, and finances. These required resources should be considered in an early stage of the project, e.g. in the outset of the project, so that the project timeline can be planned accordingly.

Connection between SEM models and SGs. The connection between SEM models and SGs can be established through different approaches. In the postfossilCities SG, we integrated the SEM model and the SG by developing connection models. Through the development of such connection models, we identified three challenges. The first challenge is the lack of a solid scientific foundation to translate actions in the game to changes in model parameters. Due to this lack, we established the relationships between actions in the game and model parameters by estimation exercises and experts judgements. The second challenge lies on the quantification of the mentioned relationships. The definition of such quantification suffers from the same lack as the first challenge, and thus the same approach was taken. The quantitative changes were programmed for the specific action cards and model parameters of the postfossilCities SG; however, a generic approach could ease the programming efforts. The generic approach could define the parameter changes based on (i) the types of change, e.g. increase or decrease, (ii) the form of change, e.g. exponential, linear, step, logistic, among others, and (iii) the duration of the change, i.e. the number of years. The use of this generic approach could reduce the modeling efforts, as many parameter changes can be defined in the same manner across different SEM models, game actions, and contexts. The third challenge corresponds to the translation of the simulated concepts in the SEM model to the everyday life language of the players. While the SEM model was developed using standard scientific terms and concepts, the information on the action cards was provided in terms that players from different backgrounds could understand. However, defining the language, terms, and concepts on the action cards is not a trivial task. In the postfossilCities SG, we refined the information on the action cards through a process of testing and adjusting game prototypes.

Combining analytical and (game) design skills. The successful development of SEM-based SGs requires a combination of analytical and game design skills. While analytical skills are necessary to achieve realistic outputs and ensure a solid scientific foundation, (game) design skills are crucial for motivating and engaging players through visualizations, game sceneries, and storytelling, among others. Game design skills include creativity, artistry, and handcraft, among others. This challenge can be addressed by ensuring that both skill sets are well covered within the game developing team.

Balancing complexity and simplicity. The high complexity of SEM and social systems requires a drastic simplification in the representation of both systems in the SG. At the same time, this simplification needs to ensure that the most important and critical aspects are still represented in the SG. Therefore, finding the right balance between complexity and simplicity is not a trivial task, which needs to be negotiated between the modelers and the game developers, as they tend to have conflicting interests. On one side, good practice for modelers is to keep the model as simple as possible to highlight the most relevant factors, while on the other side, game developers have an interest to spice up the game with popular but potentially less relevant intervention options. There is no specific methodology for such simplification process; however, we found that a clear definition of the objective and scope of the game together with a process of developing, testing, and adjusting game prototypes can support the simplification step, and thus the game development itself.

3.3. Conclusions and outlook

Solving the climate crisis requires a transformation of the physical and social systems, which implies that CCM strategies need to consider both systems. In this thesis, we argue that connecting SEM models and SGs allows for an integration of the two systems, and thereby provides a set-up to explore CCM strategies with the boundary conditions of both systems, i.e. physical and social constraints. In addition, SEM-based SGs can widen the target audience of SEM research by means of interaction tools that trigger experiential and affective learning processes. These learning processes tend to result in long-lasting memories and critical reflections of one's own attitudes.

Furthermore, this research has demonstrated that designing CCM strategies with both technology-driven (e.g. replacement of fossil fuels by renewable energies or higher energy system efficiency) and lifestyle-driven (e.g. smaller stock for the same service demand or lower energy demand) measures is crucial for transforming physical systems towards low-energy and carbon-neutral systems that comply with all climate goals. Technology- and lifestyle-driven measures are fundamentally different with regards to their deployment in the physical system. While technology-driven measures are highly time-restricted, most lifestyle-driven measures can be implemented using the existing stock, which usually means that they can be deployed very quickly, and thus have a rapid impact on CCM. Due to their fast impact, lifestyle-driven measures gain significance in climate scenarios with a late (technology) stock transformation, which implies a late decline in GHG emissions. By contrast, the mitigation potential of technology-driven measures is expected to be severely delayed by the time it takes to replace the existing (technology) stock. Consequently, a longer delay in the implementation of technology-driven measures would require more drastic lifestyle-driven measures based on "old" technologies to reach the climate goals by 2050.

In overall, this thesis provides first environmental assessments of alternative CCM strategies composed of highly different measures, in terms of the core driver (technology vs lifestyle), the deployment into the system (fast- vs slow-deployment), and the level of radicalness (disruptive measures or emerging technologies). These assessments can set the ground for enlarging and diversifying the current portfolio of CCM strategies, and thus informing decision-making processes.

Further research for designing and developing CCM strategies should focus on refining the link between sectors through material, energy, and GHG emissions flows. This link requires therefore a better understanding of the dependencies and dynamics across sectors. An example of such dependency is observed between the stocks (e.g. building stock or car fleet) and material industries, as the stock size and the stock dynamics drive material demand. The refinement of the links across sectors allows for a more comprehensive evaluation of the systemic impacts or direct and indirect emissions associated with CCM measures.

The refinement of the links between different sectors can also provide a solid basis for improving the understanding of the (systemic) effects of behavioral change. While the modeling of technology-driven measures can draw on high-quality and robust datasets and existing scientific studies, this background is rather limited for lifestyle-driven measures. Therefore, efforts to improve (1) lifestyle-related data, (2) the comprehension of the acceptable limits around lifestyle and behavior changes, and (3) the understanding of systemic dynamics triggered by lifestyle-driven measures, can support the assessment of CCM strategies, and thus strengthen the policy recommendations.

The combination of SGs and SEM models is a powerful tool for knowledge transfer, and thus for bridging scientific research and society in general. The field of SGs is rapidly evolving, especially through the use of new trends and technologies, such as virtual reality (e.g. through using googles and wired clothing), augmented reality (e.g. through virtual computer graphics), or real location-based features (e.g. through integrating real places in games), among others. Therefore, SEM-based SGs can be enhanced by the implementation of such trends and technologies, and thereby make the experience of playing SGs highly engaging and motivating. In this way, large audiences with no prior knowledge of the topic can easily become familiar with CCM and can learn about the challenges and opportunities of developing strategies for CCM.

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Appendix A

Paper I

Pathways toward a carbon-neutral Swiss residential building stock

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RESEARCH

Pathways toward a carbon-neutral Swiss residential building stock

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Abstract

Current policies to reduce energy consumption and CO_2 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_2 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_2 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_2 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^2/cap, (b) increasing the renovation rate from 1.3% to 3.0%, and (c) replacing buildings consuming > 140 kWh/m^2/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_2 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_2 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_2 emissions; when emissions associated with electricity production are included, these emissions account for 23% (IPCC 2018).

Strategies to reduce direct energy consumption and CO_2 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_2e 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_2 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_2 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_2 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

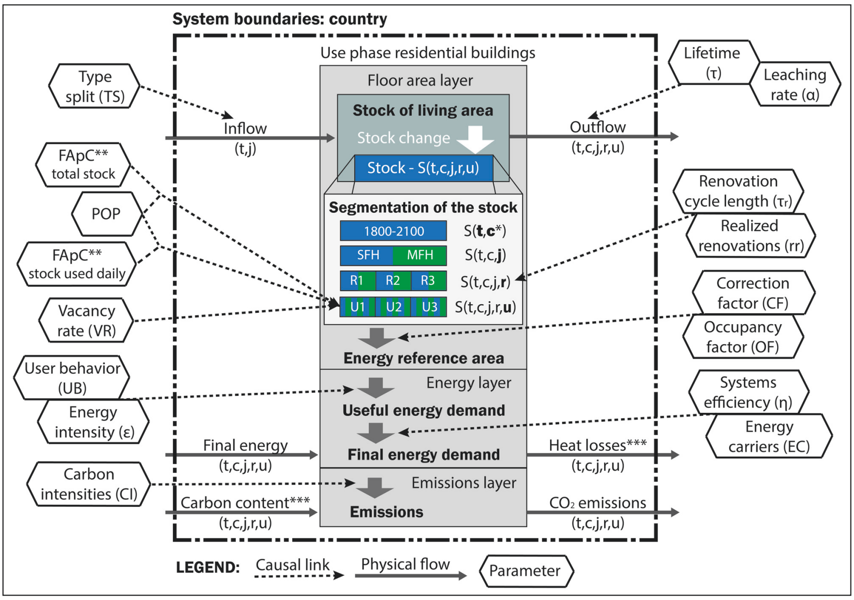


Figure 1: System definition and model description for the use phase of residential buildings, including floor area stock, direct energy consumption and direct emissions. System variables: stock, stock change, inflow, outflow, energy reference area (ERA), useful energy, final energy and CO_2 emissions.

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; τ_r = renovation cycle length; rr = realised renovations; VR = vacancy rate; CF =correction factor; OF = occupancy factor; UB = user behaviour; ε = energy intensity; η = 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_2 emissions; therefore, other greenhouse gas emissions are not accounted given that CO_2 accounts for 99% of the CO_2e 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; Vásquez *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.

