How can the Diffusion of Energy-Efficient Renovations be Accelerated? Policy Implications from a System Dynamics Modeling Study for Switzerland

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Abstract

We report on modeling work that shows how the market, technology, civil society and the state govern the diffusion of energy-efficient renovations in Switzerland's stock of residential, multifamily buildings. The particular focus of this article is on the policy implications that we drew from an extensive System Dynamics modeling study. We conclude that energy efficiency is important yet not sufficient in order to reach the goals of a 1-ton-CO_2-society by 2100. In addition to promoting energy efficiency, Switzerland should aim for a widespread decarbonization of heating systems. We discuss what kind of instruments can be used to address various intervention levers in order to accelerate the diffusion of energy-efficient renovations. We propose two regulations that could serve as a framework for ambitious long-term decarbonization efforts. Finally, we propose a service innovation that could assist building owners in complying with the ambitious regulations required.

Contents

1 Introduction

The building sector accounts for about a quarter of global energy-related greenhouse gas emissions and consequently it is a key lever in climate change mitigation efforts (Levine, Ürge-Vorsatz, Block, Geng, Harvey, Lang, Levermore, Mongamell, Mirasgedis, Novikova, Rilling & Yoshino 2007). Such emission reductions may come at a negative price in a substantial share of cases (Ürge-Vorsatz & Metz 2009). Particularly the renovation of old buildings is seen to be among the most cost-effective ways to reduce CO_2 emissions in industrialized countries (Galvin 2010). In the long run this calls for nothing less than a radical transformation of the built environment (Barrett 2009).

Buildings provide crucial services such as shelter, personal space or warmth. While these services are very important for the population in general, the technical aspects of energy use in buildings hardly ever draw the interest of the general population, as long as the services are available at reasonable cost. All in all, sustainability in the construction sector is probably just a minor element of the design, use, management and maintenance of the built environment (Lovell 2005). This lack of interest from the general public contrasts remarkably with the importance of the stock of buildings as a policy lever in the context of energy policy and climate policy.

In a recent study, we analyzed the diffusion of energy-efficient renovations in Switzerland's stock of residential, multifamily buildings (Ulli-Beer & Müller 2006, Müller & Ulli-Beer 2008*a*, Müller & Ulli-Beer 2008*b*, Müller & Ulli-Beer 2010, Müller submitted). Specifically, we built a System Dynamics model that explains how the market, technology, civil society and the state govern the diffusion of energy-efficient renovations and the CO_2 emissions of the stock of buildings. The resulting model allowed us to analyze the following research question: *How can the diffusion of energy-efficient renovations of buildings be accelerated in order to reduce the CO_2 emissions from the stock of buildings?*.

In this article, we aim to concisely present the most important results from that study. By doing so we hope to provide practically relevant insights for public policy. Beyond the narrow 'use value' of our research we hope to make several exemplary contributions to research in the spirit of ecological economics and sustainability science. For example, our study might be seen as an illustration as to how different fields of society (e.g. the market, technology, civil society and the state) are intertwined and involved in the creation and governance of environmental issues.

Before we indulge in the results, we must briefly describe how we proceeded methodologically. The research design[1] that we followed is best described as theory building with System Dynamics (Schwaninger & Grösser 2008, Schwaninger & Pifster 2007). In order to arrive at an empirically grounded simulation model, we followed a research design that relied on five distinct steps. The first step consisted of orienting ourselves in the field and clarifying the relevant research questions. Second, we conducted exploratory (N=7), systematic (N=14) and validating (N=7) interviews. While the interviewees were from heterogeneous backgrounds, most of them can be described as either academic researchers or practitioners (architects, representatives of building owners, representatives of construction companies). We recorded and transcribed the interviews and analyzed them using the MAXQDA software package. We were mostly interested in the information given by the interviewees and did not focus on meaning. Hence, we deemed content analysis (Flick 2005, 280) to be sufficiently rigorous and abstained from any analysis methods that strive for deeper analysis. As a third step, we developed several analytical perspectives. Specifically, we analyzed the context, we built a small simulation model of the stock of buildings (Müller & Ulli-Beer 2010), we analyzed actors and we developed an endogenous theory of the causal drivers of the diffusion of energy-efficient renovations. In a fourth step, we integrated insights obtained from the analytical perspectives into a quantitative simulation model, implemented in the VENSIM simulation environment. As a fifth step, we conducted policy analysis with the simulation model. These five steps were not followed in a strictly linear fashion. Instead, we iterated as we deemed fit. Further, throughout the research process, we conducted desktop research and we routinely tested and verified our results. In particular, model testing entailed evaluating the simulation model against many of the standard tests described in the literature (Barlas 1996, Sterman 2000, Schwaninger & Grösser 2009). Because behavioral data against which the model behavior could be tested against was mostly not available, we strongly relied on model structure tests and general tests such as model purpose test.

The remainder of this article is structured as follows. In section 2, we briefly describe the context within which the diffusion of energy-efficient renovations occurs. In particular, we propose to conceptualize that context as a societal problem situation. In section 3.1 we describe the main structure of causality that governs the diffusion process. Then, in section 3.2, we carry the analysis further by elaborating on the

[1]See Müller (submitted, chapter 2) for the complete documentation of the research design and the methods we used.

stocks and flows that yield undesirable dynamics in the stock of buildings. In section 4, we show key findings from the simulation model. In particular, we discuss the implications of our findings for public policy. In section 5, we propose policy measures that could be used to accelerate the diffusion of energy-efficient renovations, such that ambitious reduction goals can be met. Finally, in section 6, we offer some concluding remarks for policy-makers.

2 Analysis of the Context and Involved Actors

Analyzing the context within which the diffusion of energy-efficient renovations takes place helped us to determine the adequate boundary in our modeling efforts. Further, it provided us with an important opportunity to learn about the issue under study. On the most general level, we found that climate change and energy security concerns should be considered to be the most important drivers of the diffusion of energy-efficient renovations. In fact, the emergence of a distinct energy policy in Switzerland can be traced to the first oil crisis in 1973, when the country's strong dependence on energy imports became evident. Since then, promoting energy efficiency has been a crucial part of Switzerland's energy policy (Linder 1999; Jegen 2003). Scientists recognized anthropogenic climate change as a dangerous possibility as early as in 1977 (Weart 2008). However, the general public was much slower in recognizing it. Only over the last decade has climate change emerged as an influential environmental discourse. As this discourse became ubiquitous, it profoundly re-shaped the way energy policy was debated (Reddy & Assenza 2009). In fact, the emergence of a climate change discourse led to an additional problematization of the current energy use patterns (Jasanoff 2010). In consequence, the mitigation of greenhouse-gase emissions became an important element of policies on the environment and energy.

These two general drivers exert pressure on the stock of buildings and the various societal fields associated with it. Eventually, this has led to the creation of a societal problem situation that involves actors in the market, actors in civil society and the state. In the wake of the emergence of a societal problem situation, established practices are destabilized and change processes are put into motion. These change processes are typically highly unstructured, uncertain and rife with conflicts of interest among different actors.

