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

Draft version V2.1
Do not quote, cite or distribute

Sergey Arzoyan[a,*], Quirin Oberpriller[b], Marc Vielle[a], Michel Zimmermann[a]

[a] *Laboratory of Environmental and Urban Economics (LEURE), École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.*
[b] *INFRAS, Zürich, Switzerland.*

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 is usually assumed to be unaffected even by policies designed to foster innovation. This project aims at introducing endogenous EEI and barriers to innovation in housing sector. Sector representations will be included into an existing simulation model, GEMINI-E3. We detail the evolution of Swiss building stock of (Single-family and Multi-family houses) and how retrofit decisions and heating system improvements may reduce energy consumption. We are building stock model and sort out all buildings into energy cohorts, labelled A–G. In any given period, a part of each cohort is retrofitted and thus becomes more energy efficient. As a result, retrofitted buildings switch to better energy cohorts. We are introducing the formal model and are using CECB (Cantonal Energy Certificate for Buildings) classification system in order to label the housing stock. Additionally, we give the descriptive statistic and exhibit in details the data sources we used in order to build the model. We demonstrate the numerical implementations of the data into the model and comparing reference scenario with two additional scenarios: subsidy on retrofit and tax on fossil energy. Consequently, we are describing the results we got. In the last part we define the links with the GEMINI–E3 model, also introducing possible further improvements that can be implemented into building stock model.

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

---

*Corresponding author
Email address: sergey.arzoyan@epfl.ch (Sergey Arzoyan)

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. Streicher et al. [13] 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 paper is structured as follow: in section 2 we detail the equations of our building stock model; section 3 describes statistics and shows data sources; in section 4 preliminary scenarios and their comparison can be found; section 5 shows how this model is linked with a macro-economic model (namely GEMINI-E3); section 6 proposes different ways to improve our building stock model.

2. The Model

2.1. General idea

We sort all buildings into energy cohorts, labelled A–G. In any given period, a fraction of each cohort is retrofitted and thus gets more energy efficient. As a result, retrofitted buildings enter better energy cohorts.

Influencing Factors

The owner's retrofit decision depends on two layers of influencing factors:

- First layer: pure economic costs, that is (1) investment costs and (2) retrofits benefits in form of saved energy costs. The pure economic costs are all alike within an energy cohort.
- Second layer: further idiosyncratic characteristics of the buildings / owners, which differ within the energy cohort. We may be able to monetarize some of those characteristics. Others can only be included using crude qualitative estimates. Those characteristics are:
  - age-distribution of the buildings,
  - building type (single *versus* multi-family homes, etc),
  - owner number and type (one or several owners; private or institutional owners, etc),
  - owner preferences, risk attitudes, etc,
  - location,
  - type and age of heating system,
  - barriers and other non-economic criteria (e.g. principal-agent problem),
  - optionally but most likely too complicated: we may consider the distribution and age of different components (windows, walls, etc) as in TEP's archetype model [8].

Micro-economic decision model on retrofit decision

The first layer allows us to determine a simple cost/benefit estimation for each possible retrofit choice. Based on the first part alone, an owner's decision to retrofit or not would thus yield the same result for all buildings within an energy cohort, as buildings within an energy cohort have per definition the same specific energy demand and the same investment costs. The second layer allows us to overlay the single (and overly simplistic) benefit/cost of the first layer with an additional structure such that we obtain a realistic retrofit rate within the cohorts (and overall).

We have two options how to include the additional structure due to the further idiosyncratic characteristics into the investment decision:

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

- *Version Histograms*: We may construct histograms or probability density functions (pdf) of benefits/costs within an energy cohort which finally determine the investment decision. That is, if net benefits are positive, the owner makes a retrofit with 100% probability; if they are negative, with 0% probability (the retrofit decision is a step function). In such a model all further idiosyncratic characteristics would have to be monetarized in some form and be included into the benefits/costs. In a first step we may merely explain the shape of the histogram/pdf using those further characteristics. To more clearly show their effects, we may - as a refinement in a second step use some of those characteristics to explicitly model the shape of a histogram (e.g. 10% of all buildings within a cohort have prohibitively high retrofit costs due to certain barriers, etc.)
- *Version Discrete Choice*: We may use the pure economic costs (first layer) as an input to a discrete choice model. The shape of the discrete choice model is determined by the characteristics of the second layer Jakob et al. [8] also uses a discrete choice approach for various parts of their model (e.g. [10]).