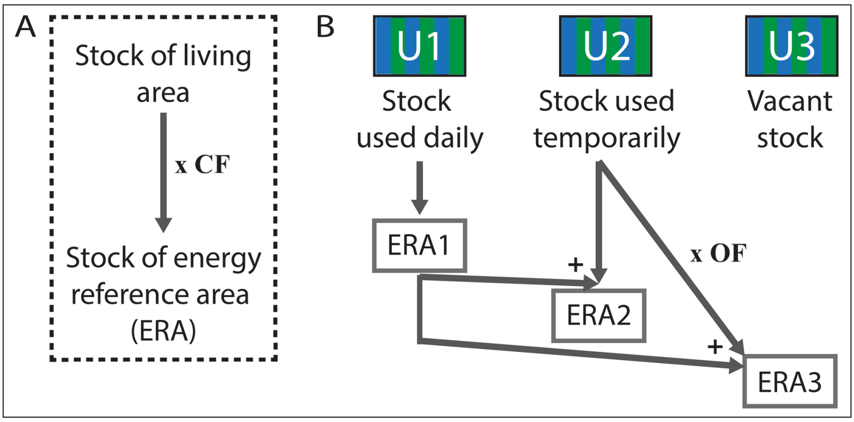


Figure 2: Energy reference area (ERA)-related calculations. **(A)** Generic ERA calculation from the stock of living area using a correction factor (CF) that accounts for heated areas beyond the dwelling area. **(B)** ERA approaches used in this study: ERA1 obtained from the stock used daily; ERA2 obtained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

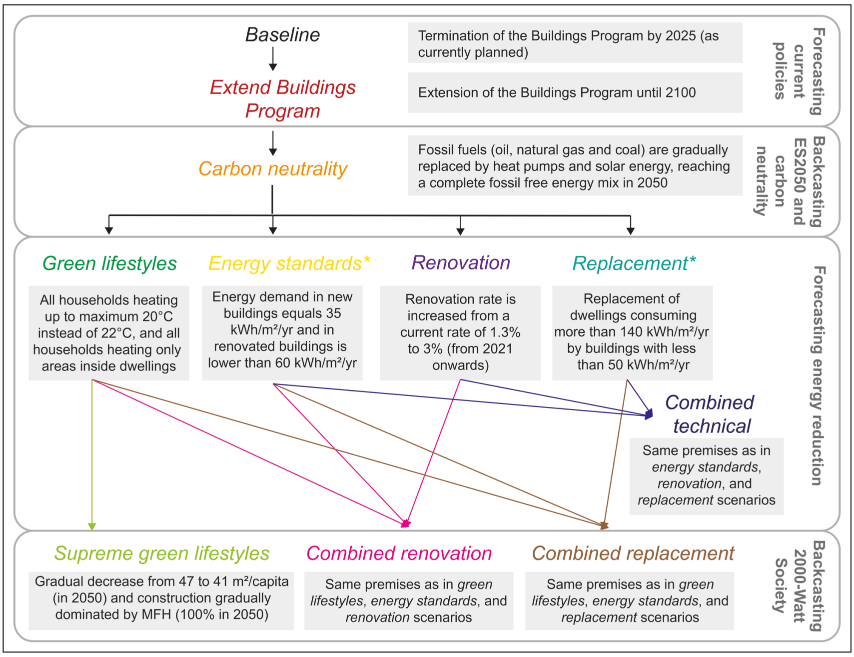
The baseline scenario was defined with current policies in place, assuming the end of the BP in 2025 (currently planned). An extension of the programme was explored in the extend Buildings Program scenario. Given that the Swiss government has officially committed to carbon neutrality and the ES2050 goals, 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[a]	See Appendix D	Bergsdal *et al.* (2007), FSO (2000, 2018c)	65 m^2/dwelling in 1800 104 m^2/dwelling in 2100	Low
People per dwelling[a]	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 *et al.* (2009)	Renovation cycle length equal to the longest lifetime of energy-relevant building components	High

Notes: [a] Stock used daily.
For appendices, see the supplemental data online.



Termination of the Buildings Program by 2025 (as currently planned)

Extension of the Buildings Program until 2100

Fossil fuels (oil, natural gas and coal) are gradually replaced by heat pumps and solar energy, reaching a complete fossil free energy mix in 2050

All households heating up to maximum 20°C instead of 22°C, and all households heating only areas inside dwellings

Energy demand in new buildings equals 35 kWh/m²/yr and in renovated buildings is lower than 60 kWh/m²/yr

Renovation rate is increased from a current rate of 1.3% to 3% (from 2021 onwards)

Replacement of dwellings consuming more than 140 kWh/m²/yr by buildings with less than 50 kWh/m²/yr

Same premises as in *energy standards*, *renovation*, and *replacement* scenarios

Gradual decrease from 47 to 41 m²/capita (in 2050) and construction gradually dominated by MFH (100% in 2050)

Same premises as in *green lifestyles*, *energy standards*, and *renovation* scenarios

Same premises as in *green lifestyles*, *energy standards*, and *replacement* scenarios

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 ±12% for historical years; therefore, future energy consumption and emissions are expected to lie

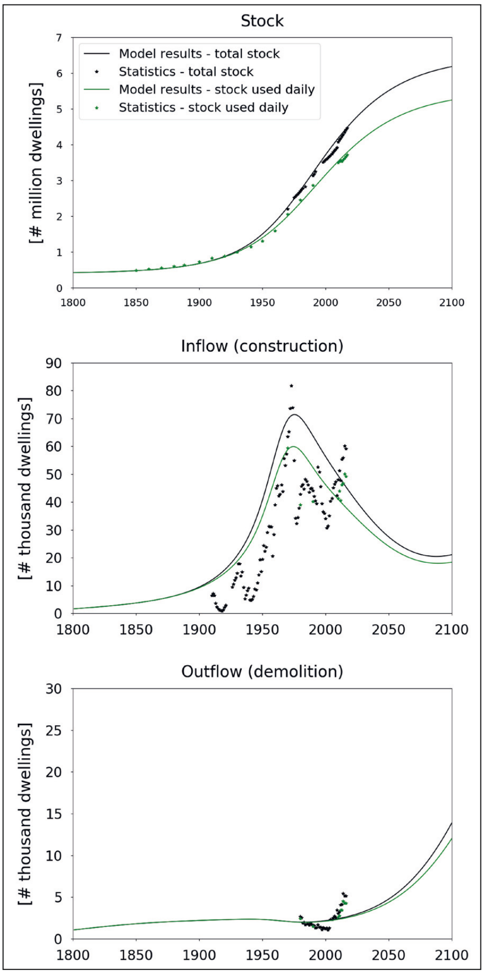


Figure 4: Evolution of the stock, inflow and outflow for the total stock and stock used daily for the period 1800–2100, for the baseline scenario. The model results are compared with statistical data.
Sources: FSO (2018a, 2019a, 2019b).

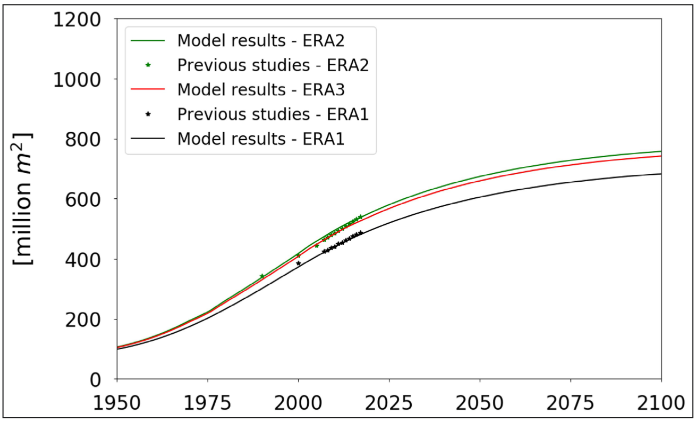


Figure 5: Stock of energy reference area (ERA) using three calculation approaches (described in Figure 2). Historical results are compared with previous studies (SFOE 2018a, Siller *et al.* 2007; Wallbaum *et al.* 2009). Future results correspond to the baseline scenario.

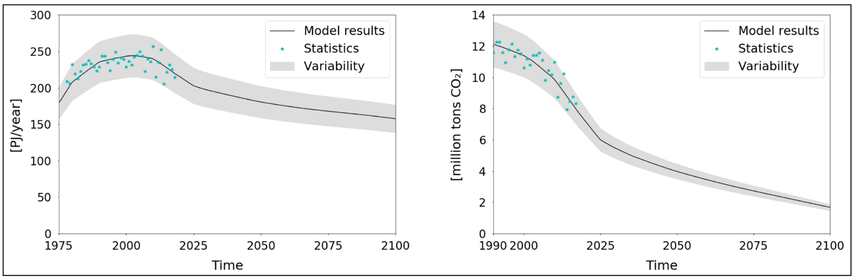


Figure 6: Evolution of direct final energy consumption and direct CO_2 emissions associated with the use phase of Swiss residential buildings for the baseline scenario, including the variability range due to annual fluctuations. The model results are compared with statistical data (FOEN 2019b; SFOE 2019).

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_2 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**).

