Endogenous energy efficiency improvement of large-scale retrofit in the Swiss residential building stock

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Abstract

Future energy use depends on energy efficiency improvement (EEI). In standard analyses of Swiss energy and climate policies, the speed and extent of EEI are usually assumed to be unaffected even by policies designed to foster innovation. This project introduces endogenous EEI and barriers to retrofit in the housing sector. To do so, we detail the evolution of the Swiss building stock and how retrofit decisions and heating system improvements may reduce energy consumption into an existing simulation model (GEMINI-E3). We introduce the formal model by using CECB (Cantonal Energy Certificate for Buildings) classification system in order to classify the housing stock. We use a two steps model that represents how homeowners take a decision about the retrofit. Furthermore, we include a model of the Swiss building stock that incorporates the energy reference area per construction periods, energy classes and takes into account the retrofit decision of property owners. Afterward, we outline the data that helped us to make and calibrate the model. We compare the reference scenario with three policy scenarios: information level, subsidy on retrofit and tax on fossil energy. Additionally, we compare the reference scenario with an additional scenario where all policies are combined. In the last part, we define the links with the GEMINI–E3 model.

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

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Contents

1. Introduction

In Switzerland, according to Swiss Federal Office of Energy[1], around 50% of primary energy consumption is attributable to buildings: 30% for heating, air-conditioning and hot water, 14% for electricity and around 6% for construction and maintenance. Energy efficiency improvement is widely considered to be the most important aspect that will lead to the continuous transformation of the Swiss national energy system. A remarkable feature of the new energy system will be the gradual decarbonisation of the housing sector in Switzerland. Streicher et al. [8] show that large-scale energy retrofit of the Swiss residential building stock using the best available technology could result in energy savings of up 84% of current energy consumption.

The goal of the project is to endogenize the energy efficiency improvement and in addition introduce barriers to retrofit in the housing sector that subsequently will be included in an existing simulation model (GEMINI-E3). With this purpose, we allocate the Swiss housing stock into energy classes. The distribution of building stock by energy classes is modeled based on the data provided by the Swiss Federal Office of Energy. The distribution of building stock shifts due to the transition matrix, which is based on the costs and benefits of a retrofit. In order to acquire genuine results and on a later stage incorporate the effects of barriers, we introduce a two steps model. The property owner first decides on doing the energy audit or not. Second, he makes the decision on doing the retrofit.

The paper is structured as follows: section 2 introduces the building stock model, in particular the two steps model; section 3 outlines data sources; section 4 contemplates various scenarios and displays the comparison of the results; section 5 presents how this model is linked with a macro-economic model (namely GEMINI-E3).

2. Description of the model

In this section, we introduce the equations of the building stock model. The names of the indices, variables, and coefficients are given in Tables 18, 19 and 20 respectively (see Appendix A). The housing stock is grouped into energy classes (*EC*) that will follow CECB (Cantonal Energy Certificate for Buildings) classification[2] which is given in Table 1. Each energy class has fixed specific space heating demand (*SHD*) in kWh per square meter and the energy classes are ranked with the following relationship:

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

2.1. Energy reference area

The quantity of housing in each class is measured by the total energy reference area (*ERA*) in a square meter, i.e. the total heated surface. The energy reference area is represented by three-dimensional matrix and is divided into energy classes (*EC*), construction periods (*CP*) and property owner types (*H*). Energy classes, energy consumption thresholds and average energy consumption for energy classes (our estimations) are given in Table 2 and construction periods are shown in Table 3. The principle of the allocation of energy reference area to energy classes is described in section 3.1.2. The overall energy reference area is allocated by the construction period and energy classes for the year 2015 in Switzerland and is represented in Figure 1.

The energy reference area changes from one period to the next because of a proportion that is demolished (*DR*), through new construction (*NC*) and through transfers between classes through retrofit with the help of a retrofit matrix (*RM*). The law of motion of the energy reference area is given in Eq.(2).

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

[1] http://www.bfe.admin.ch/themen/00507/00607/?lang=en#

[2] see https://www.cecb.ch/

Table 1: CECB energy classes

	Efficiency of the building envelope	Overall energy efficiency
A	Excellent thermal insulation with triple-glazed windows.	State-of-the art technical installations in the building for the production of heat (heating and domestic hot water) and light; use of renewable energies.
B	New building achieved a B rating, according to the legislation in force.	Standard for new buildings and technical installations; use of renewable energies.
C	Older properties where the building envelope has been completely renovated.	Older properties that have been completely renovated (building envelope and technical installations), most often using renewable energies.
D	A building that has been satisfactory and completely insulated retrospectively, but with some thermal bridges remaining.	The building has been renovated to a large extent but presents some obvious shortcomings, or does not use renewable energies.
E	A building with significantly improved thermal insulation, including the installation of new insulating glazing.	A partially renovated building, with a new heat generator and possibly new appliances and lighting.
F	A partially insulated building.	A building partially renovated at best, with the replacement of some equipment or use of renewable energies.
G	A non-renovated building with retrofitted insulation that is incomplete or defective at best, and having the extensive potential for renovation.	A non-renovated building with no use of, renewable energies and with extensive potential for renovation.

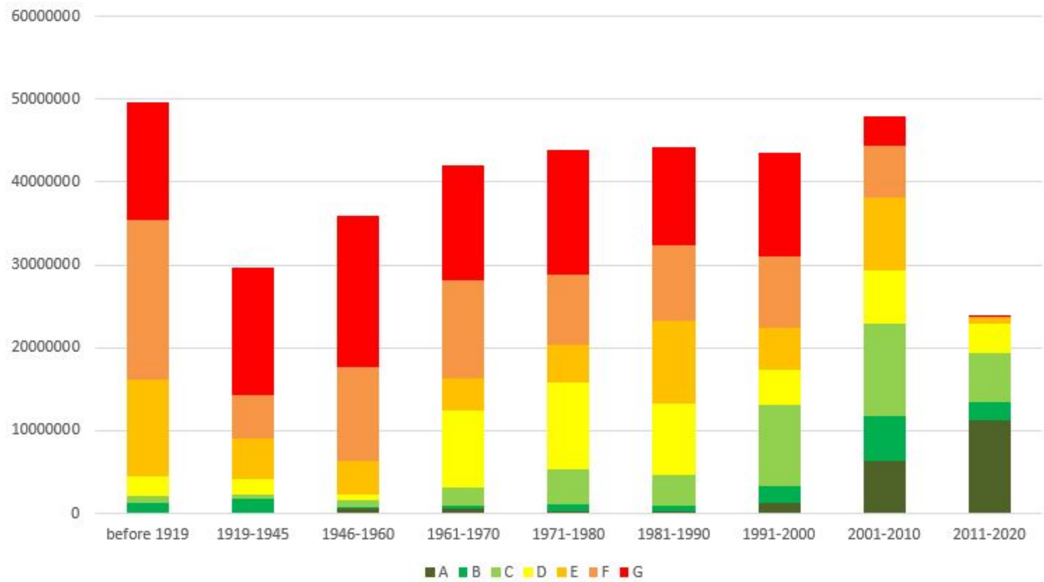

Figure 1: Energy reference area in m^2 per construction periods and energy classes, the year 2015 (source: our estimations, using data from SFOE)

Table 2: Energy consumption of energy classes

Energy class	Energy consumption thresholds in kWh/m^2	Average energy consumption in kWh/m^2 (source: own estimations)
A	< 20	10
B	20-40	30
C	40-60	50
D	60-80	70
E	80-100	90
F	100-120	110
G	>120	170

Table 3: Construction periods

Corresponding index	Year of construction
I	before 1919
II	1919-1945
III	1946-1960
IV	1961-1970
V	1971-1980
VI	1981-1990
VII	1991-2000
VIII	2001-2010
IX	2011-2020
X	2021-2030
XI	2031-2040
XII	2041-2050

2.2. *The decision of retrofit*

In order to describe how property owners make a decision regarding retrofit we introduce a two steps model:

- First step: Probability of being triggered.

  In the first step, the owner of the house is triggered (for example: by receiving a letter from the community, speaking with his/her spouse) and orders an energy audit.

- Second step: Decision on retrofit.

  Depending on the result of the energy audit, he decides on doing the retrofit or not.

2.2.1. *First step*

The probability of doing the energy audit (Π) is represented by Eq. 3. The owner of the house takes the decision based on the current energy class of the house, the cost of heating and the awareness level (called "Information level"). The probability to do the audit increases when the energy class of the building is decreasing. The impact of energy price on the probability is represented through an (Θ) elasticity function of the energy price change with respect to a reference price ($\overline{PEC}$). Finally, the probability is also an increasing function of the information level (Inf: $\{1; 2; 3; 4\}$). For example, if the information level equals to '4', it might stem from a large-scale of information campaign.

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

2.2.2. *Second step*

In the second step, the probability of doing the retrofit (Ω) by the property owner is represented by Eq. 8. This decision is based on retrofit gain (RG), that has to be positive and the largest for all possible energy classes. Logically, if the energy class of the building is A, the probability of doing the retrofit is equal to 0 (Δ_{EC}^{CP}=0). Afterward, we suppose that for B class building, the probability of doing the retrofit is 0.5 percent and so on till G class with 3 percent of probability. We have also defined four different property owner types

(H) that have different discount rates. Taking into account discount rates of each group r^H: $\{3\%; 4\%; 5\%; 6\%\}$, we compute the percentage of buildings that are retrofitted.

Retrofit gain is given in Eq.(4), where (SHD) is a space heating demand, (ψ_t) is a fixed cost on retrofit, ($\tau_{RC,t}$) is technical progress on retrofit (exogenous parameter), ($\tau^{CP,t}_{EC,EC'}$) is a subsidy on retrofit and (PI) is a price on investment.

$$RG^{CP,H,t}_{EC,EC'} = \sum_{t'=t}^{t+T^R} \frac{SHD^{t'}_{EC} \cdot PEC^{CP,t'}_{EC} - SHD^{t'}_{EC'} \cdot PEC^{CP,t'}_{EC'}}{(1+r^H)^{t'-t}} - \frac{RC^{RC,t}_{EC,EC'} + \psi_t}{\tau_{RC,t}} \cdot (1-\tau^{CP,t}_{EC,EC'}) \cdot PI_t \tag{4}$$

Energy price per energy class (PEC) and construction period is represented through a two steps CES (Constant elasticity of substitution) function that is shown in Eq.5, where (λ) and (α) are CES function parameters.

$$PEC^{CP,t}_{EC} = \lambda^{CP}_{EC} \left(\sum_i \alpha^{CP}_{EC,i} \cdot \left(PEK^{CP,t}_{EC,i} \right)^{(1-\sigma^{CP}_{EC})} \right)^{\frac{1}{(1-\sigma^{CP}_{EC})}} \tag{5}$$

The price of heating (PEK) is computed in Eq. 6, where (λ'), ($\alpha\prime$) and (σ') are CES parameters, (PE) is a price of energy sources and (PK) is a price of heating equipment (i.e boiler, heatpump and etc.).

$$PEK^{CP,t}_{EC,i} = \lambda'^{\,CP}_{EC,i} \left(\alpha'^{\,CP}_{EC,i} \cdot (PE_{i,t} \cdot (1+\tau_{i,t}))^{(1-\sigma'^{\,CP,t}_{EC})} + (1-\alpha'^{\,CP}_{EC,i}) \cdot PK_i^{(1-\sigma'^{\,CP}_{EC})} \right)^{\frac{1}{(1-\sigma'^{\,CP}_{EC,i})}} \tag{6}$$

Retrofit cost (RC) is given in Eq.(7), where α_{RC} (= 2.3) is a linear parameter to retrofit cost and β_{RC} (=0.009) is quadratic co-parameter to retrofit cost.

$$RC^{CP,t}_{EC,EC'} = \alpha_{RC} \cdot (SHD_{EC,t} - SHD_{EC\prime,t}) + \beta_{RC} \cdot \left(SHD_{EC,t} - SHD_{EC\prime,t} \right)^2 \tag{7}$$

$$\Omega^{H,t}_{EC,EC'} = 1 \ \text{ if} \begin{cases} RG^{H,t}_{EC,EC'} > 0 \quad \textit{and} \\ RG^{H,t}_{EC,EC'} > RG^{H,t}_{EC,\overline{EC}} \ \ \forall \, EC' < EC \end{cases} ;0 \text{ otherwise} \tag{8}$$

We get retrofit from EC to EC' if:

1. The economic gain from EC to EC' is positive.
2. The retrofit gain is higher than any other retrofit, that can be done from EC.
3. Otherwise, the retrofit success is equal to zero.

