Policy Analysis for the Transformation of Switzerland's Stock of Buildings. A Small Model Approach

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Abstract

This paper reports on preliminary work on a small System Dynamics model of Switzerland's stock of residential, multifamily buildings over the time period 1975 to 2100. It is used to study the dynamic implications of carrying out different shares of renovation strategies on the composition of the stock of buildings. Of particular interest is the question, how the mostly non-energy-efficient stock of buildings can be transformed to a state of higher energy-efficiency. The model is empirically grounded and it was tested in collaboration with experts. The model is used to analyze three ideal-typical scenarios. Model analysis indicates that ambitious energy standards in building codes are of central importance, that the scope of said standards should be broadened to include as many situations as possible and that non-energy-efficient renovations should be avoided. Making renovations mandatory seems a less viable scenario. As the decarbonization of heating systems emerges as an interesting alternative we propose two regulations which could achieve a thorough transformation of Switzerland's stock of buildings.

Keywords

Construction, policy analysis, residential housing, energy, sustainability.

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1 Introduction

Increasing evidence of dangerous, anthropogenic climate change (IPCC 2007), as well as concerns about energy security and the nearing end of cheap fossil fuels (IEA 2008) have spurred various levels of government in Switzerland to aim for ambitious goals in the domain of energy policy[1].

In the year 2000, the Swiss average demand for gross energy was about 5100 watts per capita, of which about 3000 watts stem from fossil sources[2]. Of this total demand, about half (2690 watts) is expended for the construction, use and maintenance of buildings. About 31% (1590 watts) of average per capita demand for gross energy is expended for buildings with residential purposes[3]. (Koschenz & Pfeiffer 2005, 8p.)

The fact that low-energy housing designs are technologically feasible and economically viable in both construction and renovation currently is demonstrated by growing number of Minergie-certified buildings (Minergie 2010*b*). Swiss building owners can get their building certified according to the voluntary Minergie standard. In order to be eligible for certification, the (weighted) energy-coefficient for residential multifamily buildings (built before the year 2000) must be 38 kWh/m^2 or less. In addition, the construction costs may not be more than 10% of a comparable conventional building. (Minergie 2010*a*). In contrast, typical multifamily buildings constructed before the year 1980 have an energy coefficient of almost 200 kWh/m^2 (Regierungsrat des Kanton Zürich 2006, 18). Due to the long service life of buildings (in the model we assume an average of 55 years until the first renovation is needed), a substantial share of Switzerland's buildings were built in a time where no or only minimal energy standards were implemented into the building code. In order to achieve the ambitious reduction

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[1] For example, the city of Zürich pursues the vision of reducing the emission of CO_2 down to one ton per inhabitant by the year 2050 (Regierungsrat des Kanton Zürich 2006, 12).

[2] The average demand for primary energy was 6400 watts per capita. Average demand for gross energy does not include losses from generation etc, hence it is smaller (Koschenz & Pfeiffer 2005, 25).

[3] Buildings in the service sector account for 16% (780 watts) of average per capita demand for gross energy. Industrial buildings account for about 6% (320 watts) (Koschenz & Pfeiffer 2005, 9).

goals in the domain of energy policy, a determined push for energy-efficient renovation of the stock of buildings is of crucial importance.

Currently, Swiss public policy is somewhat limited in its ability to conduct strong interventions in the stock of buildings. In Switzerland a building permit is required only for constructing a new building. Such permit can only be obtained if the current regulations on energy and other domains are adhered to. However, once a building is constructed according to the regulations of the time, it is deemed adequate also when the regulations on energy in buildings change. Energy regulations only apply when a substantial sum (generally about 25k-50k or more Swiss Francs) is invested into renovation work. Therefore, building owners can decide to do only basic maintenance and leave the building's demand for energy quite unaltered, without facing consequences.

It is in this context, that the research presented in this paper investigates how different renovation strategies would change the composition of Switzerland's stock of multifamily buildings from non-energy-efficient to energy-efficient and how this would contribute towards the reduction of CO_2-emissions. More specifically, we ask how the transformation process would unfold, if half of renovations would implement energy-efficient building designs (baserun scenario), if almost all renovations were to implement energy-efficient building designs (energycode scenario) and if renovations implementing energy-efficient housing designs were made mandatory within a specific time period (mandatory scenario).

The reasons that we focus on residential multifamily buildings is that they are responsible for a very large share of heated floor space and that because they are generally rented to tenants, there is an investor-user dilemma, which may prevent building owners to invest significantly into renovations. Future research by the authors will recur on this model.

The structure of this article is as follows: Section 2 provides a brief review of the literature on energy in Switzerland's stock of buildings. Section 3 enlightens on the research design and the methodology employed in this paper. Section 4 describes the structure of our simulation model. In section 5, scenarios corresponding to different policy measures are analyzed and based on that, in section 6, a regulatory framework within which the transformation of Switzerland's stock of buildings could be set is proposed. Section 7 concludes and addresses further research needs.

2 Review of Current Knowledge[4]

Several contributions address the past, current and future structure of the stock of buildings in Switzerland. In the following, a brief review of the most important sources of current knowledge, such as data, reports, models and publications, is given.

Every few years since the mid-1970s, the Swiss Federal Office of Energy has prepared a series of reports (*energy perspectives*), in order to provide a long-term view on Swiss energy policy. In the year 2004, work was begun to produce the newest perspectives, which look as far as until the year 2035. (BFE 2010) Among the work conducted, Hofer (2007) addresses a large number of variables which directly relate to the stock of buildings. For example, it contains data and projections for the heated floor area over the period from 1990 to 2035, diffusion patterns for various heating systems, temporal data on average energy coefficients of new and existing buildings. Frequently, the work presented in the energy perspectives draws on previous work (Wüest & Gabathuler 1991, Wüest & Partner 1994).

Kost (2006) developed a highly disaggregated simulation model of Switzerland's stock of residential buildings, which includes changes in floor space over time and tracks a series of energy-related metrics. The purpose of that model was to conduct scenario analysis and compare simulation results with the vision of the 2000 watt society. Based on that model, it is found that a reduction of final energy by the factor 3 and a reduction of CO_2 emissions by the factor 5 is possible until the year 2050. (Kost 2006, Siller, Kost & Imboden 2007) The authors argue, that the implementation of stricter energy standards and low-emission technology for water and space heating are the most effective options to achieve this. The refurbishment of existing buildings is deemed to be of higher importance than new constructions.

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[4] This section is to be considered a first draft and hence may change substantially.

Schulz (2007) investigates intermediate steps towards the 2000-watt society in the year 2050, and as a part of his work includes the residential sector in his model. Considering Switzerland's energy system as a whole, he finds that during the first half of the 21st century "only intermediate steps towards the 2000-Watt society can be achieved." (113) Related to buildings, he finds that heating systems based on heating oil and gas can be largely avoided, even if the heated floor area would rise by 40% in the year 2050. This can be achieved by relying on heat pumps and district heating based on combined heat-power generation (CHP) from natural gas and biomass. In the residential building sector, doing so would lower the CO_2 emissions by about 10 million tones, or 20% of Switzerland's current emissions. (118)

TEP & ETH (2009) provide the currently most up-to-date model of the stock of buildings in Switzerland. It partially builds on the work of Hofer (2007) and follows a similar approach as Kost (2006) and Schulz (2007) by modeling consecutive cohorts of buildings, with specific parameters for each cohort.