Concurrent improvement of the heating system

The concurrent improvement of the heating system (e.g. the change from oil heating to a heat pump) can be considered as follows:

- Certain retrofit types entail heavy construction work and habitants have to be resettled. If a change in the heating system seems appropriate (e.g. age close to live-time), it is likely that this is done at the same time as a retrofit;
- After a retrofit, houses need less high-temperature energy if e.g. a floor heating is installed. Therefore e.g. heat-pumps get more cost efficient in relation to oil-burners. This additional aspect may be included into the micro-economic decision model;
- On the other hand, if the replacement of an oil-burner is necessary, this may trigger a retrofit as a prerequisite for a heat-pump;
- Weighted final energy figures use a weighting factor (g) with respect to the heating energy source (Electricity g=2; oil/gas g=1; solar g=0) and therefore already include this aspect. The MuKEn-Norm [2] requires a maximum weighted final energy demand for new buildings. We may in some form use that number to estimate improvements in the energy systems of new buildings.

Initial distribution

To set the initial distribution of buildings within the energy cohorts we merge data on (1) energy reference area per vintage (construction years) with (2) specific space heating demand (SHD) for a given vintage (see [6]. Additional sources may be used as well. The start year of the model may be in the past or in the present.

2.2. Formal model

We describe in this section the equations of our building stock model. The names of the variables, coefficients and indices are given in Table 3. The housing stock is grouped into energy cohorts EC that will follow CECB (Cantonal Energy Certificate for Buildings) classification[3]. This classification is given in Table 1. Each energy cohort has fixed specific SHD $SHD_{EC,t}$ (kWh/m^2) and the energy cohorts are ranked with the following relationship:

$$SHD_{A,t} < SHD_{B,t} < \ldots < SHD_{F,t} < SHD_{G,t} \quad \forall t \tag{1}$$

The quantity of housing in each cohort is measured by the total energy reference area ERA (m^2) of the buildings that belong to that cohort, i.e. the total heated surface. The ERA changes from one period to the next because of a proportion that is demolished, through new construction and through transfers between cohorts through retrofit Eq.(2). A cohort loses buildings whose energy efficiency is improved to a better (i.e. lower)

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

[3] see `https://www.cecb.ch/`

Table 1: CECB labels

	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 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 extensive potential for renovation.	A non-renovated building with no use of, renewable energies and with extensive potential for renovation.

EC label. On the other hand, it gains buildings from less efficient cohorts that get improved to its own EC label. These transitions are represented by a retrofit matrix RM.

The law of motion of the energy reference area is given in Eq.(2).

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

In order to compute the retrofit matrix we should firstly compute the retrofit gain. Retrofit gain is equal to discounted heating cost before retrofit minus discounted heating cost after retrofit minus the cost of retrofit. We do not take into account changes in operation and maintenance costs as they can be considered in building retrofit as negligible [13].

Retrofit gain is given in Eq.(3).

$$RG_{EC,t}^{EC'} = \sum_{t'=t}^{t+T^R} \frac{SHD_{EC,t'}\cdot PEC_{EC,t'} - SHD_{EC',t'}\cdot PEC_{EC',t'}}{(1+r)^{t'-t}} - \frac{RC_{EC,t}^{EC'}+\psi_t}{\tau_{RC,t}}\cdot(1-\tau_{EC,t}^{EC'})\cdot PI_t \tag{3}$$

$$RM_{EC,t}^{EC'} = RS_{EC,t}^{EC'}\cdot ERR_{EC,t} \tag{4}$$

In order to understand the retrofit matrix we should also understand what is retrofit success. We have positive retrofit success 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 zero

Retrofit success is given in Eq. 5

$$RS_{EC,t}^{EC'} = 1 \ \text{ if} \begin{cases} RG_{EC,t}^{EC'} > 0 \\ RG_{EC,t}^{EC'} > RG_{EC,t}^{\overline{EC}} \ \ \forall\, \overline{EC} > EC \end{cases} ;0 \text{ otherwise} \tag{5}$$

We assume that a fixed share (ERR_t) of the capital stock is retrofitted each year. The retrofit matrix RM (Eq. 6) is equal to energy reference area $ERA_{EC,t}$ divided by refurbishment success RS multiplied on $ERA_{EC',t}$. Then this expression is multiplied on exogenous refurbishment rate ERR_t and on the sum of $ERA_{EC,t}$.

$$RM_{EC,t}^{EC'} = \frac{ERA_{EC,t}}{\sum_{\overline{EC}} \sum_{EC''} RS_{\overline{EC}}^{EC''} \cdot ERA_{EC',t}} \cdot ERR_t \cdot \sum_{\overline{EC}} ERA_{\overline{EC},t} \quad if \quad \sum_{EC'} RS_{EC}^{EC'} \neq 0 \quad and \quad ERA_{EC,t} \neq 0 \tag{6}$$

New construction for energy cohort EC is equal to its share in construction ($\phi_{EC,t}$) multiplied by total building construction (Eq. 7).

$$NC_{EC,t} = \phi_{EC,t} \cdot (\overline{ERA_t} - \sum_{EC}((1 - DR_{EC,t-1}) \cdot ERA_{EC,t-1})) \tag{7}$$

Desired reference area is linked to population, and we assume the size of housing per capita is increasing with time.

