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Endogenous energy efficiency improvements in large-scale retrofits to Swiss residential building stock

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Abstract.

In standard analyses of Swiss energy and climate policies, the speed and extent of energy efficiency improvements (EEI) are usually assumed to be unaffected, even by policies designed to foster innovation. This project introduces endogenous EEI and barriers to retrofitting in the housing sector. In order to achieve this, we explain how Swiss building stock has evolved and how retrofitting decisions and heating system improvements may reduce energy consumption. We use a two-step model to illustrate how homeowners take decisions about retrofitting, then we consider several scenarios. Our results showed that in order to achieve deep decarbonisation in the building sector, a number of different economic instruments need to be used simultaneously.

Keywords: Building stock model, Switzerland, residential, hybrid modeling, top-down and bottom-up models.

1. Introduction

According to the Swiss Federal Office of Energy (SFOE) around 50% of primary energy consumption in Switzerland is attributable to buildings: 30% for heating, air-conditioning, and hot water, 14% for electricity, and around 6% for construction and maintenance. Improving energy efficiency is widely considered to be the most important means of transforming the Swiss national energy system on an ongoing basis. The gradual decarbonisation of the housing sector in Switzerland will be a notable feature of the new energy system.

The purpose of this paper is to endogenize energy efficiency improvements and also to introduce barriers to retrofitting in the housing sector. With this aim in mind, we divide Swiss housing stock into energy classes and construction periods. The distribution of building stock varies in accordance with a transition matrix, which is based on the costs and benefits of retrofitting. In order to obtain genuine results and in a later stage incorporate the effects of barriers, we use a two-step model. The property owner first decides whether or not to carry out an energy audit. Then he decides whether or not to go ahead with retrofitting.

2. Description of the model

Housing stock is grouped into seven energy classes (EC) that comply with the Cantonal Energy Certificate for Buildings classification system. Each energy class has a fixed specific space heating demand (SHD) expressed in kWh per square metre (kWh/m^2) and energy classes are ranked using the following expression:



$$SHD_A < SHD_B < \dots < SHD_F < SHD_G \tag{1}$$

2.1. Energy reference area

The quantity of housing is measured by the total energy reference area (*ERA*) in square metres i.e. the total heated surface. The energy reference area is represented by a three-dimensional matrix and is divided into energy classes (*EC*), construction periods (*CP*) and property owner types (*H*). The total energy reference area for each construction period and energy class for Switzerland in 2015 is illustrated in Figure 1.

The energy reference area changes from one period to the next because of a some housing is demolished (*DR*), there will be an element of new construction (*NC*) and some housing will change class as a result of retrofitting, calculated using a retrofit matrix (*RM*). Eq.(2) describes the law of motion for the energy reference area.

$$ERA_{EC}^{CP,H,t+1} = (1 - DR^{CP,t}) \cdot ERA_{EC}^{CP,H,t} + NC_{EC}^{CP,H,t} - \sum_A^{EC' < EC} RM_{EC,EC'}^{CP,H,t} + \sum_{EC' > EC}^G RM_{EC',EC}^{CP,H,t} \tag{2}$$

2.2. The decision of retrofit

We use a two-step model to describe how property owners decide whether or not to retrofit:

- Step 1: Probability of trigger event
In the first step, a trigger event causes the house owner to have the initial idea (e.g. by receiving a letter from the council, having a conversation with their partner) and commissions energy audit.
- Step 2: Retrofit decision
Depending on the result of the energy audit, they decide whether or not to proceed with retrofitting.

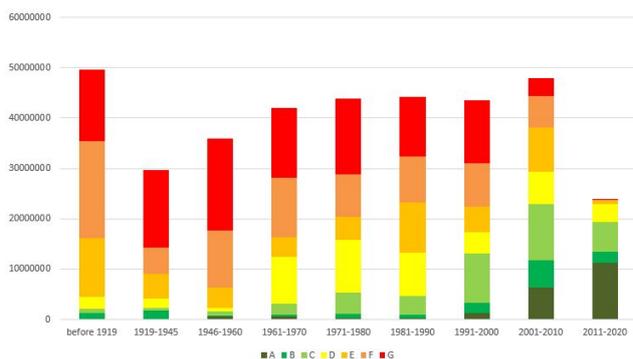


Figure 1. Energy reference area in m² per construction period and energy class in 2015 (source: our estimates, using data from SFOE).

