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Citation for the original published paper (version of record):
Nägeli, C., Jakob, M., Catenazzi, G. et al (2020). Policies to decarbonize the Swiss residential building stock: An agent-based building stock
modeling assessment. Energy Policy, 146. http://dx.doi.org/10.1016/j.enpol.2020.111814

Energy Policy 146 (2020) 111814

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

Policies to decarbonize the Swiss residential building stock: An agent-based building stock modeling assessment

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ARTICLE INFO

Keywords:
Climate policy
Scenario assessment
Building stock modeling
Bottom-up model
Agent-based modeling

ABSTRACT

In light of the Swiss government's reduction targets for greenhouse gas (GHG) emissions under the Paris Agreement, this article investigates how and with which policy measures these reduction targets can be met for the Swiss residential building sector. The paper applies an agent-based building stock model to simulate the development of the Swiss residential building stock under three different policy scenarios. The scenario results until 2050 are compared against the reduction targets set by the Swiss government and with each other. The results indicate that while the current state of Swiss climate policy is effective in reducing energy demand and GHG emissions, it will not be enough to reach the ambitious emission-reduction targets. These targets can be reached only through an almost complete phase-out of fossil-fuel heating systems by 2050, which can be achieved through the introduction of further financial and/or regulatory measures. The results indicate that while financial measures such as an increase in the CO_2 tax as well as subsidies are effective in speeding up the transition in the beginning, a complete phase-out of oil and gas by 2050 is reached only through additional regulatory measures such as a CO_2 limit for new and existing buildings.

1. Introduction

The 2015 Paris Agreement to limit climate change to a global average temperature increase of below 2 °C emphasizes the need to reduce GHG emissions. Under the Paris Agreement, Switzerland has vowed to decrease emissions by 50% by 2030 compared to 1990 levels (CH, 2015). This is in line with the Swiss climate strategy of a 20% reduction by 2020, 50% by 2030, and 70–85% by 2050 (EnDK, 2016). In terms of buildings, however, Swiss climate policy aims for a 40% reduction already in 2020, and the goal is to further reduce direct building emissions by at least 80% by 2050 (EnDK, 2016). To meet these GHG emission-reduction targets, a considerable change in the building stock is required. Next to the decarbonization of the energy supply, this also includes a significant reduction in the current energy consumption of buildings.

The current policy framework to address the decarbonization of the Swiss building stock is a mixture of national and regional regulative and financial policies. In terms of financial instruments, the main policies are the CO_2 tax on fossil-fuel energy carriers, introduced in 2008 (CH, 2011) as well as national and regional subsidy programs (Sigrist and Kessler, 2016). The regulatory aspects are laid out in a national model building code (MBC) (EnDK, 2015). This MBC defines the minimum energy standard of new buildings and retrofits, provides restrictions on the installation of heating systems (e.g., banning central direct electrical heating), and establishes requirements on the use of renewable energy sources (RES) for new and existing buildings. These restrictions are, however, not introduced in all states (cantons) of Switzerland simultaneously. Instead, they must be implemented into legislation individually in the different cantons, which results in different parts of the code being adopted at different rates (EnDK, 2018).

To reach the ambitious reduction targets by 2050, the currently implemented policy measures will probably not be enough, and further measures will be needed (EnDK, 2016). Proposed are a further strengthening and extension of the regulatory framework through the imposition of RES requirements (EnDK, 2016) or the introduction of a ban of fossil-fuel heating systems or GHG emission limits for new and existing buildings (FOEN, 2018a). Moreover, an extension of financial incentives such as an increase in the CO_2 tax is being considered as well (FOEN, 2018b). The revenue from the CO_2 tax partially funds subsidy programs for buildings, meaning these programs could also be expanded. With all of these options on the table and the revision of the Swiss CO_2 law currently under discussion, the question is: How can the

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https://doi.org/10.1016/j.enpol.2020.111814
Received 9 September 2019; Received in revised form 16 June 2020; Accepted 1 August 2020
Available online 21 August 2020
0301-4215/

reduction targets set by the Swiss government be achieved for buildings, and what policies are needed to do so?

Bottom-up building stock models (BSM) can provide fundamentals to answer these types of questions (Kavgic et al., 2010; Swan and Ugursal, 2009). BSMs can simulate the energy demand and GHG emissions of the building stock by modeling the changes in the stock through new construction, demolition, and retrofits of existing buildings as well as through changes in the deployment of energy efficiency measures and building technologies. As such, BSMs can be used to develop scenarios for the future development of the energy and GHG emissions of the stock, which can highlight discrepancies, tradeoffs, and priority areas for policy-makers (Sandberg et al., 2017). They have been applied on a transnational and national scale (Heeren et al., 2013; Kranzl et al., 2013; Loga et al., 2012; Mata et al., 2014; McKenna et al., 2013; Sandberg et al., 2017), an urban scale (Mastrucci et al., 2014; Österbring et al., 2016), and a district scale (Fonseca et al., 2016).

When modeling the development of the building stock, common BSM approaches rely on exogenously defined rates, such as new construction, demolition, retrofit, and substitution rates, or top-down system dynamics approaches to model changes in the stock (Mastrucci et al., 2017; Sandberg et al., 2017). This limits the expressiveness of the model results in answering the questions of policy-makers, because policy measures such as a CO_2 tax or subsidies are not modeled explicitly. One way to address this shortcoming is by modeling a building owner's decision using agent-based modeling (ABM) techniques in BSMs.

This paper applies an agent-based building stock model (ABBSM) that was developed and calibrated based on the historic development of the Swiss residential building stock (Nägeli et al., 2020). The ABBSM uses an agent-based modeling (ABM) approach to model stock development in terms of new construction, envelope retrofit, and replacement of heating systems by modeling individual decisions at the building scale through the application of microeconomic utility theory. This highly disaggregate model couples a decision model that simulates a building owner's investment decisions under economic and policy framework conditions with a building energy demand simulation model to assess the energy and GHG emissions of the building stock over time. As a result, the model can be used to study the effects of different policy scenarios on the long-term transformation of the building stock, while taking into account drivers such as technological change, building stock growth, and tradeoffs between investment in energy efficiency and renewable energy supply measures when it comes to reducing the GHG emissions of the building stock.

By applying the ABBSM to model the future development of the Swiss residential building stock, this study aims to assess the effect of various policy scenarios on the long-term development of the Swiss building stock by answering the following research questions:

1. What is the long-term energy demand and GHG emissions of the Swiss building stock under different policy scenarios?
2. What are the potential future effects of regulatory or financial policy instruments on the development of the Swiss residential building stock in terms of cost, energy, and GHG emissions?
3. What implications do the modeled results have for the priority setting and the further development of Swiss climate policy in the building sector and climate policy-making in general?

2. Methodology

2.1. System boundary

The research questions posed in the introduction are studied in the Swiss residential building stock through analysis of the currently proposed climate policies, as outlined in the introduction. Therefore, the focus lies on the analysis of the effect of these policies on energy efficiency of buildings and the uptake of renewable heating system technologies in both new and existing buildings as well as how that affects the achievement of the emission-reduction targets proposed for buildings.

The analysis primarily covers building-related energy demand and related GHG emissions coming from space heating, hot water, ventilation, and general building electricity use. The electricity uses from appliances and lighting, while included in the model, is not discussed in the model results. GHG emissions related to energy use are examined both in terms of direct emissions as well as total emissions (including indirect emissions from upstream processes). However embodied emissions of construction materials or building technologies are not within the scope of this analysis. The time frame of the analysis is from 2017 to 2050, with special reference given to the years 2020, 2030, and 2050 because intermediate reduction targets are defined for these years.

2.2. Agent-based building stock model

The policy assessment is carried out using the ABBSM developed by Nägeli et al. (2020). The ABBSM is a highly disaggregated agent-based building stock model that models the stock development and the related energy and GHG emissions through individual decisions of building agents. By modeling individual disaggregate investment decisions that are based on the specific building case (i.e., building state, costs, and availability of RES), the model can explicitly model policy interventions such as CO_2 tax, subsidies, or technology restrictions (e.g., RES requirements for heating systems) that affect this decision (see section 2.2.3). A more detailed description of the model than is included in this paper can be found in the supporting information of Nägeli et al. (2020).

Fig. 1 provides an overview of the structure and work flow of the ABBSM. The model includes two main work steps; first, the initial state of the stock is initialized by generating an initial building agent population (see section 2.2.1). Afterward, the model simulates the future development of the stock by modeling the demolition, retrofit, and replacement of the existing buildings as well as adding new buildings to the stock. Heating system choices for new and existing buildings as well as envelope retrofit decisions are modeled through a dedicated decision model (see section 2.2.3). The effect of changes in the building agents states on the energy and GHG emissions of each building agent are modeled through an integrated energy demand model, which calculates the energy demand of building agents individually.

2.2.1. Initialization

The status quo is initialized by synthetically generating a representative sample stock of the building stock of Switzerland for the year 2017 based on the method described in Nägeli et al. (2018). The method creates a disaggregate, representative sample stock based on aggregate data, which is used to generate the initial agent population in three steps: 1) building stock initialization, 2) building characterization, and 3) updating building characteristics (cf. Fig. 1). The model is initialized with an agent population of 50,000 building agents at the model start, which yields fairly stable results for the stochastic behavior of the model within the computational limits of the model implementation. Each building agent is defined by general building characteristics, the building geometry, various building components, and HVAC systems. Depending on the building type, the agent has one to several different dwellings. The agent further includes building owner (e.g. decision criteria) and location-specific attributes (e.g. availability of RES). Each of these synthetically created buildings is representative of several buildings in the actual stock, which is characterized by a scaling factor (in terms of number of buildings) and a representative floor area in the model, which is used to scale results from the building agent to the stock level.

The structure of the initial building stock is based on aggregate data from the Swiss building and dwelling statistics (BDS) (FOS, 2019). The BDS includes information about the number of buildings and dwellings according to building type, construction period, number of floors,

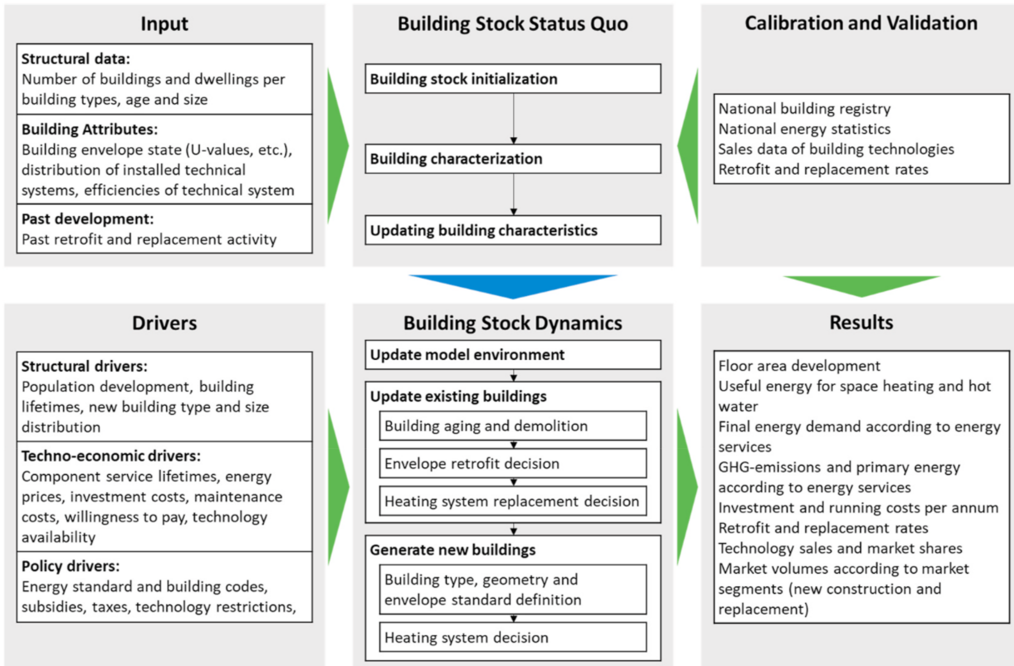

Fig. 1. Overview of the structure of the agent-based building stock model (Nägeli et al., 2020).

number of dwellings, dwelling size, and type of heating and hot water system. However, the information on the heating system is not consistently updated, which is why the data of the BDS is updated through iterative proportional fitting[1] using data from a representative survey, which assessed the distribution of heating systems in the stock (FOS, 2017). The heating and hot water system structure defined in BDS data is then mapped to the technology definition used in the ABBSM. (See Table 7 in the appendix for a list of the used heating technologies).