We found that societal actors was particularly important in understanding the diffusion of energy-efficient renovations. This is because this diffusion process is not primarily driven by markets and prices. Instead, it is a diffusion process that is substantially driven by societal actors who want to influence public policy according to their interests. In particular, it was mostly societal actors (e.g., environmental pressure groups) who began to call for the transformation of the stock of buildings. These claims were generally intended as a contribution to the public good, undertaken with the intention of reducing energy security risks and avoiding the dangers of global climate change. Eventually, such environmental discourses and the prospects of strong state regulations cause other societal actors (e.g., industrial associations) to voice opposed views and participate in a competition for the publics' endorsement.

In the literature, the effect of such societal actors on the policy process has been described in the context of the advocacy coalition framework (Sabatier 2007, Weible, Sabatier & McQueen 2009). That framework has been used to understand the policy process, particularly policy change over long time periods, generally lasting a decade or longer. Several contributions empirically analyzed the effect of advocacy coalitions in various policy domains in Switzerland. For example in the domain of energy policy (Kriesi & Jegen 2000, Kriesi & Jegen 2001, Jegen 2003), climate policy (Lehmann & Rieder 2002, Ingold 2007, Ingold 2010) or environmental policy in general (Bornstein 2007). From that literature, we were able to confidently derive the existence of an advocacy coalition that generally demands further public policy interventions into the stock of buildings ("pro ecology") and an advocacy coalition that generally opposes further interventions ("pro growth").

While policy change in response to climate change and energy security concerns is an important element of the diffusion of energy-efficient renovations, developments in the market are important too. Once societal actors had influenced public policy to initiate and promote energy efficiency technology and low-emission energy systems, market-mechanisms come to play a stronger role in the diffusion of energy-efficient renovations. Based on a series of interviews, we identified building owners, architects and tenants to be the most important actors in the market. We found that construction companies hardly influence the decisions related to energy efficient renovations. Therefore, we did not model them explicitly. Based on our interviews, we proposed to further categorize building owners according to the amount of professional know-how they have. Building owners without professional know-how turned out to be an important target group for the service innovation we describe in section 5.3).

We found two particularly strong barriers to a low-emission stock of buildings. First, building owners implement energy-efficient renovations only if and only when they want to. There are no regulations forcing them to increase the energy efficiency of their building if they do not want to. Building owners, for example, may choose to do nothing at all or simply paint their façade instead of insulating it. Energetically relevant regulations only become relevant once substantial renovation is actually undertaken. Then, pre-defined levels of energy efficiency have to be achieved in the elements under renovation. The second barrier refers to the "investor-user dilemma." This occurs when a building owner carries the costs of an investment into energy efficiency and the tenant accrues the actual savings. In such a situation, the building owner has an incentive to invest into the level of energy efficiency which has the lowest investment cost, regardless of the actual profitability of that investment. As long as the tenant does not compensate the building owner in some form, even economically profitable investments may be prevented (OECD/IEA & AFD 2008, 36; Schleich 2009).

It is noteworthy that the level of technological maturity and the economics of energy-efficiency now no longer are substantial barriers. The last decade has brought about spectacular technological and economical progress in energy-efficient construction (Erhorn-Kluttig & Erhorn 2007). In fact, CEPE & HBT (2002, 314) recall that the rapid technological progress achieved over the last decades would have been called a super-efficient development in the early 1980ies. In the future, the potential for technological and economical breakthroughs is rather limited. Instead, incremental cost reductions, further improved performance and the integration of various technologies should be expected (IEA 2008, 183p.).

3 The Simulation Model

3.1 The Governance Structure Implemented in the Model

The structure of causality that governs the diffusion of energy-efficient renovations is best described by means of a causal loop diagram. Causal loop diagrams are useful for visually representing the structure of causality that was implemented into a quantitative simulation model. Given the high level of complexity and detail in simulation models, they are very valuable to communicate key elements of simulation models (Sterman 2000).

Figure 1 shows a causal loop diagram that contains the most important feedback loops that we implemented into the simulation model[2]. The diagram consists of variables that are linked with an arrow according to the direction of causality: A positive causal relationship (marked with a "+") is postulated to exist between the Number of NEE buildings and the Number of renovations implementing EE building designs. Both variables move in the same direction. An inverse causal relationship (marked with a "–") is postulated to exist between the Number of renovations implementing EE building designs and the Number of NEE buildings. When the Number of renovations implementing EE building designs rises then the Number of NEE buildings falls.

As can be seen, several interrelated feedback loops were conceived. Loop A shows how energy-efficient renovations transform the stock of buildings. In fact, this loop is a simplification of the building stock model sector described in the subsequent section 3.2. Loop B describes the demand for and loop C describes the supply of energy-efficient housing. Together, loops B and C represent the two sides of the housing market that control the stock of buildings. Loops D and E represent technological and economical progress. Due to learning effects, economies of scale and scope, energy-efficient building designs in renovations improve and become cheaper. Loop D shows that technological and economical progress makes energy-efficient building designs more attractive for building owners. Loop E shows that technological progress makes energy-efficient housing more attractive for tenants. Loop F shows how public policy reacts to the emergence of energy security concerns and climate change and supports research and development of technology. Loop G shows that the availability of adequate technology intensifies adaptive pressure on public policy. Consequently, public policy accelerates the diffusion of energy-efficient building designs by creating financial incentives (loop H). Eventually, public policy also tightens mandatory standards (loop I) and increases the cost of fossil fuels (loop J).

Together, these feedback loops provide an"endogenous point of view" (Richardson 2011) on the diffusion of energy-efficient renovations. In fact, this representation of the structure of causality may be considered as an interdisciplinary synthesis of var-

[2]Due to limitations in space, the following description is substantially abbreviated. A complete account of the feedback loop perspective is available in Müller (submitted, ch. 6).

ious individual pieces of empirical and theoretical research. However, causal loop diagrams have limitations. They are less detailed compared to actual simulation models and they can not be simulated by themselves (Sterman 2000).