Desired reference area is given in Eq.8

$$\overline{ERA_t} = (\theta_{1,t} + \theta_{2,t} \cdot t) \cdot Pop_t \tag{8}$$

Space heating demand equals energy consumption for the base year (γ_{EC}) multiplied by heating degree day (HDD) divided by an exogenous technical progress μ_{EC} (Eq. 9).

$$SHD_{EC,t} = \frac{\gamma_{EC} \cdot HDD_t}{(1 + \mu_{EC})^t} \tag{9}$$

The share of cohort EC in construction is given in Eq.10. We assume that new constructions will be of a high EC as they must match the threshold set by SIA 380/1 or MuKEn.

$$\phi_{EC,t} = 0 \text{ if } EC \in \{C, D, E, F, G\} \qquad \text{and } \sum_{EC} \phi_{EC,t} = 1 \; \forall t \tag{10}$$

Energy consumption for heating for energy cohort EC equals SHD multiplied by reference area.

Energy consumption for heating is given in Eq.11

$$ECH_{EC,t} = SHD_{EC,t} \cdot ERA_{EC,t} \tag{11}$$

The energy consumption (E) by each EC is a constant elasticity function (CES) of energy source, which implies in Eq.12, for each energy source (i, i.e. oil, natural gas, district heating, heat pump, wood, etc) [1].

$$EK_{EC,i,t} = ECH_{EC,t} \cdot \lambda_{EC} \cdot \alpha_{EC,i} \cdot \left(\frac{PEC_{EC,t}}{PEK_{i,t}} \right)^{\sigma_{EC}} \tag{12}$$

with $PEC_{EC,t}$ computed from the following equation:

$$PEC_{EC,t} = \lambda_{EC} \left(\sum_i \alpha_{EC,i} \cdot (PEK_{i,t})^{(1-\sigma_{EC})} \right)^{\frac{1}{(1-\sigma_{EC})}} \tag{13}$$

$$E_{EC,i,t} = EK_{EC,i,t} \cdot \lambda' \cdot \alpha_{EK,i} \cdot \left(\frac{PEK_{i,t}}{PE_{i,t} \cdot (1 + \tau_{i,t})} \right)^{\sigma_{EC}} \tag{14}$$

$$K_{EC,i,t} = EK_{EC,i,t} \cdot \lambda' \cdot (1 - \alpha_{EK,i}) \cdot \left(\frac{PEK_{i,t}}{PK_{i,t}} \right)^{\sigma_{EC}} \tag{15}$$

$$PEK_{i,t} = \lambda_{EK,i} \left(\alpha_{EK,i} \cdot (PE_{i,t} \cdot (1 + \tau_{i,t})^{(1-\sigma_{EC})} + (1 - \alpha_{EK,i}) \cdot PK_{i,t}^{(1-\sigma_{EC})} \right)^{\frac{1}{(1-\sigma_{EC})}} \tag{16}$$

Table 2: 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

Total heating energy consumption per source is computed by summing consumption of that source by all cohorts (Eq. 17).

$$ET_{i,t} = \sum_{EC} E_{EC,i,t} \tag{17}$$

Total investment in retrofit and construction are computed by the following equations:
Total investment in new building is given in Eq.18

$$Inv_t^N = NC_{A,t} \cdot PNC_{A,t} + NC_{B,t} \cdot PNC_{B,t} \tag{18}$$

Total investment in retrofit is given in Eq.19

$$Inv_t^R = \sum_{EC} \sum_{EC'} RM_{EC,t}^{EC'} \cdot ERA_{EC} \cdot \frac{(RC_{EC,t}^{EC'} + \psi_t)}{\tau_{RC,t}} \cdot PI_t \tag{19}$$

Net revenue taxes from housing (taxes minus subsidies) are calculated by multiplying energy consumption on price of energy sources and on tax rate on energy consumption. From the resulting number we deduct the total investment in retrofit multiplied on subsidy on retrofit (see Eq.20).