In the second and third steps of the initialization procedure, the individual building agent's characteristics are defined and updated to represent the state the building at the model start year of 2017. This includes the definition of the building geometry (i.e., surface area of components), the energy standard of the building envelope (e.g., U-values), the technical characteristics of the HVAC systems (e.g., heating system efficiencies), the dwelling occupancy-related attributes, and the owner and building location-specific attributes based on random sampling from input distributions according to the methodology of Nägeli et al. (2018). This way, the heterogeneity of the current state of the building stock in terms of various building characteristics and states can be reproduced in the initial building agent population. Table 8 in the appendix gives a full overview over the different data sources used in this step. The resulting building stock representation was then validated against the current state of the stock (both in the structure of the stock and its energy demand). Fig. 12 in the appendix shows the result of the comparison of the modeled energy demand compared with the national energy statistics.

2.2.2. Model process

The model process works with a timestep of one year, which starts by updating the model environment based on exogenous inputs, particularly adjusting energy prices, the costs of measures, the availability of technologies, and the policy variables depending on the scenario. After the model environment is updated, the model updates the state of all existing building agents one by one. Fig. 2 illustrates a representation of the lifecycle a building agent goes through.

As a first step, each building agent is aged by one year and the building agent's representativeness is adjusted to account for buildings represented by the building agent being demolished. Demolition is accounted for by reducing the scaling factor and representative floor area and thereby reducing the number of buildings represented by the building agent. The scaling factor is adjusted based on the survival function of the log-logistic function (see equation (1)), which was calibrated based on survival data from Aksözen et al. (2017b, 2017a).

$$S(t,\alpha,\beta) = 1 - \frac{1}{1+\frac{t}{\alpha}^{-\beta}} \qquad (1)$$

S Survival probability of the building

t lifetime of the building.

α scale parameter.

Β shape parameter.

Next to the building as a whole, each individual component is also aged by one year until it reaches the its assigned maximum lifetime after which it either needs to be reinstated, retrofitted, or replaced. The maximum lifetime of each component is assigned randomly based on a Weibull distribution (see equation (2)) when the agent is created or whenever a component has been replaced last. The lifetime distributions for each of the components is defined based on data from Agethen et al. (2010); IP BAU (1994). If an envelope component or the heating system has reached the end of its lifetime, the respective retrofit or replacement decision is modeled according to the decision model described below. After both the envelope retrofit and heating system replacement have been carried out, the energy demand and the related GHG emissions and energy costs of the building agent are updated accordingly.

$$F(t,k,\lambda) = 1 - e^{-\left(\frac{t}{\lambda}\right)^{k}} \qquad (2)$$

F Cumulative density function of the Weibull distribution

[1] Iterative proportional fitting adapts the individual elements of a data table in a way that the marginal totals along various dimensions (e.g., the number of buildings per construction period and building type) equal a defined distribution. This way, the distribution of heating systems in the input data can be updated, while keeping the data constant along other dimensions (e.g., construction period, etc.).

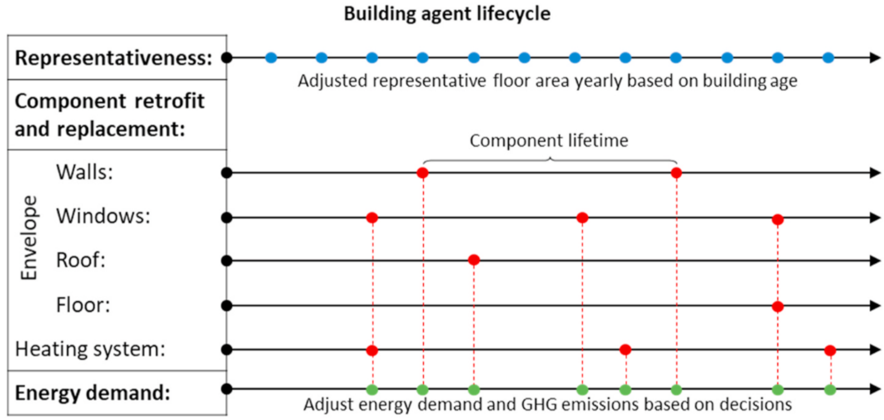

Fig. 2. Representative lifecycle of a building agent including different processes resulting in a change in the building state. Blue dots represent an update of the scaling factor and representative floor area, red dots represent a retrofit or replacement decision, green dots represent an update of the energy demand and GHG emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

t lifetime of the building component
λ scale parameter
k shape parameter.

After all existing buildings have been updated, the model calculates the demand for new construction in a given timestep based on the population development and a derived demand for living space. Based on the demand for new construction, the number of new building agents is determined depending on the ratio of modeled buildings and the number of agents. The new building agents are then generated in a similar procedure to the initial building agents by defining the various building attributes one after the other. In this manner, first the building type, size, geometry, and envelope standard are defined. Thereafter, the heating system is chosen according to the decision model described below. Finally, energy demand and related GHG emissions and energy costs are calculated to conclude the new building agent characterization.

2.2.3. Decision model

The ABBSM applies a decision model to represent the decision processes of building agents to retrofit envelope components, heating system replacement, and the choice of heating systems in new buildings. The general decision model applied for these different decision instances is built on the general model of the strategic decision process (Mintzberg et al., 1976) and the theory of innovation (Rogers, 1995) in combination with a discrete choice model (Train, 2003) as well as an application of the principle of bounded rationality (Simon, 1955). The decision model is structured based on the three steps of the model for the strategic decision-making process of Mintzberg et al. (1976): 1) identification, 2) development, and 3) selection. The identification step triggers the decision model, which is due either to a new agent being created (heating system decision for new buildings) or a component reaching the end of its assigned lifetime.

During the development step, the building agent constructs the choice set for a given decision. Based on a universal choice set for each of the decision types, which includes all possible options, the consideration choice set is constructed, which includes only the options considered in detail by that agent. In the case of the retrofit decision, the choice set is directly formed from the universal choice set, which includes a reinstatement option (i.e., no energy efficiency improvements) as well as retrofit options with increasing levels of energy efficiency based on the retrofit standard of that timestep. For the heating system decisions, the model first excludes all inapplicable and unfeasible options for a given building agent from the choice set based on feasibility and policy-based restrictions (see Table 1). Afterward, the model applies the concept of bounded rationality to narrow the selection process down to only a few options, which are considered in depth by the building agent. For this purpose, first the size of the consideration choice set is defined based on a gamma distribution; see equation (3).

$$p(n,\alpha,\theta) = \frac{1}{\Gamma(\alpha)\theta^{\alpha}} e^{-\frac{n}{\theta}} n^{\alpha-1} \tag{3}$$

n number of choices in the choice set.
α shape parameter.
Θ scale parameter.

The choice set composition is then chosen through weighted random sampling of the remaining options. The weights of the different options are defined based on the market shares of the technologies of the previous timestep; see equation (4). This accounts for the inertia in the market as well as the fact that building owners do not consider all possible options in the market (Lehmann et al., 2017). By randomly assigning the composition of the choice set, the model ensures that more novel options are also considered by some of the building agents.

Table 1
Choice set restrictions applied for the different decision types.

Decision type	Restrictions
Heating system replacement	Location-based restriction of unavailable heating system options (e.g., gas, district heating, but also ground and groundwater source heat pumps)
	Technical feasibility of certain options due to minimum or maximum power thresholds
	Exclude decentral heating options if the building has already a central heating system
	Building agents with district heating only consider options that include district heating (i.e., no disconnection from heating grid)
	Building agents connected to gas grid do not consider switching to oil
	Building agents with a heat pump do not consider switching to a fossil-fuel heating system
	Building agents with solar collectors consider only options that include solar collector
	Exclude options that are restricted due to policy intervention (e.g., ban on direct electric heating systems)
Heating system choice in new buildings	Location-based restriction of unavailable heating system options (e.g., gas, district heating, but also ground and water source heat pumps)
	Technical feasibility of certain options due to minimum or maximum power thresholds
	Exclude options that are restricted due to policy intervention (e.g., ban on direct electric heating systems)
	Exclude options that do not meet the new construction standard (e.g., RES requirements)

Furthermore, in the case of the heating system replacement decision, the currently installed system is always included in the choice set (except if it is no longer available due to policy restrictions) to account for the status quo bias of building owners (i.e., the homeowner's preference to keep the current system) (Lehmann et al., 2017; Michelsen and Madlener, 2012).

$$P_{ni} = \frac{e^{\sum w_{mn} MS_{mi}}}{\sum_j^S e^{\sum w_{mn} MS_{mj}}} \tag{4}$$

P_{ni}: Probability of option i being included in consideration choice set of decision-maker n

w_{mn}: Weight of technology m for decision-maker n.

MS_{mi}: Market share of technology m which is part of option i.

In the third step, the building agent evaluates each option in the consideration choice set and finally decides which option to choose. In order to model the selection process, the model applies a discrete choice modeling (DCM) approach to simulate this stage of the agent's decision-making process. The DCM method applied is a multinomial logit (MNL) model, which is the most commonly applied discrete choice model (Train, 2003). The MNL model calculates the probability of a decision-maker making a certain choice based on a utility function, according to equation (5) (Train, 2003). In the ABBSM, the option is then randomly selected based on the calculated probability of each of the options in the choice set.

$$P_i = \frac{e^{V_i}}{\sum_j^S e^{V_j}} \tag{5}$$

P_i: Choice probability of option i.

V_i: Observed utility of option i.

The utility of a given option is calculated based on an assessment of the lifecycle costs of the option including investment, maintenance, and energy costs (see equation (6)). In order to make investment costs comparable to recurring costs—such as energy or maintenance costs—the investment costs are converted to equivalent annual costs (EAC). The willingness to pay (WTP) reflects additional attributes of a technology not covered by the other factors (e.g. increased comfort through new windows as well as preferences for a certain technology option),which is calculated based on a percentage of the equivalent annual investment costs.

$$V_i = \beta_{AC} EAC_{I,i} + \beta_{MC} C_{M,i} + \beta_{EC} C_{E,i} + \beta_{WTP} WTP_i \tag{6}$$

V_i: Observed utility of option i.