Similarly as we did in this paper, Filchakova, Wilke & Robinson (2009) used the concept of the ageing-chain, to model the evolution of the city of Basel's stock of buildings. By differentiating between embodied energy and energy consumption, they treated energy use by the stock of buildings in a more detailed manner as we did in this paper. Filchakova et al. (2009) call for further modeling work in which "the stimuli for decisions to renovate were modeled" such that strategies for increasing renovation frequency could be tested. While the model presented in our paper does not include (yet) the feedback loops that explain temporal variation of the decisions for specific renovation strategies, we add a distinct policy perspective to the otherwise similar modeling approach of Filchakova et al. (2009).

Further, not explicitly model-based contributions are to be found in the literature: The Swiss association of engineers and architects (SIA) provides a planning tool addressed to politicians, building owners and planners to achieve a "reduction path" towards the vision of a 2000 watt society by the year 2050 (SIA 2006). It includes several assumptions from experts concerning the future development and the target values for the stock of buildings. In a contribution by Novatlantis (Jochem 2004), the authors ask what technologies need to be developed to achieve the goal of a 2000 watt society in various sectors. Regarding the building sector they find that technically a "one liter" (heating fuel, per m^2, per year) building is possible (20). They conclude that the energy demand from the stock of buildings will be dominated by the stock of existing buildings[5].

3 Methodology and Research Design

The research presented in this article falls into a methodological domain which is best described as computer-assisted theory building with System Dynamics (Hanneman 1988, Schwaninger & Grösser 2009). System Dynamics is a methodology for developing and testing computer simulation models of problem situations and implementing the insights derived from them (Forrester 1961, Sterman 2000). Variables are differentiated into *stocks* (capable of accumulating), *flows* (quantities flowing in or out of stocks) and *auxiliary variables* such as constants or parameters. Model structures are typically visualized with a stock-and-flow diagram: A box represents a stock, a double arrow going in or out of a stock represents a flow and a single arrow is used to represent that any variable influences an auxiliary variable or a flow (see figure 1 on page 16). The equations of the model are entered into a simulation program such as Ventana System's Vensim DSS 5.9e which was used in this study. With stocks, flows and auxiliary variables as building blocks, a model of the problem situation under study can be built.

System Dynamics modeling proceeds rather inductive than deductive. In developing the simulation model, information from the analysis of a large range of data can be used to specify the model as close as necessary to reality: Information from the literature, statistical databases, insights from interviews, workshops and observation can all be used to develop the simulation model as a dynamic theory regard the issue under study. Simulation thus yields behaviour. Computer-assisted theory building with System Dynamics now emerges as a methodology with a certain similarity to grounded

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[5] This only holds for the energy demand. For energy-efficient renovations, the construction sector is of major importance because it is in the construction of new buildings where innovations in the field of energy technology are first implemented before they are employed in the renovation of buildings. See the ongoing research by Stefan Grösser & Silvia Ulli-Beer.

theory (Glaser & Strauss 1967), because it too proceeds iterative, integrates knowledge from all available data sources and understands testing as a continuous aspect of theory building.

System Dynamics simulation models can range from very precise (such as simulations of simple physical systems) to highly conceptual, depending on the availability and quality of data that can be used to calibrate the model. Hence, simulation and System Dynamics modeling can be highly beneficial even in situations where no or insufficient numerical data is available. System Dynamics modeling forces to explicate assumptions and by simulating models, the logical consequences of assumptions are calculated by the computer. Simulation then yields the dynamic behavior of the assumptions underlying the model. This constitutes a substantial additional benefit compared to theory building that relies only on written word as a vehicle of theory – as long as it remains clear that quantification does not per se translate an assumption into an quasi-empirical fact.

The field of System Dynamics has a track record of producing large, detailed and dynamically complex models. These are rather difficult to communicate, particularly to decision- and policy-makers who generally lack the time and perhaps the training to indulge into detailed simulation models. In response to this, *group model building* (Vennix 1996) was developed as a way to involve policy-makers into model development. *Small models* can be seen to be an alternative approach to convey insights from System Dynamics modeling to non-experts. Similarly, *model simplification* (Saysel & Barlas 2006) is the practice of reducing large, complex models to small models, while retaining it's most important behavioral characteristics. Concept models, in contrast, are tiny elements of the System Dynamics methodology that are used to introduce the visual language and framing assumptions in group model building sessions. (Richardson 2006).

According to Ghaffarzadegan, Lyneis & Richardson (2009, 3), "for many public policy problems a small model is sufficient to explain problem behaviour and build intuition regarding appropriate policy responses." The model presented in this paper is such a small model, aimed at policy-makers, members of parliaments and the general public. By using the simplest adequate model structure we could conceive of, by justifying the assumptions used and by showing the dynamic behavior of the model over several scenarios, we hope to provide an analytical tool that allows anybody with basic scientific training to use and understand the model.

The research design underlying this study follows the research design of the research project, in the context of which this work was carried out: Based on a review of the literature, interviews with practitioners from the construction industry and a workshop with said experts a dynamic theory of the diffusion of energy-efficient renovations in form of a System Dynamics computer model was developed. The model presented in this paper is a part of the larger model. While the larger model contains an endogenous explanation of how the shares of different renovation strategies change over time, this small model takes the share of each renovation strategy as an exogenous input. The purpose of exogenously applying different shares of the renovation strategies to the model of the stock of buildings is that this allows to conduct policy experiments.

We maintain that the model presented in this paper is not intended to give exact point estimates for the future. It's usefulness rather lies in it's ability to give insights into the dynamics of Switzerland's stock of residential multifamily buildings under different policy scenarios. In particular, we aim to investigate how different policy measures alter the transformation pattern of Switzerland's stock of buildings and how this affects the trajectory of CO_2 emissions.

4 Structure of the Model

4.1 General Setup

Reference Mode The reference mode of this model is the CO_2-emission rate, which should be reduced.

Temporal Dimension The model runs over a time of 125 years, from the year 1975 to the year 2100. The period spanning the years 1975 to 2000 is based on empirical data for the total number of buildings.

Level of Aggregation The simulation model has a high level of aggregation. The aim is to include a small number of key characteristics and look at their interrelations. For example, buildings are treated as identical objects differentiated only over the attributes *quality state* and *level of energy-efficiency*. Differences which in the real world account for a substantial degree of variance in rental prices, such as the floor space, the number of rooms or the amount of sun light received, are not explicitly included into the model. Instead, such attributes can be assumed to be implicitly included at their mean value and uniformly distributed across all reference buildings.

Model Boundaries The model provides no endogenous explanation why the shares of the three different renovation strategies change. It does however simulate the effect of the shares of renovation strategies changing over time. Further, the model does not explain by which combination of technologies (heating systems, ventilation or insulation) energy-efficient housing designs are implemented. In the model, only the energy use for heating purposes is addressed. Energy use for warm water and appliances in the building are not addressed, because only the energy used for heating is substantially affected by energy-efficient building designs.

Sectors The model has two important sectors. In the main sector, the behavior of the stock of buildings over time is modeled. In the second sector the CO_2-emissions are calculated based on the stock of buildings.

4.2 Definition of the Standard Building

In the real world, each building is unique. Statistically oriented scientific studies, for example Geiger (2006), try to account for the wide diversity of buildings by conceptualize buildings as a cluster of many attributes of the building and it's neighborhood. For the purpose of this study, a highly aggregated perspective is sufficient as high level analysis will be conducted.

This aggregated perspective is implemented by defining a standard building with a very small number of attributes. Of those attributes, variation only takes place in two attributes, specifically in the *energetic* and *quality* state of buildings (see below). Over all six possible combinations of energetic and quality state, all the other attributes are implicitly defined to be invariant and normally distributed around their mean value.