2.2.3. Retrofit matrix

Transitions between classes are represented by a retrofit matrix (RM) (see Eq. 9). The (RM) is calculated by multiplying the probability of doing the audit (Π) by the probability of doing the retrofit (Ω) as well as by energy reference area (ERA).

$$RM^{CP,H,t}_{EC,EC'} = \Pi^{CP,t}_{EC} \cdot \Omega^{H,t}_{EC,EC'} \cdot ERA^{CP,H,t}_{EC} \tag{9}$$

2.3. New construction

New construction for energy class is equal to its share in construction ($\phi_{EC,t}$) multiplied by total building construction (Eq. 10), where (DR) is a demolition rate of the building stock.

$$NC^{CP,H,t}_{EC} = \phi_{EC,t} \cdot (\overline{ERA_t} - \sum_H \sum_{EC} \sum_{CP} ((1-DR^{CP,t-1}) \cdot ERA^{CP,H,t-1}_{EC})) \tag{10}$$

Desired reference area ($\overline{ERA}$) (See Eq.11) is linked to population, and we assume that the size of housing per capita is increasing with time.

$$\overline{ERA_t} = (\theta_{1,t} + \theta_{2,t} \cdot t) \cdot Pop_t \tag{11}$$

The share of an energy class in construction is given in Eq. 12. We assume that new constructions will be of a high energy class as they must match the threshold set by SIA 380/1 [3] or MuKEn [4].

$$\phi_{EC,t} = 0 \text{ if } EC \in \{C, D, E, F, G\} \quad \text{and} \sum_{EC} \phi_{EC}^{t} = 1 \; \forall t \tag{12}$$

2.4. Energy consumption

Energy consumption for heating (ECH) is given in Eq.13

$$ECH_{EC}^{CP,t} = SHD_{EC}^{t} \cdot \sum_{H} ERA_{EC}^{CP,H,t} \tag{13}$$

The energy consumption (E) (see Eq.14) by each energy class is a CES function for each energy source (i, i.e. oil, natural gas, district heating, heat pump, wood, etc) [1], which also depends on construction period as well as on CES scale parameters (λ') and (α).

$$E_{EC,i}^{CP,t} = ECH_{EC}^{CP,t} \cdot \lambda_{EC,i}^{\prime\, CP} \cdot \alpha_{EC,i}^{CP} \cdot \left(\frac{PEC_{EC}^{CP,t}}{PEK_{EC,i}^{CP,t}} \right)^{\sigma_{EC,i}^{\prime\, CP}} \tag{14}$$

Total heating energy consumption per source (ET) is computed by summing up the consumption of the particular energy source in all energy classes (Eq. 15).

$$ET_{i,t} = \sum_{EC} E_{EC,i}^{CP,t} \tag{15}$$

2.5. Other variables

Total investment in the retrofit and construction are computed by the following equations:

Total investment in a new building (Inv_N) is given in Eq.16, where (PNC) is the price of a new building:

$$Inv_{N}^{t} = NC_{A}^{H,t} \cdot PNC_{A}^{CP,t} + NC_{B}^{H,t} \cdot PNC_{B}^{CP,t} + NC_{C}^{H,t} \cdot PNC_{C}^{CP,t} \tag{16}$$

Total investment in the retrofit (Inv_R) is given in Eq.17;

$$Inv_{R}^{t} = \sum_{EC} \sum_{EC'} \sum_{CP} \sum_{H} RM_{EC,EC'}^{CP,t,H} \cdot ERA_{EC}^{CP,H,t} \cdot \frac{(RC_{EC,EC'}^{CP,t} + \psi_t)}{\tau_{RC}^{t}} \cdot PI^{t} \tag{17}$$

Net tax revenue from housing ($NetTax$) (taxes minus subsidies) is calculated in Eq.18 , where (τ_i^t) is the tax rate on energy consumption.

$$NetTax_t = \sum_{EC} \sum_{CP} \sum_{i} E_{EC,i}^{CP,t} \cdot \tau_i^t \cdot PE_i^t - \sum_{EC} \sum_{EC'} \sum_{CP} \sum_{H} RM_{EC,EC'}^{CP,H,t} \cdot ERA_{EC}^{CP,H,t} \cdot \frac{(RC_{EC,EC'}^{CP,t} + \psi_t)}{\tau_{RC}^{t}} \cdot \tau_{EC,EC'}^{CP,t} \cdot PI^{t} \tag{18}$$

CO_2 emissions from fossil fuel consumption are computed by multiplying fossil energy consumption by the coefficient for a particular energy carrier. Coefficients (ξ) [5] are given in Table 4.

$$CO_2{}_{EC}^{CP,t} = \sum_{EC} \sum_{CP} (\xi_{oil} \cdot E_{EC,oil}^{CP,t} + \xi_{oil} \cdot E_{EC,gas}^{CP,t} + \xi_{oil} \cdot E_{EC,coal}^{CP,t}) \tag{19}$$

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[3] https://https://awel.zh.ch/internet/baudirektion/awel/de/energie_radioaktive_abfaelle/energienachweis/sia_380_1_thermischeenergieimhochbau.html

[4] https://www.endk.ch/de/dokumentation/gebaude_muken

[5] https://www.nrcan.gc.ca/energy/efficiency/industry/technical-info/benchmarking/canadian-steel-industry/5193

Table 4: CO_2 Emission Factors

Oil	0.078 kg CO_2/MJ
Gas	0.056 kg CO_2/MJ
Coal	0.093 kg CO_2/MJ

3. Descriptive statistics and data sources

In this section, we demonstrate the statistics on the Swiss housing building stock and the data sources that are used to calibrate the model.

3.1. Energy reference area

3.1.1. Energy reference area per construction period

The data on occupied houses per construction periods were collected from the Swiss Federal Office of Energy (SFOE) [6]. Additionally, we used the data on the average surface of houses acquired from SFOE [7]. From this data, we could calculate the energy reference area in square meters per construction period for the year 2015 in Switzerland. The results can be seen in Figure 2.

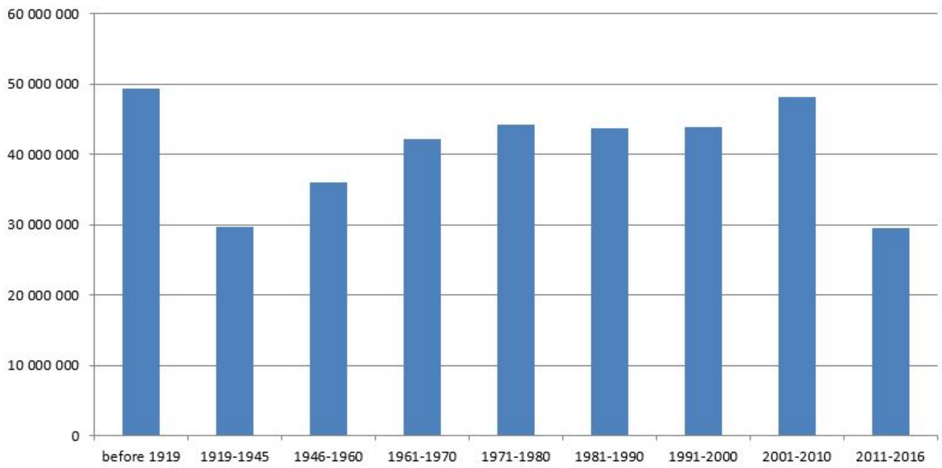

Figure 2: Overall energy reference area (m^2) in Switzerland, the year 2015 (source: our estimations, using data from SFOE)

3.1.2. Allocation of construction periods per energy classes

Cities' data description and sources. In order to allocate the construction periods per energy classes, firstly we needed to collect the data from separate surveys. The surveys helped us to get the energy reference area per construction periods and energy classes for building stock in different cities. The data were provided by Société Coopérative d'Habitation Lausanne (SCHL), Allgemeine Baugenossenschaft Zürich (ABZ), Estia and die Mobiliar. The details of data provided are shown in Table 5.

[6] https://https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.4582090.html

[7] https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.3822846.html

Table 5: Data collected

City	Source	Number of dwellings	Year taken	Energy
Lausanne	SCHL	2 011(app.)	2016/2017	Heating
Zürich	ABZ	4 540 (app.)	2016/2017	Heating + Hot water
Geneva	ESTIA	17 983 (app. + buildings)	2015	Heating + Hot water
Different cities	Mobiliar	236 (buildings)	2015	Heating

Table 6: Derivation of the parameter: Standardized energy demand hot water. INFRAS

	SFH	MFH
Annual heat demand (useful energy) in kWh / m^2 / a	13.9	20.8
Annual utilization rate of heat generation	70%	70%
Annual final energy demand in kWh / m^2 / a	19.8	29.8
Share of building category in the total energy reference area of residential buildings	30%	70%

Since the initial data for some of the surveys were provided including the energy for heating water, we needed to find a way to subtract this energy from our data. With this purpose, we used the data acquired from [5], that shows how much energy for hot water is used per square meter in each apartment (see Table 6) .

Since initially for Zürich and Geneva the data on heating and hot water is incorporated, we subtracted the energy used for hot water. For Lausanne and die Mobiliar surveys this was not necessary.

The distribution of buildings. Moreover, we calculated the distribution of energy reference area of buildings for all four surveys in each energy class and in each construction period.

For SCHL (see Figure 3) we took into account heating degree days and climate corrections (see the total correction in Table 7). For ABZ (see Figure 4), Geneva (see Figure 5) and die Mobiliar's (see Figure 6) dwellings the heating degree days were already taken into account in the initial data provided.