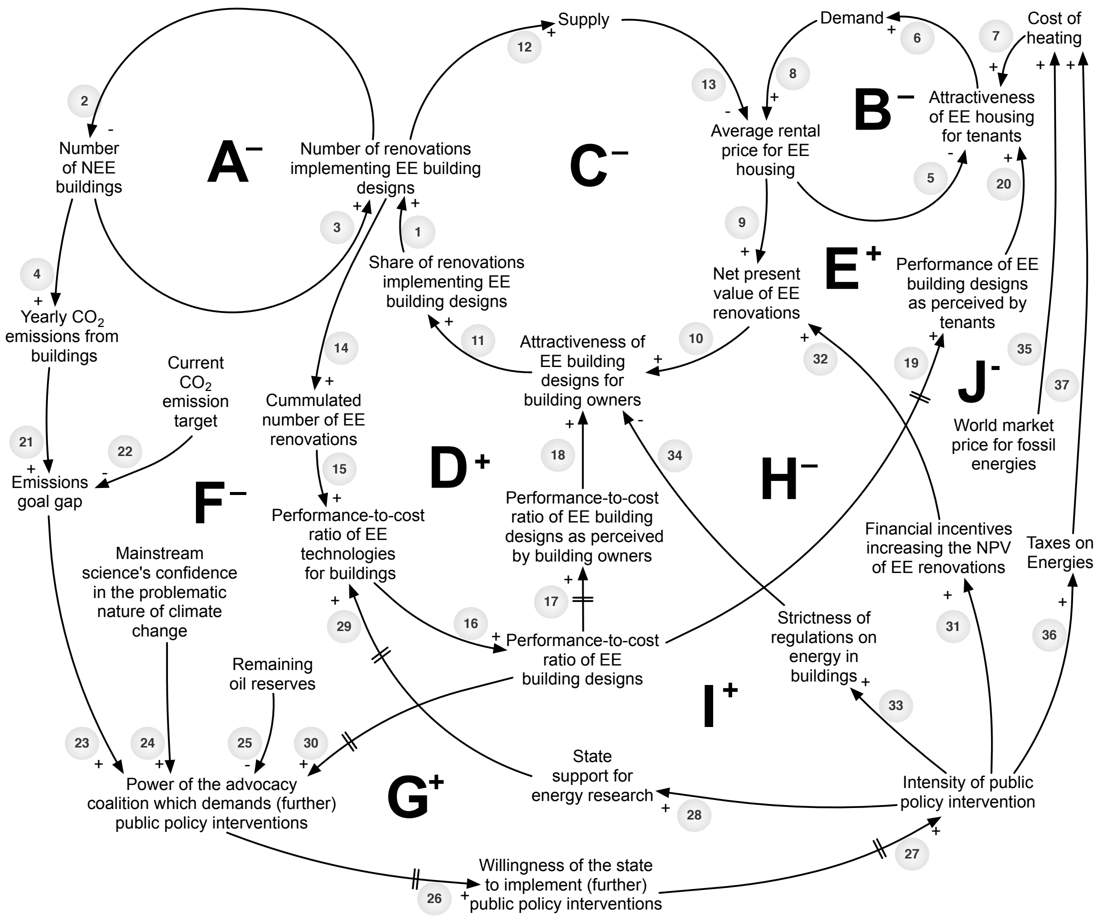

Figure 1: Causal loop diagram of the main structures of causality in the simulation model. Note that loop A represents the building stock model sector described below. Note that loops B to J govern the transformation of the stock of buildings by way of the variable SHARE OF RENOVATIONS IMPLEMENTING EE BUILDING DESIGNS.

3.2 Building Stock Model Sector

Figure 2 shows a stock-and-flow diagram of the building sector of our model[3] [4]. Stock-and-flow-diagrams are used to represent the structures of a system in close relation to the equations that are actually simulated.

We consider buildings to be either in a new condition, in a good condition or in a bad condition. Over time, as buildings age, new buildings become buildings in good condition and eventually they become buildings in bad condition. Only buildings in bad condition are renovated. We assume that it in average takes 55 years for a building to pass through all three stages and eventually be renovated. With the three stocks and the aging rates an aging chain was formed.

Buildings are further differentiated according to their energy efficiency into energy-efficient (ee) or non-energy-efficient (nee) buildings[5]. Nee buildings in bad condition can be renovated with one of the following three basic renovation strategies. When a PAINTJOB RENOVATION is implemented, then a nee building in bad condition becomes a nee building in good condition. The energy efficiency remains unaltered. When an EEUPGRADING is implemented, then a building is moved into the energy-efficient aging chain and is also seen to be in good condition. Buildings can be torn down and RECONSTRUCTED. In such a case, a building in new condition is built. Depending on the regulations at the time of building, the building is reconstructed as an nee or an ee building.

Crucial in this building stock model are the variables SHARE OF EEUPGRADINGS and SHARE OF PAINTJOB RENOVATIONS. They control what share of the buildings currently under renovations are renovated according to the corresponding renovation strategy. The number of buildings under renovation in any year is calculated by dividing the NEE BUILDINGS IN BAD CONDITION trough the YEARS NEE BUILDINGS IN BAD CONDITION ARE LEFT UNRENOVATED.

[3] In order to produce computer simulations, equations have to be specified in a computer simulation software such as VENSIM.

[4] Due to limitations in space, the following description is substantially abbreviated. A complete account of the building stock model sector is available in Müller & Ulli-Beer (2010) and Müller (submitted, ch. 4).

[5] Specifically, buildings are seen to be non-energy-efficient (nee) if the energy coefficient for heating is 193 MJ/m^{2}a or higher and they are considered to be energy-efficient (ee) if the energy coefficient for heating is below 193 MJ/m^{2}a. These values correspond to the Swiss Minergie label after 2003 and the mandatory governmental regulations after 2008 as defined by the Swiss conference of the cantonal energy directors (EDK 2008, 13).

By underlying the diagram shown in figure 2 with equations and parameters we were able to simulate the evolution of the stock of buildings over time. In addition to the building sector shown in figure 2, we relied on further model sectors to track energy coefficients, floor spaces and calculate CO_2 emissions. Further, we rely on a series of exogenous inputs to simulate the model. Specifically, we relied on past and projected data for the diffusion rates of oil and gas heating systems, the efficiency of heating systems, heated floor spaces and energy coefficients.

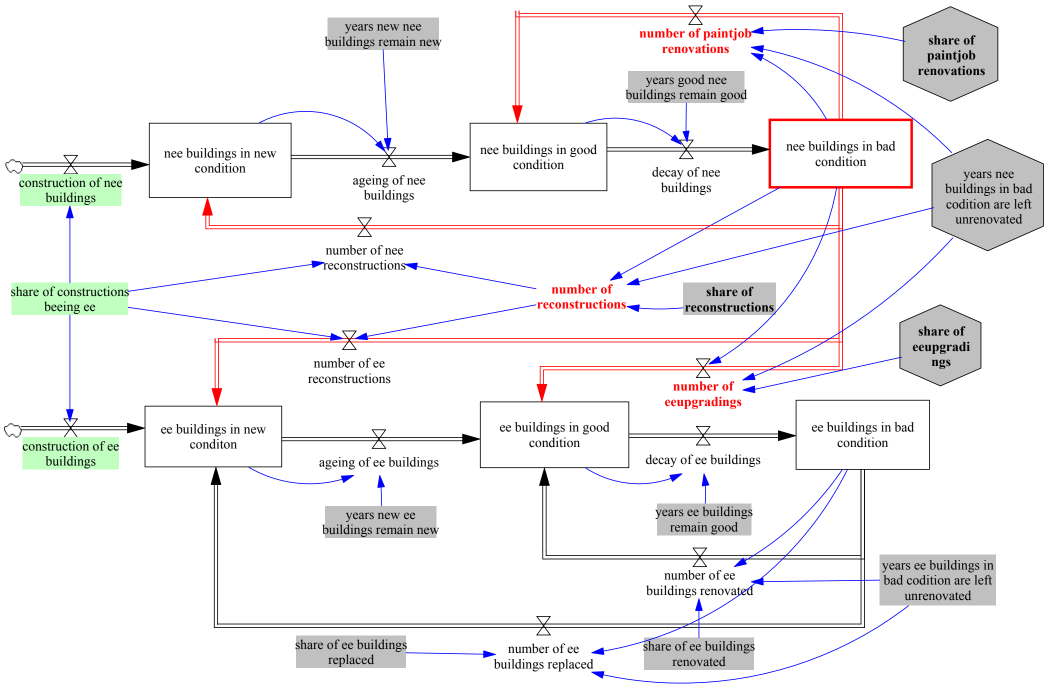

Figure 2: Stock-and-flow-diagram of the building sector.