For example, attributes such as "number of housings per buildings", "number of rooms per housing" or "surface area per housing" are either defined to be constant or are not even explicitly defined because they are not relevant in the aggregate perspective. The following attributes are relevant:

Quality states of buildings: In the model, buildings have one of the following three different quality states:

- **New condition:** These are buildings that were recently built. They correspond to the recent demands of the market and all the construction elements are in new or nearly new condition.
- **Good condition:** These are buildings that are in a good, but no longer new condition. While the construction elements of the building generally are in good shape, first traces of wear and tear show.
- **Bad condition:** Buildings in a bad condition are characterized by the fact that the life-cycle of construction elements in several aspects is either reached or already has been exceeded.

Without renovations, buildings move over time from a new condition to a good condition, and later from a good condition to a bad condition. This is because their physical substance ages and because the configuration of buildings often become outdated as societal trends change. The process of buildings becoming outdated and less attractive to the premium market segment is called "filtering". (Eekhoff 1987, 19pp; Frey 1990, 144p.) Consequently, buildings in new and good condition frequently inhabited by households with an income at or above the average. Conversely, buildings in bad condition in average are frequently inhabited by households with an income below average. Filtering processes can be reversed by renovations: After remaining some time in a bad condition, buildings are either renovated or reconstructed. Renovations change a buildings condition to a good condition and reconstructions change a building to a new condition.

Typology of energetic states of standard buildings: In the model, a fundamental differentiation is made between non-energy-efficient buildings and energy-efficient buildings. The energetic state of a building is expressed by it's energy coefficient.

- **Energy-efficient** (ee) buildings are defined as having an energy coefficient below 193 MJ per m^2 and year.
- **Non energy-efficient** (nee) buildings are defined as having an energy coefficient below 193 MJ per m^2 and year.

4.3 Renovation Strategies

The following three renovation strategies are relevant in order to understand the transformation of the stock of buildings to a higher level of energy-efficiency. It is assumed that for each renovation strategy the energetic level either remains constant or that it is improved:

- **Paintjob renovation:** The energetic state of the building remains non-energy-efficient, only the level of quality is increased from bad to good.
- **Energy-efficient upgrading:** A non-energy-efficient building in bad condition is brought to a condition that corresponds to a building in good condition. In addition, it is made energy-efficient. Energy-efficient upgradings start to occur only after the year 2000, as prior to then the technology available to conduct energy-efficient renovations is not yet widely used.
- **Reconstruction:** A non-energy-efficient building in bad condition gets torn down and is replaced by a new one. By definition, a newly constructed building is of new quality. The share of newly constructed buildings built as either non energy-efficient or as energy-efficient changes over time (see figure 3).

4.4 The Building Sector

Stock and Flow Diagram Figure 1 shows how the two levels of energy-efficiency, the three levels of quality and the three renovation strategies can be meaningfully combined into a stock-and-flow diagram (Sterman 2000) of the stock of residential, multifamily buildings. By underlying this diagram with the appropriate equations and parameters it is possible to simulate the evolution of the built environment over time.

In addition to the three renovation strategies described in section 4.3, two further renovation strategies are included for the sake of conceptual consistency. Those are the renovation of energy-efficient buildings in bad conditions (analog to the paintjob renovation strategy) and the replacement of energy-efficient buildings by energy-efficient buildings in new condition (analog to reconstruction). However, as these two flow variables do not change the number of energy-efficient buildings they are not relevant for policy analysis and are hence held constant over time.

Equations For each year, the values for the stocks at the end of the year are calculated by adding the inflows to and subtracting the outflows from the stock of buildings. For example, the number of nonee buildings in bad condition is given by calculating equation 1. The values for the other five stocks are calculated analogously.

$$N_t = \mathrm{N}_{t-1} + DEC_{t-1} - neeREN_{t-1} - eeREN_{t-1} - neeREC_{t-1} - eeREC_{t-1} \quad (1)$$

with:

N:	nonee buildings in bad condition
DEC	decay of nonee buildings
neeREN	number of paintjob renovations
eeREN	number of energy-efficient renovations
neeREC	number of nonee reconstructions
eeREC	number of ee reconstructions

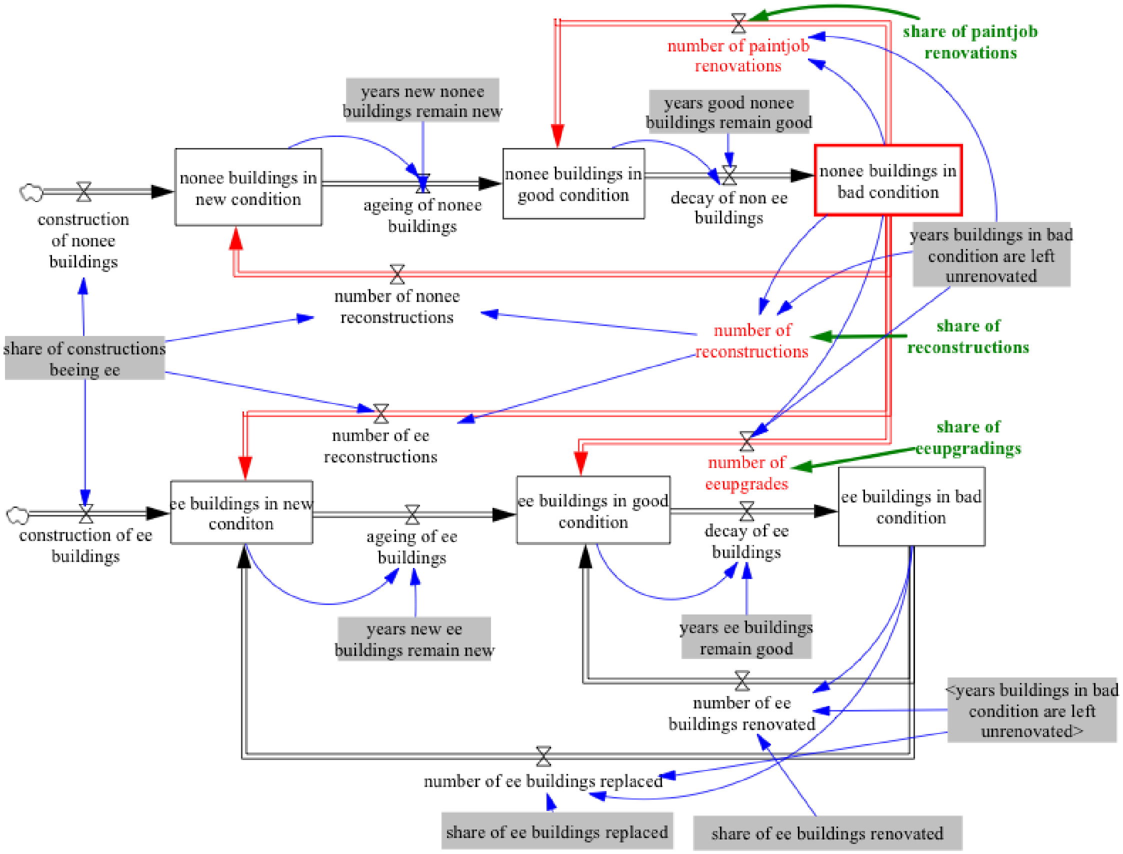

Figure 1: Stock-and-flow diagram of the simulation model's main sector. The flows (double arrows) plotted in red show the flow of nonee buildings in bad condition to an other condition. (The variables in green bold control these flows and by definition add up to unity.)