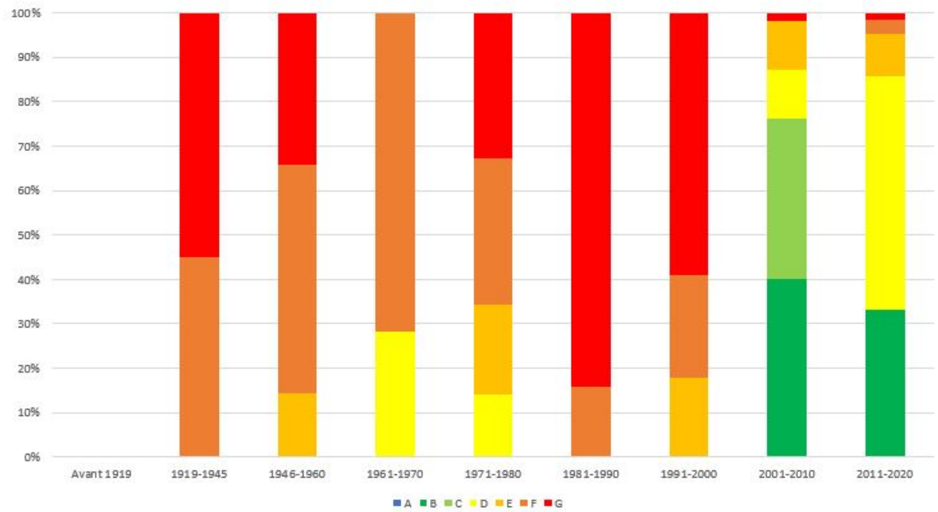

Figure 3: Distribution of ERA (source: SCHL - Lausanne)

The data were provided for different years for each separate survey. In order to take the same climate conditions for all three cities, we did climate corrections with the help of Swiss Meteo data [8]. Thus, the energy consumption of each city was multiplied on total correction coefficient (see Table 7).

Additionally, the overall energy reference area for three cities and die Mobiliar dwellings is shown in Figure 7.

[8] https://www.hev-schweiz.ch/vermieten/nebenkostenabrechnungen/heizgradtage-hgt/

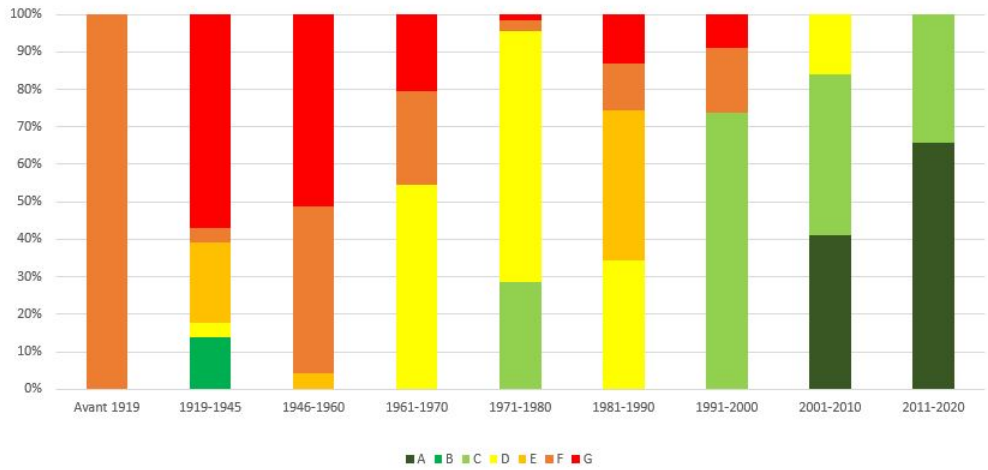

Figure 4: Distribution of ERA (source: ABZ - Zürich)

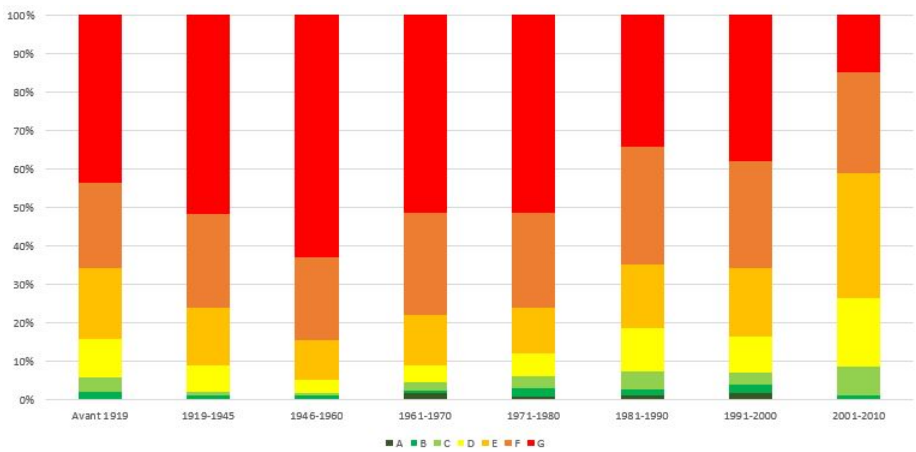

Figure 5: Distribution of ERA (source: ESTIA - Geneva)

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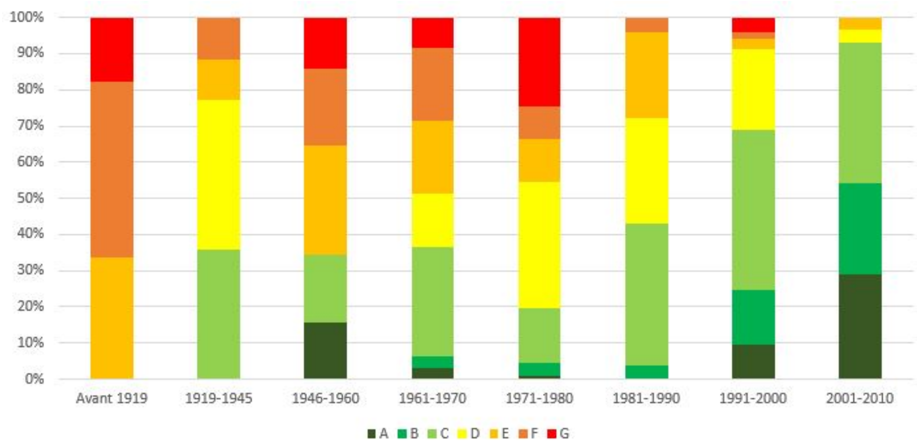

Figure 6: Distribution of ERA (source: die Mobiliar - different cities)

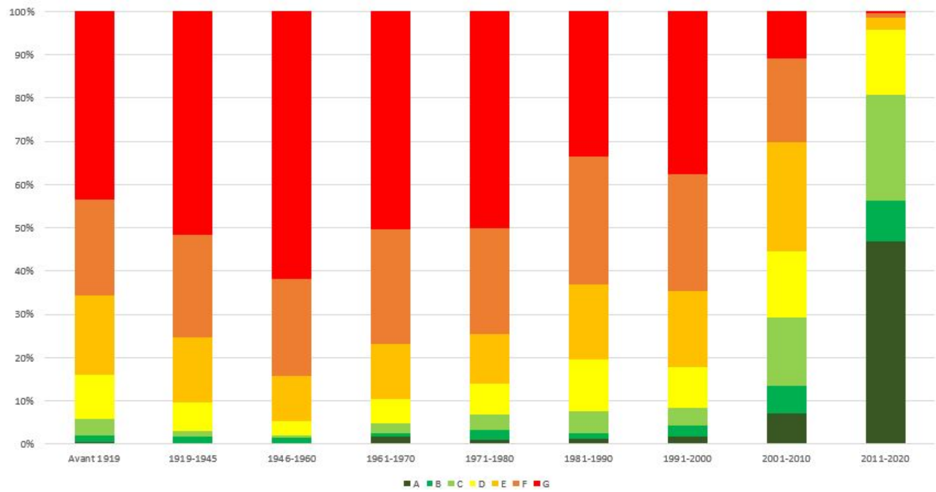

Figure 7: Distribution of ERA: three cities and die Mobiliar

Table 7: Heating degree days and climate corrections

City	years 2001-2010 (days)	the year 2015 (days)	the year 2016 (days)	the year 2017 (days)	Temporal correction	Spatial correction	Total correction
Lausanne Pully		2586	2866	2751	0.92	1.19	1.09
Zürich Fluntern		3060	3335	3233	0.92	1	0.93
Geneva Cointrin		2795	3008	2902	1	1.1	1.1
Switzerland	3310	3075	3281	3233			

Table 8: Energy consumption by energy carrier (TJ)

	Our estimations	SFOE	Prognos
Oil	65 609	81 430	70 700
Gas	32 170	48 990	37 500
Electricity	8 780	68 680	9 000
Wood	13 559	19 060	16 500
Heat pump	3 519		13 900
District heating	6 743	7 540	6300
Others	4 472		600
Sum	134 852	240 710	154 500

3.2. Energy consumption by energy carrier

Here we computed the distribution of dwellings by energy carriers for each energy class. As it was already mentioned in section 3.1.2, we have four different surveys. The overall energy consumption by all construction periods is allocated by energy carriers and energy classes. Since the 95.6 % of energy reference area in all surveys is represented only by Geneva survey, we needed to use the weighted average method and calculate adjustment factors in order to properly account for all four surveys. Thus, after making the calculations we obtain more representative results for all four surveys. The final results are summed up and eventually compared with the reference data that was taken from SFOE and Prognos paper (see [6]) in order to check whether our estimations and calculations are reasonable. The results of our estimations and the comparison with other sources are shown in Table 8.

As we can see, there is a big difference between electricity consumption from our estimations, Prognos, and SFOE data. This is mainly due to the fact that in Prognos, the electricity consumption includes only the electricity used for the heating when in the data from SFOE the appliances (i.e washing machines, microwaves and etc.) are also taken into account.

3.3. Retrofit variables

Retrofit cost. In order to estimate the retrofit costs that are necessary to reduce a building's space heating demand sufficiently for it to move to a better energy class, we use estimates from a study by SFOE [9]. These estimates describe the investment costs that accrue when both a representative single-family house (SFH) and multi-family house (MFH) currently in energy class G, are retrofitted by the means of energy efficiency measures and subsequently satisfy the space heating demand standard of class A (i.e. building moves from G to A). The estimates are 410 Fr. /m^2 ERA for SFH and 250 Fr./m^2 ERA for MFH, as is shown in the top-right cell in Table 9 and 10 respectively. By assuming a linear cost function, we can then interpolate the retrofit costs that are required to move a building from a given energy class to any higher one. Retrofit costs used in our model are weighted averages between retrofit costs of single and multi-family houses.

Retrofit lifetime. The lifetime of a retrofit (T^R) is the time untill the retrofit has to be repeated. Based on Table 11 obtained from SFOE ([9] we use a lifetime of 40 years.

3.4. New construction

From the Federal Statistical Office (FSO)[10] we acquired the data on the average surface per inhabitant and amount of new constructions in Switzerland as well as the population in Switzerland from 1980-2016 by each

[9] https://www.endk.ch/de/dokumentation/harmonisiertes-foerdermodell-der-kantone-hfm

[10] https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.3502054.html

Table 9: Matrix for investment cost for SFH (in CHF/m^2)

	A	B	C	D	E	F	G
A		68	136	204	272	340	410
B			68	136	204	272	340
C				68	136	204	272
D					68	136	204
E						68	136
F							68
G							

Table 10: Matrix for investment cost for MFH (in CHF/m^2)

	A	B	C	D	E	F	G
A		41	82	123	164	205	250
B			41	82	123	164	205
C				41	82	123	164
D					41	82	123
E						41	82
F							41
G							

Table 11: Retrofit lifetime

Component	Reference technical service lifetime under medium load	Reference technical service lifetime under heavy load
Facade	70	70
Windows, exterior doors, gates	50	30
Roof	40	30
Sun protection	40	30
Heater	40	30
Ventilation	40	20
Air conditioning, refrigeration	25	20
Sanitary	45	40

year. We wanted to check if our estimations are compatible with the data provided by SFOE. With this purpose we have calculated the total surface of new constructions and, also by having the data on the population in the corresponding year, we consequently determine the surface of new constructions per capita in Switzerland. The results can be found in Figures 8 and 9. We use this data in the model, which will eventually help us to determine the increase of energy reference area in the future.