$EAC_{I,i}$: Specific equivalent annual investment costs of option i in CHF/year $m^2_{floor\ area}$

$C_{M,i}$: Specific operation and maintenance costs of option i in CHF/year $m^2_{floor\ area}$

$C_{E,i}$: Specific energy costs of option i in CHF/year $m^2_{floor\ area}$

WTP_i: Willingness to pay for option i

β_n Weighting factor for decision criteria n.

2.2.4. Energy demand and GHG emissions assessment

The individual building agent's energy demand and the related GHG emissions are assessed using an integrated energy demand model calculating the demand for space heating, hot water, ventilation, appliances, lighting, and auxiliary building services (e.g., pumps). The calculation of the space heating and hot water demand is made using a single-zone monthly steady-state model based on ISO EN 52016-1 (ISO, 2017) or the Swiss equivalent SIA 380/1 (SIA, 2016). The model accounts for part of the performance gap[2] in terms of actual energy consumption and theoretically calculated energy demand by adjusting the indoor air temperature based on the energy-efficiency standard of the building according to the method developed by Loga et al. (2003). Based on the calculated energy demand, the model then calculates the related direct and indirect GHG emissions using emission and primary energy factors of the various energy carriers.

[2] The performance gap describes the discrepancy between calculated energy demand based on standard user behavior and the actual (measured) energy consumption of buildings (Majcen et al., 2013).

2.3. Scenario assessment

The ABBSM is used to model three different scenarios for the development of the Swiss residential building stock an overview of which is given in Table 2. A more detailed description of the different drivers and policy measures of the scenarios is given in the following subchapters.

2.3.1. Common drivers and input data

The different scenarios share some common input data and modeling assumptions, which are illustrated in Table 3. A more complete list of all input data is given in the Appendix. The growth of the building stock by 2050 is driven by the population development, which is based on the reference population scenario by 2045 according to FOS (2015), which is extrapolated to 2050 to cover the full modeling period.

Key drivers of the different modeled decisions are the energy prices as well as the technology costs (both investment costs and operation and maintenance costs) as they affect the costs and thereby the utility of the different options. The current (2017) level of energy prices is based on data from Prognos (2018) and ProPellets (2019), while the development (excluding CO_2 tax) is based on Betschart et al. (2016); Iten et al. (2017). The current level of cost factors for envelope retrofit measures is based on CRB (2011); Jakob et al. (2014, 2010, 2002) and includes costs for a reinstatement option as well as different energy efficiency levels (insulation thickness or U-value) for each envelope component. The heating system costs are based on HSLU (2019); Jakob et al. (2014) and are specified for different system sizes (e.g., nominal power) as well as differentiated between retrofit (i.e., switch to a different system), direct replacement (one-to-one replacement of the current system), and installation in a new building as costs differ between these different applications (e.g., they may or may not include costs for demolition). Moreover, cost factors are varied randomly per building agent to account for a variation in investment costs for various measures based on factors such as the building location or complexity of installation.

The most important data sources for the current and past development of the efficiency of the different heating technologies are Aebischer et al. (2002); Jakob et al. (2016, 2014); Prognos (2018); Stettler and Betbèze (2016). The future development of the efficiency is based on a continuation of the past development trends with a moderate increase for more established technologies such as oil and gas boilers and more significant increase in the efficiencies of RES technologies such as the different heat pump types (see Table 3). The energy standard for building retrofits and new constructions are based on the latest version

Table 2
Overview of the modeled scenarios for the Swiss residential building sector.

Scenario	Description
Reference scenario	The reference scenario describes the development of the stock based on the currently decided policy in Switzerland. Some trends and developments are continued but no major new polices are included.
Incentive scenario	The incentive scenario adds additional policies compared to the reference scenario in order to achieve the emission-reduction targets. The focus lies primarily on financial incentives, meaning an increase of the existing CO_2 tax on fuels as well as an extension of the subsidy program.
Regulation scenario	The regulation scenario extends the current policy framework primarily through a tightening of regulations such as stricter restrictions on the installation of fossil fuel-based heating systems, including the implementation of a GHG emission limit for new and existing buildings.

Table 3
Common drivers and frame conditions between scenarios.

Driver		unit	2017	2020	2025	2030	2040	2050	Sources
Population		million	8.42	8.67	9.1	9.46	10.01	10.26	FOS (2015)
Energy prices (without CO_2 tax)	Oil	CHF/MWh[a]	58	67	82	97	104	111	(Betschart et al., 2016; Iten et al., 2017; Prognos, 2018; ProPellets, 2019)
	Gas	CHF/MWh[a]	78	82	89	97	100	104	
	Electricity	CHF/MWh[a]	201	244	248	248	248	248	
	Wood	CHF/MWh[a]	75	77	81	91	95	102	
	District heating	CHF/MWh[a]	80	81	82	83	85	87	
Cost development	Material costs	Index	100	100	100	100	100	100	–
	Labour costs	Index	100	100	100	100	100	100	
Efficiency development[b]	Oil boiler	%	87%	87%	89%	90%	90%	90%	Aebischer et al. (2002); Jakob et al. (2016, 2014); Prognos (2018); Stettler and Betbèze (2016)
	Gas boiler	%	87%	87%	89%	90%	90%	90%	
	Wood boiler	%	73%	73%	73%	73%	73%	73%	
	District heating	%	95%	96%	96%	96%	97%	97%	
	Heat pump air/water	%	297%	301%	305%	309%	317%	326%	
	Heat pump ground/water	%	336%	341%	346%	351%	361%	371%	
	Heat pump water/water	%	378%	388%	397%	406%	425%	444%	
	Electric resistance heating	%	95%	95%	95%	95%	95%	95%	
	Electric resistance heater	%	100%	100%	100%	100%	100%	100%	
	Combined hot water systems	%	76%	76%	77%	78%	79%	80%	
	Electric water heater	%	76%	76%	77%	78%	79%	80%	
	Heat pump water heater	%	221%	226%	231%	236%	246%	256%	
	Gas water heater	%	54%	55%	57%	58%	59%	60%	
	Solar collectors	%	90%	90%	91%	91%	91%	92%	
Energy standard new construction	Opaque Elements	W/m^2K	0.17	0.17	0.17	0.17	0.17	0.17	EnDK (2015)
	Windows	W/m^2K	1	1	1	1	1	1	
Energy standard retrofit	Opaque Elements	W/m^2K	0.25	0.25	0.25	0.25	0.25	0.25	EnDK (2015)
	Windows	W/m^2K	1	1	1	1	1	1	
Ventilation with heat recovery	Single-dwelling building	%	35%	35%	35%	35%	35%	35%	Jakob et al. (2016)
	Multi-dwelling building	%	25%	25%	25%	25%	25%	25%	
GHG Emission factors (incl. indirect emissions)	Oil	gCO_2-eq/kWh	301	301	301	301	301	301	KBOB (2016)
	Gas	gCO_2-eq/kWh	228	228	228	228	228	228	
	Electricity	gCO_2-eq/kWh	97	83	64	49	29	17	
	Wood	gCO_2-eq/kWh	27	27	27	27	27	27	
	District heating	gCO_2-eq/kWh	88	85	81	77	70	63	

[a] 1 CHF is equivalent to about 0.95 EUR. All costs are given for 2017 prices.
[b] All efficiencies are based on the upper heating value of the different fuels.

of the MBC (EnDK, 2015) and are kept constant over the modeling period as the current standard is already fairly ambitious. The share of new buildings equipped with ventilation systems with heat recovery is based on (Jakob et al., 2016) and is assumed to remain constant as well.

The current level of GHG-emission factors for the various energy carriers are based on KBOB (2016), which includes both direct and indirect emissions, and FOEN (2019) for only direct emissions. The emission factors are kept constant for all energy carriers except district heating and electricity, where a reduction of the carbon intensity is assumed.

2.3.2. *Scenario-specific drivers*

The different policies and barriers included in the scenarios and how they are implemented in the model are described in Table 4. The financial policy instruments such as the CO2 tax and subsides are taken into account in the economic comparison of different options according to the decision model (see section 2.2.3). The regulatory policies as well as barriers due to the limited availability of certain energy sources are implemented by removing options from the choice set in the decision model. An example of these regulatory policies are the RES requirements according to EnDK (2015) or a CO_2 limit.

The resulting scenario drivers that are differentiated between the three scenarios are illustrated in Table 5. The reference scenario freezes the current implementation status of the last version of the MBC in terms of RES requirements for existing buildings and restrictions on the installation of direct electric heating (EnDK, 2018). These restrictions on direct electric heating includes a ban on the installation of new systems as well as mandatory replacement of existing systems within 15 years after implementation (EnDK, 2015). The CO_2 tax remains at the current level of 96 CHF/tCO_2 (85 EUR/tCO_2) as do the subsidy levels for

Table 4
Included polices and barriers to building retrofit and heating system adoption and their model implementation.

Policies and barriers	Model implementation
Subsidies	Subsidies are given for building retrofits and RES heating technologies according to Sigrist and Kessler (2016). Building agents take the subsidies into account as a reduction in the investment costs in the utility function of the decision model (see section 2.2.3).
CO_2 tax	A CO_2 tax is levied on all fossil fuels (primarily oil and gas), which results in an increase in the energy price of these fuels based on their CO_2 intensity according to FOEN (2019). Building agents take the change in energy price into account in the utility function of the decision model (see section 2.2.3).
Energy source availability	Some energy sources are restricted due to their limited availability at a given building location because their grid bound (gas and district heating) or legal restrictions exist (ground water availability and protection results in restrictions in the availability of ground and groundwater heat pumps). The availability is defined based on exogenous assumptions on the availability based on Lehmann et al. (2017); VFS (2017); VSG (2017). Each building agent is randomly assigned an availability of each of these resources at the moment of its initialization. In the case of the gird-bound technologies this availability may be adapted according to the scenario (see Table 5 for scenario assumptions) based on exogenous evaluation of the future potential.
Ban and mandatory replacement of direct electric heating	Already the previous version of the MBC places restrictions on the new installation of heating system technologies such as the new installation of direct electric heating in new and existing buildings (EnDK, 2008). The new MBC additionally suggests a mandatory replacement of already installed direct electric heating systems (EnDK, 2015). These restrictions result in removing the technology option from the choice set in the decision model (see Table 1). The additional replacement obligations are put into legislation on a regional (Canton) level, which is why they are introduced at different rates across the country (EnDK, 2018). This is accounted for by implementing the restriction by step wise increasing the share of the building agents that this restriction applies to (see Table 5 for scenario assumptions).
RES requirements	The MBC further gives requirements on the share of renewable energy for heating system of both new and existing buildings (EnDK, 2014). The requirements for new buildings have been implemented already across the country but the restriction for existing buildings is implemented same at different rates as the technologies ban stated above. The RES requirements are implemented by removing options that do not fulfill the requirements from the choice set of the building agent. The requirements are set according to the "standard solutions" outlined in the MBC (EnDK, 2014). Each standard solution is a combination of efficient envelope and heating system (the more efficient the envelope, the fewer restrictions on the use of the heating system).
CO_2 limit for heating systems	The CO_2 limit for heating systems of new and existing buildings. The CO_2-limit reflects a limit on the direct GHG emissions a building is allowed to emit, heating system options that do not fulfill these requirements are removed from the choice set of the building agent at the time of the decisions. For existing buildings, the CO_2 limit would, therefore, become relevant when the existing heating system has to be replaced (FOEN, 2018a). Secondary effects such as an impact on the decisions on building envelope retrofits are not considered.

envelope retrofits and RES heating technologies, which are based on Sigrist and Kessler (2016). Furthermore, the reference scenario includes a moderate increase in the availability of district heating as a continuation of the current trends in the expansion of district heating in Swiss cities.