The probability of carrying out an energy audit (Π) is represented by Eq. (3). The house takes the decision based on the buildings current energy class, costs and their awareness level (or "Information level"). It is more likely than an audit will be carried out if the buildings energy class is decreasing. The impact of energy prices on this probability is represented by an (Θ) elasticity function of the energy price change with respect to a reference price (\overline{PEC}). Finally, the probability also increases as a function of the information level ($Inf: \{1; 2; 3; 4\}$). For example, if the information level is equal to '4', this might be as a result of a large-scale information campaign.

$$\Pi_{EC}^{CP,t} = \Delta_{EC}^{CP} \cdot \left(1 + \Theta_{EC}^{CP,t} \cdot \log \left(\frac{PEC_{EC}^{CP,t}}{PEC_{EC}^{CP}} \right) \right) \cdot \mu \cdot Inf \quad (3)$$

In the second step, the indicator variable (Ω) is represented by Eq. (5). This decision is based on retrofit gain (RG), which has to be positive and as high as possible for all energy classes. We also defined four different property owner types (H) with different discount rates. We can calculate the percentage of buildings that are retrofitted, taking into account discount rates for each group r^H : {3%; 4%; 5%; 6%}.

Retrofit gain is shown in Eq. (4), where (PEC) is an energy price per energy class, (ψ_t) is a fixed retrofit cost, ($\tau_{RC,t}$) is technical retrofit progress (exogenous parameter), ($\tau_{EC,EC'}^{CP,t}$) is a retrofit subsidy and (PI) is the price of investment.

$$RG_{EC,EC'}^{CP,H,t} = \sum_{t'=t}^{t+T^R} \frac{SHD_{EC}^{t'} \cdot PEC_{EC}^{CP,t'} - SHD_{EC'}^{t'} \cdot PEC_{EC'}^{CP,t'}}{(1+r^H)^{t'-t}} - \frac{RC_{EC,EC'}^{RC,t} + \psi_t}{\tau_{RC,t}} \cdot (1 - \tau_{EC,EC'}^{CP,t}) \cdot PI_t \quad (4)$$

$$\Omega_{EC,EC'}^{H,t} = 1 \text{ if } \begin{cases} RG_{EC,EC'}^{H,t} > 0 & \text{and} \\ RG_{EC,EC'}^{H,t} > RG_{EC,\overline{EC}}^{H,t} & \forall EC' < EC \end{cases} ; 0 \text{ otherwise} \quad (5)$$

We achieve retrofit from EC to EC' if:

- (i) the economic gain from EC to EC' is positive.
- (ii) the retrofit gain is higher than any other retrofit, based on EC .

2.2.1. Retrofit matrix Transitions between classes are represented by a retrofit matrix (RM) (see Eq. (6)). The (RM) is calculated by multiplying the probability of carrying out the audit by the indicator variable and by the energy reference area.

$$RM_{EC,EC'}^{CP,H,t} = \Pi_{EC}^{CP,t} \cdot \Omega_{EC,EC'}^{H,t} \cdot ERA_{EC}^{CP,H,t} \quad (6)$$

3. Simulation Results

3.1. Reference scenario

Figure 2 shows the evolution of the energy reference area per energy class driven by new construction and refurbishment decisions.

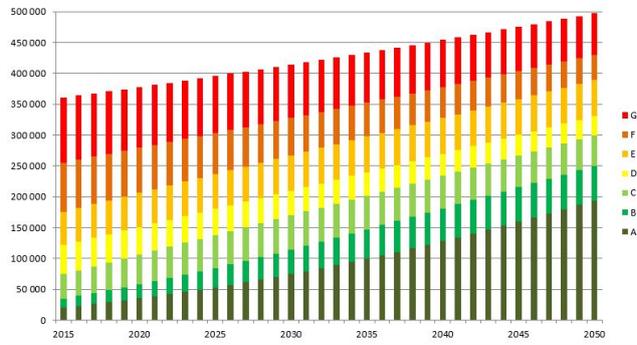


Figure 2. Energy reference area in m^2 - Reference scenario.

Retrofit decisions are shown in Figure 3. Buildings are mainly retrofitted in energy class A and to a lesser extent in class E. The retrofitted energy classes are G, F, D, C and B. As can be seen in Figure 2 the surface of energy class E increasing slightly.