4 Model Behavior

Single intervention levers We used the simulation model to analyze whether the manipulation of a single intervention lever could increase the TOTAL SHARE OF EEUPGRADINGS close to its maximum value of 0.95. As a first step, we identified potential intervention levers by reviewing the model. In particular, we looked for practically relevant intervention levers that could be addressed with policies and instruments. As a second step, we analyzed each intervention lever in a standardized manner. Specifically, we used VENSIM's STEP function to increase an intervention lever by 50% in the year 2010.[6] Then, we analyzed how the model behaved relative to the base scenario in the year 2020.

The analysis of individual intervention levers indicated that there is no single "silver bullet" that is capable of accelerating the diffusion of energy-efficient renovations such that the CO_2 emissions are reduced substantially faster compared to the base scenario. However, we identified a small number of particularly promising intervention levers. These are the following:

- Building owners' perception of the technological quality of energy-efficient building designs
- Building owners' preference for energy-efficient building designs
- Probability that architects promote energy-efficient building designs
- Tenants' perception of technological quality of energy-efficient building designs
- Tenants' utility from co-benefits of energy efficiency
- Pressure from fossil energy shortage
- Longterm minimum energy coefficient of construction (decreased by 50%)

Package of powerful intervention levers By conjointly increasing those intervention levers by 50% after the year 2010, we were able to increase the TOTAL SHARE OF EEUPGRADINGS near to unity (see exhibit on the left of figure 3). In reality, such an increase would constitute an enormous success for Switzerland's energy policy as well as for its environmental policy. The exhibit on the right of figure 3 shows the behavior of the CO_2 EMISSIONS in the base run (solid line) and after such a broad series of interventions (dotted line). In both scenarios there are substantial reductions of the CO_2 emissions over time. This shows that the CO_2 emissions can indeed be reduced in a substantial manner. The crucial question is whether the emission reductions obtained in our simulation runs are sufficient to achieve public policy goals.

[6] Because the model is highly inert, we decided to use the STEP function rather than the PULSE function. The PULSE function tends to produce weaker impacts. This is because after some time, the shock reverts to its original state. In contrast, the STEP function remains at a higher value for the rest of the time. Consequently, it produces stronger impacts. In addition, the model is affected by only one change, whereas the PULSE function shocks the model twice. One shock occurs when the PULSE function rises and the other occurs when it reverts to its initial stage.

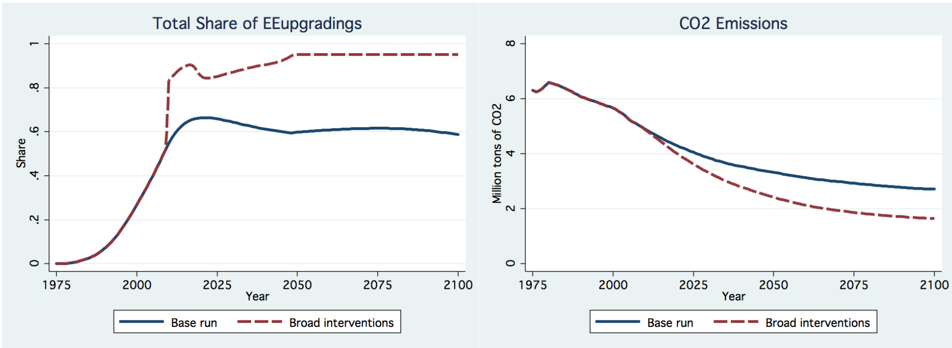

Figure 3: Behavior of the simulation model in the base run (straight line) and after implementing a broad series of interventions (dotted line).

In particular, it is important to understand to what degree the emission reductions observed in our model are consistent with the vision of a 1-ton-CO_2 society by 2100. According to that vision, the average Swiss resident should reach an emission rate of 2 tons CO_2 per capita in the year 2050 and an emission rate of 1 ton CO_2 per capita in the year 2100 (Novatlantis 2007). Unfortunately, comparing per-capita-emissions with findings in the literature proved difficult and not particularly conclusive. On the one hand, this is because of the narrow focus of our study on the floor space heating in multifamily buildings. On the other hand, this is due to different time horizons.

In order to compare our model results with results reported in the literature, we calculated the emission reductions in percent. Because various base years are used in the literature, we provide emission reductions in percent for both, the year 1990 as well as the year 2010. As figure 4 shows, in our most optimistic scenario the CO_2 emissions can be reduced by about 51% by 2050 and by about 66% by 2100. In the base scenario, emission reductions by about 32% by 2050 and by about 45% by 2100 were attained.

Note that the emission trajectories that we obtained should not be interpreted as precise results, but rather as rough quantifications. Our model was built to roughly quantify the effect of various interventions on the share of energy-efficient renovations and the CO_2 emission rate. Hence, it is crucial that our model of the building sector is not confused with highly detailed engineering-type models of the stock of buildings. Nevertheless, we find that it is rather unlikely that emission reductions obtained trough energy-efficient renovations alone would be sufficient to achieve the vision of a 1-ton-CO_2 society by 2100. This becomes apparent when we

Year	Base run			Broad interventions		
	Mio.t.p.a.	*Δ 1990*	*Δ 2010*	Mio.t.p.a.	*Δ 1990*	*Δ 2010*
1990	6.1			6.1		
2010	4.9	*-20%*		4.9	*-20%*	
2050	3.3	*-46%*	*-33%*	2.4	*-61%*	*-51%*
2100	2.7	*-56%*	*-45%*	1.6	*-74%*	*-67%*

Figure 4: Emissions and emission reductions in the "base run" and the "broad interventions" scenarios. Gives the emissions of the stock of buildings in the two scenarios in million tons of CO_2 per year (Mio.t.p.a.) and the emission reductions as percent changes relative to the years 1990 and 2010.

compare the emission reductions we obtained with emission reductions demanded in the literature.

- Siller, Kost & Imboden (2007), for example, argue that limiting global warming to 2°C would require greenhouse gas reductions of around 80% by 2050 (with 1990 as the base year). In their study of Switzerland's residential building sector, they find that such emission reductions can be achieved based on a very strong combination of energy efficiency and renewables.

- TEP & ETH (2009) provide a model of the whole stock of residential buildings in Switzerland and they consider space heating as well as warm water generation and appliances. They find that greenhouse-gases emissions (estimated at about 20 million tons of CO_2-equivalent) can be reduced by 28% to 65% by 2050, depending on what assumptions are made.

- Schulz (2007) finds that heating systems based on oil and gas fuels could be largely avoided, even if the heated floor area would rise by an estimated 40% until the year 2050. This could be achieved by relying on heat pumps and district heating based on combined heat-power generation (CHP) from natural gas and biomass. That would lower the CO_2 emissions of residential buildings by about 10 million tones, which corresponds about to 20% of Switzerland's current emissions (118).

Decarbonization of heating systems The emission reductions achieved in the 'broad interventions' scenario are not necessarily realistic projections. However, that scenario leads to the most ambitious emission reductions possible based on energy efficiency alone. This finding leads us to argue that further measures, in addition to energy efficiency, are needed. In particular, we call for a far-reaching decarbonization of Switzerland's stock of buildings.