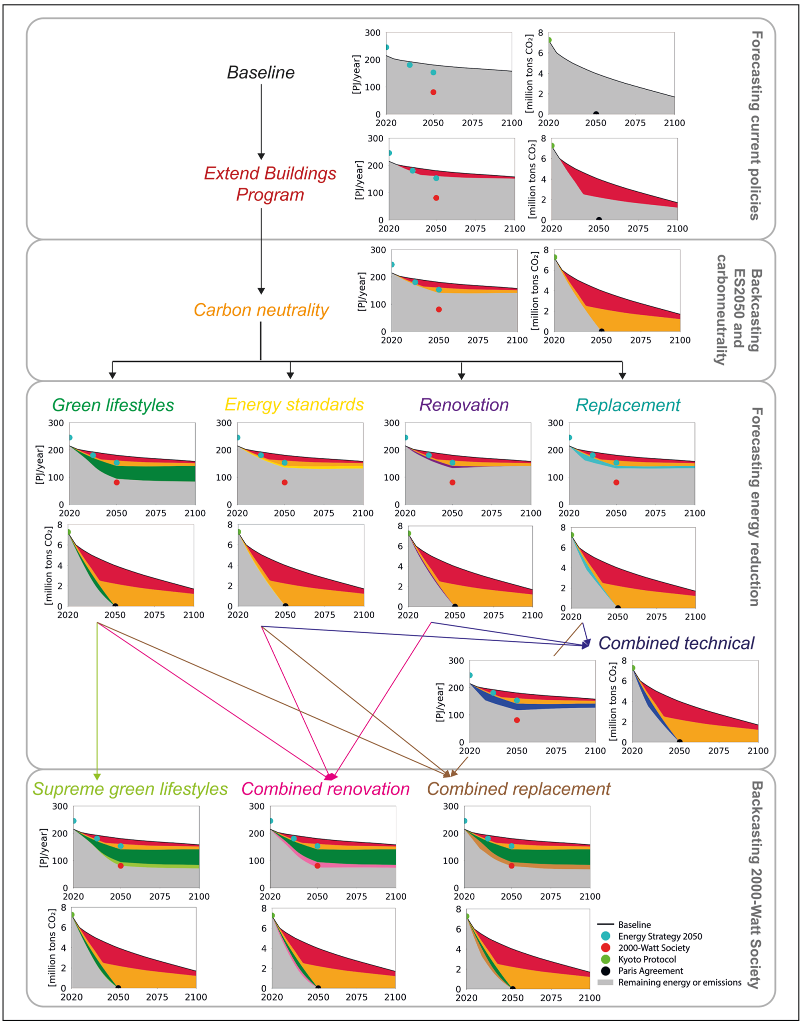


Figure 7: Direct final energy consumption and direct CO_2 emissions pathways associated with the use phase of Swiss residential buildings for 11 scenarios and compared with the Kyoto Protocol, Paris Agreement, ES2050 and 2000-Watt Society goals. The energy and emissions savings are segmented according 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_2 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.

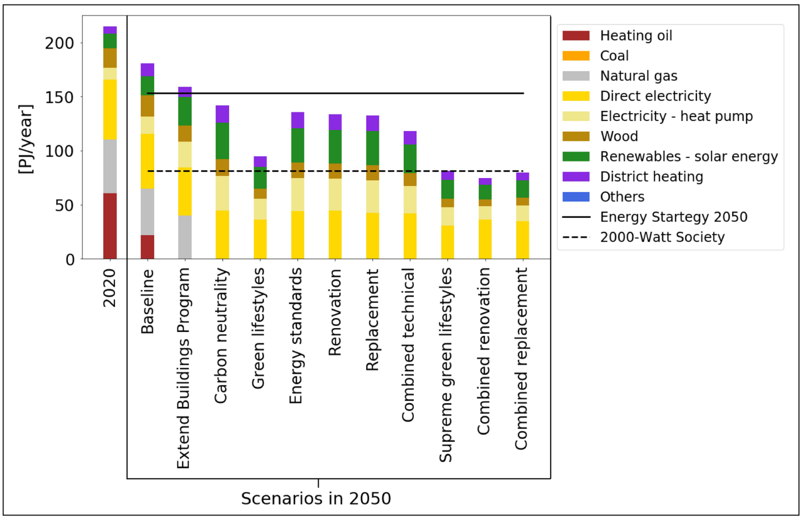


Figure 8: Direct final energy consumption for the use phase of Swiss residential buildings segmented by energy carriers in 2020, and in 2050 for the 11 scenarios compared with the ES2050 and the 2000-Watt Society goals.

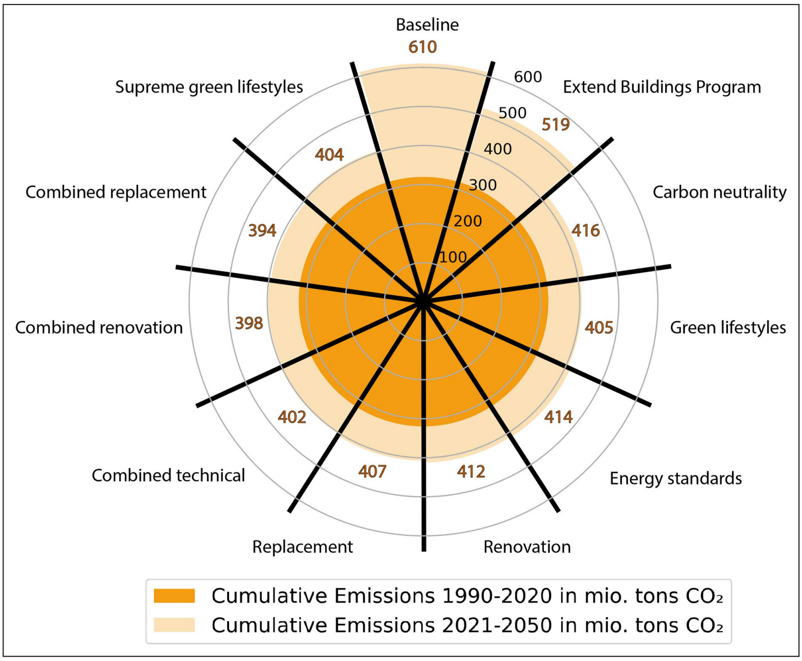


Figure 9: Cumulative CO_2 emitted during the periods 1990–2020 and 2021–50 for all scenarios. The exact value for the entire time period is provided for each scenario.

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_2 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_2 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 $kWh/m^2/yr$. 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_2 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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Supplementary Information

Contents

Appendix A:

Cohorts definition

The complete list of the 17 cohorts used in this study is presented in ***Table A1***.

Table A1: Cohorts definition.

Cohort number	Cohort years
1	1800-1919
2	1920-1945
3	1946-1960
4	1961-1970
5	1971-1980
6	1981-1990
7	1991-2000
8	2001-2010
9	2011-2020
10	2021-2030
11	2031-2040
12	2041-2050
13	2051-2060
14	2061-2070
15	2071-2080
16	2081-2090
17	2091-2100

Appendix B:
Model description (lifetime approach)

The model was built with a stock-driven approach. The driving force of this approach is defined as the provision of a stock that satisfies a desired or required service level, in this case, the service is defined by the floor area per capita (Müller 2006; Vásquez et al. 2016). The dimensions considered in the model are: time (t), cohorts (c), building types (j), renovation states (r), and intensity of use (u). The model was implemented with the convention of calculating the stock at the end of the year, and flows occurring during the year. The complete list of system variables and parameters used in the model is presented in ***Table B1***. The description explained in this appendix considers only the lifetime approach.

Table B1: List of system variables and parameters used in the model.

Abbreviation	Description	Type	Units
S	Stock of living area. The living area accounts for the area available for the occupant/s inside the dwelling	System Variable	m^2 number of dwellings
dS	Stock change	System Variable	m^2 number of dwellings
I	Inflow of new stock (construction)	System Variable	m^2 number of dwellings
O	Outflow from the stock (demolition)	System Variable	m^2 number of dwellings
ERA	Stock of energy reference area, which accounts for the effective heated area including areas beyond dwellings (e.g. staircases, attics, basements)	System Variable	m^2
Useful Energy	Demand of useful energy for operating the stock of dwellings for either technical or real energy*	System Variable	TJ
Final Energy	Demand of final energy for operating the stock of dwellings for either technical or real energy*	System Variable	TJ
Emissions	Direct emissions stemming from the operation of dwellings	System Variable	tons CO_2
POP	Population	Parameter	capita
FApC	Floor area per capita for the total and the stock used daily. FApC is given in terms of living area	Parameter	m^2/capita
FApD	Floor area per dwelling for the total and the stock used daily. FApD is given in terms of living area	Parameter	m^2/dwelling
PpD	People per dwelling for the total and the stock used daily	Parameter	capita/dwelling
TS	Type split of construction among the building types	Parameter	%
$\boldsymbol{\tau}$	Average lifetime	Parameter	years
$\boldsymbol{\sigma}$	Lifetime standard deviation	Parameter	years
α	Leaching rate of the stock	Parameter	%
$\boldsymbol{\tau_r}$	Average time between renovations realized in a dwelling (renovation cycle length)	Parameter	years
$\boldsymbol{\sigma_r}$	Renovation cycle length standard deviation	Parameter	years
$\boldsymbol{rr}$	Realized renovations	Parameter	%
VR	Vacancy rate (empty stock)	Parameter	%
CF	Correction factor from stock of living area to stock of ERA	Parameter	%
OF	Occupancy factor of stock used temporarily	Parameter	%

ε	Technical energy intensity* of dwellings segmented by cohorts, renovation states and energy uses	Parameter	kWh/m^2/yr
UB	User behavior corrects the technical energy intensity for SH by providing real energy consumption*	Parameter	%
EC	Energy carriers supplying the demand of energy	Parameter	%
η	Efficiency of the heating systems in converting final energy into useful energy	Parameter	%
CI	Carbon intensities of the energy carriers	Parameter	tons CO$_2$/TJ

*Technical energy refers to the calculated (theoretical) energy demand of a building, whereas real energy corresponds to the energy demand by households.