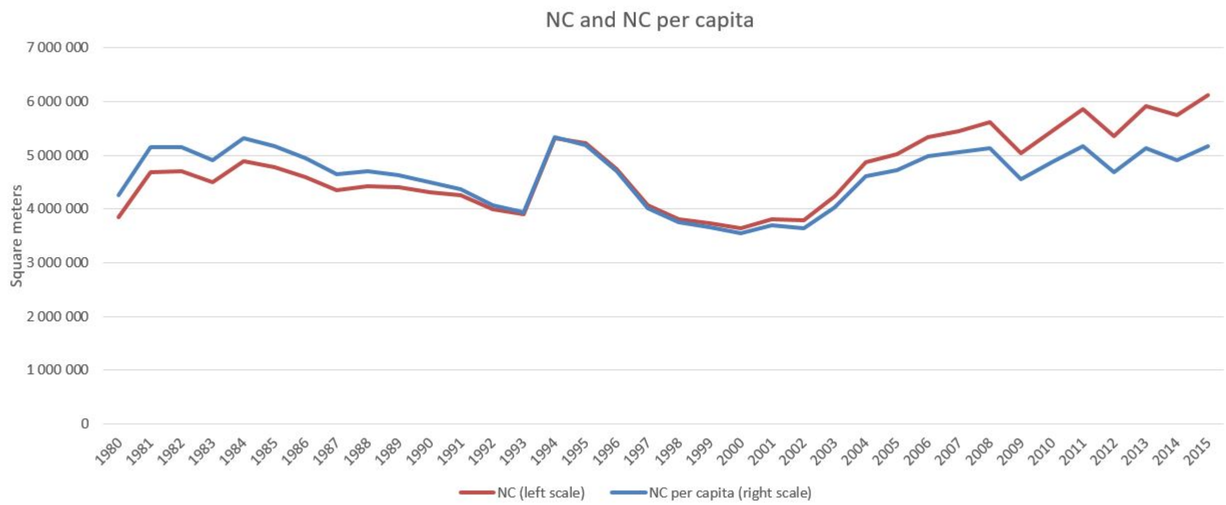

Figure 8: New construction and new construction per capita (source: FSO)

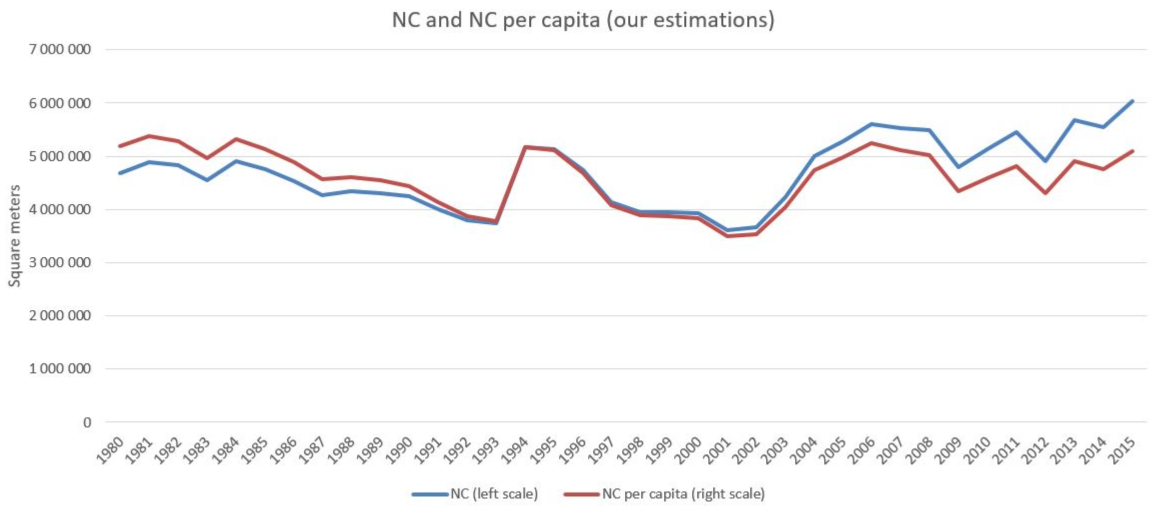

Figure 9: New construction and new construction per capita (source: our estimations)

3.5. Estimated demolition rates

To estimate demolition rates we use the statistic on occupied houses in square meters from 2010-2016 categorized by classes. For each construction period, we compute the decrease in occupied houses from 2016 to 2010. Some classes are unfortunately not represented in the statistics; for these classes, we interpolate the data between classes. Figure 10 shows the demolition rates.

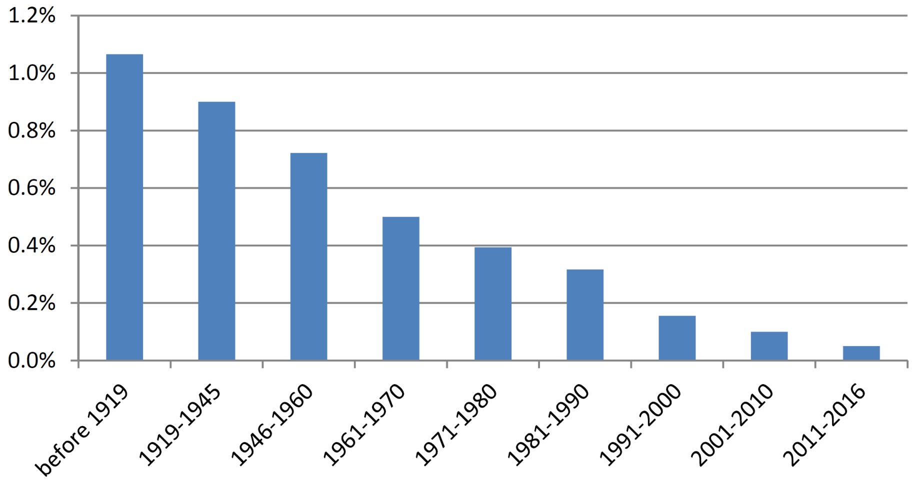

Figure 10: Estimated yearly demolition rate in % per construction period (source: our estimations, using data from SFOE)

3.6. Price of energy

We obtain the prices of energy carriers from different sources (see Table 12). The prices of electricity, gas, and oil are obtained from SFOE [10]. According to SFOE [9] the price of pellets, for 6600 kg is around 2000 CHF, thus 0.201 CHF per kWh. Price of the remote heat according to IWB [11] is equal to 0.0835-0.0856 CHF/KWh and according to Energie 360 [12] it is equal to 0.086 CHF/KWh. We decided to use the price of 0.085 CHF/KWh in our model.

Table 12: Expense of energy per KWh

Price CHF/KWh	2016	Source
Electricity	0.201	SFOE
Gas	0.093	SFOE
Oil	0.079	SFOE
Wood	0.059	SFOE
Solar	0.001	Our estimations
District heating	0.085	IWB and Energie 360
Others	0.201	Our estimations

We also calculate the prices of energy carriers with the help of data from the city of Zürich [13] (see Table 13). In the table, we can see the energy carriers and their capital cost: cost of equipment (i.e heating system) per kWh of energy and the maintenance cost of the equipment related to the particular energy carrier. We do not take into account changes in operation and maintenance costs as they can be considered in building retrofit as negligible [8].

4. Numerical implementations

In this section, we report preliminary experiments with the model presented in section 2.1.

[11]https://www.iwb.ch/Fuer-Zuhause/Fernwaerme/Fernwaermetarife-01.03.2018.html

[12]https://www.energie360.ch/fileadmin/image/inhaltsbilder/waermeverbund_kappelenring/Tarifmodell_Informationen_Waermeverbund-Kappelenring.pdf

[13]https://www.stadt-zuerich.ch/gud/de/index/beratungen_bewilligungen/ugz/Liegenschaftsbesitzende/energie-coaching/faktenblaetter.html

Table 13: Price of energy 2015

Energy Carrier	Capital cost CHF/year	Maintenance cost CHF/year
Oil	0.048	0.021
Coal	0.046	0.018
Gas	0.045	0.017
Electricity	0.097	0.033
Wood	0.072	0.022
Heat pump	0.090	0.022
Solar	0.086	0.030
Remote heat	0.059	0.013

4.1. Reference scenario

We assume four property owner types, each representing 25% of the owners with the respective discount rates, 3%, 4%, 5%, and 6%.

Figure 11 shows the evolution of the energy reference area per energy classes driven by new constructions and refurbishment decisions. New construction is given in Figure 8. We assume that at the beginning of our simulation, new constructions are mainly done in energy classes C and B with respective shares equal to 35% and 45%. The remaining part (i.e. 20%) is represented by energy class A. The share of energy class A is supposed to increase and progressively replace energy classes C and B, constructions with these classes disappear in 2032 and 2049 respectively.

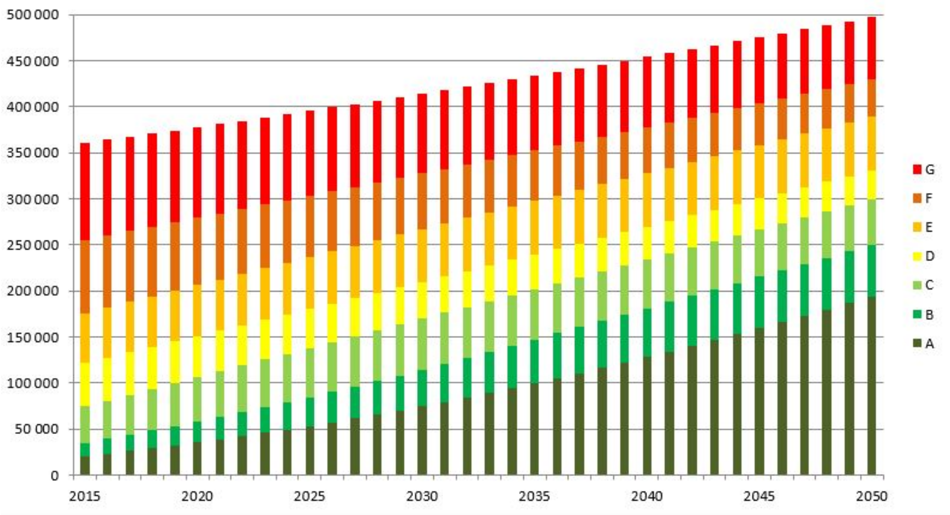

Figure 11: Energy reference area in m^2 - Reference scenario

Retrofit decisions are shown in Figure 12. 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 it can be seen in Figure 11 the surface of energy class E is slightly increasing.

On the whole period, the average retrofit share is equal to 0.6%. The average heating consumption in kWh per square meter decreases from 92 kWh to 53 kWh in 2050. CO_2 emissions decrease by 36% from 2015 to 2050, representing an annual decline rate equal to 1.3%.