In order to show how the decarbonization of Switzerland's heating systems would impact on the CO_2 emission rate, we conducted a further simulation. Specifically, we simulated the effect of a forced substitution process by multiplying the diffusion rates of oil and gas heating systems (see figure 8 in the appendix) with the Substitution Rate shown in the left hand exhibit in figure 5. The exhibit on the right hand in figure 5 shows the resulting CO_2 emissions. It becomes evident that the CO_2 emissions could indeed be reduced nearly to zero if an ambitious substitution program were implemented.

Our call for a far-reaching decarbonization of Switzerland's floor space heating systems is consistent with long-term emission reduction goals of the European Union. Recently, the European Union communicated long-term emission reduction goals in the contexts of its "roadmap for moving to a competitive low carbon economy in 2050" (EU 2011). For the residential and service sector the roadmap calls for CO_2 emission reductions around 90% by 2050 (relative to 1990 emission rates). While Switzerland is not member of the EU, EU policies do influence Switzerland's policy-making, as the country typically strives to roughly align with the EU.

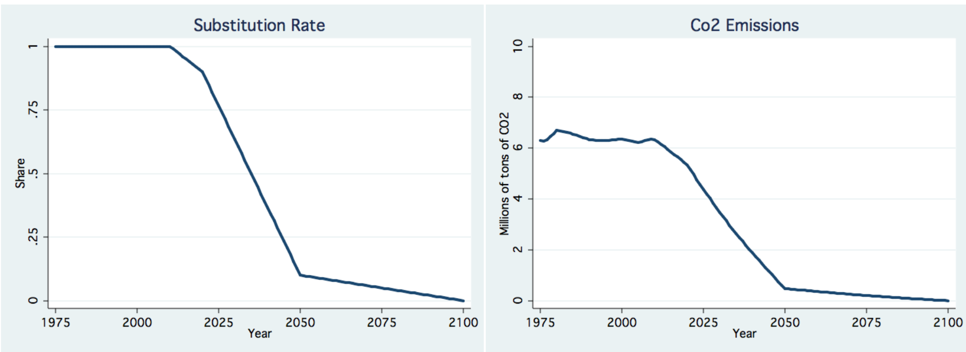

Figure 5: Gradual substitution of fossil heating systems until 2050. The exhibit on the left shows the assumed substitution rate. The exhibit on the right shows the resulting emission trajectory.

5 Policy Measures and Instruments

There is a wide range of possible interventions that public policy can pursue in order to contribute to the governance of the stock of buildings toward lower emissions. Table 1 contains major intervention levers that we identified in the building stock model sector and evaluates the potential of that lever. As can be seen, there are a series of intervention levers that have been used in the past and hence are no longer available to increase the intensity of intervention. In particular, the construction of additional nee buildings has been prevented by the gradual tightening of the building code and reductions in the energy coefficient demanded in the energy code (Jakob 2008). In contrast, limiting the construction of new buildings is not a realistic policy option as a growing population's demand for floor space is prioritized. In Müller (submitted), we showed that accelerating the renovation cycle by about 5 years does not impact the CO_2 emission rate in the long term and hence is of questionable importance. This is because the accelerated renovation of nee buildings in bad condition might reduce the supply of housing for low-income households and thus reduce the societal acceptance of public policies in the building sector. In contrast, we find that it is crucial that once renovations are conducted that they lead to highly energy-efficient buildings. Eventually, decarbonizing heating systems and increasing the share of energy-efficient renovations appear to be the two by far most powerful intervention levers.

Lever	Evaluation
Limit the construction of new buildings	Unrealistic
Make new constructions energy-efficient	Substantial success achieved
Increase share of eeupgradings	Crucial challenge
Speed up renovations	Of questionable importance
Decarbonize heating systems	Crucial challenge
Increase efficiency of heating systems	Substantial success achieved
Reduce the energy coefficient in the energy code	Substantial success achieved

Table 1: Evaluation of high-level policy levers.

5.1 Instruments for Intervention Levers

The evaluation of high-level policy levers presented above needs to be further substantiated. Hence, in this subsection we present a typology of instruments that can be used to influence important policy levers in a desirable direction. This typology draws on a review of policies and instruments described in Müller (submitted, ch.

3). Further, the typology draws on intervention levers that were identified in a review of the simulation model, as described in section 4. The resulting typology is of a conceptual nature. Nevertheless it could be used to analyze a country's policy related to buildings or for systematically searching for further interventions.

Types of interventions This list contains descriptions of instruments as well as actions that could influence an intervention lever.

- **Change institutional framework**. This refers to efforts by civil society actors and the state to change the institutional framework within which the diffusion of energy-efficient renovations occurs. By changing laws to be consistent with energy-efficient construction practices, energy-efficient building designs become part of the mainstream.
- **Continuous training** By offering chances for training, actors in the construction and real-estate sector can obtain the know-how required to implement energy-efficient building designs.
- **Energy counseling** This is a service, wherein an expert reviews built structures and user patterns and gives advice regarding how the energy demand may be reduced. Increasing the availability and accessibility of energy counseling services should improve the quality of decisions made by actors.
- **Emission regulations for heating systems** Emission regulations can refer to any regulation that sets emission limits for various gases. By regulating the emissions of heating systems, the application of current technology can be enforced and technological progress may be induced.
- **Establish standards** The establishment of standards, such as the Minergie standard, reduces information and transaction costs. For example, building owners might have to negotiate various technical details with architects prior to the Minergie standard. By referring to the Minergie standard, building owners can now easily demand an energy-efficient building design without having to discuss technical details.
- **Facilitate exchange among practitioners** By supporting the sharing of experiences among practitioners in the construction and real-estate sector, the diffusion of energy-efficient building designs and key technologies is accelerated.

- **Information campaigns** This refers to the communication of knowledge and the creation of awareness to a specific group. For example, Switzerland's federal office for energy distributes newsletters to all building owners. While information campaigns usually are an element of marketing campaigns, they generally do not entail the offering of products and services.

- **Labeling** Labels communicate and certify the existence of certain attributes of a product. They are particularly useful to communicate attributes that are difficult to observe.

- **Marketing campaigns** This is an endeavor to inform and convince potential customers of a product or service. By marketing energy-efficient building designs and selected components, such as ventilation systems, the chance is increased that potential customers become actual costumers.

- **Participate in the political process** Participation in the political process may be a highly effective intervention if the institutional framework can be shaped to support energy-efficient building designs.

- **Pilot and demonstration initiatives** Such initiatives allow us to learn from early applications and demonstrate key aspects of new technologies and building designs. By implementing pilot and demonstration initiatives, actors in the construction and real-estate sector can become acquainted with innovations. This, in turn, accelerates the diffusion process.

- **Relaxation of regulations** Several regulations restrict the economic profitability of construction projects. For example, there are regulations governing the maximum floor space that may be built on lots. Further, there are regulations that impose minimum distances between built structures and the borders of the lot. By slightly relaxing such regulations for energy-efficient renovations, the economic attractiveness of such renovations is increased.