The stock in terms of square meters of living area was determined by population (POP), and floor area per capita (FApC) (Eq. B1). The FApC was calculated with the floor area per dwelling (FApD) and the people per dwelling (PpD) (Eq. B2).

$$S(t) = POP(t) \cdot FApC(t) \qquad \text{(B1)}$$

$$FApC(t) = \frac{FApD(t)}{PpD(t)} \qquad \text{(B2)}$$

The stock change (dS) was calculated by the stock size variation between two consecutive years (Eq. B3).

$$dS(t) = S(t) - S(t-1) \qquad \text{(B3)}$$

The inflow (I) was described as the construction needed to replace the demolished stock (O) and satisfy the stock change (dS), segmented by the type split (TS) (Eq. B4).

$$I(t,j) = \big(O(t) + dS(t)\big) * \ TS(t,j) \qquad \text{(B4)}$$

The outflow (O) was determined by multiplying the inflows (I) with the difference between the cumulative distribution function (cdf) of two consecutive years (Eq. B5). The cumulative distribution function (cdf) corresponds to a normally distributed lifetime (τ) with a certain standard deviation (σ). The cdf refers to the area under the probability density function (pdf). The pdf is defined as the probability for the stock of a given cohort to reach end of life in a given year.

$$O(t,c,j) = I(t,j) \cdot (cdf(t,c) - cdf(t-1,c)) \qquad \text{(B5)}$$

The stock (S) segmented by cohorts was obtained by applying the survival function (sf) to the inflow (I) (Eq. B6). The sf is defined as $1 - \ cdf$, and represents the probability of the stock to be standing at a certain time.

$$S(t,c,j) = I(t,j) \cdot sf(t,c) \qquad \text{(B6)}$$

Renovation activity was modelled with a normally distributed cyclic probability density function ($pdfr$), which represents its multiple occurrences throughout the building's lifetime. The cycle length corresponded to the time between renovations (τ_r) with a standard deviation (σ). The probability of renovation (Rc) was calculated by multiplying the probability density function of renovation ($pdfr$) by the survival function (sf) shifted by τ_r. The shift avoided the renovation of a dwelling today, and its demolition tomorrow; further explanation in Sartori et al. (2008). This resulted in a probability of renovation (Rc) damped over time since the standing stock of a specific cohort decreases over time. The flow to renovation ($Fren$) was calculated by applying *Rc* and the realized renovation (*rr*) to the inflow (I) (Eq. B7). According to Siller, Kost and Imboden (2007), not all renovations are realized when the renovation cycle is reached, due to economic and logistics limitations.

$$Fren(t,c,j) = I(t,j) \cdot Rc(t,c) \ * rr(t,c,u) \qquad \text{(B7)}$$

The stock segmented by renovation states was calculated based on the approach presented by Sandberg et al. (2017). The R2 stock, stock renovated with the technologies available between 1971-2020, was built from the flow to renovation during the mentioned period (Eq. B8). Similarly, the R3 stock, was built from the flow to renovation during 2020-2100 (Eq. B9).

$$S(t,c,j,R\mathbf{2}) = Fren(t,c,j) + S(t-1,c,j,R\mathbf{2}) \qquad \text{for: } 1971 \le t \le 2020 \qquad \text{(B8)}$$

$$S(t,c,j,R\mathbf{3}) = Fren(t,c,j) + S(t-1,c,j,R3) \qquad \text{for: } t > 2020 \qquad \text{(B9)}$$

The R2 and R3 stock were corrected for demolition, by calculating the fraction of the total outflows corresponding to R2 and R3 stock (Eq. B10). The ratio between R2 or R3 stock in respect to the total stock was calculated with a time shift (τ_r). The time shift prevented the demolition of renovated dwellings during the time period equal to the renovation cycle length (further explanations in Sandberg et al. (2017)).

$$S(t,c,j,\boldsymbol{r}) = S(t,c,j,\boldsymbol{r}) - \left(O(t,\ c,\ j) \ \cdot \ \frac{S(t-\tau_r,c,j,r)}{S(t-\tau_r,c,j)}\right) \qquad \text{for r=R2 and r=R3} \qquad \text{(B10)}$$

The R1 stock (non-renovated stock) is calculated following the principle that the total stock is equal to the segmented stock by renovation states (Eq. B11).

$$S(t,c,j,\boldsymbol{R1}) = S(t,c,j) - S(t,c,j,\boldsymbol{R2}) - S(t,c,j,\boldsymbol{R3}) \tag{B11}$$

The previous set of equations B1-B11 was performed for both FApCs accounting for the total stock and the stock used daily, thus obtaining $S(t,c,j,r,u)$ for the total stock, and $S(t,c,j,r,U1)$ for the stock used daily. The complete segmentation of the stock into intensity of uses was calculated by multiplying the vacancy rate (VR) with the total stock (S) to obtain the vacant stock (U3) (Eq. B12). The stock used temporarily (U2) was determined by subtracting the vacant (U3), and the stock used daily (U1) from the total stock (u) (Eq. B13).

$$S(t,c,j,\boldsymbol{U3}) = S(t,c,j,r,u) * VR(t,c,j,U3) \tag{B12}$$

$$S(t,c,j,r,\boldsymbol{U2}) = S(t,c,j,r,u) - S(t,c,j,\boldsymbol{U1}) - S(t,c,j,r,\boldsymbol{U3}) \tag{B13}$$

The previous calculations were calculated in terms of square meters; however, the statistics are typically reported as number of dwellings. Therefore, the previously calculated variables are converted to number of dwellings by using the $FApD$ parameter.

The stock in terms of square meters accounted for the living area, and it was extrapolated to the energy reference area (ERA) by applying a correction factor (CF). ERA was calculated using the following stocks of living area: (1) stock used daily (ERA1), (2) stock used daily and stock used temporarily considered as daily (ERA2), and (3) stock used daily together with stock used temporarily corrected by the occupancy factor (OF) (ERA3) (Eq. B14-B16). The OF described the occupancy of the stock used temporarily throughout the year.

$$ERA1(t,c,j,r) = S(t,c,j,r,U1) * CF(t,c,j,r,u) \tag{B14}$$

$$ERA2(t,c,j,r) = ERA1(t,c,j,r,U1) + S(t,c,j,r,U2) \tag{B15}$$

$$ERA3(t,c,j,r) = ERA(t,c,j,r,U1) + (S(t,c,j,r,U2) * OF(t,c,j,r,U2)) \tag{B16}$$

The useful technical energy was calculated separately for SH, DHW and other usages, by multiplying the corresponding energy intensities with ERA. Exemplified for SH in Eq. B17.

$$Useful\_Technical\_Energy(t,c,j,r)_{SH} = ERA(t,c,j,r) * \mathcal{E}_{SH}(t,c,j,r) \tag{B17}$$

The useful real energy for space heating was calculated by multiplying the user behaviour (UB) with the useful technical energy demand (Eq. B18).

$$Useful\_Real\_Energy(t,c,j,r)_{SH} = Useful\_Technical\_Energy(t,c,j,r)_{SH} * UB(t,c,j,r) \tag{B18}$$

The useful energy was translated to final energy by applying the energy carriers (EC) distribution and the efficiencies (η) (Eq. B19).

$$Final\_Energy(t,p) = (Useful\_Energy(t) * EC(t,p))/\eta(t,p) \quad \text{where } p\text{=energy carriers} \tag{B19}$$

The emissions were found by multiplying carbon intensity (CI) with final energy (Eq. B20).

$$Emissions(t) = Final\_Energy(t,p) * CI(t,p) \tag{B20}$$

Appendix C:
Combined lifetime-leaching approach

The implementation of the combined lifetime-leaching approach was modelled with two steps: (1) calculation of inflow and outflow from the stock with the lifetime (LT) approach (explained in ***Appendix B***, and referred below as inflowLT, outflowLT and stockLT), and (2) correction of the previous variables by the leaching (LE) approach (referred below as inflowLE, outflowLE and stockLE). The second step requires the definition of the leaching by the following aspects: (1) execution time of the leaching, (2) leaching rate, and (3) affected segment. The leaching was defined by an execution time span of 10 years, 2021-2030, the leaching rate followed a gradual increase leading to a 100% demolition in year 2030 and the affected segment was the non-renovated stock built before 1990 (equal to buildings consuming more than 140 kWh/m^2/yr). The second step needs a distinct consideration of the following stock segments:

1- *Non-affected* by the leaching
2- *Affected segment* (demolished stock segment)
3- Stock built from the start of the *execution of the leaching* until the end of the simulated time (replacement of the stock by highly energy efficient buildings)

The *non-affected* segment of the stock (stockLE) was described by the stock obtained with the lifetime approach (stockLT) (Eq. C1). The outflow for the *non-affected* segment was obtained with the same equation C1 but using outflowLE and outflowLT.

$$stockLE(t,c,j,r,u) = stockLT(t,c,j,r,u) \tag{C1}$$

For the *affected segment*, the outflows (outflowLE) and the stock (stockLE) during the first year of leaching (t_l=first year of leaching) were obtained using the stock calculated with the lifetime approach (stockLT). More specifically, the outflow (outflowLE) was obtained by multiplying the leaching rate (α) with the stock obtained by the lifetime approach (stockLT) (Eq. C2). The stock (stockLE) was found by subtracting the calculated outflow (outflowLE) to the stock obtained by the lifetime approach (stockLT), as shown in Eq. C3. The stockLT in Eq. C2 and C3 is defined for $t_l - 1$ in order to comply with the convention used in the model of calculating the stock at the end of the year.

$$outflowLE(t_l,c,j,r,u) = stockLT(t_l-1,c,j,r,u) * \alpha(t_l,c,j,r,u) \tag{C2}$$

$$stockLE(t_l,c,j,r,u) = stockLT(t_l-1,c,j,r,u) - outflowLE(t_l,c,j,r,u) \tag{C3}$$

For the *affected segment*, the outflows (outflowLE) and the stock (stockLE) after the first year of leaching were obtained using the stockLE from Eq. C3 and with similar formulations as in Eq. C2-3. Precisely, the outflowLE is defined by the multiplication of stockLE with the leaching rate (α) (Eq. C4), and stockLE is obtained as the subtraction of outflowLE to stockLE (Eq. C5).

$$outflowLE(t,c,j,r,u) = stockLE(t-1,c,j,r,u) * \alpha(t,c,j,r,u) \tag{C4}$$

$$stockLE(t,c,j,r,u) = stockLE(t-1,c,j,r,u) - outflowLE(t,c,j,r,u) \tag{C5}$$

The inflow for the *affected cohorts* remained the same as for the lifetime approach.