4.2. Information level scenarios

In the reference scenario, the information level (Inf) is equal to 1, in this section we perform several scenarios where we increase this information level. Table 14 shows the impacts of these scenarios on a selected number of indicators. Increasing the information level augments the probability of doing an audit but does not change the economic profitability of the retrofit decision. Therefore, we find that the marginal gain of the information level is decreasing with respect to the average retrofit rate. With the information level 4, the average energy consumption reaches 39 kWh per m^2 and CO_2 emissions decrease by 56% with respect to 2015 levels. In 2050, energy class A represents 58% of the Swiss building stock, but there are still very inefficient buildings. Indeed, buildings from category G to E account for 25% of the Swiss building stock.

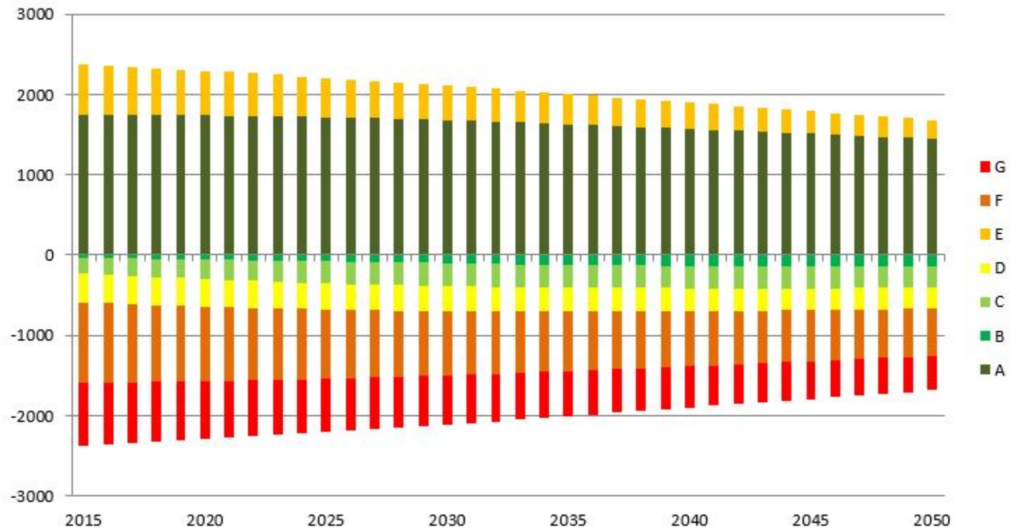

Figure 12: Retrofit in m^2 - Reference scenario (negative numbers are buildings that are subtracted, positive numbers are buildings that are added to an energy class)

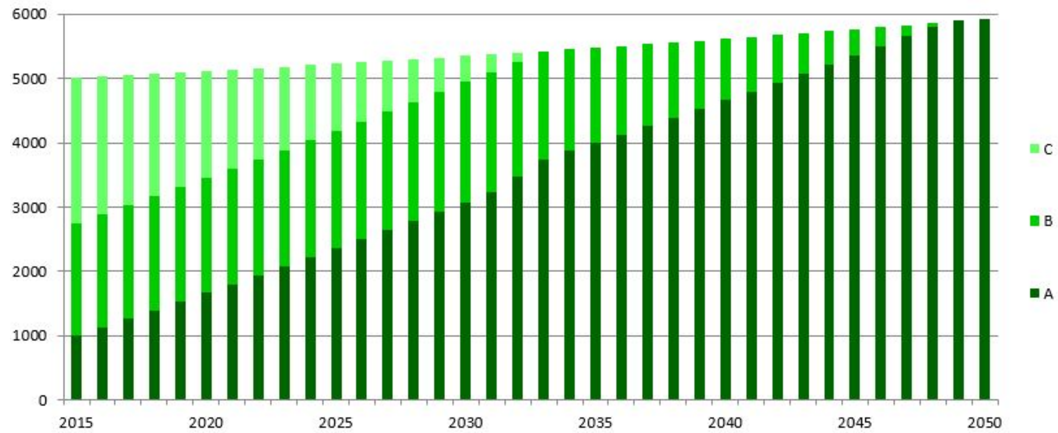

Figure 13: New construction in m^2 - Reference scenario

We can conclude that if we want to obtain more CO_2 abatements, it is necessary to combine information level policy with economic instruments that will affect the economic profitability of the retrofit decision.

4.3. Subsidy on retrofit

In this scenario, we assume that the government implements a subsidy on the retrofit cost concerning energy classes G and F (i.e. $\tau_{EC,G}^{CP,t}$ and $\tau_{EC,F}^{CP,t}$) . We perform several scenarios with a subsidy rate ranging from 10% to 40%. Table 15 shows the results. If the subsidy increases the retrofit of energy class G, it does not affect the renovation decision for energy class F whose share is unchanged within different scenarios. It is worth noting, that when the subsidy rate is above 20%, no more retrofit is implemented (i.e. the share of energy class G is unchanged in 2050), but it affects the energy class in which the retrofit is done (i.e. the share of energy class A is increasing and the share of energy class E is decreasing). Regarding 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.

We assume now that the subsidy is implemented in a different way. The government decides to subsidize retrofit of buildings that is done from any energy class to the highest energy class A (i.e. $\tau_{A,EC}^{CP,t}$). These scenarios are presented in Table 16. In these scenarios, per definition, only the share of energy class A is increasing. We find similar results when subsidies for energy classes G and F are implemented, except that it also affects energy class E where its share is decreasing.

4.4. Tax on fossil energy scenarios

In this scenario, we assume that the government puts a tax on fossil energy ranging from 10% to 50%. As can be seen in Table 17, the impact is rather limited in comparison to other economic instruments and does

Table 14: Information level scenarios

Information level	Ref=1	2	3	4
Average retrofit rate in %	0.6%	1.0%	1.3%	1.5%
Average energy consumption in 2050 in kWh/m^2	54	47	43	39
CO_2 emissions change with respect 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%

Table 15: Subsidy rate scenarios on energy classes F and G

	Ref	10%	20%	30%	40%
Average retrofit rate in %	0.6%	0.6%	0.7%	0.7%	0.7%
Average energy consumption in 2050 in kWh/m^2	54	51	49	48	46
CO_2 emissions change with respect 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 16: Subsidy rate scenarios in retrofit done in energy class A

	Ref	10%	20%	30%	40%
Average retrofit rate in %	0.6%	0.6%	0.6%	0.7%	0.7%
Average energy consumption in 2050 in kWh/m^2	54	53	50	47	45
CO_2 emissions change with respect 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%

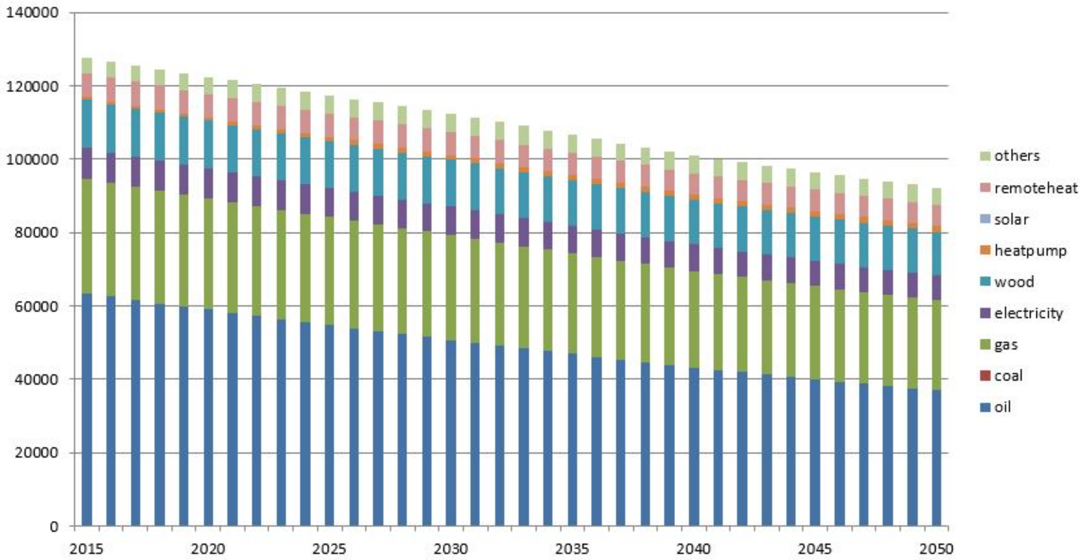

Figure 14: Energy consumption by energy carriers in TJ - Reference scenario

not impact significantly the retrofit decision.

Table 17: Tax on fossil energy scenario

	Ref	10%	20%	30%	40%	50%
Average energy consumption in 2050 in kWh/m^2	54	54	53	53	53	53
CO_2 emissions change with respect 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%

4.5. Combining economic instruments

We perform a scenario where we combine all economic instruments: the information level is equal to 4, ($\tau_{A,EC}^{CP,t}$) equals 0.4 and the fossil fuel tax equals 50%. Figure 15 illustrates the impact on the energy reference area per energy class. Energy classes A et B represent respectively 77% and 9% of the Swiss building stock. Classes G and F represent only 1% and 2% respectively. In this scenario, 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%.

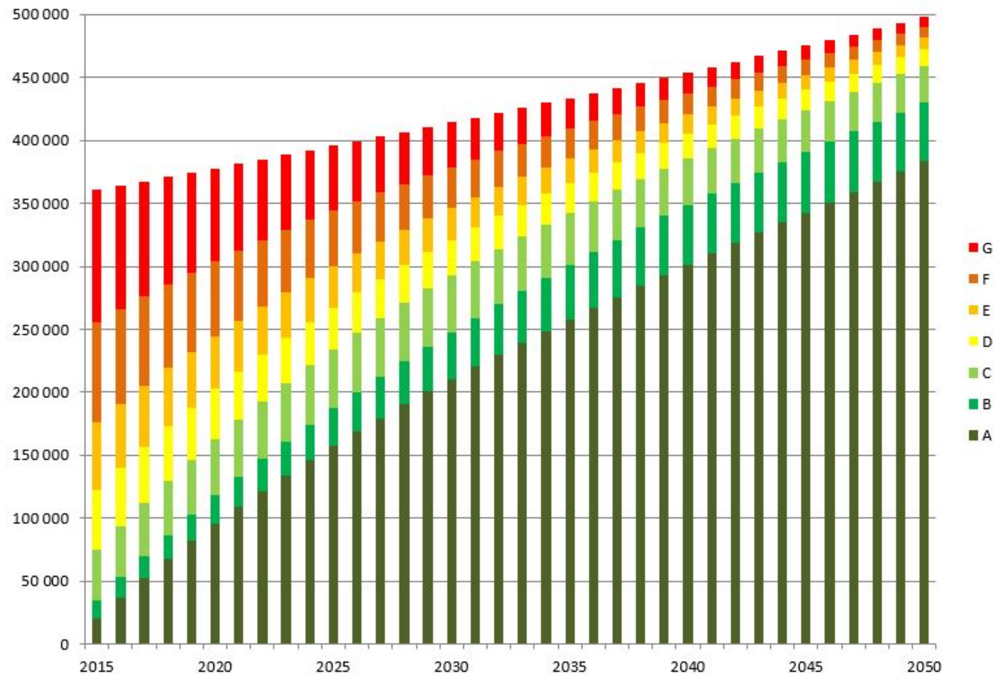

Figure 15: Energy reference area in m^2 - all economic instruments

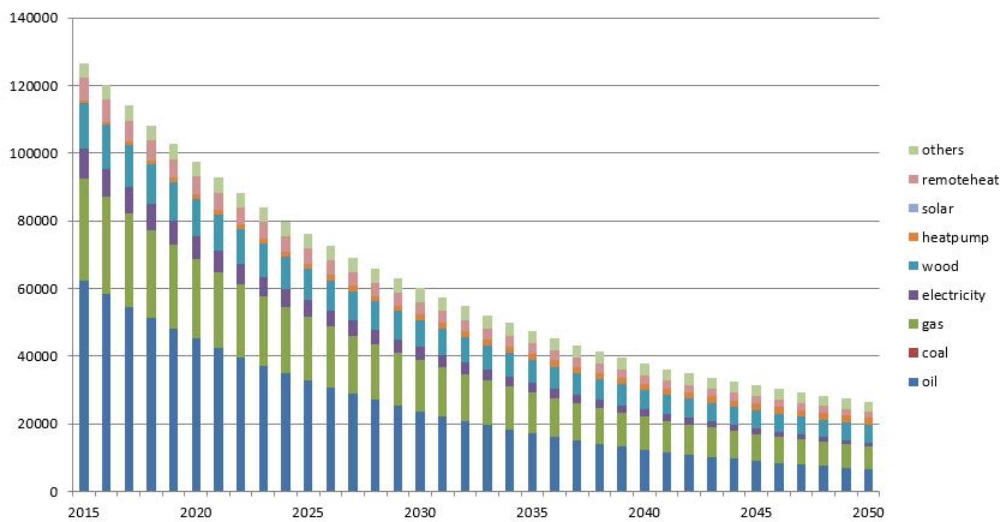

Figure 16: Energy consumption by energy carriers in TJ - all economic instruments