- **Research and development initiatives** This includes the initialization and support of research and development that leads to better or more cost-effective technologies and processes.

- **Subsidies for energy efficiency** This entails the partial funding of investments into energy efficiency by actors other than the owners of such investments.

- **Subsidies for low-emission heating systems** This entails the partial funding of investments into low-emission heating systems by actors other than the owners of such investments.
- **Taxation of fossil-fuels** This entails the taxation of fossil-fuels. A tax on fossil-fuels is seen to lead individuals to use less fossil-fuels. Further, alternative heating systems may become more attractive.
- **Taxation of fossil heating systems** This entails the taxation of heating systems that use fossil-fuels. A tax on such heating systems would increase the attractiveness of alternative heating systems.
- **Word of mouth** Word of mouth refers to the attitudes and expectations that are communicated about a product or service among its potential or actual customers. For example, an architect owner may informally ask colleagues about their experiences with energy-efficient building designs. While the spreading of positive word of mouth might generally happen coincidentally, it could actually be an intervention that is at the disposal of actors in the construction and real-estate sectors.

Intervention levers Instruments from the general typology listed above can be used to address selected intervention levers. Tables 2 to 6 list the interventions levers to which such instruments can be applied. For each intervention lever (shown in the left column), we state what type of instrument might be used to influence it (shown in the right column). Further, for each type of instruments we state what kind of actor might be able to implement it (abbreviations in brackets).

Table 2 shows selected intervention levers related to the stock of buildings. Recall that I already provided a brief discussion of the most important levers related to the stock of buildings above (see table 1). Now, I complete that analysis by proposing types of instruments that can address those intervention levers.

Intervention Lever	**Interventions and actors that could implement them**
Energy-efficiency of heating systems	Continuous training (I, S), energy counseling (C, G, I), emission regulations for heating systems (G), establish standards (C, G, I, S), facilitate exchange among practitioners (C, G, I), information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (I), research and development initiatives (G, I, S), subsidies for energy efficiency (C, G), taxation of fossil-fuels (G).

Intervention Lever	Interventions and actors that could implement them
Diffusion of fossil-based heating systems	Change institutional framework (C, G, I), energy counseling (C, G, I), establish standards (C, G, I), information campaigns (C, G, I), marketing campaigns (I), Participate in the political process (C, G, I), relaxation of regulations (G), subsidies for low-emission heating systems (C, G), taxation of fossil-fuels (G), taxation of fossil heating systems (G).

Table 2: Interventions addressing the stock of buildings.
Abbreviations: B: building owners; C: civil society actors; G: governments of various levels; I: industry actors (such as construction companies and architects); S: scientists and actors from academia; T: tenants.

On the next page, table 3 shows interventions addressing building owners and table 4 shows interventions addressing tenants. On the page following that, table 5 shows interventions addressing technology and table 6 shows interventions addressing civil society.

Intervention Lever	Interventions and actors that could implement them
Building owners' perception of the technological quality of energy-efficient building designs	Information campaigns (G, I), pilot and demonstration initiatives (G, I, S), word of mouth (B, T).
Building owners' delay in the perception of technological quality	Information campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), word of mouth (B, T).
Financial attractiveness of eeupgradings for BOs	Relaxation of regulations (G), research and development initiatives (C, G, I), subsidies for energy efficiency (G), subsidies for low-emission heating systems (G), taxation of fossil-fuels (G), taxation of fossil heating systems (G), word of mouth (B, T).
Probability that architects promote energy-efficient building designs	Continuous training (C, G, I, S), establish standards (G, I), facilitate exchange among practitioners (C, G, I), information campaigns (C, G, I), marketing campaigns (C, G, I), relaxation of regulations (G).
Building owners' preference for energy-efficient building designs	Energy counseling (C, G, I), emission regulations for heating systems (G, I), establish standards (G, I), information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), relaxation of regulations (G), subsidies for energy efficiency (G), subsidies for low-emission heating systems (G), taxation of fossil-fuels (G), taxation of fossil heating systems (G), word of mouth (B, T).
Increasing the share of professional building owners	Implement "Immobility" cooperative society (C, G, I).

Intervention Lever	Interventions and actors that could implement them

Table 3: Interventions addressing building owners.
Abbreviations: B: building owners; C: civil society actors; G: governments of various levels; I: industry actors (such as construction companies and architects); S: scientists and actors from academia; T: tenants.

Intervention Lever	Interventions and actors that could implement them
Tenants' perception of technological quality of energy-efficient building designs	Information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), word of mouth (B, T).
Tenants' utility from co-benefits of energy efficiency	Information campaigns (C, G, I), labeling (C, G, I), marketing campaigns (C, G, I).

Table 4: Interventions addressing tenants.
Abbreviations: B: building owners; C: civil society actors; G: governments of various levels; I: industry actors (such as construction companies and architects); S: scientists and actors from academia; T: tenants.

Intervention Lever	Interventions and actors that could implement them
Effect of learning on construction costs of eeupgrading designs	Continuous training (C, G, I, S), facilitate exchange among practitioners (C, G, I), research and development initiatives (C, G, I).
Effect of stricter standards on construction costs	Facilitate exchange among practitioners (C, G, I), research and development initiatives (C, G, I), relaxation of regulations (G), subsidies for energy efficiency (G).
Architects' perception of technological quality of energy-efficient building designs	Continuous training (C, G, I, S), establish standards (G, I), marketing campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), research and development initiatives (C, G, I), word of mouth (B, T).

Table 5: Interventions addressing technology levers.
Abbreviations: B: building owners; C: civil society actors; G: governments of various levels; I: industry actors (such as construction companies and architects); S: scientists and actors from academia; T: tenants.

Intervention Lever	Interventions and actors that could implement them
Yearly emissions of CO_2 compatible with the 2 degree goal	Participate in the political process (B, C, I, S, T).
Pressure from fossil energy shortage	Marketing campaigns (C, G, I), participate in the political process (B, C, I, S, T), taxation of fossil-fuels (G), taxation of fossil heating systems (G).

Intervention Lever	Interventions and actors that could implement them
Perception of technological quality by civil society actors	Establish standards (G, I), information campaigns (C, G, I), pilot and demonstration initiatives (B, C, G, I), word of mouth (B, T).
Threshold value until which subsidies are given	Change institutional framework (G), participate in the political process (B, C, I, S, T).
Reductions of the legal energy coefficient	Change institutional framework (G), emission regulations for heating systems (G, I), establish standards (G, I), participate in the political process (B, C, I, S, T), research and development initiatives (C, G, I), subsidies for low-emission heating systems (G), taxation of fossil-fuels (G), taxation of fossil heating systems (G).

Table 6: Interventions addressing civil society levers.
Abbreviations: B: building owners; C: civil society actors; G: governments of various levels; I: industry actors (such as construction companies and architects); S: scientists and actors from academia; T: tenants.

5.2 Two Regulations in Support of the Decarbonization of Switzerland's Stock of Buildings

In the following, we discuss how a far-reaching decarbonization of Switzerland's heating systems could be achieved. In particular, we propose two regulations for discussion. In doing so, we are very well aware that several questions regarding political approval and practical implementation will remain open. Note that we propose these regulations as a complementary framework within which current efficiency-oriented energy policies would remain effective. We do not propose to replace current energy policies with the two regulations.