The incentive scenario primarily includes an expansion of the already implemented financial policies. The CO_2 tax is increasing stepwise from 2020 until 2030 up to 310 CHF/tCO_2 based on continuation of the trend of the currently proposed revision of the CO_2 law (FOEN, 2018b). The increased revenue from the CO_2 tax will be used to expand the current subsidy schemes and increase the subsidy level by 75% until 2030. These measures are accompanied by increased expansion of the availability of district heating as well as a slow implementation of the RES requirements for existing buildings according to EnDK (2015) by 2030.

The regulation scenario builds on a relatively quick implementation of the RES requirements for existing buildings as well as the ban and replacement obligations of direct electric systems by 2025. Additionally, the RES requirement is reinforced by a CO_2 limit for new and existing buildings of 20 kgCO_2/m^2 year in 2030, which is reduced stepwise every five years down to 0 kgCO_2/m^2 year. These regulative changes are underpinned by an expansion of the availability of district heating in Swiss cities equal to the incentive scenario.

3. Results

3.1. Building stock energy and GHG emission development

Over the modeling period, the building stock is projected to grow by 26%–704 million m^2 in 2050 (see Table 6). The development of the resulting useful energy demand reveals only marginal differences between the three scenarios, as the additional policies target the energy supply more (i.e., heating system choice). Nevertheless, over the modeled period, the specific useful energy demand for space heating and hot water decreases by 18–19%, from 96 kWh/m^2 year to 77–78 kWh/m^2 year depending on the scenario. Due to the increase in the size of the stock, the total useful energy demand remains almost constant. The scenarios differ more significantly in terms of delivered final energy demand and GHG emissions, although in all scenarios—including the reference scenario—delivered final energy demand and GHG emissions decrease, meaning the growing stock is offset by efficiency gains in the heat supply. The policies to speed up the decarbonization of the Swiss building stock demonstrate their effect in both the incentive and regulation scenarios, where total GHG emissions decline to 2.0 million tCO_2-eq (an 85% decrease) and 1.5 million tCO_2-eq (an 89% decrease), respectively. This is a significantly larger decrease compared to 5.5 million tCO_2-eq (a 57% decrease) in the reference scenario.

The development in terms of final energy demand according to energy carrier indicates decreasing shares of fossil fuels and growing use of electricity, district heating and wood by 2050 in all three scenarios. In the reference scenario, the decrease of oil and gas happens slowly and is evenly distributed over the entire modeled period, lowering demand by 68% and 33%, respectively. In the incentive and regulation scenarios, the phase-out of these two energy carriers happens more quickly after 2025 when the additional policies begin to take effect. The decrease of oil and gas slows down after 2040 in both scenarios but is almost complete by 2050, with oil and gas demand decreased by 96% and 85%, respectively, in the incentive scenario and 98% and 95%, respectively,

Table 5
Scenario-specific drivers.

Driver		unit	Reference Scenario						Incentive Scenario						Regulation Scenario					
			2017	2020	2025	2030	2040	2050	2017	2020	2025	2030	2040	2050	2017	2020	2025	2030	2040	2050
CO_2 tax		CHF/tCO_2	96	96	96	96	96	96	96	120	240	310	310	310	96	96	96	96	96	96
Subsidies	Retrofit	Index	100	100	100	100	100	100	100	125	150	175	175	175	100	100	100	100	100	100
	RES	Index	100	100	100	100	100	100	100	125	150	175	175	175	100	100	100	100	100	100
Expansion district heating	Single-dwelling building	%[a]	6%	6%	6%	7%	7%	8%	6%	6%	6%	7%	9%	12%	6%	6%	6%	7%	9%	12%
	Multi-dwelling building	%[a]	13%	13%	14%	16%	18%	20%	13%	13%	16%	22%	38%	44%	13%	13%	16%	22%	38%	44%
Replacement obligations	central direct electric heating	%[a]	25%	25%	25%	25%	25%	25%	25%	20%	70%	100%	100%	100%	25%	30%	100%	100%	100%	100%
	decentral direct electric heating	%[a]	26%	26%	26%	26%	26%	26%	26%	20%	70%	100%	100%	100%	26%	30%	100%	100%	100%	100%
	direct electric water heater	%[a]	6%	6%	6%	6%	6%	6%	6%	20%	70%	100%	100%	100%	6%	30%	100%	100%	100%	100%
RES requirements	new construction	%[a]	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Replacement	%[a]	6%	6%	6%	6%	6%	6%	6%	20%	70%	100%	100%	100%	6%	30%	100%	100%	100%	100%
CO_2 limit for heating systems	new construction	kgCO_2/m^2 year	–	–	–	–	–	–	–	–	–	–	–	–	–	–	20	15	5	0
	Replacement	kgCO_2/m^2 year	–	–	–	–	–	–	–	–	–	–	–	–	–	–	20	15	5	0

[a] Percent refers to the share of buildings in the stock to which these criteria apply for a given year.

in the regulation scenario. Oil- and gas-based heating systems are primarily replaced by heat pumps, which can be seen in Fig. 3 in the large increase in ambient heat use, as well as district heating.

The resulting GHG emissions development, illustrated in Fig. 4, reveals that the 2020 reduction target is not met in all three scenarios. Moreover, the later targets in 2030 and 2050 are also not met in the reference scenario, highlighting the need for additional policies. These targets are met for both the regulation and incentive scenarios as fossil fuel-based heating systems are almost completely phased out by then (see Fig. 3) resulting in 98% and 94% reductions in direct emissions by 2050, respectively, compared to the 1990 level.

The decreasing GHG emissions of the Swiss residential building stock in the different scenarios are also reflected in the development of the GHG emission intensities in the stock (see Fig. 5). ISO, 2017, the majority of the stock still emitted more than 20 kgCO2-eq/m^2 year, but buildings with less than 5 kgCO2-eq/m^2 year already make up 20% of the total heated floor area. This share is increased significantly under all three scenarios as new, carbon-efficient buildings are added to the stock along with building retrofits and heating system replacements that contribute to lowering GHG emission intensities in the existing stock. In the reference scenario, the total floor area of buildings with more than 5 kgCO2-eq/m^2 year is reduced to 225 million m.[2] In the incentive and regulation scenarios, this share is even lower (106 million m^2 and 84 million m,[2] respectively).

3.2. Retrofit and replacement activity

The results reveal only marginal changes in the average retrofit rate of the various envelope components between the reference and regulation scenarios (see Fig. 6) as the additional policies in regulation scenario target only the heating system choice of building owners. However, the incentive scenario does indicate an increase in retrofit rates (and corresponding decrease in reinstatement) compared to the reference scenario as a result of the increase in the CO_2 tax and subsidies. This increase of the retrofit rate in the incentive scenario is most pronounced for walls and roofs.

The development of the market shares of heating system adoption in both existing and new buildings are illustrated in Fig. 7. Oil and gas boilers already comprise only a minority of heating systems being adopted in new construction due to existing RES requirements for new buildings, which is in line with empirical data (Wüest und Partner, 2018). There are, however, still some oil and gas boilers being installed in combination with solar collectors or in buildings with an efficient envelope that also meet the RES requirements for new buildings. The market shares of the different heating systems remain fairly stable in the reference scenario. In the incentive and regulation scenarios, however, there is higher adoption of district heating due to the assumed expansion and development of district heating networks. In the regulation scenario, the CO_2 limit for buildings leads to a complete phase-out of fossil-fuel heating systems after 2035, at which point the limit is lowered to 10 kgCO_2-eq.

Oil and gas boilers still have large shares in the replacement market, together comprising more than 50% of all heating systems being adopted at the model start. The market share of oil and gas is slowly decreasing by 2050 in the reference scenario, by which time they together comprise 21% of the adoptions. In the incentive scenario, the share of oil and gas heating systems decreases more rapidly than in the reference scenario to about 7% of the market share by 2030 and then remains almost constant until 2050. They are primarily replaced by heat pumps and to a lesser degree wood and district heating. In the regulation scenario, the shares of oil and gas first decrease more slowly, but the fast introduction of RES requirements for existing buildings results in a sharp decrease by 2025, followed by a slow phase-out through the introduction of the CO_2 limit in 2030.

Table 6
Summary of key indicators for the years 2017, 2020, 2030, and 2050 for the three scenarios (ref = Reference scenario, inc = Incentive scenario, reg = Regulation scenario). Useful energy is given for space heating and hot water, delivered final energy (not including solar and ambient heat), and total GHG emissions for space heating, hot water, ventilation, and auxiliary building services.

Indicator	Unit	2017	2020			2030			2050		
		ref	ref	inc	reg	ref	inc	reg	ref	inc	reg
Heated floor area	million m^2	557	574	574	574	628	628	628	705	705	705
Useful energy	TWh	53	53	53	53	54	54	54	55	54	55
	kWh/m^2	96	93	93	93	86	86	86	78	77	78
Delivered final energy	TWh	63	61	61	61	54	50	50	43	36	35
	kWh/m^2	113	106	106	106	87	80	80	62	51	50
Total GHG Emissions	tCO_2-eq.	12.9	12.1	12.0	12.0	9.6	8.0	7.7	5.5	2.0	1.5
	$kgCO_2$-eq/m^2	23.1	21.1	20.9	20.9	15.3	12.8	12.3	7.9	2.8	2.1

Table 7
List of heating technologies defined in the model.

Technology Group	Technology Name	System type
Heating Systems	Oil boiler	central
Heating Systems	Gas boiler	central
Heating Systems	Wood boiler	central
Heating Systems	Heat pump air/water	central
Heating Systems	Heat pump ground/water	central
Heating Systems	Heat pump water/water	central
Heating Systems	District heating	central
Heating Systems	Electric resistance heating	central
Heating Systems	Coal boiler	central
Heating Systems	Oil stove	decentral
Heating Systems	Gas stove	decentral
Heating Systems	Wood stove	decentral
Heating Systems	Electric resistance heater	decentral
Heating Systems	Coal stove	decentral
Heating Systems	Heat pump air/air	decentral
Hot Water Systems	Combined with main heating system	central
Hot Water Systems	Electric water heater	decentral
Hot Water Systems	Heat pump water heater	decentral
Hot Water Systems	Gas water heater	decentral
Solar Systems	Solarthermal System	central

3.3. Costs, taxes, and subsidies

Fig. 8 illustrates the development of the annual investments for retrofit and reinstatement of envelope components, heating system replacement, and heating systems for new buildings as well as the aggregate energy costs from residential energy use (excluding electricity use for appliances and lighting) for the three different scenarios. The investment costs demonstrate some stochastic behavior, while the shift in energy costs comes from changes in the energy costs and CO_2 tax. The investments into heating system replacement are higher in the incentive and regulation scenarios compared to the reference scenario due to a switch to heating systems with higher investment costs. Similarly, the retrofit and reinstatement costs are marginally higher in the incentive scenario due to the higher retrofit rate. The total cost for heating systems in new construction slowly decreases as the new construction rate declines until 2050. It is almost the same between the three scenarios as adoption patterns are more or less the same for new buildings under the different scenarios. Energy costs increase in the short and midterm and then decrease in all three scenarios by 2050. Compared to the reference scenario, energy costs increase more significantly in the incentive scenario in the short and medium terms due to the increase in the CO_2 tax, but then decrease more rapidly due to the phase-out of gas and oil heating systems.