For *execution of the leaching,* the inflow was obtained by summing the stock change and outflowLE. Given that TS changes over time, the inflowLE was calculated using the corresponding *TS* as shown in Eq. C6. Consequently, the leaching has an effect in accelerating the change in building type distribution of the stock.

$$inflowLE(t,j) = \big(dS(t) + outflowLE(t)\big) * \ TS(t,j) \tag{C6}$$

For the *execution of the leaching*, the calculations of the outflow (outflowLE) and stock (stockLE) were performed using Eq. B5 and B6, with the recalculated inflow (inflowLE).

Given that the stock is segmented by renovation states, the following correction is required.

Correction of R3 stock affected by the leaching:

Since R1 (non-renovated) stock was renovated to R3 between 2021-2100, the demolition of R1 also affects R3 stock. Furthermore, R2 stock was also renovated to R3 during the same time span. Consequently, the R3 stock remaining after the leaching was recalculated by only accounting for R2 stock renovating to R3, since R1 stock is demolished. This correction was implemented with the following calculation procedure: (1) calculate the flow out from R2 stock due to natural demolition and renovation to R3. (2) Calculate the natural demolition of R2 stock by applying Eq. B11. (3) Calculate the flow from R2 to R3 by subtracting the natural demolition obtained in step 2 to the flow calculated in step 1. (4) Build up R3 stock with the flow from R2 to R3. (5) Calculate the natural demolition of R3 stock by applying Eq. B11. (6) Subtract the natural demolition of R3 to the R3 stock obtained in step 4.

Segmentation of the highly-energy efficient stock into R1 and R3

Stock replacing the demolished stock was segmented into R1 and R3 by applying Eq. B7-12.

Appendix D:

Estimation and calibration of parameters and sensitivity analysis method

Table D1 provides an overview of the input data, parameter assumptions and calibration, and evaluation of historical data uncertainty for the complete set of parameters. Specific details of each part of the table are presented after the table. The input data refer to the period 1800-2100; however, in order to account for the stock constructed before 1800 and avoid a big inflow in 1800, we expanded the timeframe by including 1600-1800. We assumed a stock in 1600 of 0 and we applied a linear regression to populate the timeframe until 1800.

Table D1: Parameter description including values, data source, assumptions and the evaluation of data uncertainty. The source corresponds to the values and assumptions. Future values correspond to *baseline* scenario.

Parameter	Value and Units	Source	Assumptions and Notes	Evaluation of data uncertainty
Population ***(POP)***	***Figure D1***	(FSO 2018b; HSSO 2012b; UN 2019)	Medium projection. Parameter calibrated with a logistic function	Low
Floor Area per Dwelling (FApD) (stock used daily)	***Figure D1***	(Bergsdal et al. 2007; FSO 2000; FSO 2018c)	65 m^2/dwelling in 1800 and 104 m^2/dwelling in 2100. Parameter calibrated with a logistic function	Low
People per Dwelling (PpD) (stock used daily)	***Figure D1***	(FSO 2017b; FSO 2019b; HSSO 2012a; Müller 2006)	5 people/dwelling in 1800 and 2 people/dwelling in 2100. Parameter calibrated with a logistic function	Low
Floor Area per Dwelling (FApD) (total stock)	***Figure D1***	(Bergsdal et al. 2007; FSO 2011; FSO 2018d)	65 m^2/dwelling in 1800 and 102 m^2/dwelling in 2100. Parameter calibrated with a logistic function	Low
People per Dwelling (PpD) (total stock)	***Figure D1***	(FSO 2019a; Müller 2006)	5 people/dwelling in 1800 and 1.7 people/dwelling in 2100. Calculated by dividing population and total number of dwellings. Parameter calibrated with a logistic function	Low
Type split (TS)	***Figure D1***	(FSO 1932; FSO 1985; FSO 1986; FSO 1987; FSO 1993; FSO 1995; FSO 2005; FSO 2012; FSO 2017a; Werczberger 1997)	The oldest value was used for 1800-1929. The data gaps between 1929-2017 were filled with the principle that the missing values were equal to an available historical data point of the same cohort. The future values were assumed to be equal to 2017, following a conservative principle used in existing literature (Vásquez et al. 2016)	Low
Lifetime (τ)	200 years ***Figures D2***	(Kornmann & Queisser 2012)	Lifetime was assumed equal for all cohorts and types. Given the scarce data, a parameter calibration was performed	High
Std. Deviation (σ)	25%	(Sartori et al. 2008)	Standard deviation for the lifetime and the renovation cycle length	-
Renovation cycle length (τ_r)	40 years	(Filchakova, Wilke & Robinson 2009)	Renovation cycle length equals to the longest lifetime of energy-relevant building components	High

Realized renovations (rr)	80%	(Siller, Kost & Imboden 2007)	The rr was assumed to be constant	High
Occupancy Factor (OF)	79%	Adapted from Heer et al. (2005)	OF was assumed to be constant. Stock used daily has an energy use of 100%	High
Correction Factor (CF)	***Figure D1***	(SFOE 2016; Streicher et al. 2019)	The CF is assumed to be 1 in 1800, and around 1.25 in 2100 for SFH and MFH. Parameter calibrated with a logistic function	Low
Vacancy rate (VR)	1.6% in 2018	(FSO 2018e)	The values were found until 2018. Future values were assumed constant and equal to 2018 value	Low
*User Behavior (**UB**)*	***Figure D3***	(Streicher et al. 2019)	The UB was obtained with the procedure described in ***Figure E4***	Low
Energy Intensity (Ɛ)	Not shown	(Filchakova, Wilke & Robinson 2009; Ostermeyer et al. 2018; Pfeiffer, Koschenz & Wokaun 2005; SFOE 2016; Siller, Kost & Imboden 2007; Streicher et al. 2019)	Ɛ was defined for technical useful energy segmented by cohorts, renovation states and energy uses (SH, DHW or others). The R1 values for the cohort 2021-2030 were assumed to follow the decreasing trend observed from 2010 until 2019 (Buildings Program in place), after 2030 the trends observed before 2010 were implemented. R2 and R3 values for SH and DHW were calculated using a 55% and 60% reduction, respectively, and compared to R1. The values for other energy uses in R2 and R3 were assumed equal to R1. The minimum energy demand for SH was assumed at 8 and 4 kWh/m^2/yr for SFH and MFH respectively, and for DHW at 12 kWh/m^2/yr	High
Energy Carriers (EC)	***Figure D4***	(FSO 1980; SFOE 2012; SFOE 2019)	The oldest value found was assumed for 1800-1970. The future values until 2025 were assumed to follow the trend during 2010-2019 (Buildings Program). After 2025, past trends before 2010 were implemented, except for gas. Gas had an increasing trend during 2010-2019, which was assumed to continue until 2035. After 2035, a -0.55%/yr was assumed, based on SFOE (2012)	Low
Heating system efficiency (η)	Not shown	(Wallbaum et al. 2009; Wang et al. 2018)	The values for 2005 and 2015 were obtained from literature, and a linear regression was applied to obtain the entire data set. A stagnation at 1 was assumed, except for heat pumps, which it was assumed at 3	Low
Carbon Intensity ***(CI)***	73.7, 92.7, 56.4 t CO_2/TJ for heating oil, coal, natural gas respectively	(FOEN 2017; Siller, Kost & Imboden 2007)	The CI were assumed constant until 2100. The CI for electricity, wood, renewable energy and district heating were 0 (only direct emissions)	Low

Input data, parameter estimation and calibration

The input data for *POP, TS, FApD, PpD* and *CF* are presented in ***Figure D1*** for the *baseline* scenario. The parameters *FApD* and *PpD* are shown for the total and the daily-used stock.