5. Links with the GEMINI-E3 Model

The building stock model will be linked to a macroeconomic representation, the model GEMINI-E3 [3]. GEMINI-E3 is a computable general equilibrium (CGE) model that has been specifically designed to assess energy and climate policies (see for example [2]). The models will be run iteratively while the coupling variables are exchanged between the two models, as shown in Figure 17. GEMINI-E3 will provide the price of energy carriers (oil, natural gas, electricity, wood, etc.), price of investment (used for retrofit cost). The building stock model will give to GEMINI-E3 heating energy carriers, the investment in retrofit and new building, as well as the net tax revenue. Tax rates on energy consumption and subsidy rates on retrofit operations will be determined based on the scenario definitions (i.e. policy design).

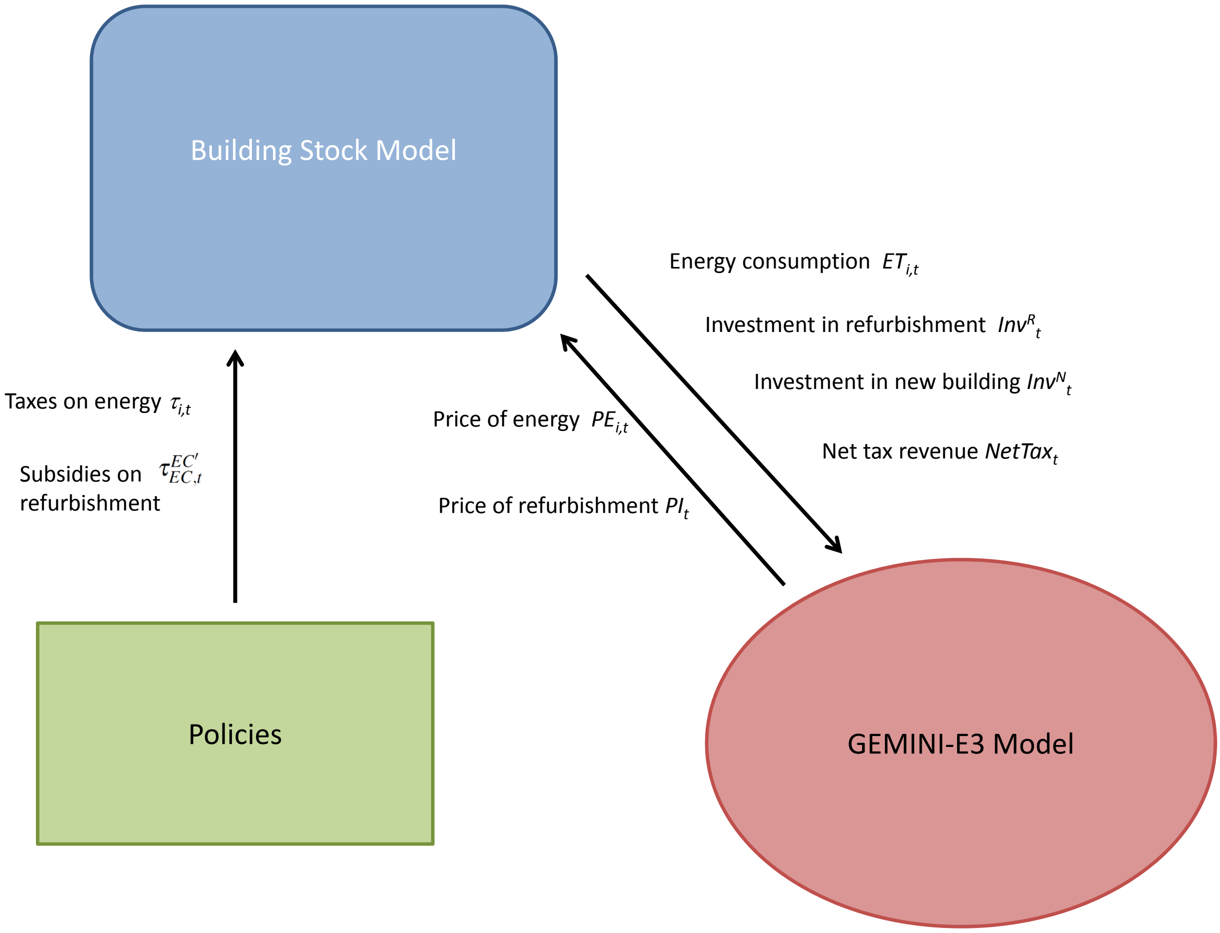

Figure 17: Coupling framework

6. References

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[10] Swiss Federal office of Energy. Schweizerische Gesamtenergiestatistik 2015 Statistique globale suisse de lénergie. 2015.

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Acknowledgements

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Appendix A Indices, variables and coefficients

Table 18: Indices

$EC, EC', \overline{EC}$	Energy class according to CECB $\in$ {A,B,C,D,E,F,G} see Table 1
i	Energy carrier
t, t'	Time period
Inf	Information level {1; 2; 3; 4}
CP	Construction Period { I; II; III; IV; V; VI; VII; VIII; IX; X; XI; XII; XIII; XIV; XV}
H	Property owner type {1,2,3,4}

Table 19: Variables

		Units
$DR^{CP,t}$	Demolition rate	ratio in %
$E^{CP,t}_{EC,i}$	Energy consumption	joule
$ECH^{CP,t}_{EC}$	Energy consumption for heating	joule
$ERA^{CP,t}_{CEC}$	Energy reference area	m^2
$\overline{ERA_t}$	Desired reference area	m^2
$ET_{i,t}$	Total heating energy	joule
HDD_t	Heating degree day	
Inv^t_N	Total investment in new building	CHF
Inv^t_R	Total investment in retrofit	CHF
$NC^{CP,H,t}_{EC}$	New construction	
$NetTax_t$	Net revenue tax	ratio in %
$PE_{i,t}$	Price of energy sources	CHF
PK_i	Price of heating equipment	CHF
$PEC^{CP,t}_{EC}$	Energy price per energy class	CHF
PI_t	Price on investment	CHF
$PNC^{CP,t}_A$	Price of new building	CHF
Pop_t	Population	
r^H	Discount rate	ratio in %
$RC^{CP,t}_{EC,EC'}$	Energy retrofit cost	CHF
$RG^{CP,t}_{EC,EC'}$	Energy retrofit gain	CHF
$CO_2{}^{CP,t}_{EC}$	Emissions from fossil fuel consumption	
$SHD_{EC,t}$	Space heating demand per m^2	kWh/m^2
T^R	Duration of retrofit	
μ_{EC}	Exogenous technical progress = 0.5% (Source: [11])	ratio in
$\tau_{i,t}$	Tax rate on energy consumption	ratio in %
$\tau^{CP,t}_{EC,EC'}$	Subsidy rate on retrofit	ratio in %
$\tau_{RC,t}$	Technical progress on retrofit	
ψ_t	Fixed cost of retrofit	ratio in %
$RM^{CP,H,t}_{EC,EC'}$	Retrofit matrix	
Δ^{CP}_{EC}	Parameter	
$\Theta^{CP,t}_{EC}$	Elasticity	
PEC^{CP}_{EC}	Price of energy per energy class	CHF
$\overline{PEC^{CP}_{EC}}$	Price of energy per energy class, base year	CHF
$PEK^{CP,t}_{EC,i}$	Price of heating	CHF
$\Pi^{CP,t}_{EC}$	Probability of doing energy audit	ratio in %
$\Omega^{H,t}_{EC,EC'}$	Probability of doing retrofit	ratio in %

Table 20: Coefficients

$\alpha^{CP}_{EC,i}$	CES share coefficient
$\lambda'^{CP}_{EC,i}$	CES share coefficient
γ_{EC}	Energy consumption for the base year
$\theta_{1,t}$	Coefficient
$\theta_{2,t}$	Coefficient
λ^{CP}_{EC}	CES scale parameter
ϕ_{EC}	Share of class EC in construction
σ^{CP}_{EC}	CES elasticity of substitution
ξ_i	Coefficient for energy carriers
μ	Coefficient of first step probability choice
α_{RC}	Linear parameter to retrofit cost
β_{RC}	Quadratic co-parameter to retrofit cost