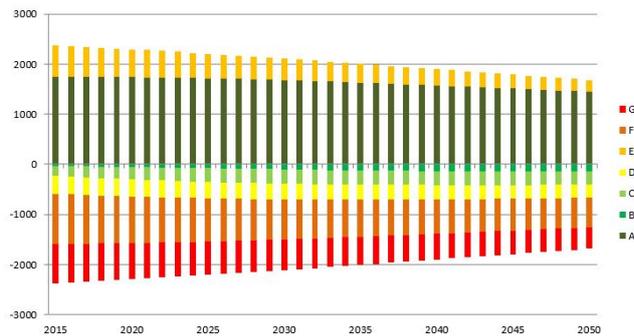


Figure 3. Retrofit in m^2 - Reference scenario (negative numbers are buildings that are subtracted, positive numbers are buildings that are added to an energy class).

3.2. Information level scenarios

In the reference scenario, the information level (Inf) is equal to 1. In this section we consider several scenarios where we increase this information level. Table 1 shows the impact of these scenarios on a selected number of indicators. With an information level of 4, the average energy consumption is as high as 39 kWh per m^2 and CO_2 emissions decrease by 56% compared to 2015 levels. In 2050, energy class A represents 58% of Swiss building stock, but there are still some very inefficient buildings. Indeed, buildings in categories E to G account for 25% of Swiss building stock.

Table 1. Information level scenarios

Information level	Ref=1	2	3	4
Average retrofit rate as a %	0.6%	1.0%	1.3%	1.5%
Average energy consumption in 2050 in kWh/ m^2	54	47	43	39
Change in CO_2 emissions compared to 2015	-36%	-46%	-52%	-56%
Share of energy classes in 2050				
A	39%	47%	53%	58%
B	11%	11%	10%	9%
C	10%	8%	7%	6%
D	6%	5%	4%	3%
E	12%	13%	13%	13%
F	8%	5%	3%	2%
G	14%	11%	10%	10%

3.3. Retrofit subsidy

In this scenario, we assume that the government offers a subsidy on the retrofit cost for energy classes G and F (i.e. $\tau_{EC,G}^{CP,t}$ and $\tau_{EC,F}^{CP,t}$) and we consider several scenarios with a subsidy rate ranging from 10% to 40%, with results shown in 2. While the subsidy increases retrofitting in energy class G, it does not affect refurbishment decisions in energy class F, where the share remains unchanged across the different scenarios. It is worth noting that when the subsidy rate is higher than 20%, no further retrofitting takes place (i.e. the share of energy class G remains the same in 2050), but this does affect the energy class in which retrofitting takes place (i.e. the share of energy class A rises and the share of energy class E falls). Let us now assume that the subsidy is implemented in a different way: the government decides to subsidise retrofitting of buildings from any energy class to the highest energy class, A (i.e. $\tau_{A,EC}^{CP,t}$). These scenarios are illustrated in 3. By definition, only the share of energy class A will increase in such a scenario. We observe similar results when subsidies are offered for energy classes F and G, although this also affects energy class E where its share decreases.

3.4. Tax on fossil energy scenarios

In this set of scenarios, we assume that the government puts a tax on fossil energy ranging from 10% to 50% (see Table 4).

Table 2. Subsidy rate scenarios for energy classes F and G

	Ref	10%	20%	30%	40%
Average retrofit rate as a %	0.6%	0.6%	0.7%	0.7%	0.7%
Average energy consumption in 2050 in kWh/m ²	54	51	49	48	46
Change in CO ₂ emissions compared to 2015	-36%	-41%	-45%	-47%	-49%
Share of energy classes in 2050					
A	39%	39%	42%	45%	47%
B	11%	14%	12%	11%	11%
C	10%	10%	10%	10%	10%
D	6%	6%	6%	6%	6%
E	12%	11%	11%	10%	8%
F	8%	8%	8%	8%	8%
G	14%	12%	10%	10%	10%

Table 3. Subsidy rate scenarios in retrofit done in energy class A

	Ref	10%	20%	30%	40%
Average retrofit rate as a %	0.6%	0.6%	0.6%	0.7%	0.7%
Average energy consumption in 2050 in kWh/m ²	54	53	50	47	45
Change in CO ₂ emissions compared to 2015	-36%	-37%	-41%	-47%	-51%
Share of energy classes in 2050					
A	39%	40%	43%	46%	48%
B	11%	11%	11%	11%	11%
C	10%	10%	10%	10%	10%
D	6%	6%	6%	6%	6%
E	12%	11%	7%	6%	6%
F	8%	8%	8%	8%	8%
G	14%	14%	14%	12%	10%