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

Regulating the emissions from heating systems should prove much easier than mandating energy-efficient renovations. 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 have exceeded their service life by 2050. With this regulation, fossil-based CO_2 emissions from heating systems would be banned. However, building owners would remain free to select the mix of insulation technology (façade insulation, efficient windows, etc.) and emission free heating system that is best suited to their situation. The reason why we propose a command-and-control-type approach rather than market-based instruments (Kaufmann-Hayoz et al. (2001)) such as a high tax on greenhouse-gases is the prevalence of the investor-user dilemma (see above in section 2). Hence, we argue that a tax on fossil CO_2 emissions might not prove an effective signal to the owners of rented buildings. However, as a complement, an environmental tax on fossil-fuels could support the transformation of the stock of buildings and it might encourage renovations in owner-occupied buildings. This particularly holds when the earnings of the environmental tax are used to subsidize renovations.

If it is possible to create the strong expectation that in the next 40 years the stock of buildings will indeed be transformed to a situation of low or zero emission, then entrepreneurs and companies can expect a large future market. This should lead to the development of technologies and business models that become increasingly better and cheaper. Therefore, we expect the implementation of such a long-term policy to alter the costs and the quality of energy-efficient building designs beyond current practices. This is because actors in the construction industry would anticipate a big market and develop technologies and business models that implement low-emission heating and building designs at competitive prices, thus unlocking the innovativeness of entrepreneurs.

Regulation 2: Until the year 2020 building owners have to submit a roadmap that details how low-emission energy systems will be implemented in their building and how they intend to finance their road to a zero-emission building.

The purpose of this second regulation is to encourage building owners to consider the implementation of decarbonized building designs long before the actual deadline arises. The development of a long–term plan should allow building owners to plan and coordinate investment decisions for their buildings. By planning a series of consecutive measures, inefficiencies should be substantially reduced. For example, a lack of coordination and long term planning might lead a building owner to first exchange windows and heating systems and only several years later to insulate the façade. Yet in order to insulate, the windows have to be unmounted and repositioned, so it would have been cheaper to replace the windows during insulation. And after insulation, the heating system might be over-dimensioned for a now efficient building. Thus, a smaller and cheaper heating system could have been bought after insulation.

Generally, such a regulation would particularly benefit non-professional building owners, who often lack a coherent long-term strategy for their buildings and are more likely to suffer from such inefficiencies. They rather decide in a step-by-step fashion, frequently based on events in their personal lives. A further benefit of having a set of measures awaiting implementation is that it could encourage building owners to order construction during times of recession, when prices for construction are relatively low.

This proposal is complementary to current energy policies because it explicitly states a long-term goal and a date for achieving it without prescribing how building owners achieve these goals. Its temporal specification is such that building owners, construction companies, and technology developers would have enough time to adapt. The two regulations could nevertheless achieve a very ambitious policy goal; namely, the far-reaching decarbonization of the stock of buildings by the year 2050. This is a crucial difference to current policies addressing emissions by buildings. Implementation of the two regulations presented here would basically guarantee a far-reaching decarbonization of Switzerland's stock of buildings. In addition, these two regulations might prove effective in other northern, industrialized countries .

Of course, implementation of these regulations would require careful further analysis. Issues such as the conservation of heritage buildings or the question as to how non-complying building owners would be sanctioned pose special difficulties. Also, current energy and climate policy regulations as well as building standards would need to be scrutinized regarding their consistency in terms of these regulations.

5.3 A Business Model in Support of Non-Professional Building Owners

Implementing near-zero-emission building designs in renovations, as implied by the two regulations introduced above, would increase the challenge of renovating. In such a situation, non-professional building owners should be considered to be a potentially relevant bottleneck, as they hardly have any chance to accumulate experience. In order to overcome this bottleneck, we propose to develop and actually implement a business model that solves several of the challenges that non-professional building owners face. By doing so, the transformation of Switzerland's stock of buildings toward low-emission, and perhaps even more generally toward sustainable housing, could be accelerated. The cooperative society that we propose may then work as a catalyst.

Specifically, the cooperative society would assist building owners in dealing with various technical, financial, and procedural complexities associated with renovations. The goal of its operation should be that the outcome of the renovation is adequate for the specific building in its specific situation; technically well built and cost-effective. Such a business model probably would need to address the following issues:

- **Long-term planning** The various elements of a building have different service lives and they should be replaced with consideration of possible path dependencies. Else, renovations may become overly expensive and ineffective. Long-term planning could avoid the risks of path dependency in sequential renovations. What is more, the business model should assist building owners in long-term financial planning for renovations.

- **Value creation** Buildings should be renovated in a way that maximizes the utility that tenants draw from it. This means that planning should raise the rent potential, reduce the risk sof vacancy, and eventually increase the value of the building. Further, the business model should ensure that social and environmental values are considered adequately.

- **Assistance with technology choice** For most building owners, searching for technical information is a time-consuming and therefore costly process. Further, a substantial share of information on technical systems comes from the producers themselves. Hence, such information is not necessarily neutral or adequate. In order to respond to this, the business model should provide neutral and up-to-date information on current technologies and cost.

- **Assistance with financial matters** The business model should assist building owners with organizing finance if sufficient reserves have not yet been and can-not be accumulated before the renovation. This entails advising building owners on what subsidies to apply for and how to optimize taxes. Further, by bundling the demand of several building owners, it may be possible to negotiate discounts.

- **Reduction of complexity** Building owners should not have to deal with several companies. Instead, the business model should coordinate among the companies involved and act as the single representative toward building owners, so that they can concentrate on the important decisions.

- **Managed care for buildings** As an important aspect, the business model should provide managed care (or comissioning, Mills, 2011) for buildings. This means that buildings should be evaluated at regular intervals in order to find optimization potential in the domains of energy and occupational health. Such a service would encourage long-term relationships with building owners. As a part of commissioning efforts, tenants should be taught as to how to use the technologies in their building in an optimal manner.
- **Strategic focus** The business model should not provide generic solutions for each type of building. Instead, the focus should be on buildings of frequent types. Its strategic focus should be on high volume of relatively similar buildings and cost reductions through economies of scale and scope and learning effects.

In order to be perceived as credible, the cooperative society should seek endorsement from other actors, such as the federal office of energy or the Minergie Association.

The business model we outlined above is probably best implemented by a cooperative society. In Switzerland, cooperative societies have a long history of providing a wide range of important services. Cooperative societies can potentially be very cost-effective. In fact, Kissling (2008, 93) argues that cooperative societies have been successful because they favor long-term success over short-term success. Further, they have a track record of contributing social and cultural values (Kissling 2008, 93).

Obviously, the idea outlined in this section needs to be further substantiated if an implementation should be attempted. Several issues would need to be considered in collaboration with experts in the construction sector and marketing practitioners[7].

6 Conclusions

In this article, we described a recent System Dynamics modeling study of the diffusion-dynamics of energy-efficient renovations in Switzerland's stock of residential, multifamily buildings. Based on a brief description of the context within

[7]We are grateful to Mark Zimmerman who communicated several issues by Email on September 21, 2011.

which the diffusion process unfolds, we presented an explanation of the structure of causality that drives the diffusion process. We described the model sector representing the stock of buildings and reported selected results from policy analysis efforts. Eventually, we proposed policy measures and instruments that we think could accelerate the transformation of the stock of buildings.