In all three scenarios, the revenue from the CO_2 tax declines due to the decreasing use of oil and gas in the long run although the increase in the CO2 tax leads to a growth in revenue in the incentive scenario in the short and medium terms (see Fig. 9). At the same time, the subsidy expenditures increase due to ever more installations of subsidized renewable heating systems. Therefore, the revenue from the CO_2 tax will at some point no longer cover the subsidy expenditures in all scenarios. This point is reached by 2035 in the reference scenario but already by 2025 in the regulation scenario, due to the faster decrease in oil and gas use. In the incentive scenario, the potential subsidy expenditure increases more quickly as the subsidy levels are raised. This growth in subsidy expenditure can initially be covered by the increase in the CO_2 tax, whose stepwise increase results in spikes in the revenue from the tax. After 2030, the revenue of the CO_2 tax falls steeply due to the phase-out of oil and gas at which point the subsidies are no longer covered.

3.4. Sensitivity to financial instruments

To study the impact of the two different financial instruments, CO_2 tax and subsidies, on the decision-making of the individual building agents, a sensitivity assessment of the decision model is carried out on top of the scenario assessment. For that purpose, the retrofit and heating system replacement decisions for various CO_2 tax and subsidy levels is assessed for each of the initial building agents. The analysis is carried out by reassessing the decision iteratively based on different subsidy and CO_2 tax levels, with all other inputs (e.g., choice restrictions) kept as set for the initial year.

The resulting assessment of the individual choice behavior of the building agents, illustrated in Fig. 10, reveals that the building agents react more sensitively to subsidies compared to increases in the CO_2 tax. Moreover, the results demonstrate that the heating system choice is more sensitive to both subsidies and the CO_2 tax compared to the retrofit decision. For roof and floor components, the retrofit share is already high, which makes a significant increase of the share possible only by raising the subsidy level to above 50%. Relatively speaking, wall components react the strongest to an increase in the CO_2 tax, primarily due to the fact that a retrofit of this component yields the highest energy savings and, therefore, the largest reduction in energy costs relative to the additional investment costs. For heating systems, the increases in subsidies as well as the CO_2 tax lead to increased shares of heat pumps and wood boilers being chosen by building agents. Initially, there is a high probability to stay with oil and gas heating systems, but the probability to switch to a renewable heating system increases with the CO_2 tax and subsidies in the sensitivity analysis. The share of district heating is primarily limited due to the low availability of the system and is, therefore, mainly unaffected by increases in the CO_2 tax and subsidies. Not unsurprisingly, buildings equipped with a heat pump demonstrate no sensitivity to the CO_2 tax in their choice behavior as these buildings remain unaffected by the tax.

The results of show Fig. 10 the relatively low sensitivity of the decision model to financial instruments, especially for the building retrofit decision. This low sensitivity results from the parameterization of the decision model based on the calibration of the model based on the historic development of the stock (see Nägeli et al. (2020) for details). The current parametrization of the decision model gives less weights to energy costs compared over investment costs equivalent to an implicit discount rate of about 15% (combinate of the modeled discount rate and the weighting factor in the utility function of the decision model, see

Table 8
Description of input data and data sources.

Aspect	Attribute	Unit	Differentiated according to	Distribution	Source
Initial Building Stock Structure	Number of Buildings	#	Building type, construction period, number of floors class, number of dwellings class, heating system type, hot water system type	–	(FOS, 2019, 2017)
	Number of Dwellings	#	Building type, construction period, dwelling Size class, number of rooms class	–	FOS (2019)
Building Geometry	Share Roof Type Pitched	%	Building type, construction period	–	Jakob et al. (2016)
	Share Buildings with Basement	%	Building type, construction period	–	Jakob et al. (2016)
	Room Height	m	Building type, construction period	Lognormal	Jakob et al. (2016)
	Height Between Floors	m	Building type, construction period	Normal	Jakob et al. (2016)
	Share One Side Attached	%	Building type, construction period	–	Jakob et al. (2016)
	Share Two Sides Attached	%	Building type, construction period	–	Jakob et al. (2016)
	Plan Depth	–	Building type, construction period	Lognormal	Jakob et al. (2016)
	Window To Wall Ratio	%	Building type, construction period	Normal	Jakob et al. (2016)
	Window Frame Ratio	%	–	Normal	(Jakob et al., 2016; SIA, 2016, 2015)
	Window Shading Factor	%	–	Normal	(Jakob et al., 2016; SIA, 2016, 2015)
	Ventilation Rate Infiltration	m^3/m^2h	Building type, construction period	Normal	(Jakob et al., 2014a, 2002)
	Internal Heat Capacity Building	kJ/K m^2	–	Normal	(SIA, 2016, 2015)
	Building Orientation	°	–	Uniform	–
Building Envelope	U-Value	W/m^2 K	Building type, construction period, building component type	Normal	(Jakob et al., 2016, 2014a; 2002; Wüest und Partner, 1998)
	g-Value Window	–	Building type, construction period	Normal	(Jakob et al., 2016, 2014a, 2002)
	Lifetime	year	Building type, building component type, renovation period	Weibull	(Agethen et al., 2010; IP BAU, 1994)
	Share Energy Efficiency Refurbishment	%	Building type, building component type, renovation period	–	Jakob et al. (2014b)
	Insulation Thickness after Refurbishment	mm	Building type, building component type, renovation period	Normal	(Jakob et al., 2016, 2014a; 2002; Wüest und Partner, 1998)
	U-Value Window after Refurbishment		Building type, renovation period	Normal	(Jakob et al., 2016, 2014a; 2002; Wüest und Partner, 1998)
	g-Value Window after Refurbishment	–	Building type, renovation period	Normal	(Jakob et al., 2016, 2014a; 2002; Wüest und Partner, 1998)
HVAC Systems	Share Mechanical Ventilation with Heat Recovery	%	–	–	Jakob et al. (2016)
	Ventilation Rate	m^3/m^2h	Building type, construction period, ventilation type	Normal	(Jakob et al., 2014a, 2002)
	Lifetime	year	Building type, building component type, renovation period	Weibull	(Agethen et al., 2010; IP BAU, 1994)
	Efficiency Space Heating	%	Heating system type, year of installation	Normal	(Aebischer et al., 2002; Jakob et al., 2016, 2014a; Prognos, 2018; Stettler and Betbèze, 2016)
	Efficiency Hot Water	%	Hot water system type, year of installation	Normal	(Aebischer et al., 2002; Jakob et al., 2016, 2014a; Prognos, 2018; Stettler and Betbèze, 2016)
	Efficiency Heat Recovery	%	Ventilation type, year of installation	Normal	(Jakob et al., 2016; SIA, 2006a)
	Specific Fan Power	W/(m^3/h)	Ventilation type, year of installation	Normal	(Jakob et al., 2016; SIA, 2006a)
Building Usage	Number of Occupants	#	Dwelling size class	Binominal	(FOS, 2019, 2004)
	Occupancy Time	h/persons day	–	Normal	(SIA, 2016, 2015, 2006a)
	Indoor Temperature	°C	–	Normal	(SIA, 2016, 2015, 2006a)
	Consumption Hot Water	l/persons day	–	Normal	(SIA, 2016, 2015, 2006a)
	Electricity Appliances	W/m^2 year	Number of rooms class	Normal	(SIA, 2006a, 2006b)
	Lighting Power	W/m^2 year	Number of rooms class	Normal	(SIA, 2006a, 2006b)
	Lighting Full Load Hours	h/year	Occupancy time	Normal	(SIA, 2006a, 2006b)
	Electricity Auxiliary Building Services	W/m^2 year	Building type	Normal	(SIA, 2006a, 2006b)
Decision parameters	Choice Set Size		Decision type	Gamma	
	Discount Rate	%		–	
	Decision Weighting Factors		Decision criteria	–	
Drivers and Scenario assumptions	Population	million persons	Year	–	(FOS, 2018, 2015)
	Labour Cost Development	%	Year	–	
	Material Cost Development	%	Building component, year	–	
	CO2 tax	CHF/kWh	Energy carrier, year	–	CH (2011)
	Subsidies	%	Building component, decision type, year	–	Sigrist and Kessler (2016)
	Willingness To Pay	%	Building component, decision type, year	–	
		%	Heating system type, building type, year	–	VSG (2017)

(continued on next page)

Table 8 (*continued*)

Aspect	Attribute	Unit	Differentiated according to	Distribution	Source
	Heating System Availability				
	Renewable Energy Requirement	%	Building type, project type, year	–	EnDK (2018)
Building Stock Development	New Building Type	%	Year	–	FOS (2019)
	New Building Characteristics	%	Building type, year, number of floors class, number of dwellings class	–	FOS (2019)
	New Dwelling Characteristics	%	Building type, year, dwelling Size class, number of rooms class	–	FOS (2019)
	Share Mechanical Ventilation with Heat Recovery	%	–	–	Jakob et al. (2016)
New Building Standard	U-Value	W/m2 K	Building type, year, building component type	Normal	EnDK (2015)
	g-Value Window	–	Building type, year, building component type	Normal	(SIA, 2016, 2015)
	Ventilation Rate Infiltration	m^3/m^2h	Building type, year, building component type	Normal	(SIA, 2016, 2015)
Retrofit Standard	Insulation Thickness	mm	Building type, year, building component type, retrofit standard	Normal	EnDK (2015)
	U-Value Window	W/m2 K	Building type, year, building component type, retrofit standard	Normal	EnDK (2015)
	g-Value Window	–	Building type, year, building component type, retrofit standard	Normal	(SIA, 2016, 2015)
	Ventilation Rate Infiltration	m^3/m^2h	Building type, year	Normal	(SIA, 2016, 2015)
Energy Carrier	Energy Price	CHF/kWh	Energy carrier, year	–	(Betschart et al., 2016; Iten et al., 2017; Prognos, 2018; ProPellets, 2019)
	Total GHG Factor	$kgCO_2$/kWh	Energy carrier, year	–	KBOB (2016)
	Direct GHG Factor	$kgCO_2$/kWh	Energy carrier, year	–	FOEN (2019)
	PE total Factor	kWh/kWh	Energy carrier, year	–	KBOB (2016)
	PE non-renewable Factor	kWh/kWh	Energy carrier, year	–	KBOB (2016)
	PE renewable Factor	kWh/kWh	Energy carrier, year	–	KBOB (2016)
Costs Opaque Components	Material Costs	CHF/m2	Building component type, insulation thickness	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
	Labour Costs	CHF/m2	Building component type, insulation thickness	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
	Additional Costs	CHF/m2	Building component type, insulation thickness	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
	Maintenance Costs	CHF/m2 year	Building component type, insulation thickness	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
Costs Transparent Components	Material Costs	CHF/m2	Building component type, U-value	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
	Labour Costs	CHF/m2	Building component type, U-value	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
	Additional Costs	CHF/m2	Building component type, U-value	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
	Maintenance Costs	CHF/m2 year	Building component type, U-value	–	(CRB, 2011; Jakob et al., 2014a, 2010, 2002).
Costs Heating Systems	Material Costs	CHF/kW	Heating system type, heating power	–	(HSLU, 2019; Jakob et al., 2014a).
	Labour Costs	CHF/kW	Heating system type, heating power	–	(HSLU, 2019; Jakob et al., 2014a).
	Additional Costs	CHF/kW	Heating system type, heating power	–	(HSLU, 2019; Jakob et al., 2014a).
	Maintenance Costs	CHF/kW year	Heating system type, heating power	–	(HSLU, 2019; Jakob et al., 2014a).
Costs Hot Water Systems	Material Costs	CHF/l	Hot water system type, hot water demand	–	(HSLU, 2019; Jakob et al., 2014a).
	Labour Costs	CHF/l	Hot water system type, hot water demand	–	(HSLU, 2019; Jakob et al., 2014a).
	Additional Costs	CHF/l	Hot water system type, hot water demand	–	(HSLU, 2019; Jakob et al., 2014a).
	Maintenance Costs	CHF/l year	Hot water system type, hot water demand	–	(HSLU, 2019; Jakob et al., 2014a).
Costs Solar Systems	Material Costs	CHF/m2	Collector area	–	(HSLU, 2019; Jakob et al., 2014a).
	Labour Costs	CHF/m2	Collector area	–	(HSLU, 2019; Jakob et al., 2014a).
	Additional Costs	CHF/m2	Collector area	–	(HSLU, 2019; Jakob et al., 2014a).
	Maintenance Costs	CHF/m2 year	Collector area	–	(HSLU, 2019; Jakob et al., 2014a).
Climate Data	Solar Irradiation	kWh/m^2 month	Month, orientation	–	SIA (2008)
	External Temperature	°C	Month	–	SIA (2008)
	Minimum External Temperature	°C		–	SIA (2008)
Other	Heat Capacity Water	Wh/m3 K		–	(SIA, 2016, 2015)
	Heat Capacity Air	Wh/m3 K		–	(SIA, 2016, 2015)
	Average Heat per Person	W/person		–	(SIA, 2016, 2015)