Table 4. Tax on fossil energy scenarios

	Ref	10%	20%	30%	40%	50%
Average energy consumption in 2050 in kWh/m ²	54	54	53	53	53	53
Change in CO ₂ emissions compared to 2015	-36%	-37%	-37%	-38%	-38%	-39%
Share of energy classes in 2050						
A	39%	39%	39%	40%	40%	40%
B	11%	11%	11%	11%	11%	11%
C	10%	10%	10%	10%	10%	10%
D	6%	6%	6%	6%	6%	6%
E	12%	12%	12%	12%	12%	12%
F	8%	8%	8%	8%	8%	8%
G	14%	13%	13%	13%	13%	13%

3.5. Combining economic instruments

We consider a scenario where all economic instruments are combined: the information level is equal to 4, ($\tau_{A,EC}^{C,P,t}$) equals 0.4 and the fossil fuel tax is 50%. Figure 4 illustrates the impact on the energy reference area per energy class. Energy classes A and B represent 77% and 9% of Swiss building stock respectively. Classes G and F represent only 1% and 2% respectively.

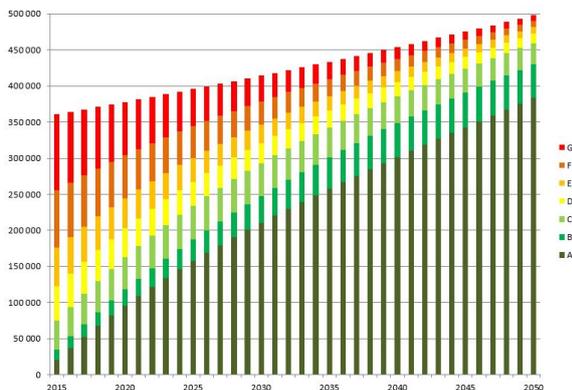


Figure 4. Energy reference area in m² - all economic instruments.

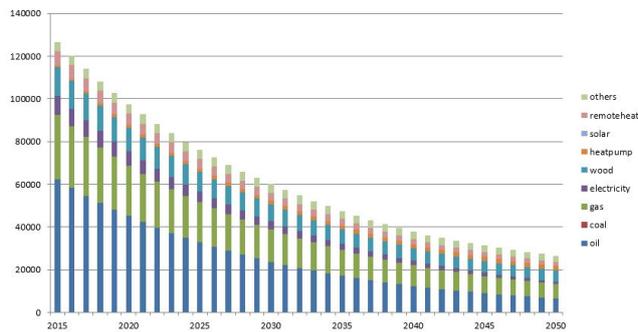


Figure 5. Energy consumption by energy carriers in TJ - all economic instruments.

4. Conclusion

In subsidy on retrofit scenario CO_2 emissions, the subsidy succeeds to increase significantly the CO_2 abatement, but again we find that the marginal CO_2 abatement is decreasing with the subsidy rate. In tax on fossil energy scenarios, the impact is rather limited in comparison to other economic instruments and does not impact significantly the retrofit decision. When combining all economic instruments the average retrofit rate is equal to 1.9%. In 2050, the average energy consumption reaches 21 kWh per square meter and CO_2 emissions decrease by 86%.

In the reference scenario the average retrofit share is equal to 0.6% across the whole period. The average heating consumption in kWh/m^2 will decrease from 92 kWh to 53 kWh in 2050. CO_2 emissions decrease by 36% between 2015 and 2050, representing an annual rate of decline equal to 1.3%.

In scenarios where we consider the information level, a higher information level increases the probability of carrying out an audit, but does not change the economic profitability of the retrofit decision. As a result, we find that the marginal gain offered by the information level decreases with respect to the average retrofit rate. We can conclude that if we want to achieve more CO_2 abatement, we need to combine our information level policy with economic instruments that will increase the economic profitability of the retrofit decision.

In retrofit subsidy scenarios, the subsidy is successful in bringing about a significant increase in CO_2 abatement, but again we find that marginal CO_2 abatement decreases with the subsidy rate. In tax on fossil energy scenarios, the impact is rather limited in comparison to other economic instruments and does not have a significant effect on the retrofit decision. When combining all economic instruments, the average retrofit rate is equal to 1.9%. In 2050, the average energy consumption will reach 21 kWh/m^2 and CO_2 emissions will have decreased by 86%.

We demonstrated a working model that allowed us to test several scenarios. We showed that, in order to achieve deep decarbonisation in the building sector, we need to combine a range of different economic instruments: information campaigns, retrofit subsidies and carbon taxes.

5. References

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