For each timestep the number of paintjob renovations, the number of eeupgradings and the number of reconstructions is calculated. Equation 2 shows the formula for the number of paintjob renovations. The formula for the other two renovation strategies is calculated analogously.

$$neeREN = \frac{s * N}{Y} \tag{2}$$

with:

neeREN	number of paintjob renovations
s	share of paintjob renovations
N	nonee buildings in bad condition
Y	years buildings in bad condition are left unrenovated

Of special importance is here the specification of the number of buildings that are renovated ($\frac{N}{Y}$) as a first-order material delay rather than a pipeline delay (Sterman 2000, 415pp.). Using a pipeline delay would correspond to assuming that all buildings are renovated after the specified time (Y). This does not make sense, because there is a lot of variation in the specific situation of each building, which may cause any individual building to be renovated after an other number of years than the average[6]. It makes much more sense to assume an average number of years (Y) that buildings in bad condition are left unaltered and assume a one-peaked, symmetric distribution around the average value. The disadvantage of using a first-order material delay is that it may take relatively long to approximate zero. The higher the value of Y is, the slower the rate of convergence becomes.

Parameter Parameter of critical importance concern the aging behavior of the stock of buildings: Table 2 shows how long buildings in average are assumed to remain in any given state. Note that in the model, the share of paintjob renovations, the share of eeupgradings and the share

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[6] One of the experts we discussed this work with proposed to use a fixed time delay rather than the first-order material delay and perhaps add a random distribution to it. In the future, we plan to test behavioral differences between the two approaches. We however do not expect substantial discrepancies.

of reconstructions are set exogenously rather than endogenously[7]. By definition, the shares of the three renovation strategies must add to unity.

Parameter	**Value**
Years new nonee buildings remain new	10
Years good nonee buildings remain good	30
Years nee buildings in bad condition are left unrenovated	15
Years new ee buildings remain new	10
Years good ee buildings remain good	30
Years ee buildings in bad condition are left unrenovated	15
Share of EE Buildings Renovated	0.75
Share of EE Buildings Reconstructed	0.25

Table 2: Various parameters used for the calibration of the building sector.

Data In Switzerland, a building permit must be obtained before a building can be constructed. The permit is given only if the building conforms to the energy regulations. Historically, these have become more and more strict (Jakob 2008, 8). Figure 3 shows the energy coefficient that newly constructed buildings must adhere to. Once the energy coefficient drops below 193 MJ/m2a, buildings are considered to be energy-efficient in this model.

In the literature, there are historical data and projections for the heated floor area of Switzerland's stock of buildings. Figure 2 gives the projections of the heated floor area used in this model. In order to obtain number of buildings, we assume the average multifamily building to have 800 m^2 of heated floor area. Dividing the floor area through 800 then gives the number of buildings at any time.

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[7] An extended version, where the shares of these three variables are modeled endogenously, will be published in the future, in the first author's dissertation

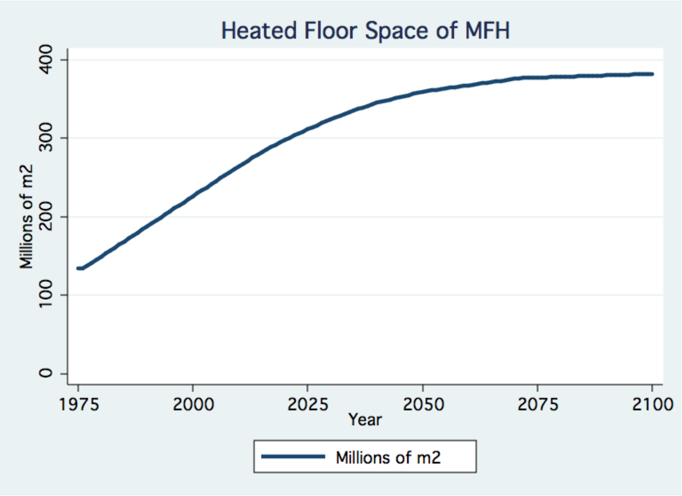

Figure 2: Heated floor area of residential multifamily buildings1975-2100. Datapoints for the years 2005 until 2050 are available in five-year intervals from TEP & ETH (2009, 26). Theoretically, datapoints for the years 1990 until 2003 are available from Wüest & Partner (2004). However, the floor space for multifamily buildings reported here is measured differently and hence lower than the numbers given in TEP & ETH (2009, 26). Therefore, own assumptions, based on the other datapoints are used instead.

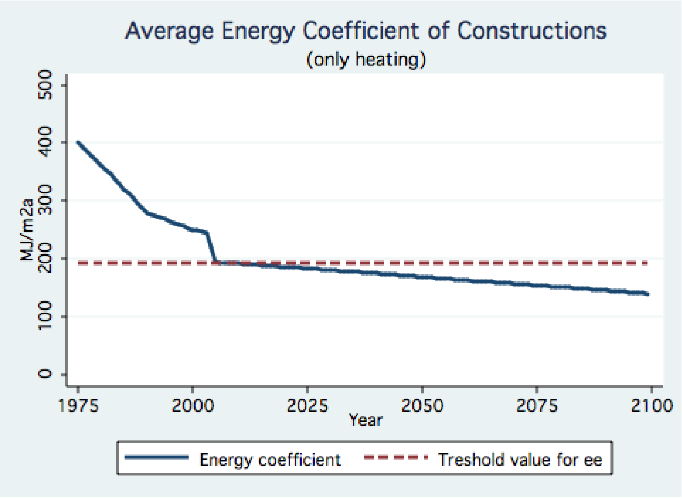

Figure 3: Average energy coefficient of new constructions. Datapoints for the years1991, 2000 and 2003 were taken from Hofer (2007, 26). Datapoints for the years 2005, 2035 and 2050 were taken from TEP & ETH (2009, 29). Datapoints for the year 1980 were taken from Jakob (2008, 34). Datapoints for the years 1975 and 2100 are own assumptions, based on the other datapoints.

Initial Values Initially in the year 1975, all buildings are classified as non-energy-efficient. The available data does not allow to differentiate the buildings into buildings of a *new*, *good* or *bad* condition. Therefore, the total initial number of buildings was distributed across the three states based on plausibility considerations. Table 3 gives the values used:

Building Condition	**Share of Total Buildings**
Nonee Buildings in New Condition	20%
Nonee Buildings in Good Condition	40%
Nonee Buildings in Bad Condition	40%

Table 3: Distribution of the initial total number of buildings over the three building quality states.

Due to the uncertainty concerning the classification of the stock of buildings into the three categories new, good and bad the share for new buildings was set relatively high. However, because between model initialization (1975) and the start of policy analysis (in 2010) a period of 35 years has passed, any deviation of five or even 10 percent away from this assumption will be balanced out by the model, as buildings move down the aging chain.

4.5 The CO_2 Accounting Sector

Factors The stock of building's emissions of CO_2 is approximated by taking several variables and constants into consideration:

- The floor space of non-energy-efficient and energy-efficient buildings
- The average energy coefficient of nee and ee floor space
- The share of buildings with an oil or gas heating (diffusion rate)
- The efficiency of oil and gas heating systems
- Emission factors for gas and oil fuels

Floor Space In a first step, the floor space of each, either nee or ee buildings, needs to be calculated. The two floor spaces are tracked by a stock each. In the stock of nee floor space, nee constructions flow in and the floor space renovated by eeupgrading and ee reconstructions is subtracted. Into the stock of ee floor space, ee constructions, eeupgradings and reconstructions flow.

Average Energy Coefficients In a second step, the average energy coefficient of nee and of ee floor space must be obtained in order to calculate the total demand for heating energy by both types of floor space.