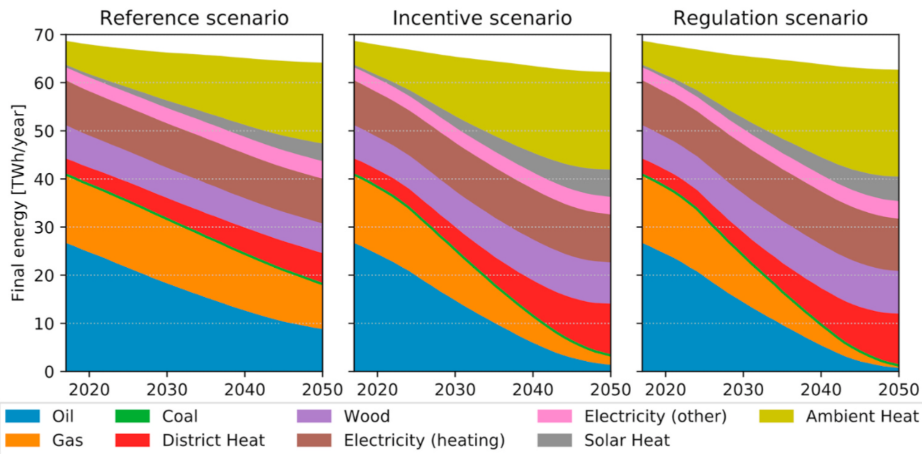

Fig. 3. Development of the final energy demand for space heating, hot water, and auxiliary energy use according to energy carrier for the three different scenarios.

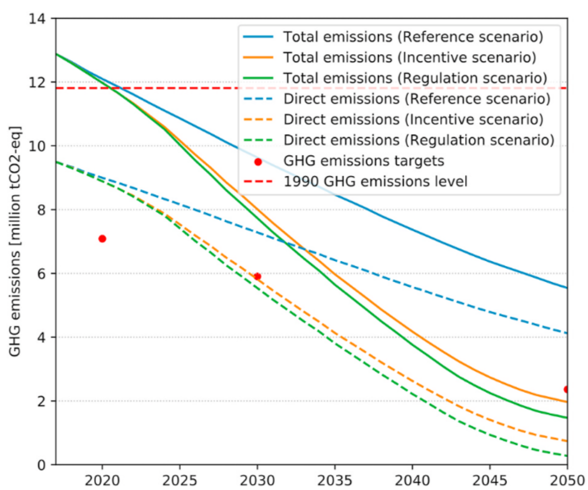

Fig. 4. Total as well as only direct GHG emissions for the three different scenarios in relation to the (intermediate) GHG emission targets (2020: 40%, 2030: 50%, 2050: 80%).

equation (6)). The low weighting of energy costs compared to the investment costs (i.e., high implicit discount rate) is a result of the calibration based on the historic development and is necessary to adequately describe the historic decision behavior. However, as environmental issues raise in popularity as well as energy costs raise (e.g. also through the increase in the CO_2 tax), this balance between energy and investment costs might shift. In order to investigate the effect of such as shift, two additional sensitivity runs were conducted with an adjusted parametrization of the decision model, where the discount rate is reduced. In both sensitivity runs we therefore apply a discount rate of 4%, however, in sensitivity 1 the weighting factors of the decision model (beta factors in equation (6)) are set to 0.5, while in sensitivity 2 they are set to 0.25 to account for two different levels of overall sensitivity to costs (the higher the beta value the more weight is given to costs, i.e. the low cost option will be chose in at a higher rate).

Both sensitivities lead to an increased reduction in final energy demand and GHG emissions (see Fig. 11) as can be expected due to the increased sensitivity on energy costs as it leads to an increased adoption of building retrofits and an accelerated phase out of fossil fuel based heating systems. The effect is more pronounced for GHG emissions compared to the final energy demand as especially the increased switch of heating systems has a stronger effect on GHG emissions. The effect of the sensitivities is strongest in the reference scenario and least in the regulation scenario, as the range of possible decisions (in the heating system choice) is reduced in the latter scenario compared to the other

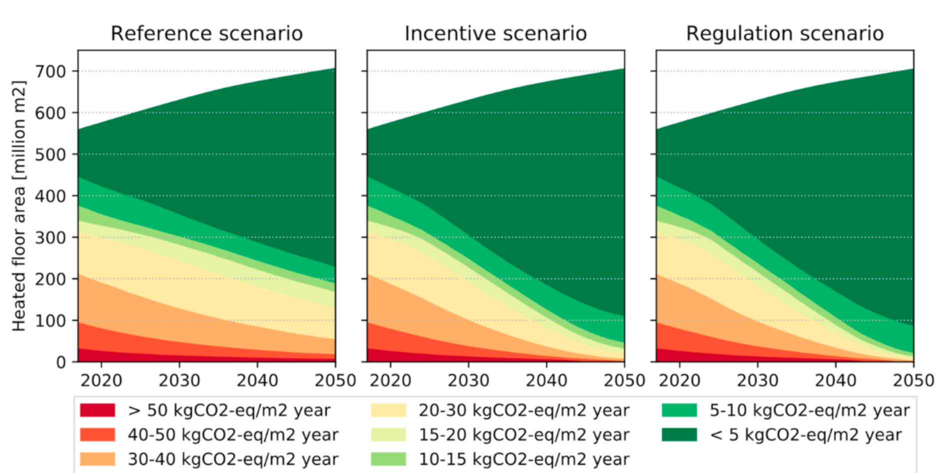

Fig. 5. Development of the (total) GHG emission intensities of the buildings in the stock for the three different scenarios.

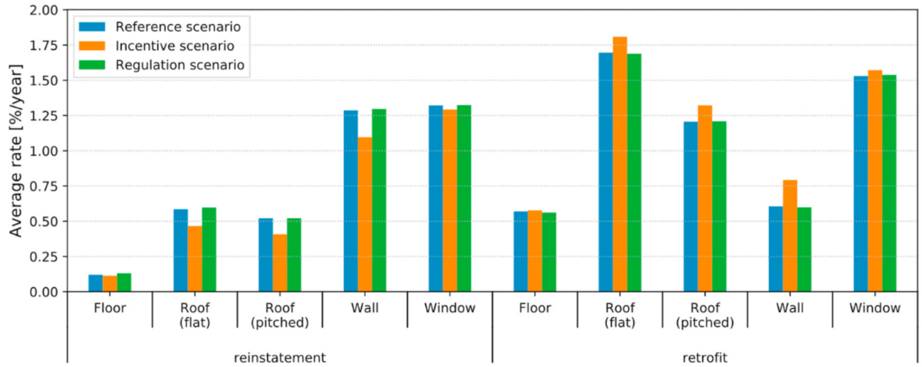

Fig. 6. Average annual rate of implemented retrofit (with energy efficiency improvement) and reinstatement measures (without energy efficiency improvements) over the modeling period for the three different scenarios.

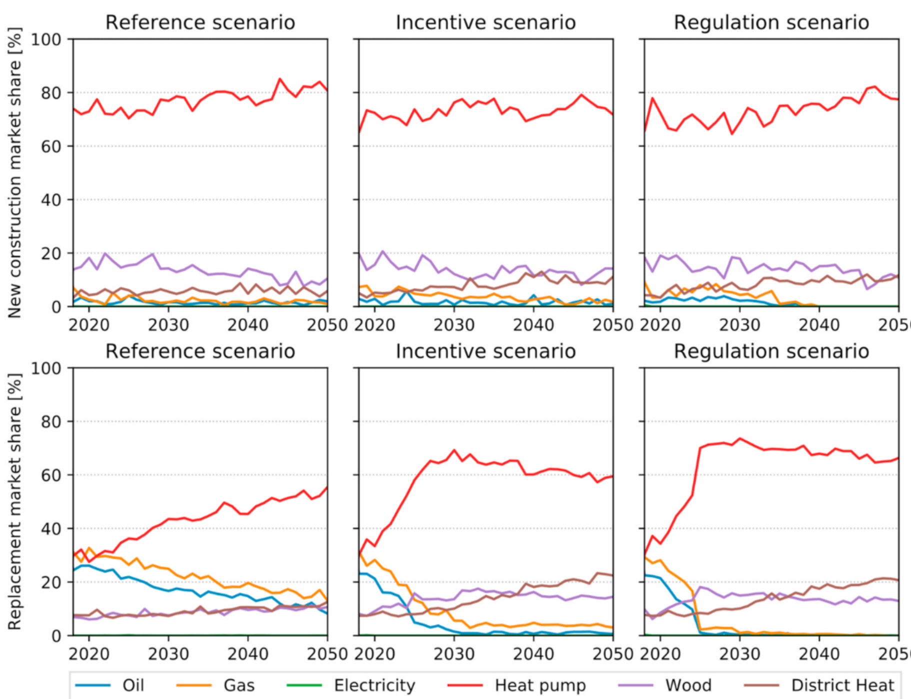

Fig. 7. Development of market shares of primary heating systems for new construction (above) and replacement (below) in the three different scenarios.

two. In terms of retrofit behavior, the sensitivities primarily lead to an increase in the retrofit rate for the building components walls and roofs and not so much for windows and floors as the latter cases are already cost effective also under the base case parameters and therefore get chosen more often than not. The increase in retrofit rate is, however, not substantial as also in the sensitivity runs only the ratio between energy efficiency retrofit and reinstatement measures is shifted. To further increase the implementation of measures, also a reduction in the lifetime of building components would need to be considered, which is currently not implemented in the model.