Appendix B GAMS® Code

```
SET
T year/2015*2100/
EC Vintage Cohort (7 cohorts)/A,B,C,D,E,F,G,H,I/

********************
* A 2011-2016
* B 2001-2010
* C 1991-2000
* D 1981-1990
* E 1971-1980
* F 1961-1970
* G 1946-1960
* H 1919-1945
* I before 1919


I Energy carrier/oil,coal,gas,electricity,wood,heatpump,solar,remoteheat,others/


alias(EC,ECP,ECB,ECD)
alias(T,TP)
alias(I,IP)

PARAMETER
DR(EC,T) Demolition Rate

ERA(EC,T) Energy Reference Area in sqm
ERAD(T) Desired Reference Area
NC(EC,T) New Construction
RM(EC,ECP,T) Transition Matrix
RS(EC,ECP,T) Refurbishment success
ERR(T) Exogeneous refurbishment rate
RG(EC,ECP,T) Refurbishment Gain
PEC(EC,T) Price of energy
PSI(T) Fixed cost
SHAREREFUR(EC,T) Share refurbishment

PHI(EC,T) Share of cohort EC in construction
THO(EC,ECP,T) Subsidies on refurbishment
PI(T) Price of investement
SHD(ECP,TP) Space heating demand per sqm
R Discount rate
RC(EC,ECP,T) Refurbishment cost
THO(EC,ECP,T) Subsidy on refurbishment
MAXIMUM(EC,T) test variable
Thetaone(T) Coefficient
Thetatwo(T) Coefficient
Pop(T) Population

SHD(EC,T) Space heating demand per sqm
HDD(T) Heating degree day
Mu(EC) Exogeneous technical progess
ECH(EC,T) Energy consumption for heating


E(EC,I,T) Energy consumtion
Lambda(EC)  CES scale parameter
Alpha(EC,I) CES share parameter
PE(I,T)  Price of energy source
Tau(I,T) Tax on energy
TauS(EC,ECP,T) Subsidy on refurbishment
Sigma(EC) Ces elasticity of substitution
ET(I,T) Total heating energy
PNC(EC,T) Price of new building
INVN(T) Total investment in new building
INVR(T) Total investment in refurbishment
NetTax(T) Net revenue Tax

X(T) test variable
Y(EC,T) test variable 2

XsumI(I)  Variable used for extracting results
XsumEC(EC)  Variable used for extracting results
;

SCALAR
TR duration of refurbishment
FLAG test parameter
TJKWh conversion parameter frm TJ to KWh
Tau_RC technical progress on refurbishment cost
```

```
;
$include Data
TJKWh=277777.7778;
TR=40;
R=0.03;
PSI(T)=0 ;
THO(EC,ECP,T)=0.00;
*THO(EC,"A",T)=0.5;
PI(T)=1;
RC(EC,ECP,T)=0;
PHI(EC,T)=0;  PHI("A",T)=0.7; PHI("B",T)=0.3;
ERAD(T)=0 ;
* From excel sheet
Thetatwo(T)= 0;
Pop("2015")= 8282000/1000;
Pop("2016")= 8372000/1000;
Thetaone(T)=SUM(EC,ERA0(EC,"2016")/1000)/Pop("2016");
Mu(EC)=0.5;
HDD(T)= 3281;
ECH(EC,T)=1;
Lambda(EC) = 1  ;
Alpha(EC,I) = 0.2 ;
PE("oil",T)=0.079;
PE("coal",T)=0.201;
PE("gas",T)=0.079;
PE("electricity",T)=0.201;
PE("wood",T)=0.069;
PE("heatpump",T)=0.201;
PE("solar",T)=0.201;
PE("remoteheat",T)=0.201;
PE("others",T)=0.201;
ECH(EC,"2016")=SUM(I,E0(EC,I,"2016"));
PEC(EC,"2016")=SUM(I,E0(EC,I,"2016")*PE(I,"2016"))/ECH(EC,"2016");
Sigma(EC) = 0.25  ;
Alpha(EC,I)=(E0(EC,I,"2016")*PE(I,"2016")**Sigma(EC))/(SUM(IP,E0(EC,IP,"2016")*PE(IP,"2016")**Sigma(EC)));
Lambda(EC) =PEC(EC,"2016")*( (SUM(I,E0(EC,I,"2016")*PE(I,"2016")**Sigma(EC)))/(PEC(EC,"2016")*ECH(EC,"2016")) )**(1/(1-Sigma(EC)));
display PEC,alpha,Lambda;
Tau("oil",T) = 0.2 ;
Tau("coal",T) = 0.2 ;
Tau("gas",T) = 0.2 ;
TauS(EC,ECP,T) =0 ;
ET(I,T)=1 ;
PNC(EC,T)=1;
Tau_RC=0.01;
DR("A",T)=0.0005;
DR("B",T)=0.001;
```

```
DR("C",T)=0.0016;
DR("D",T)=0.0032;
DR("E",T)=0.0039;
DR("F",T)=0.005;
DR("G",T)=0.0072;
DR("H",T)=0.009;
DR("I",T)=0.01;

DR(EC,T)=0.005;

* From SHD zurich
SHD("I",T)=135;
SHD("H",T)=170;
SHD("G",T)=170;
SHD("F",T)=165;
SHD("E",T)=165;
SHD("D",T)=123;
SHD("C",T)=90;
SHD("B",T)=70;
SHD("A",T)=60;

RC(EC,ECP,T)=MAX(0,(SHD(EC,T)-SHD(ECP,T))*41/20)/((1+Tau_RC)**(Ord(T)-2));


display RC;

RC(EC,"I",T)=0;

ERA(EC,T)=ERA0(EC,T)/1000;


ERR(T)=0.03;




PEC(EC,T)=(Lambda(EC))*(SUM(I,(Alpha(EC,I))*(((PE(I,T)*(1+Tau(I,T)))**(1-Sigma(EC)))**(1/(1-Sigma(EC))))));

display PEC;


loop(T$(ord(T) gt 1) ,

POP(T+1)=POP(T)*(1+0.009224349);

ERAD(T)= Thetaone(T)*POP(T+1);

X(T)=SUM(ECP,(1-DR(ECP,T))*ERA(ECP,T));

NC(EC,T)= PHI(EC,T)*(ERAD(T)-SUM(ECP,(1-DR(ECP,T))*ERA(ECP,T)));

NC(EC,T)=NC(EC,T)$(NC(EC,T) gt 0)+0;

RG(EC,ECP,T)= (SHD(EC,T+1)*PEC(EC,T+1)-SHD(ECP,T+1)*PEC(ECP,T+1))/(1+R)
             +(SHD(EC,T+2)*PEC(EC,T+2)-SHD(ECP,T+2)*PEC(ECP,T+2))/(1+R)**2
             +(SHD(EC,T+3)*PEC(EC,T+3)-SHD(ECP,T+3)*PEC(ECP,T+3))/(1+R)**3
             +(SHD(EC,T+4)*PEC(EC,T+4)-SHD(ECP,T+4)*PEC(ECP,T+4))/(1+R)**4
             +(SHD(EC,T+5)*PEC(EC,T+5)-SHD(ECP,T+5)*PEC(ECP,T+5))/(1+R)**5
             +(SHD(EC,T+6)*PEC(EC,T+6)-SHD(ECP,T+6)*PEC(ECP,T+6))/(1+R)**6
             +(SHD(EC,T+7)*PEC(EC,T+7)-SHD(ECP,T+7)*PEC(ECP,T+7))/(1+R)**7
             +(SHD(EC,T+8)*PEC(EC,T+8)-SHD(ECP,T+8)*PEC(ECP,T+8))/(1+R)**8
             +(SHD(EC,T+9)*PEC(EC,T+9)-SHD(ECP,T+9)*PEC(ECP,T+9))/(1+R)**9
             +(SHD(EC,T+10)*PEC(EC,T+10)-SHD(ECP,T+10)*PEC(ECP,T+10))/(1+R)**10
             +(SHD(EC,T+11)*PEC(EC,T+11)-SHD(ECP,T+11)*PEC(ECP,T+11))/(1+R)**11
             +(SHD(EC,T+12)*PEC(EC,T+12)-SHD(ECP,T+12)*PEC(ECP,T+12))/(1+R)**12
             +(SHD(EC,T+13)*PEC(EC,T+13)-SHD(ECP,T+13)*PEC(ECP,T+13))/(1+R)**13
             +(SHD(EC,T+14)*PEC(EC,T+14)-SHD(ECP,T+14)*PEC(ECP,T+14))/(1+R)**14
             +(SHD(EC,T+15)*PEC(EC,T+15)-SHD(ECP,T+15)*PEC(ECP,T+15))/(1+R)**15
             +(SHD(EC,T+16)*PEC(EC,T+16)-SHD(ECP,T+16)*PEC(ECP,T+16))/(1+R)**16
             +(SHD(EC,T+17)*PEC(EC,T+17)-SHD(ECP,T+17)*PEC(ECP,T+17))/(1+R)**17
             +(SHD(EC,T+18)*PEC(EC,T+18)-SHD(ECP,T+18)*PEC(ECP,T+18))/(1+R)**18
             +(SHD(EC,T+19)*PEC(EC,T+19)-SHD(ECP,T+19)*PEC(ECP,T+19))/(1+R)**19
             +(SHD(EC,T+20)*PEC(EC,T+20)-SHD(ECP,T+20)*PEC(ECP,T+20))/(1+R)**20
             +(SHD(EC,T+21)*PEC(EC,T+21)-SHD(ECP,T+21)*PEC(ECP,T+21))/(1+R)**21
             +(SHD(EC,T+22)*PEC(EC,T+22)-SHD(ECP,T+22)*PEC(ECP,T+22))/(1+R)**22
             +(SHD(EC,T+23)*PEC(EC,T+23)-SHD(ECP,T+23)*PEC(ECP,T+23))/(1+R)**23
             +(SHD(EC,T+24)*PEC(EC,T+24)-SHD(ECP,T+24)*PEC(ECP,T+24))/(1+R)**24
             +(SHD(EC,T+25)*PEC(EC,T+25)-SHD(ECP,T+25)*PEC(ECP,T+25))/(1+R)**25
             +(SHD(EC,T+26)*PEC(EC,T+26)-SHD(ECP,T+26)*PEC(ECP,T+26))/(1+R)**26
```

```
              +(SHD(EC,T+27)*PEC(EC,T+27)-SHD(ECP,T+27)*PEC(ECP,T+27))/(1+R)**27
              +(SHD(EC,T+28)*PEC(EC,T+28)-SHD(ECP,T+28)*PEC(ECP,T+28))/(1+R)**28
              +(SHD(EC,T+29)*PEC(EC,T+29)-SHD(ECP,T+29)*PEC(ECP,T+29))/(1+R)**29
              +(SHD(EC,T+30)*PEC(EC,T+30)-SHD(ECP,T+30)*PEC(ECP,T+30))/(1+R)**30
              +(SHD(EC,T+31)*PEC(EC,T+31)-SHD(ECP,T+31)*PEC(ECP,T+31))/(1+R)**31
              +(SHD(EC,T+32)*PEC(EC,T+32)-SHD(ECP,T+32)*PEC(ECP,T+32))/(1+R)**32
              +(SHD(EC,T+33)*PEC(EC,T+33)-SHD(ECP,T+33)*PEC(ECP,T+33))/(1+R)**33
              +(SHD(EC,T+34)*PEC(EC,T+34)-SHD(ECP,T+34)*PEC(ECP,T+34))/(1+R)**34
              +(SHD(EC,T+35)*PEC(EC,T+35)-SHD(ECP,T+35)*PEC(ECP,T+35))/(1+R)**35
              +(SHD(EC,T+36)*PEC(EC,T+36)-SHD(ECP,T+36)*PEC(ECP,T+36))/(1+R)**36
              +(SHD(EC,T+38)*PEC(EC,T+37)-SHD(ECP,T+37)*PEC(ECP,T+37))/(1+R)**37
              +(SHD(EC,T+39)*PEC(EC,T+38)-SHD(ECP,T+38)*PEC(ECP,T+38))/(1+R)**38
              +(SHD(EC,T+40)*PEC(EC,T+39)-SHD(ECP,T+39)*PEC(ECP,T+39))/(1+R)**39
              +(SHD(EC,T+40)*PEC(EC,T+40)-SHD(ECP,T+40)*PEC(ECP,T+40))/(1+R)**40
              -(RC(EC,ECP,T)+PSI(T))*(1-THO(EC,ECP,T))*PI(T);

RG(EC,"I",T)=-100000;
RG("A","H",T)=-100000;RG("B","H",T)=-100000;RG("C","H",T)=-1000001;RG("D","H",T)=-100000;RG("E","H",T)=-100000;RG("F","H",T)=-100000;RG("G","H",T)=-100000;
RG("A","G",T)=-100000;RG("B","G",T)=-100000;RG("C","G",T)=-100000;RG("D","G",T)=-100000;RG("E","G",T)=-100000;RG("F","G",T)=-100000;
RG("A","F",T)=-100000;RG("B","F",T)=-100000;RG("C","F",T)=-100000;RG("D","F",T)=-100000;RG("E","F",T)=-100000;
RG("A","E",T)=-100000;RG("B","E",T)=-100000;RG("C","E",T)=-100000;RG("D","E",T)=-100000;
RG("A","D",T)=-100000;RG("B","D",T)=-100000;RG("C","D",T)=-100000;
RG("A","C",T)=-100000;RG("B","C",T)=-100000;
RG("A","B",T)=-100000;


MAXIMUM(EC,T)=-10000000000;

LOOP(EC,
LOOP(ECP,
IF (RG(EC,ECP,T) GT MAXIMUM(EC,T), MAXIMUM(EC,T)=RG(EC,ECP,T) )
    )
    )
;


RS(EC,ECP,T)=0;



LOOP(EC,
FLAG=0;
LOOP(ECP,
IF ((RG(EC,ECP,T) EQ MAXIMUM(EC,T)) and (MAXIMUM(EC,T) gt 0) and (FLAG eq 0), RS(EC,ECP,T)=1; FLAG=1;  )
    )
    )
;


SHAREREFUR(EC,T)=(ERA(EC,T)/sum(ECB,sum(ECD,RS(ECB,ECD,T)*ERA(ECB,T))))$((sum(ECB,RS(EC,ECB,T) ne 0)) and (ERA(EC,T) ne 0));


RM(EC,ECP,T)=SHAREREFUR(EC,T)*RS(EC,ECP,T)*ERR(T)*SUM(ECB,ERA(ECB,T));

RM(EC,ECP,T)=MIN(RM(EC,ECP,T),ERA(EC,T));

ERA(EC,T+1)=(1-DR(EC,T))*ERA(EC,T)+NC(EC,T) - SUM(ECP,RM(EC,ECP,T)) + SUM(ECP,RM(ECP,EC,T));

loop( EC, if( ERA(EC,T+1) lt 0,ERA(EC,T+1)=0));


ECH(EC,T)=SHD(EC,T)*ERA(EC,T)*1000/TJKWh  ;


E(EC,I,T)=ECH(EC,T)* Lambda(EC)* Alpha(EC,I)*(PEC(EC,T)/(PE(I,T)*(1+Tau(I,T))))**(Sigma(EC)) ;


ET(I,T) = SUM(EC,E(EC,I,T))  ;

INVN(T) = NC("A",T)*PNC("A",T)+NC("B",T)*PNC("B",T) ;

INVR(T)= SUM(EC,SUM(ECP,(RM(EC,ECP,T))*ERA(EC,T)*((RC(EC,ECP,T)+ PSI(T)))*PI(T)));

NetTax(T)=SUM(EC,SUM(I,E(EC,I,T)*PE(I,T)*Tau(I,T)))- SUM(EC,SUM(ECP,(RM(EC,ECP,T))*ERA(EC,T)*((RC(EC,ECP,T)+ PSI(T)))*THO(EC,ECP,T)*PI(T)));
```

```
);

display SHAREREFUR,RS,RM,RG,RC,ERAD,NC,X,DR,RC;

$include Sortie
```