Initially, there is a given amount of nee floor space and the energy demand of nee floor space is set at 400 MJ/m^{2}a. Yet as time progresses, nee floor space with a decreasing energy coefficient is added to the initial stock of nee floor space. Consequently, the average energy coefficient of nee floor space slightly decreases over time. In order to calculate the average energy coefficient (see figure 4), each year the newly constructed nee floor space is multiplied with the current energy coefficient for constructions and added to a stock (floor space times energy coefficient of nee buildings). By dividing the value of that stock through the total nee floor space, the average energy coefficient of nee floor space can be obtained. In order to account for the effect of eeupgradings or reconstructions, the floor space renovated is multiplied with the average energy coefficient of nee floor space and the result is subtracted from the stock. This way, energetic renovations do not affect the average energy efficiency of nee floor space.

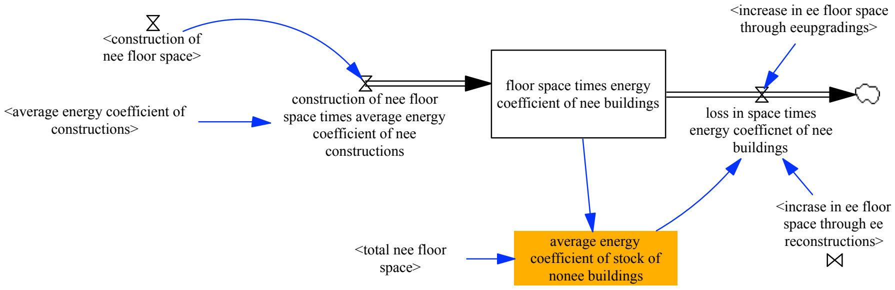

Figure 4: Calculation of the average energy coefficient of nee buildings.

The calculation of the average energy coefficient of the ee floor space follows the same logic. The product of new floor space and the current energy coefficient of constructions is added to a stock (floor space times energy coefficient of ee buildings, not shown in any figure). That stock is divided through the total ee floor space and in consequence the average energy coefficient of ee floor space is obtained.

Diffusion rates Figure 5 shows the diffusion rates of oil and gas heating systems over various states of buildings. In exhibit 1, the diffusion rates for the stock of non-energy-efficient buildings is shown. Here, a substitution process from oil to gas is visible[8]. In exhibit 2, the diffusion rates of oil and gas heating systems in the stock of energy-efficient buildings is shown. This contains buildings that were constructed, reconstructed or eeupgraded to be energy-efficient.

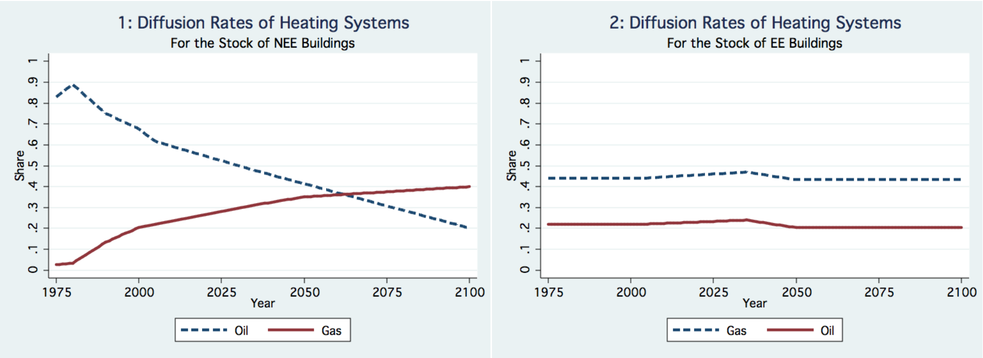

Figure 5: Diffusion rates of heating systems. Exhibit 1 shows the share of oil and gas heatings in the stock of non-energy-efficient buildings. Exhibit 2 shows the shares of oil and gas heatings in the stock of energy-efficient buildings. Source: TEP & ETH (2009).

Efficiency Figure 6 shows the increasing average efficiency of oil and gas heating systems over time. As the efficiency increases, the amount of energy input (oil or gas as a fuel) used to provide the desired energy output (heat) decreases.

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[8] Note that other heating systems, such as heat pumps or wood heatings are excluded, and the shares of oil and gas heating hence do not add up to unity. This is because they are considered to be emissions free. In Switzerland, almost all electricity is produced by hydro or nuclear plants.

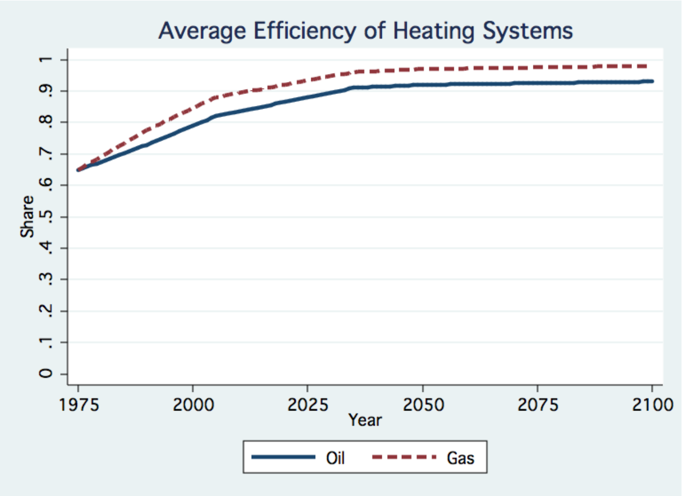

Figure 6: Efficiency of heating systems. Source: TEP & ETH (2009).

Emission Factors In order to calculate the emissions of CO_2 for floor space heated with fossil fuels, emission factors need to be known. According to BAFU (2009), 73.7 tons of CO_2 are emitted per Terajoule when useing light heating oil. And 55 tons of CO_2 are emitted per Terajoule when gas is used for heating.

Calculating CO_2 Emissions Based on the factors discussed above, the CO_2 emissions of the stock of buildings can be calculated as follows. In a first step, the ee and the nee floor spaces heated (space) with oil and gas need to be calculated (see equation 3).

$$\begin{aligned} \text{Nee space}_{oil} &= \text{NEE floor space} * \text{diffusion rate of oil heating in nee} \\ \text{Nee space}_{\ gas} &= \text{NEE floor space} * \text{diffusion rate of gas heating in nee} \\ \text{EE space}_{oil} &= \text{EE floor space} * \text{diffusion rate of oil heating in ee} \\ \text{EE space}_{gas} &= \text{EE floor space} * \text{diffusion rate of gas heating in ee} \end{aligned} \tag{3}$$

In a second step, the demand for useful energy (UE) is calculated for each of the four types of floor space. As shown in equation 4, this is done by multiplying the four types of floor space obtained above with the corresponding average energy coefficient (AEC).

$$\begin{aligned} \text{UE Nee space}_{oil} &= \text{NEE floor space}_{oil} * \text{AEC}_{Nee} \\ \text{UE Nee space }_{gas} &= \text{NEE floor space}_{gas} * \text{AEC}_{Nee} \\ \text{UE EE space}_{oil} &= \text{EE floor space}_{oil} * \text{AEC}_{EE} \\ \text{UE EE space}_{gas} &= \text{EE floor space}_{gas} * \text{AEC}_{EE} \end{aligned} \tag{4}$$

In a third step, the efficiency of the heating systems needs to be considered in order to obtain the demand for final energy (FE). This is done by dividing the useful energy obtained above through the average efficiency of the heating system used (see equation 5).

$$\begin{aligned} \text{FE Nee space}_{oil} &= \text{UE Nee space}_{oil}/\text{Efficiency}_{oil} \\ \text{FE Nee space }_{gas} &= \text{UE Nee space}_{gas}/\text{Efficiency}_{gas} \\ \text{FE EE space}_{oil} &= \text{UE EE space}_{oil}/\text{Efficiency}_{oil} \\ \text{FE EE space}_{gas} &= \text{UE EE space}_{gas}/\text{Efficiency}_{gas} \end{aligned} \tag{5}$$

Once final energy for each type of floor space is obtained it can be multiplied with the corresponding emission factor. By summarizing the emissions from all four types of floor space, the total emissions for each year are obtained.