4. Discussion

4.1. *Structural change in the building stock*

The scenario results reveal that despite a growing building stock, the total delivered final energy as well as the GHG emissions of the stock decrease under all three scenarios. In the reference scenario, however, GHG emission-reduction targets are not met primarily due to the slow phase-out of oil and gas from the existing building stock. Therefore, additional policies are needed to meet the reduction targets. Both the incentive and the regulation scenarios lead to an almost complete phase-out of oil and gas and are replaced primarily by heat pumps and to a lesser degree wood and district heating. Therefore, these scenarios meet the defined reduction targets.

The decarbonization of the building stock is primarily driven by an increased adoption of heat pumps, especially in the period from 2025 to 2040. While heat pumps already made up the majority of heating systems in newly constructed buildings at the start of the modeling period, they become the dominant technology also in the existing stock in all three scenarios by 2050. The efficient operation of these heat pumps does, however, depended on the energy standard of the building, therefore, the adoption of heat pumps is aided by efficiency improvements in the existing stock through the ongoing envelope retrofit described above as it reduces costs for their implementation. Furthermore, though not modeled explicitly in this study, the improvements in

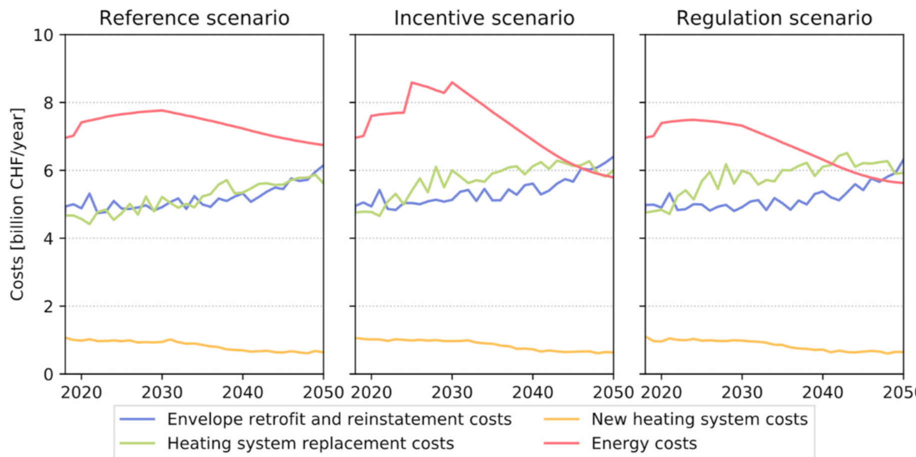

Fig. 8. Development of the annual investment costs (not including subsidies) for new construction, retrofit, and reinstatement as well as the energy costs (including CO_2 tax) from residential energy use (excluding electricity use for appliances and lighting) for the three different scenarios.

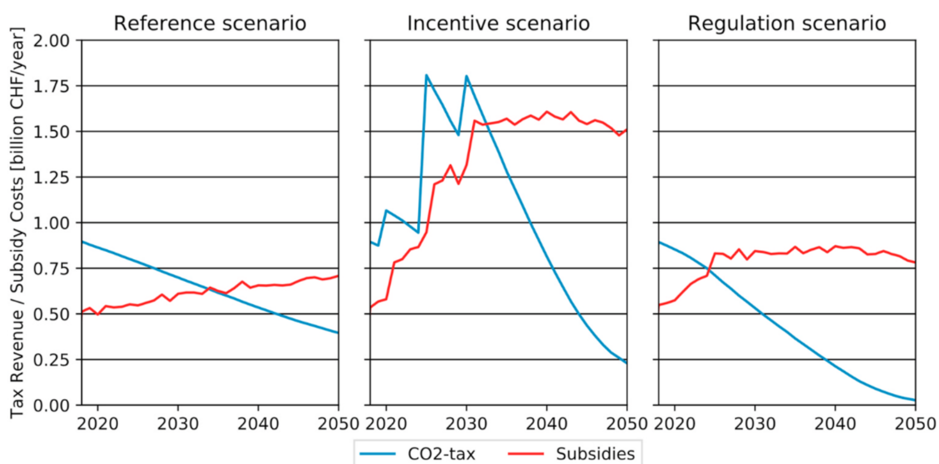

Fig. 9. Development of the annual revenue of the CO_2 tax and public spending on subsidies for the three different scenarios.

the building envelope aid in the improvement of the efficiency of the heat pumps as it allows for lower distribution temperatures in the building. Moreover, the climate impact (including indirect emissions) of heat pump-heated buildings strongly depends on the emission intensity of the electricity mix. Therefore, the reduction in the climate impact of these buildings is tied to decarbonization of the electricity mix. While the Swiss electricity mix is already relatively GHG-non-intensive—Swiss electricity production is mostly from hydropower and nuclear power, which is complemented by more carbon-intensive imports; see (KBOB, 2016)—it is assumed to be further reduced as part of the scenarios (cf. Table 3).

Next to the increased use of heat pumps in the residential building sector, the model results also indicate an increased use of wood as well as district heating. Switzerland already has a significant share of wood-heated buildings, although these also include older buildings with old wood stoves. Therefore, the growth of wood-based heating systems includes replacing older wood stoves, including wood log-fired systems. Moreover, wood is already a relatively highly exploited resources and the use of wood as a heating fuel stands in competition with other uses. Adding to these issues potential restrictions for the use of wood due to air-quality problems, especially in urban settings, the degree to which wood can be used as a heating fuel as suggested by the results remains to be seen. Similarly, the use of district heating is limited by its geographically bounded availability. Building up these network infrastructures takes time and large investments, which is why, the diffusion of these systems takes more time compared to decentral systems such as heat pumps. While district heating networks have been expanded and more buildings have been connected in recent years (VFS, 2018), how far this trend continues will depend on factors beyond the scope of this paper. That said, the model results suggest that given an increase in the availability of district heating, especially in urban areas, district heating (including smaller heating networks) has an important contribution to make to the decarbonization of the Swiss building stock.

4.2. *Impact of policy instruments*

The reduction targets can be met through the implementation of further policy instruments as outlined in the incentive and regulation scenarios. The results of the incentive scenario suggest that even with a substantial increase in financial incentives, both through subsidies and a higher CO_2 tax, the envelope retrofit rate is not increased substantially. This is supported by findings from other studies that suggest that financial incentives alone are not enough to overcome current barriers to increasing retrofit activity in the residential building sector (Friege, 2016; Pettifor et al., 2015). Moreover, the CO_2 tax decreases in its effectiveness in this regard as the share of buildings with a fossil-fuel

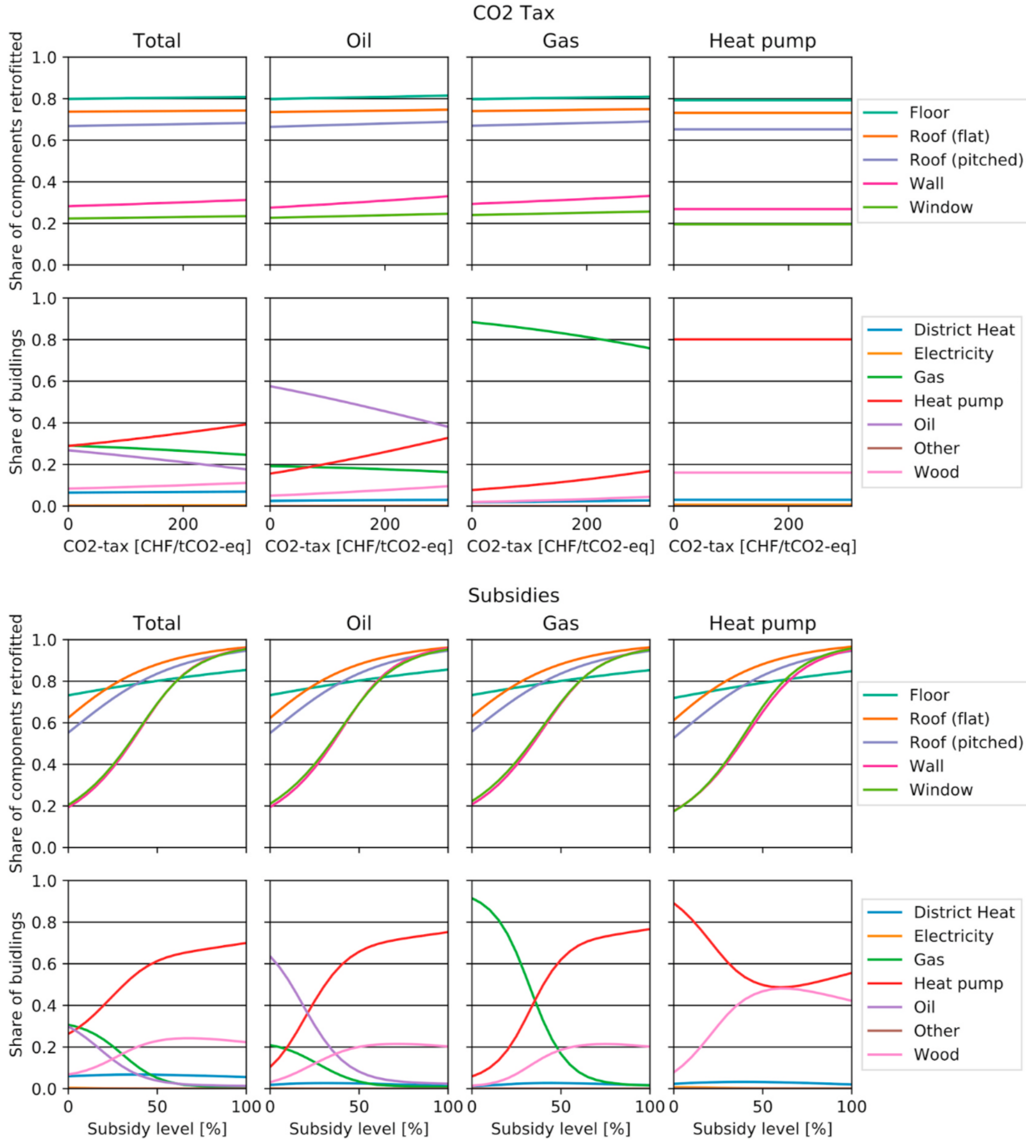

Fig. 10. Analysis of the decision sensitivity of building agents to the modeled financial instruments: CO_2 tax (above) and subsidies (below). Percentages reflect the shares of building agents existing at the model start that make a decision to retrofit a component or choose a certain heating system. The share of building agents is given for different segments of the stock: the total building stock as well as only the building agents with either an oil boiler, gas boiler, or heat pump as a heating system.

heating system decreases rapidly, especially after 2030. The results from the assessment of individual agents' decisions suggest that subsidies are the more effective financial means as they help lower investment costs for building owners, which is the more crucial incentive compared to higher energy costs. That said, the CO_2 tax plays an important role in financing the subsidy scheme, especially in the short and medium terms as the model results indicate.