Appendix C Meteo stations for each canton

C.1 Heating degree day

We use a climatic index based on an average daily temperature, the heating degree day (HDD) [4]. Following recommendations of the Swiss professional association of engineers and architects, we compute the HDD using Eq 20.

$$HDD(\theta_i, \theta_{th}) = \sum_{k=1}^{365} m_k \cdot \left(\theta_i - \theta_{e,k}\right) \tag{20}$$

with $m_k = 1$ if $\theta_{e,k} \leq \theta_{th}$ and $m_k = 0$ otherwise.

In this equation, θ_i is the target indoor temperature, $\theta_{e,k}$ is the average daily temperature for day k and θ_{th} is the threshold outside temperature under which heating becomes necessary. The formula for HDD computes and sums up daily differences between the inside and outside temperatures, whenever the daily mean temperature is lower than the threshold temperature, which reflects the quality of housing insulation. The better the insulation of buildings, the lower the value of the threshold temperature. Values of the parameters of the Eq. 20 that are commonly used for Switzerland are the following [4, 7]: $\theta_i = 20°$ and $\theta_{th} \in \{8, 10, 12°\}$. Following Christenson et al. [4], we make the assumption that the energy demand for heating is proportional to the value of HDD (Unit: days). We compare 3 different numbers of θ_{th} of all cantons in Figure 18.

Data on HDD by cantons and their stations were collected from Meteo Swiss. We obtain the HDD for each canton (see section C.2)

To add, we have the number of buildings in each canton (source: SFOE) and also HDD (for 3 different θ_{th}: 8, 10 and 12°). We calculate the average HDD in Switzerland, the results with different θ_{th} we compare with the HDD for Zurich for the same θ_{th}. The results demonstrate that our computations are close to the HDD Zurich sources' computations (see Figure 18).

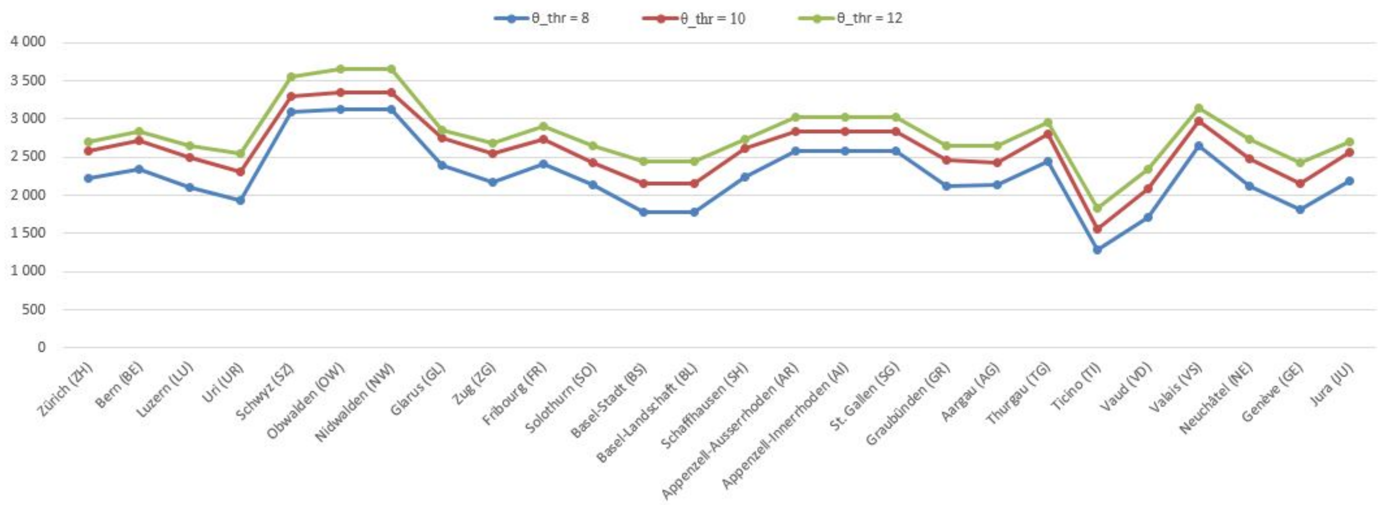

Figure 18: Heating degree days by cantons: θ_{th}=8° , θ_{th}=10°, θ_{th}=12°

C.2 HDD for each canton

In Table 21 we can see the cantons with the coresponding stations' names, locations, longitudes, latitudes, coordinates, altitudes and corresponding numbers of θ_{th}.

Several cantons did not have stations, the stations for these cantons were chosen according to their proximity to other stations: for example for canton Nidwalden (NW) was chosen the station of canton Obwalden (OW).

Additionally, big cantons like Zürich had numerous of stations, so the station was chosen according to its proximity to population point and/or the altitude of the point were it was built.

For cantons of Basel-Stadt (BS) and Basel-Landschaft (BL) was take the station of Basel-Stadt (BS).

For Appenzell-Ausserrhoden (AR) and Appenzell-Innerrhoden (AI) was staken the station of St. Gallen (SG).

For Solothurn (SO) and Aargau (AG) was taken the station of Biel/Bienne.

In Neuchâtel (NE)there were two convenient stations to take, we decided to make the calculation by taking 80% of Neuchâtel station plus 20% of La Chaux-de-Fonds station.

Table 21: List of meteo stations per canton

Canton	Name	Location	Longitude	Latitude	Altitude	θ_{th}=8	θ_{th}=10	θ_{th}=12
Aargau (AG)	BIL	Biel/Bienne	715	4707	433	2’130	2’435	2’642
Appenzell-Ausserrhoden (AR)	STG	St. Gallen	923	4725	775	2’581	2’834	3’029
Appenzell-Innerrhoden (AI)	STG	St. Gallen	923	4725	775	2’581	2’834	3’029
Basel-Landschaft (BL)	BAS	Basel / Binningen	735	4732	316	1’773	2’159	2’450
Basel-Stadt (BS)	BAS	Basel / Binningen	735	4732	316	1’773	2’159	2’450
Bern (BE)	BER	Bern / Zollikofen	727	4659	552	2’349	2’711	2’835
Fribourg (FR)	GRA	Fribourg / Posieux	706	4646	634	2’404	2’738	2’905
Genève (GE)	GVE	Genève-Cointrin	607	4614	420	1’813	2’158	2’427
Glarus (GL)	GLA	Glarus	904	4702	516	2’397	2’746	2’845
Graubnden (GR)	CHU	Chur	931	4652	556	2’117	2’464	2’648
Jura (JU)	DEL	Delémont	720	4721	415	2’186	2’569	2’707
Luzern (LU)	LUZ	Luzern	818	4702	454	2’095	2’500	2’649
Neuchâtel (NE)	80%NEU + 20% CDF	Neuchâtel	657	4700	485	2’116	2’470	2’741
	NEU	Neuchâtel	657	4700	485	2’116	2’470	2’741
	CDF	Neuchâtel	647	4704	1018	3’014	3’304	3’616
Nidwalden (NW)	ENG	Engelberg	824	4649	1’035	3’123	3’352	3’646
Obwalden (OW)	ENG	Engelberg	824	4649	1’035	3’123	3’352	3’646
Schaffhausen (SH)	SHA	Schaffhausen	837	4741	438	2’248	2’608	2’739
Schwyz (SZ)	EIN	Einsiedeln	845	4707	910	3’097	3’295	3’550
Solothurn (SO)	BIL	Biel/Bienne	715	4707	433	2’130	2’435	2’642
St. Gallen (SG)	STG	St. Gallen	923	4725	775	2’581	2’834	3’029
Thurgau (TG)	TAE	Aadorf / Tnikon	854	4728	539	2’448	2’805	2’954
Ticino (TI)	LUG	Lugano	857	4600	273	1’286	1’566	1’837
Uri (UR)	ALT	Altdorf	837	4653	438	1’936	2’313	2’547
Valais (VS)	SIO	Sion	719	4613	482	2’655	2’974	3’142
Vaud (VD)	PUY	Pully	640	4630	455	1’703	2’086	2’340
Zug (ZG)	WAE	Wädenswil	840	4713	485	2’179	2’549	2’679
Zürich (ZH)	SMA	Zürich / Fluntern	833	4722	555	2’217	2’576	2’697