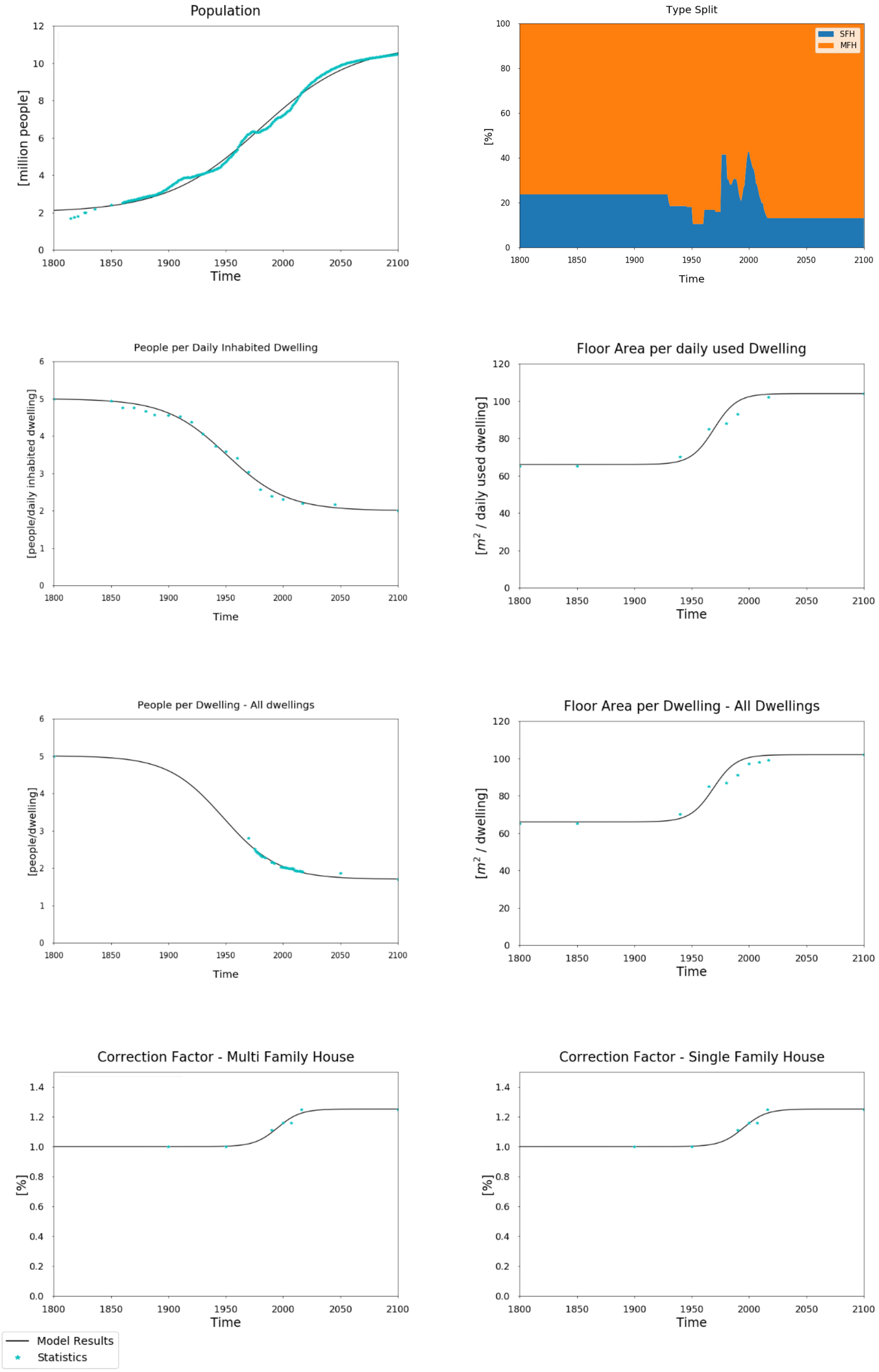

Figure D1: Model input parameters: *POP*, *TS*, *PpD*, *FApD*, and *CF* for the *baseline* scenario

The parameters *POP, FApD, PpD* and *CF* were calibrated using a non-linear regression with a logistic function (Eq. D1). The logistic function used was:

$$c(t) = \frac{c_1 - c_0}{(1 + e^{(-(c-t_i)/tau)}) + c_0} \tag{D1}$$

where $c(t)$ is the vector of observation, c_1 is the end value, c_0 is the start value, t_i is the inflection time, and tau is the transition time coefficient.

The *lifetime* parameter was obtained through a process of parameter calibration and model validation using different lifetimes based on the findings of Kornmann and Queisser (2012), which quantified that Swiss dwellings have lifetimes longer than 200 years (***Figures D2***). A lifetime of 200 years was chosen based on a qualitative analysis of the calibration results and on a conservative principle considering the scarce data and findings on a national scale.

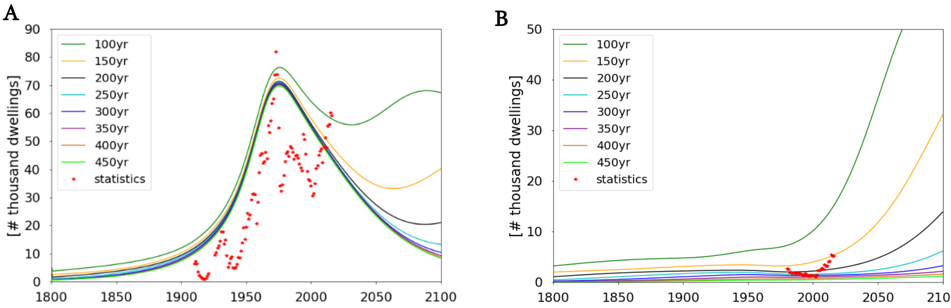

Figure D2: Inflow (A) and outflow (B) results with different lifetimes, compared against statistical data (FSO 2018a).

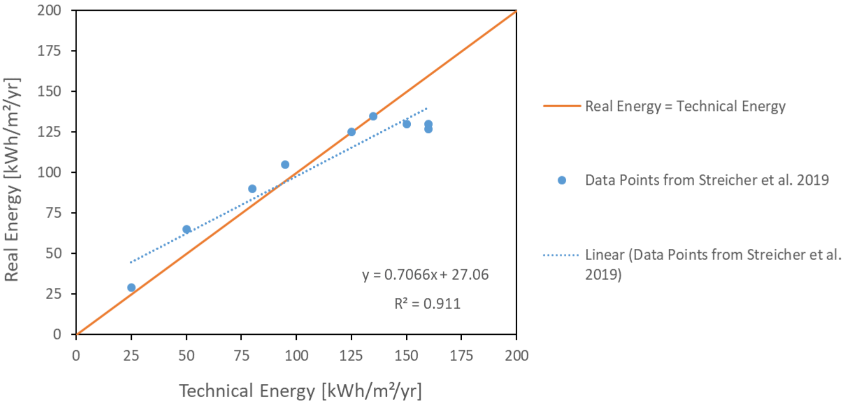

Figure D3: User behavior trendline obtained from measured data (real energy) versus calculated technical energy.

The UB parameter was obtained as described in Sandberg et al. (2017) by calculating the ratio between technical and real energy for SH (***Figure D3***). The linear trendline was calculated from the data points obtained from Streicher et al. (2019). The 45° line presents the situation in which technical and real energy are equal. The obtained linear trendline (blue dotted line) is less steep than the 45° line, which shows that in highly energy-consuming buildings (e.g. 150 kWh/m^2/yr) the real energy is lower than the technical energy, whereas for low consuming buildings (e.g. 50 kWh/m^2/yr) the real energy is higher than the technical.

The input data for the energy carriers to supply the demand of SH is presented in ***Figure D4***.

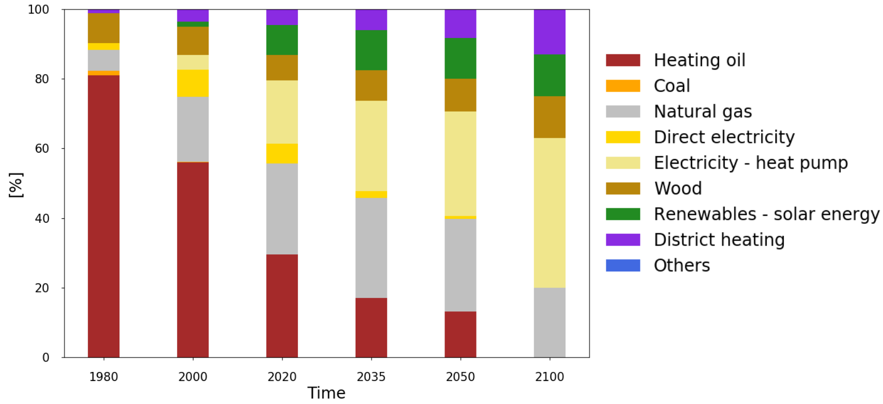

Figure D4: Input data for energy carriers for SH and *baseline* scenario.

Sensitivity Analysis - Evaluation of data uncertainties (historical analysis)

The evaluation of the uncertainty associated with data sources was based on previous publications (Mattinen et al. 2014; Sandberg et al. 2017). The parameters populated using data from official statistics sources or from previous studies (including validation of model results) were regarded as low. This is the case for *POP, FApD, PpD, TS, CF, VR*, *UB, EC,* η and *CI.* The lifetime parameter was evaluated with high uncertainty, given that data sources on a national scale were scarce. Similarly, τ_r *(renovation cycle length)*, *rr (realized renovations)*, *OF (occupancy factor)* and Ɛ (technical *energy intensity* of R1 and R2) were regarded as highly uncertain given that data sources were either scarce, adapted from other studies or with uncertainty.

Sensitivity Analysis – Method to analyze uncertainty related to future input parameters

The sensitivity analysis for future input data was implemented as a parameter variation in 2050 with ±10% changes of the *baseline* scenario. The input data during 2020-2050 was populated using a logistic function for the parameters *POP, FApD, PpD* and *CF* or a linear regression for all other parameters, and the input data before 2020 remained unchanged. This approach is based on a series of publications (Bergsdal et al. 2007; Charlier & Risch 2012; Sandberg, Sartori & Brattebø 2014; Sandberg et al. 2017). The contribution of single energy carriers was studied only for the relevant carriers for SH and DHW: heating oil, natural gas, heat pumps, renewable energies and district heating. Similarly, the heating system efficiency was analyzed for the mentioned relevant carriers, and a ±2% parameter variation was used to avoid efficiencies higher than 1, which are impossible.