The results of both the incentive and regulation scenarios reveal that restrictions on the installation of fossil-fuel heating systems is key to achieving the reduction targets. Both in the incentive and regulation scenarios, additional minimal RES requirements for existing buildings are introduced on top of the already existing requirements for new buildings. The results demonstrate the effectiveness of these requirements in decreasing the market share of oil and gas heating systems in the heating system replacement market. The financial incentives on top of the regulatory aspects lead to an even faster increase in the share of renewable heating systems in the incentive scenario. To reduce the market share of oil and gas to zero, however, stricter restrictions such as the CO_2 limit assumed in the regulation scenario are needed. Moreover, in order to decarbonize the building sector by phasing-out oil and gas completely by 2050, additional measures such as mandatory replacement might be needed. That said, the remaining gas demand, could however, also be covered by gas from renewable sources (e.g. power to gas using renewable energy or biogas).

The increase in the CO_2 tax in the incentive scenario leads to higher energy costs in the medium term compared to the reference scenario, as costs for buildings with a fossil-fuel heating system grow substantially. This additional tax revenue is also needed to cover the increase in subsidy levels included in the incentive scenario. In the incentive scenario as well as in the other two, the revenue from the CO_2 tax is not enough to cover the expenditure for subsidies in the long run. The model assumes that all eligible building owners claim the subsidy, which in reality will not be true as additional bureaucratic burdens or lack of knowledge leads them to forgo subsidies. Moreover, total available

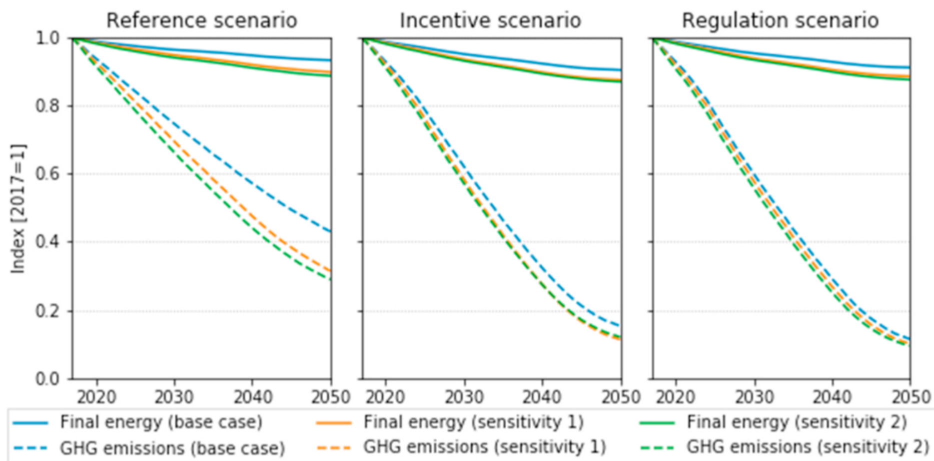

Fig. 11. Sensitivity analysis of different decision model parametrization. Sensitivity 1 (discount rate = 4%, beta decision model = 0.5), Sensitivity 2 (discount rate = 4%, beta decision model = 0.25).

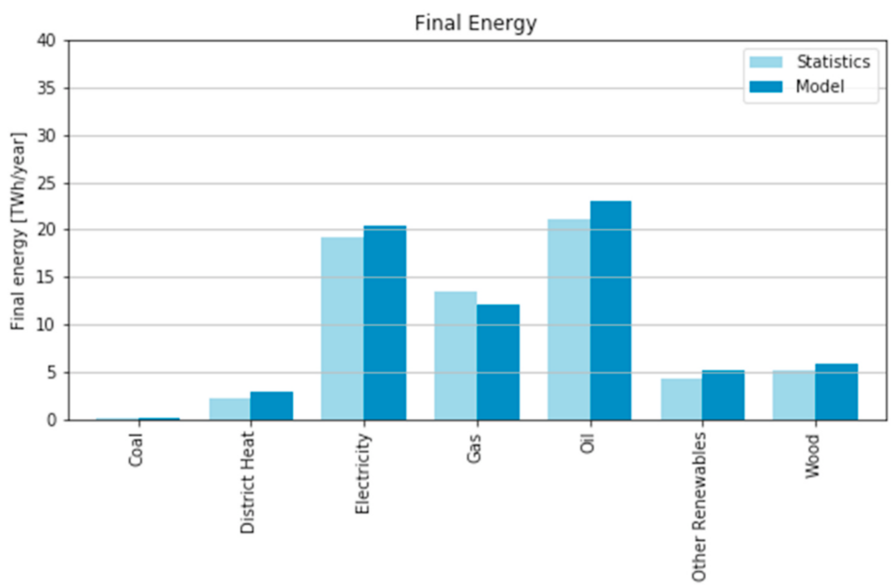

Fig. 12. Validation of the initial state of the model in terms of final energy demand distribution (weather adjusted based on (Prognos, 2018)) and compared with the national energy statistics for the residential sector (FOE, 2018).

funds for the subsidy program limit the total expenditures. Currently, the budget is limited to approximately 450 million CHF/year as only one-third of the revenue of the CO_2 tax is going to the building subsidy program; regional governments contribute the difference. Therefore, the calculated tax revenue and subsidy expenditure can be seen as a maximum boundary for the available and needed funding for the subsidy program.

To some degree, the gap in revenue may also be addressed by reducing subsidy levels again as a further reduction in costs of RES and retrofit measures can be expected due to technological learning in the sector. Moreover, subsidizing RES technologies after the requirements on heating systems are in place may not be needed any longer as the requirements are enough to continue the phase-out of oil and gas. In that case, subsidies could be reserved for extreme cases where the additional costs are an unjustifiable burden for certain building owners (e.g., low income segment or technologically challenging implementation).

The economic impact of the regulation and incentive scenarios compared to the reference scenario in terms of an increase in the needed investments falls primarily on additional costs for heating system replacements, as the differences in retrofit and heating system costs for new buildings are less significant. For individual building owners the additional investment needed for a renewable heating system can be significant, which provides a persuasive argument for the continued use of subsidies at least in the short to medium terms. In the incentive scenario, this burden on building owners due to higher investment costs is alleviated by higher subsidies and the burden is shifted to building owners that are staying with fossil-fuel heating systems due to higher energy costs from the CO_2 tax. In regulation scenario, the additional costs purely fall on building owners replacing their heating system as no additional subsides are introduced.

4.3. *Limitations of results*

The model was calibrated based on the historic development in the Swiss residential building stock from 2000 to 2017 as outlined in Nägeli et al. (2020). The calibration led to a parameterization of the model, resulting in a fairly insensitive model behavior to energy costs compared to the investment cost of the different measures, as is illustrated in Fig. 10. While this is supported to some degree by other studies assessing the investment decisions affecting residential energy use (Schleich et al., 2016), it is debatable whether this holds true even when energy costs are increased substantially (e.g., due to a substantial increase in the CO_2 tax) because in that case owners attention to the retrofit topic could be increased disproportionally. Moreover, the parametrization of the decision model is constant over time and the model does not include changes in preferences (e.g., willingness to pay) and decision criteria of building agents over time. However, due to the acceptance of certain technologies as well as other factors, these parameters may be subject to change. For example, willingness to pay for renewable heating systems or retrofit measures may increase as these technologies become more mainstream.

The effect of the stochasticity of the model is visible in the model results, especially in terms of market shares and investments, as these results are based on a marginal number of building agents each year (i. e., only the building agents taking a decision). While this could have been remedied by increasing the total number of building agents, this was not possible due to the overly long model run time this would entail. The effect of the stochasticity was, however, investigated through multiple model runs and while it does affect the fluctuations of the results, the overall trend of the results remains the same. Therefore, only results from a single model run are presented here for simplicity's sake.

The model currently covers only retrofit measures and changes to the heating system based on aging of the building components. Other triggers of renovation, such as the sale of the building, may lead to renovation especially when it comes to retrofitting the envelope (Friege, 2016; Friege et al., 2016). Moreover, other aspects of renovation such as change of usage (e.g., conversion of apartments) or amenities are also not covered as they may not have a direct impact on the energy demand. However, they may be triggers to other further measures undertaken in the building. Furthermore, the current model is limited primarily to the assessment of building retrofits as well as heating and hot water-related technologies. Other technologies (e.g., increasing use of space cooling also in the residential sector) or other energy technologies (especially photovoltaic systems) as well as changes in appliances use are currently not covered. Moreover, results currently do not include the impact that climate change might have on reducing heat demand, by reducing the need for space heating due to raising average outdoor temperatures in the future. Perceptively, this would lead to an even lower heat demand on average as average winter temperatures increase.

Missing or incomplete data on the current state of the building stock and its development make the use of building stock models necessary, but also introduce substantial uncertainties into their analysis. The model applied in this study has been substantially validated based on the historic development of the Swiss building stock both in the models ability to represent the existing stock as well as reproduce the stock dynamics (see Nägeli et al. (2020) in order to minimize these uncertainties. Nevertheless, some uncertainty remains and should be taken considered when interpreting these results. Such work is currently ongoing as part of the IEA Annex 70 on building energy epidemiology.

5. Conclusions and policy implications

This paper reveals an assessment of the effect of climate policy on the development of the energy demand and GHG emissions of the Swiss residential building stock through an agent-based building stock model. The results indicate that while the current state of Swiss climate policy is effective in reducing energy demand and GHG emissions, it will not be enough to reach the emission-reduction targets set for the Swiss building sector. These reduction targets can be reached only through an almost complete phase-out of fossil-fuel heating systems by 2050, which can be achieved through the introduction of further financial and/or regulatory measures, as indicated by the results of the incentive and regulation scenarios.

The results of the modeled incentive scenarios demonstrate that financial incentives are an effective way to speed up the transition. Such measures may be easier to implement as both the CO_2 tax and subsidy scheme are already in place and the incentive scenario merely involves an expansion of these measures. In the long run, however, the revenue from the CO_2 tax will not be enough to cover the expenditures of the subsidy scheme, at which point other revenue streams to finance the subsidy scheme would be needed or subsidies only targeted to specific segments. However, cost reductions due to technological learning as well as the expansion of regulatory measures might make a reduction or phase-out of subsidies possible in the long run. Therefore, further regulatory requirements—such as the expansion of RES requirements or a more stringent CO_2 limit for new and existing buildings—will probably be needed to completely phase out fossil-fuel heating systems. However, these regulatory measures might be more difficult to implement as they are a stronger intervention compared to financial instruments. Moreover, the slow implementation of the current regulatory framework through the individual states (cantons) (EnDK, 2018) demonstrates that it will take a while for these requirements to be implemented across Switzerland.

That said, the results show that long component lifetimes lead to low retrofit rates and a slow phase out of heating systems. Therefore, it is crucial that the relevant policies are in place by 2025 at the latest in order to phase out systems during their "natural" replacement cycle. Otherwise more costly measures have to be taken as systems and components need to be replaced before the end of their lifetime and measures cannot be implemented at marginal costs any longer.

CRediT authorship contribution statement

Claudio Nägeli: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Martin Jakob:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Giacomo Catenazzi:** Software. **York Ostermeyer:** Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the EIT Climate-KIC for funding the PhD studies of Claudio Nägeli and the project Building Market Briefs as well as the Swiss Federal Office of Energy for funding TEP Energy's contribution to the IEA-EBC Annex 70.

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