5 Scenario Analysis

5.1 Scenarios

In the following, three different scenarios analyzed. Each scenario represents the transformation of Switzerland's stock of residential multifamily buildings under different policies. This will allow to address the question, how the emission dynamics of CO_2 play out due to energy-efficient building designs.

- **Baserun:** In this first scenario, the share of energy-efficient renovations rises to 0.5 once the required technology is available. This scenario is closest to the current situation in Switzerland, where a substantial share of renovations currently do not reach an energy-efficient level.
- **Energy Code:** In this scenario, each non-energy-efficient building in bad condition that is renovated must be made energy-efficient, which corresponds to a prohibition of the paintjob renovation strategy. However, whether and when a building is renovated is decided by the building owner. Consequently, buildings in bad condition in average are left as they are for a long time.
- **Mandatory:** As in the previous scenario, paintjob renovations are effectively prohibited once the eeupgrading renovation strategy becomes a viable option. In addition, mandatory requirements are implemented that stipulate that a non-energy-efficient building in bad condition must be renovated within a few years.

These scenarios are simulated by adapting the values for three variables, while all other parameters as well as the model structure remain identical across the scenarios. For the scenario *Energy Code*, the variables SHARE OF PAINTJOB RENOVATIONS and SHARE OF EEUPGRADES are used to simulate what would happen if all the paintjob renovations were replaced by eeupgradings. For the scenario *mandatory* the variable YEARS NEE BUILDINGS IN BAD CONDITION ARE LEFT UNRENOVATED is reduced to 5 years in order to model the effect of making the (energy-efficient) renovation of nee buildings in bad condition mandatory.

Figure 7 shows which share of buildings are carried out by a specific renovation strategy. Exhibit a) gives the values for the *baserun* scenario. Over the time period 1975 to 1995, only paintjob renovations are carried out. This is because neither the technology for energy-efficient renovations were readily available, nor was there a widespread realization that climate and energy constitute an urgent problem that needs rapid action. Over the period 1995 to 2015, energy-efficient upgrading gradually emerge as a technically feasible and financially viable renovation strategy. After a diffusion process of 20 years, eeupgrading is here modeled as achieving a market share of 50% by the year 2015. In correspondence with the literature on the diffusion of innovation (Rogers 2003, Stoneman 2002), the diffusion process is modeled as a logistic s-curve. In exhibit b), the diffusion process of the eeupgrading renovation strategy is modeled as achieving a market share of 95% by the year 2015. As explained above, this is due to the effective prohibition of paintjob renovations, which occurs in both the *energycode* and the *mandatory scenario*.

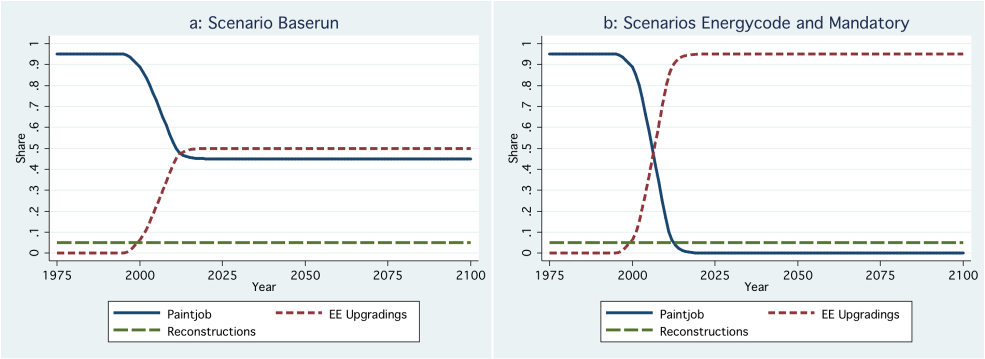

Figure 7: Shares of the three renovation strategies over time. Values for the scenario *baserun* are given in graph a). The shares of the three renovation strategies are the same in the scenarios *eeupgrading* and *mandatory* (see graph b). (In the mandatory scenario, the YEARS BUILDINGS IN BAD CONDITION ARE LEFT RENOVATED are reduced from 15 to 5 years.)

For each scenario, figure 8 show the behavior of the six stocks of buildings obtained by simulation. In the *baserun scenario*, where we assumed that half of the non energy-efficient buildings in bad condition are upgraded to a higher state of energy-efficiency, the transformation process takes very long. This is mostly due to the fact that in the *baserun scenario*, buildings can move upstream in the inefficient aging chain by way of the paintjob renovation strategy. Consequently, a substantial number of non-energy-efficient buildings cycle between a good and a bad state. However, this number diminishes because 50% of all renovations are carried out by the eeupgrading strategy which drains the number of buildings for which paintjob renovations could be considered. However, by the year 2100 still about 94 300 buildings are in the non-energy-efficient stream. Therefore, the realization of the baserun scenario would constitute a substantial setback for energy and climate policy. Because of the long time a paintjob-renovated building stays in service before the next renovation is necessary, in the *baserun* scenario the transformation of the stock of buildings is sluggish at best.

In the *energy code scenario*, the reduction of the stock of nee buildings in bad condition is initially rather small compared to the baserun scenario. Over time, however, the gap widens gradually as the stock of nee buildings in good condition is depleted without being replenished by paintjob renovations. In the long run (until the year 2100), an almost complete transition to energy-efficiency is achieved. In this scenario there are about 26 600 buildings in the non-energy-efficient stream by the year 2100.

The success of the *mandatory scenario* in achieving a quick reduction of the nee buildings in bad shape is apparent in figure 8. Following the introduction of mandatory renovations, a sharp decline in the number of nee buildings in bad condition can be seen. However, the depletion speed of the stock of nee buildings in good condition is the same as with the energy code scenario, thus limiting the higher effectiveness of the mandatory scenario compared to the energy code scenario. The success of the mandatory scenario lies in the fact that the number of nee buildings in good condition is substantially reduced before the year 2050. In the long run (until the year 2100), the mandatory scenario converges toward the energy code scenario (16 500 nee buildings by 2100).

Over all, the built environment's speed of transformation to energy efficiency is fastest in the mandatory scenario. However, this speed may come at a price: By mandating the renovation of nee buildings in bad condition,