Sensitivity Analysis – Relative sensitivities method

The relative sensitivities (RS) were calculated as the relative change in model results (x) over the relative change in input data of parameters (p) as shown in Eq D2.

$$RS_{i,j} = \frac{\Delta x_i / x_i}{\Delta p_j / p_j}, \quad i = 1, \ldots, n \; and \; j = 1, \ldots, m \tag{D2}$$

Appendix E:

Scenario descriptions and specifications

The scenarios were analyzed against the goals described in ***Section 1*** (main manuscript). The goals were defined on a sectorial basis by assuming an equal contribution of all sectors. The carbon neutrality goal was considered as zero emissions in 2050, and the 2000-Watt Society vision was defined as a reduciton of the energy consumption per capita by a factor of 3 in 2050 compared to 2000 (Siller, Kost & Imboden 2007). The assumptions and specifications of each scenario are presented in ***Table E1***. The scenario analysis was performed until 2050; therefore, the values after 2050 were assumed equal to 2050 or to follow past trends.

Table E1: Scenario specifications (affected parameters) and assumptions.

Scenario	Parameters	Assumptions
Baseline	Ɛ, *EC*	Explanation in ***Appendix D***
Extend Buildings Program	Ɛ, *EC*	Trends observed for Ɛ (R1) and *EC* during the period 2010-2019 (Buildings Program) were assumed to continue until 2100. The Ɛ for R3 was calculated as a 65% reduction compared to R1. The remaining parameters were defined as in *baseline*
Carbon neutrality	*EC*	The share of fossil fuels was determined by a linear decrease until reaching 0 in 2050. Fossil fuels were replaced by heat pumps and renewable energies based on previous scenarios (SFOE 2016; Siller, Kost & Imboden 2007; Wallbaum et al. 2009). Additionally, the replacement was constrained by the cumulative principle used to build the scenarios, which requires an extensive use of highly energy-efficient technologies (heat pumps) to facilitate meeting the energy reductions goals in stemming scenarios (e.g. backcasting scenarios for the 2000-Watt Society goal). This study does not consider the effects of using different technologies beyond energy and emissions (e.g. district heating as waste management). The remaining parameters were defined as in *extend Buildings Program*
Green lifestyles	*UB, CF*	The UB values above 1 (real energy higher than technical energy) were assumed to linearly decrease until reaching 1 in 2050. After 2050, the values were assumed to be 1 (real energy equals technical energy). The CF was assumed to gradually decrease until reaching 1 in 2050 (areas beyond dwellings surface are not heated up). The gradual decrease was modelled with a logistic function (Eq.D1). After 2050, the value was assumed at 1. The remaining parameters were defined as in *carbon neutrality*
Energy standards	Ɛ	The Ɛ (including SH, DHW and other uses) of new construction (R1) was assumed to be around 35 kWh/m^2/yr from 2021 onwards, which is equal to the best standard (Minergie-A). The Ɛ for R3 was set at a 75% reduction compared to R1, which leads to Ɛ of about 60 kWh/m^2/yr (Minergie-P) for the stock built during the period 1800-1990, and around 35 kWh/m^2/yr (Minergie-A) for the rest. The remaining parameters were defined as in *carbon neutrality*
Renovation	τ_r, rr	The renovation activity was assumed to increase by: (1) renovating more frequent, τ_r was assumed at 30 years from 2021 onwards, and (2) realizing all renovations, rr is equal to 100%. The remaining parameters were defined as in *carbon neutrality*
Replacement	*α*	The leaching rate was defined by: (1) an execution time during 2021-2030, (2) a gradually increasing rate until reaching 100% in 2030, (3) affecting the non-renovated (R1) stock in which the Ɛ is higher than 140 kWh/m^2/yr (non-renovated stock built before 1990). The remaining parameters were defined as in *carbon neutrality*
Combined technical	Ɛ, τ_r, α	The premises defined in *energy standards*, *renovation*, and *replacement* scenarios were assumed
Supreme green lifestyles	*FApD* (for total and stock used daily), *TS*	The FApD was assumed to decrease reaching 94 and 84 m^2/dwellings in 2050 for total and stock used daily respectively. The FApD was assumed to continue decreasing after 2050, reaching 92 and 83 m^2/dwellings in 2100 for total and stock used daily respectively. The decrease was modelled with a logistic function (Eq. D1). The *TS* was assumed to linearly be dominated by MFH, reaching 100% in 2050; SFH was assumed to decrease accordingly. After 2050, the shares were kept constant. The remaining parameters were defined as in *green lifestyles*
Combined renovation	*UB, CF,* Ɛ, τ_r	The premises defined in *green lifestyles*, *energy standards,* and *renovation* scenarios were assumed
Combined replacement	*UB, CF,* Ɛ, *α*	The premises defined in *green lifestyles*, *energy standards,* and *replacement* scenarios were assumed

Appendix F:

Additional results of baseline scenario and uncertainty analysis

Validation of final energy consumption segmented by energy carriers

The validation of the historical final energy consumption segmented by energy carriers is provided in ***Figure F1***, together with the future values of the *baseline* scenario.

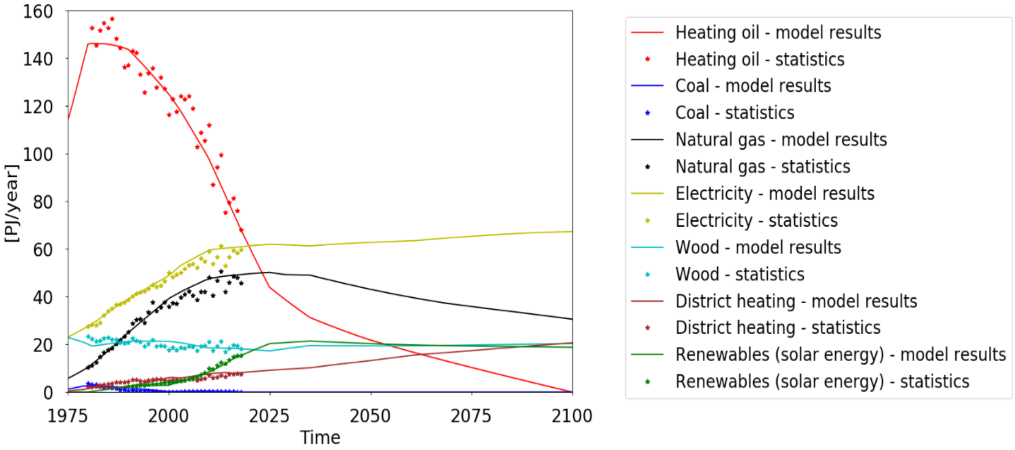

Figure F1: *Validation of final energy consumption results segmented by energy carriers compared to statistical data (SFOE 2019) and future values for the* baseline *scenario.*

Comparison of results using different ERA approaches, user behavior and previous studies

The direct final energy consumption obtained by using the three ERA approaches is presented in ***Figure F2***. Energy results are compared to two studies (Siller, Kost & Imboden 2007; Wallbaum et al. 2009), which considered the entire Swiss residential building stock and future energy consumption. Both studies used the ERA2 approach; thus, their results are compared to the model results using ERA2. The results of the two studies were adapted to have a consistent scope across studies. The two studies were conducted before 2010 (start of the BP); therefore, their results do not reflect the trend shift triggered by the BP, which leads to an overestimation of statistical data and model results beyond 2010. Nevertheless, the adapted historical results from the two studies before 2010 are comparable with our results.

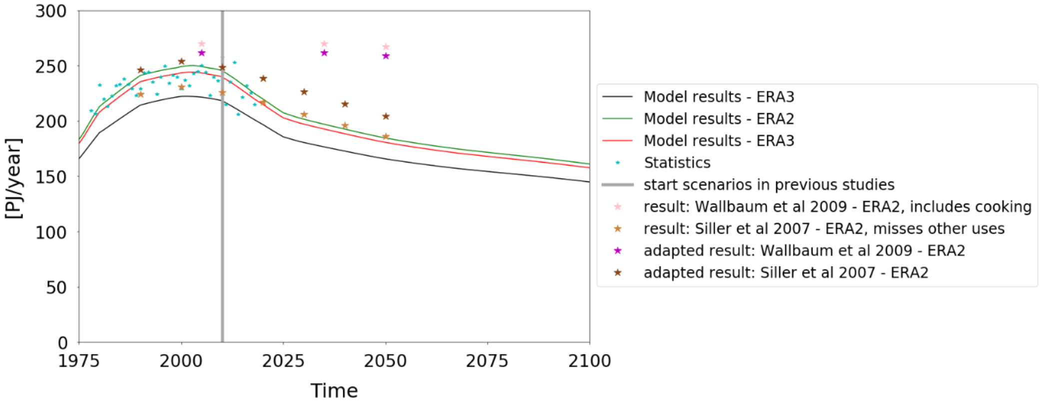

Figure F2: Direct final energy consumption using the ERA approaches presented in Figure 2 (main paper) and compared to statistical data (SFOE 2019) and previous studies. The results from previous studies were adapted to fit the scope: energy related to cooking activities was subtracted from the results of Wallbaum et al. (2009), energy related to other uses was added in the results of Siller, Kost and Imboden (2007). The adaptations were based on SFOE (2018).