Moving beyond the specific policy measures and instruments that we elaborated in the preceding section, we deem the following insights particularly relevant for policy-makers:

- The diffusion of energy-efficient renovations as well as calls for the transformation of the whole energy sector towards greater sustainability are substantially caused and partially governed by external developments of a global scale.
- Because of the long service life of buildings, the stock of buildings is highly inert. We think that the inertia of the stock of buildings needs to be fully acknowledged. Ambitious climate and energy policy interventions into the stock of buildings are long term policy challenges (Sprinz 2008) and need to be thought about in decades rather than years.
- The emission trajectories shown in figure 3 should be interpreted as rough quantifications and not as precise prognosis. A key insight of our modeling work is that as the share of renovations that implement energy-efficient building designs rises, the CO_2 emission trajectory is shifted downwards. This relationship holds even when there is uncertainty regarding the precise current CO_2 emission rate.
- Unfortunately, it seems that the goals of the 1-ton-CO_2-society are rather not reached based on energy efficiency alone. This holds even in the scenario where we assume that after 2015 almost every building under renovation implements energy-efficient building designs.
- A logical conclusion from our findings is that widespread decarbonization should complement Switzerland's energy efficiency-oriented policies. In line with other authors (Herring 2009, Barrett 2009), we argue that the primary goal of public policy addressing energy in the built environment should be to reduce carbon emissions rather than the use of energy. This entails that the sustainable provision of services of buildings rather than buildings by themselves, should be the objective of policies.

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A Data Inputs and Key Parameter

A.1 Calibration of Building Sector

Parameter	Value
Years new nee buildings remain new	10
Years good nee 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 7: Various parameters used for the calibration of the building sector.

A.2 Heated Floor Area of Residential Multifamily Buildings

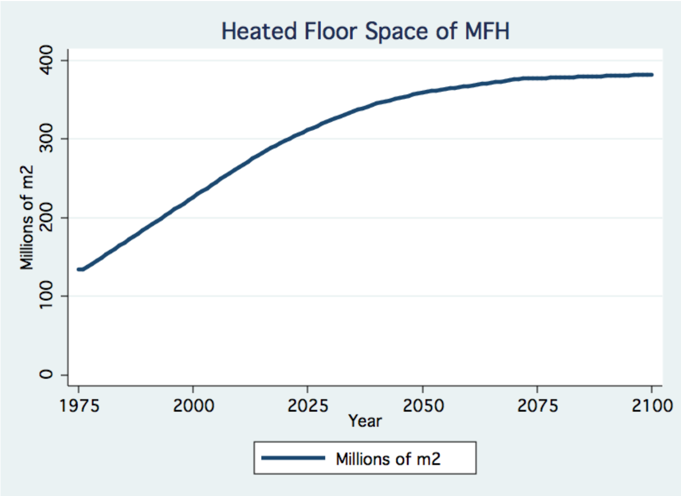

Figure 6: Heated floor area of residential multifamily buildings 1975-2100. Datapoints for the years 2005 until 2050 are available in five-year intervals from TEP & ETH (2009, 26). Theoretically, datapoints for the years 1990 until 2003 are available from BFE (2004). However, the floor space for multifamily 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.

A.3 Energy Coefficient of New Constructions

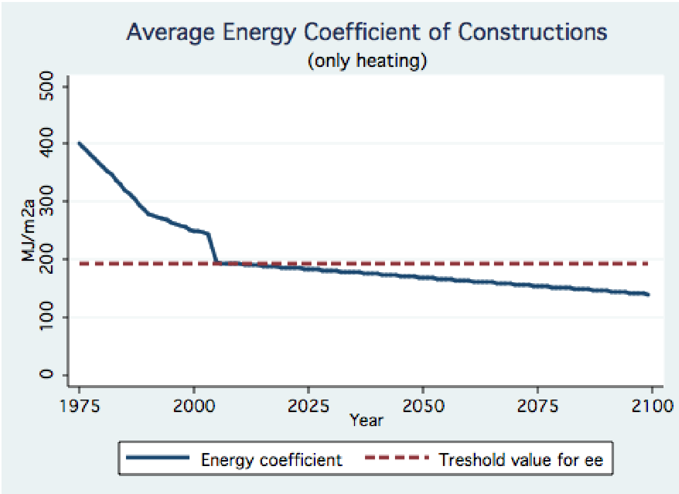

Figure 7: Past empirical and projected average energy coefficient of new constructions as used in the model. Datapoints for the years 1991, 2000 and 2003 were taken from Hofer (2007, 26). Datapoints for the years 2005, 2035 and 2050 were taken from TEP & ETH (2009, 29). Datapoints for the year 1980 were taken from Jakob (2008, 34). Datapoints for the years 1975 and 2100 are own assumptions based on the other datapoints.

A.4 Distribution of the Initial Total Number of Buildings over the Three Building Quality States

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

Table 8: Distribution of the total number of buildings over the three building quality states. Note that in the year 1975 only nee buildings existed.

A.5 Diffusion Rates of Heating Systems

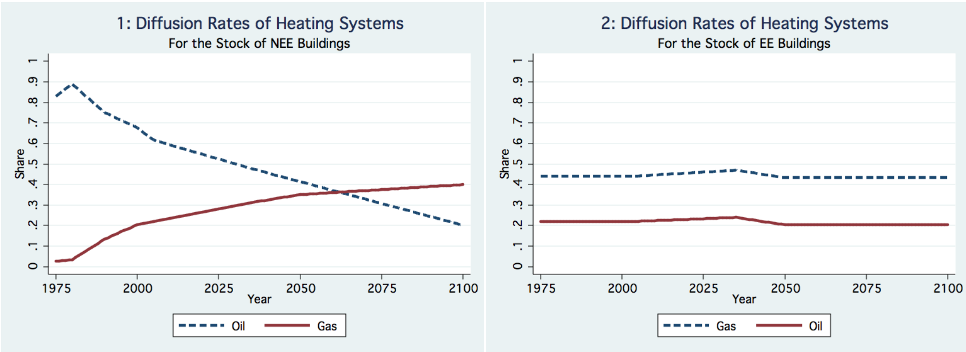

Figure 8: Diffusion rates of heating systems. Source: TEP & ETH (2009).

A.6 Efficiency of Heating Systems

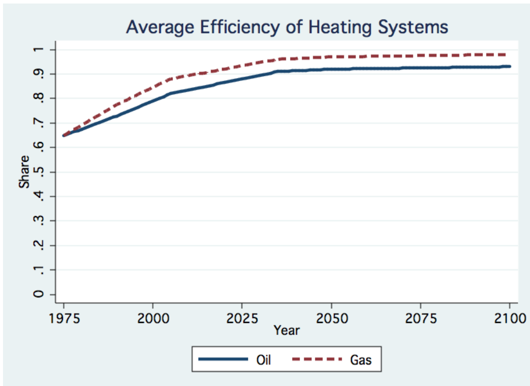

Figure 9: Efficiency of heating systems. Source: TEP & ETH (2009).