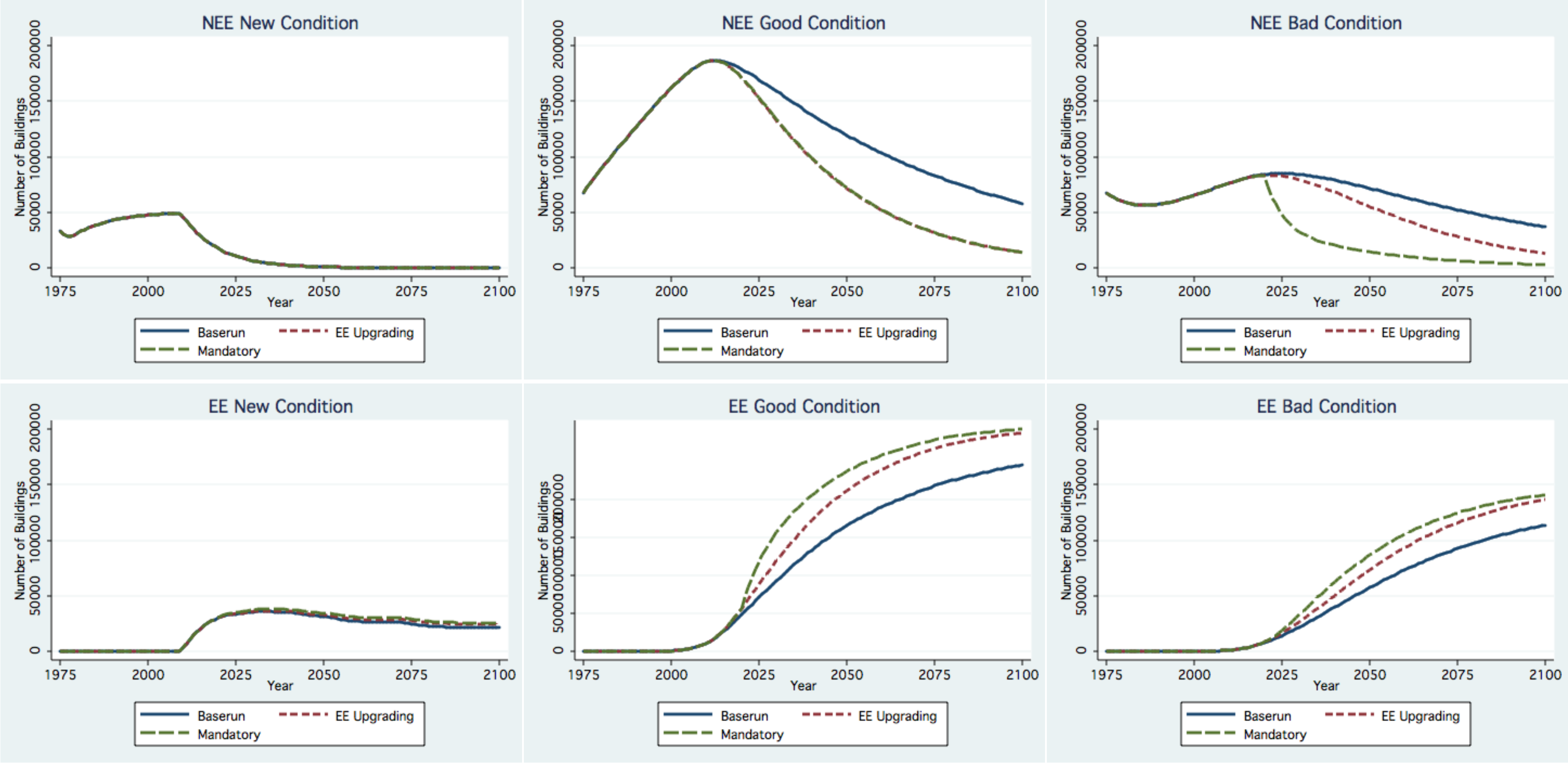

Figure 8: Behavior of the six stocks of buildings for the three scenarios.

the demand for construction services may drive up prices for construction services and materials, thus undermining the cost-effectiveness of investments into energy-efficiency in buildings. Further research also needs to address, the question whether the share of buildings in bad condition, which declines sharply in the mandatory scenario, reduces the availability of housing for low income households. This would be an undesirable effect and would threaten the social sustainability of the mandatory policy package.

Figure 9 shows the current emission rate of CO_2 for each of the three policy scenarios. For all three scenarios the model predicts an emission peak of 7.624 million tons of CO_2 per year emitted by residential multifamily buildings in Switzerland in the year 2010. Compared to this maximum, substantial reductions are realized even in the baserun scenario: By 2050, emissions are cut to an emission rate of 5.666 million tons per year. In the energy code scenario emissions in 2050 amount to 4.894 million tons per year, and in the most determined *mandatory scenario* emissions are cut to an emission rate of 4.424 million tons CO_2 per year.

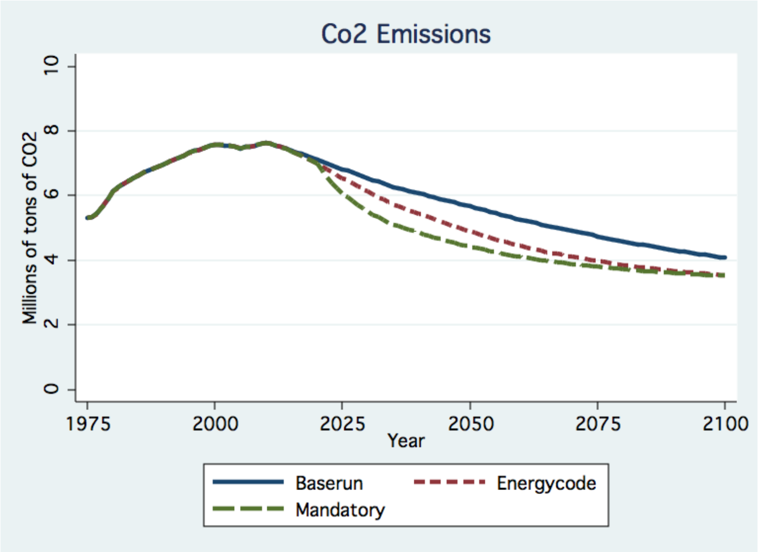

Figure 9: Yearly emissions of CO_2 by the stock of buildings in the three scenarios.

By the year 2100 further progress is made, and the three scenarios converge to the emission level of a fully energy-efficient stock of buildings. However, the reduction of CO_2-emissions is generally weaker than the transformation of the stock of buildings. This is because a part of the efficiency gains made by making buildings energy-efficient is compensated by the expansion of total number of buildings.

In the year 2008, Switzerland had about 7.7 million permanent residents (FSO 2010*a*). Switzerland's federal statistical office estimates in its medium scenario that by 2050 the Swiss population will consist of about 8.3 million permanent residents (FSO 2010*b*). For the *baserun scenario*, dividing the CO_2-emissions from all residential multifamily buildings (5.666 million tons) by the expected population (8.3 million persons) yields an annual per capita emission of 0.77 tons CO_2 per capital for residential multifamily buildings in the year 2050. The corresponding figures for the *energy code scenario* is 0.64 tons CO_2 per capita, and for the mandatory scenario it is 0.57 tons CO_2 per capita.

How should these reduction successes be evaluated in light of the goal of a CO_2-emission rate of one ton per capita per year (Regierungsrat des Kanton Zürich 2006, 12)? Currently, the construction, use and maintenance of buildings with residential purposes (single- and multifamiliy buildings) used about 31% of Switzerland's demand for gross energy (Koschenz & Pfeiffer 2005, 8p.). Conservatively subtracting the energy used for single family buildings and the energy used for construction and maintenance, we should expect that the stock of multifamily buildings' demand for energy should be around 15 to 25% of the Swiss total. Assuming that this roughly corresponds to the share of CO_2-emissions, the stock of multifamily buildings for residential purposes should emit in the range of about 0.15 to 0.25 tons of CO_2 per capita per annum. Table 4 summaries these results and compares the per capita emissions of the stock of residential multifamily buildings to a target range that is compatible with the goal of the 1-ton-CO_2 per capita society.

	Baserun	**Energycodes**	**Mandatory**
Target Range:	0.15-0.25	0.15-0.25	0.15-0.25
Emissions 2010:	0.99	0.99	0.99
Discrepancy 2010:	0.84-0.74	0.84-0.74	0.84-0.74
Emissions 2050:	0.68	0.59	0.53
Discrepancy 2050:	0.53-0.43	0.44-0.44	0.38-0.28
Emissions 2100:	0.49	0.43	0.41
Discrepancy 2100:	0.34-24	0.28-0.18	0.26-0.16

Table 4: Per capita CO_2 emissions (in tons) from the stock of multifamily buildings under the three scenarios, compared to a range of emission rates defined as sustainable. Note that for both, the year 2050 and the year 2100 a population of 8.3 million was assumed.