The direct final energy consumption calculated with and without user behavior (corresponding to real and technical energy respectively) is depicted in ***Figure F3***. The results show a performance gap (difference between technical and real energy consumption) of 20% in 2050, which is comparable to previous studies (Schneider et al. 2017).

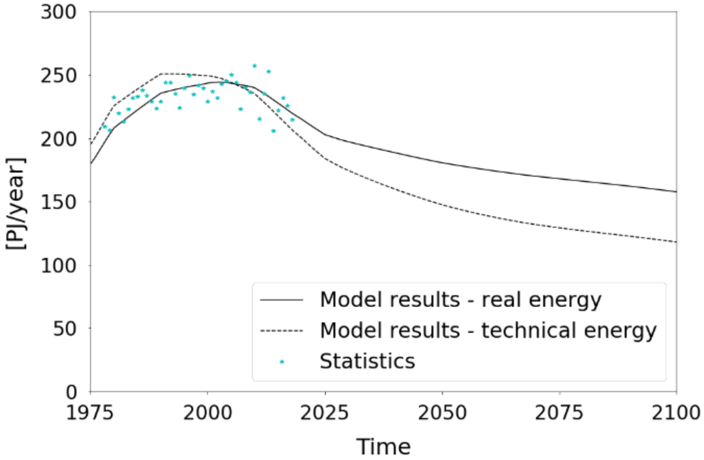

Figure F3: Direct final energy consumption computed with and without user behavior, which corresponds to real and technical energy consumption respectively. The model results are compared to statistical data (SFOE 2019).

The emissions results from previous studies were not compared with the results of this study given that the granularity of the results was insufficient for the comparison.

Results of the sensitivity analysis in 2050

The relative sensitivities in 2050 are presented in ***Table F1*** for a parameter variation of +10%.

Table F1: Relative sensitivities in 2050 with +10% of input parameter (negative values indicate that the parameter increase leads to an output decrease).

Parameters	Energy results	Emissions results
Population	0.72	0.71
Floor Area per Dwelling (total stock)	0.47	0.46
People per Dwelling (total stock)	-0.63	-0.62
Type split (lower SFH)	-0.01	-0.01
Lifetime	0.02	0.02
Renovation cycle length	0.18	0.24
Realized renovations	-0.05	-0.07
Occupancy Factor	0.08	0.08
Correction Factor	0.82	0.82
Vacancy rate	-0.01	-0.01
User Behavior (higher overheating)	0.57	0.76
Energy Intensity, Others, R1, R3	0.04	0
Energy Intensity, SH, R1	0.07	0.09
Energy Intensity, SH, R3	0.24	0.32
Energy Intensity, DHW, R1	0.03	0.04
Energy Intensity, DHW, R3	0.08	0.11
Energy Carriers - Contribution heating oil	0.01	0.40
Energy Carriers - Contribution natural gas	0.01	0.45
Energy Carriers - Contribution heat pumps	-0.20	-0.27
Energy Carriers - Contribution renewable energies	0.02	-0.10
Energy Carriers - Contribution district heating	0.01	-0.07
Heating system efficiency – heating oil	-0.08	-0.25
Heating system efficiency – natural gas	-0.11	-0.28
Heating system efficiency – heat pumps	-0.04	0
Heating system efficiency – renewable energies	-0.12	0
Heating system efficiency – district heating	-0.03	0

Appendix G:
Additional scenario analysis results

The high construction and demolition activities triggered in the *replacement, combined technical* and *combined replacement* scenarios is presented in ***Figure G1***.

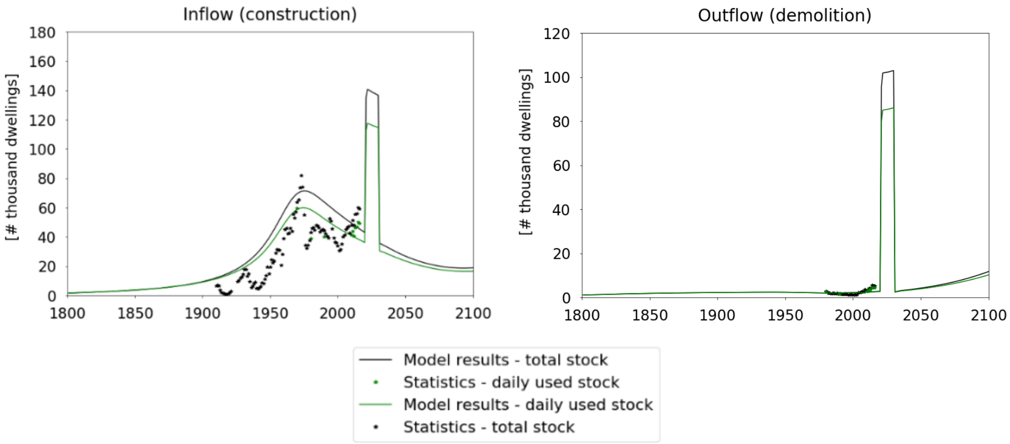

Figure G1: Inflows and outflows for the *replacement, combined technical* and *combined replacement* scenarios, historical results are compared to statistical data (FSO 1919; FSO 1931; FSO 1945; FSO 1963; FSO 1986; FSO 2018a).

The energy consumption segmented by SH, DHW, and other uses is shown in ***Figure G2***.

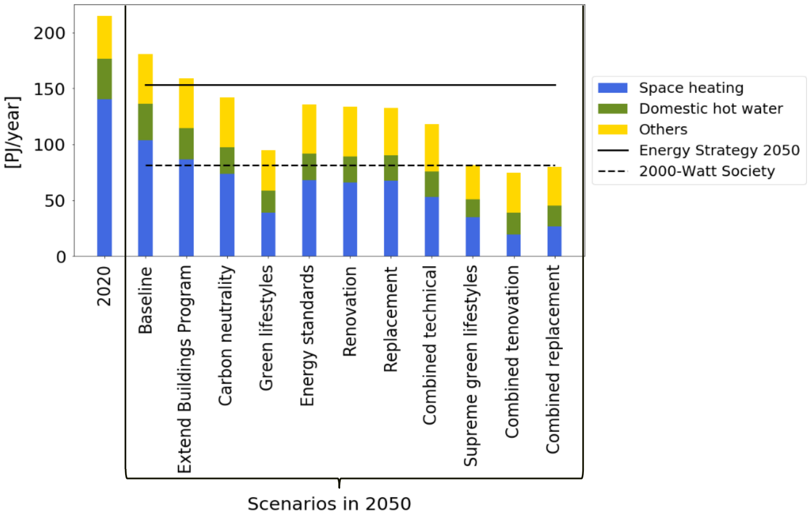

Figure G2: Direct final energy consumption for the use phase of Swiss residential buildings segmented by use of energy in 2020 and for all scenarios in 2050, compared to the Energy Strategy 2050 and the "2000 W society".

The stock of dwellings segmented by cohorts and renovation states for the *replacement* scenario shows that the stock built before 1990 and non-renovated (R1) was demolished during the period 2021-2030 (***Figure G3***). The demolished stock was replaced by dwellings built during the period 2021-2030 to preserve the total stock. This highlights that the combined lifetime-leaching approach captures both the heterogeneity of the stock and the increased targeted replacement. Similar results were obtained for the *combined technical* and *combined replacement* scenarios; therefore, they are not presented.

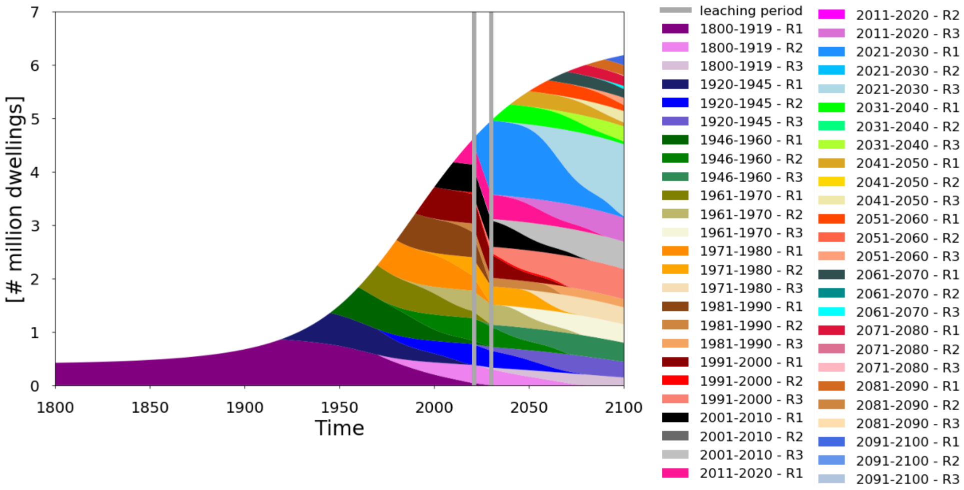

Figure G3: *Stock of dwellings segmented by cohorts and renovation states for the* replacement *scenario*.

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Appendix B

Paper II

Modeling the transition toward a carbon-neutral car fleet: Integrating electrification, shared mobility, and automation

Marta Roca-Puigròs, Charles Marmy, Patrick Wäger, and Daniel B. Müller. In review by *Transportation Research Part D: Transport and Environment, 2022*

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Appendix C

Paper III

Linking Socio-Economic Metabolism models and Simulation Games: Reflections on benefits and challenges

Marta Roca-Puigròs, Andreas Gerber, Markus Ulrich, Matthias Y. Reich, Daniel B. Müller, and Patrick Wäger. In review by *Journal of Industrial Ecology, 2022.*

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