In none of the three analyzed scenarios can the emission of CO_2 be reduced to a target range compatible with the goal of a one ton CO_2-emission society by the year 2050, or even for the year 2100. These results prompt the question what could be done to further reduce the CO_2 emissions from Switzerland's stock of multifamily buildings. As the energy-efficient renovation of buildings in good or even new condition does not make sense from a financial perspective, the heating systems become the most important policy lever. By decarbonizing the heating systems, the emission of CO_2 could be reduced substantially. A profound discussion of carbon-free or carbon-reduced heating systems is not possible here. However, based on our model we find that the replacement of carbon-based heating systems would substantially reduce the emission of CO_2. Further, because heating systems are less expensive than full-scale renovations of buildings and because they generally have a substantially lower service life, the transformation of the stock of heatings systems potentially could be achieved in shorter time and potentially at lower cost.

5.2 Discussion

The analysis of the three scenarios presented above leads to several important insights. First, it clearly shows that the occurrence of paintjob renovations delays the transformation process. This is because in the baserun scenario, paintjob renovations replenish the stock of nee buildings in good condition. In the energy code scenario, a substantial transformation of the stock of buildings is achieved. This is mostly, because the ageing chain with nee buildings is drained consequently. However, in the short to medium run, the transformation and CO_2-emission reduction speed is slower compared to the mandatory scenario. But in the long run (towards the year 2100), the energy code scenario converges towards the same state as the mandatory scenario. Mandatory renovations were the most effective policy package to achieve a quick and determined transformation of the stock of buildings to high state of energy-efficiency. However, determined policy efforts aimed at implementing mandatory renovations probably would come at the expense of a part of the population that relies on low-cost housing. In conclusion, we find that the transformation of the stock of buildings towards energy-efficiency must be complemented with policy measures which aim at the decarbonization of the heating systems.

Pressing for the decarbonization of heating systems theoretically is a well-suited alternative to implementing mandatory renovations. Due to the shorter service life of heating systems, their decarbonization should be able to achieve within 10 to 20 years. Due to the lower cost of a new heating system compared to the cost of an energy-efficient renovation this option also promises to be economically and socially more sustainable than the mandatory renovation of buildings.

However, the long service life of buildings implies that even with very ambitious policy packages the transformation of Switzerland's stock of residential multifamily buildings towards energy-efficiency will take several decades to achieve. This finding is true, regardless of which scenario is used. Consequently, it seems very unlikely that energy-efficiency alone is sufficient to achieve Switzerland's climate and energy policy targets.

6 Intervention Possibilities for Public Policy

Based on our model, we find that public policy has several intervention possibilities in order to support the transformation of Switzerland's stock of buildings to a level of higher energy-efficiency. In the following, we briefly evaluate potential policy levers. Then we propose some ideas how public policy could address the long-term challenge (Sprinz 2008), which the stock of buildings poses.

As seen in table 5, we find that the prevention of paintjob renovations and the decarbonization of the heating systems are the two crucial challenges. The prevention of paintjob renovations is crucial for the achievement of energy policy targets, whereas the decarbonization of the heating systems is the crucial challenge for Swiss climate policy. In contrast, we find that speeding up renovations by a few years is of questionable value. This is because the stock of buildings has a very long turnover rate, and because the accelerated renovations of nee buildings in bad condition might create pressures for low-income households and thus undermine the necessary political momentum to implement ambitious policies.

Lever	**Evaluation**
Reduce the construction of new buildings	Unrealistic
Make new constructions energy-efficient	Substantial success achieved
Prevent paintjob renovations:	Crucial challenge
Speed up renovations:	Of questionable importance
Decarbonize heating systems:	Crucial challenge

Table 5: Evaluation of policy levers.

In order to contribute to the development of a political strategy for the transformation of the stock of buildings, we propose the following set of regulations for discussion. In doing so, we are well aware that policy-making in Switzerland's building sector is an incremental process, aiming to find pragmatic approaches. As we propose the following approach to long-term policy-making we are well aware that several difficult and crucial questions are currently neglected in this paper.

Regulation 1 *Until the the year 2050, zero- or low CO_2 emission heating technology has to be implemented in every residential multifamily building built before the year 2000.*

Regulating the emissions from the heating systems is much easier than regulating energy-efficient renovations, because in Switzerland there are laws agains air pollution, whereas the squandering of energy can not be directly regulated. Because the service life of a heating system is much shorter compared to the service life of a building, almost all heating systems should be expected to exceed their service life in the time until 2050. Because the emissions from heating systems are regulated, building owners remains free to select the mix of insulation and energy technology (insulation, windows, energy source, etc.) which is best suited to their building.

Implementing such a long-term policy would probably significantly alter the costs and quality of energy-efficient building designs. This is because actors in the construction industry would anticipate a very big market and develop technologies and business models, which implement low-emission heating and building designs at competitive prices.

We propose a command-and-control approach rather than a high tax on greenhouse gases because in rented apartments the tenant's pay the costs of heating, whereas the building owner invests in the heating system. Therefore, a tax on fossil fuels might not create the same pressure for action as mandatory regulations.

Regulation 2 *Until the year 2020 building owners have to submit a plan, which details how low-emission energy systems will be implemented in their building and how this is financed.*

This second regulation is to ensure that building owners think about the implementation of measures long before the actual deadline arises. The development of a long-term plan should allow building owners to plan investment decisions for their buildings. In addition, by planning a series of consecutive measures, inefficiencies from path-dependencies can be avoided. This would particularly benefit non-professional building owners, who currently often lack a coherent long-term strategy for their buildings. They rather decide step by step, frequently based on events. In addition, having a set of measures awaiting implementation potentially allows building owners to do construction during times of recessions when construction costs are relatively low.

7 Conclusions

In this paper, we pursued the question how the transformation process of Switzerland's stock of residential multifamily buildings to high levels of energy-efficiency and low levels of CO_2 would unfold under different scenarios. Using a small System Dynamics simulation model we were able to analyze how different policy packages impact on the behavior of the CO_2 emission rate of the stock of buildings. The added value of using a small model is that the main characteristics of the problem situation can be easily communicated to policy-makers and the general public. A limitation of relying on a small model, however, lies in the lack of detail.

We conclude that of the three scenarios analyzed, the energy-code scenario seems the most attractive. While in the mandatory scenario the transformation initially is much more pronounced, the negative social and economic implications it carries reduce its attractiveness. Hence, ensuring that all renovations implement energy-efficient housing designs should become a policy priority. This could be implemented by the two regulations we proposed or by other innovative policy measures, such as introducing operating licenses for buildings similar to motor vehicles.

The research presented in this article is the first result of a research project investigating the diffusion dynamics of energy-efficient renovations. Further publications will report on the causal mechanisms changing the shares of the three renovation strategies (paintjob, eeupgrading, reconstruction) over time and provide further intervention possibilities to accelerate the transformation of Switzerland's stock of buildings. Beyond the scope of our subject, we propose that the model of the stock of buildings presented here may be suitable towards the analysis of depreciation, maintenance and reinvestment of capital goods.

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B Documentation of the Model

The model described in this paper and the data used to run it is available upon request from Matthias Müller. Future versions will be available online. The model is implemented in Vensim. A current version of Vensim or the free model reader are available from `http://www.vensim.com`.

C Model Testing

[To be completed]