$$NetTax_t = \sum_{EC} \sum_{i} E_{EC,i,t} \cdot PE_{i,t} \cdot \tau_{i,t} - \sum_{EC} \sum_{EC'} RM_{EC,t}^{EC'} \cdot ERA_{EC} \cdot \frac{(RC_{EC,t}^{EC'} + \psi_t)}{\tau_{RC,t}} \cdot \tau_{EC,t}^{EC'} \cdot PI_t \tag{20}$$

CO_2 emissions from fossil fuel consumption are computed by multiplying fossil energy consumption on coefficient for particular energy carrier. Coefficients (ξ) [4] are given in Table 2.

$$CO2_{EC,t} = \sum_{EC} (\xi_{oil} \cdot E_{EC,oil,t} + \xi_{oil} \cdot E_{EC,gas,t} + \xi_{oil} \cdot E_{EC,coal,t}) \tag{21}$$

3. Descriptive statistics and data sources

We give in this section statistics on the Swiss housing building stock and the data source that are used to build these figures.

The Swiss building stock will be divided into seven energy classes A-G (according to CECB-GEAK[5] energy standards), each representing a different range of space heating demand (SHD) (kWh/m^2), as shown in Figure 1.

It describes the efficiency of the thermal insulation of a given building compared to a reference value (which corresponds to 100%). We define this reference as 40 kWh/m^2/a, based on the average SHD per year of new single-family and multi-family houses as described by SIA 380/1. For instance, all buildings of the Swiss building stock requiring less than 20 kWh per m^2 of energy reference area (ERA) will be classified as an A-Building, corresponding to 50% of the SHD of the reference case, and all buildings that require more than 120 kWh/m^2(ERA) will be in energy class G, corresponding to 300%, respectively. Table 5 shows on overview of the different ranges of space heat demand and corresponding energy classes.

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

[5] https://onlinelibrary.wiley.com/doi/epdf/10.1002/bapi.201110014

Table 3: Names of indices, variables and coefficients

Indices		
$EC, EC', \overline{EC}$	Energy cohort according to CECB $\in$ {A,B,C,D,E,F,G} see Table 1	
i	Energy carrier	
t, t'	Time period	
Variables		Units
$DR_{EC,t}$	Demolition rate	percentage
$E_{EC,i,t}$	Energy consumption	joule
$ECH_{EC,t}$	Energy consumption for heating	joule
$ERA_{EC,t}$	Energy reference area	m^2
$\overline{ERA}_t$	Desired reference area	m^2
ERR_t	Exogenous retrofit rate	percentage
$ET_{i,t}$	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
$NC_{EC,t}$	New construction	number
$NetTax_t$	Net revenue tax	percentage
$PE_{i,t}$	Price of energy sources	CHF
$PEC_{EC,t}$	Energy price per energy cohort	CHF
PI_t	Price on investment	CHF
$PNC_{A,t}$	Price of new building	CHF
Pop_t	Population	number
r	Discount rate	percentage
$RC_{EC_t,}^{EC'}$	Energy retrofit cost	CHF
$RG_{EC,t}^{EC'}$	Energy retrofit gain	CHF
$RM_{EC_t}^{EC'}$	Retrofit matrix	
$RS_{EC_t}^{EC'}$	Retrofit success	
$SHD_{EC,t}$	Space heating demand per m^2	kWh/m^2
T^R	Duration of retrofit	number
μ_{EC}	Exogenous technical progress = 0.5% (Source: [15])	percentage
$\tau_{i,t}$	Tax rate on energy consumption	percentage
$\tau_{EC,t}^{EC'}$	Subsidy on retrofit	percentage
ψ_t	Fixed cost of retrofit	percentage
$\tau_{RC,t}$	Technical progress on retrofit	
Coefficients		
$\alpha_{EC,i}$	CES share coefficient	
γ_{EC}	Energy consumption for the base year	
$\theta_{1,t}$	Coefficient	
$\theta_{2,t}$	Coefficient	
λ_{EC}	CES scale parameter	
ϕ_{EC}	Share of cohort EC in construction	
σ_{EC}	CES elasticity of substitution	
ξ_i	Coefficient for energy carriers	
$CO2_{EC,t}$	Emissions from fossil fuel consumption	

Table 4: Thresholds energy classes and their SHD

kWh/m^2(ERA)	< 20	20-40	40-60	60-80	80-100	100-120	> 120
Energy class	A	B	C	D	E	F	G

Table 5: Thresholds energy classes and their SHD

kWh/m^2(ERA)	< 31	63	94	126	157	189	> 189
Energy class	A	B	C	D	E	F	G

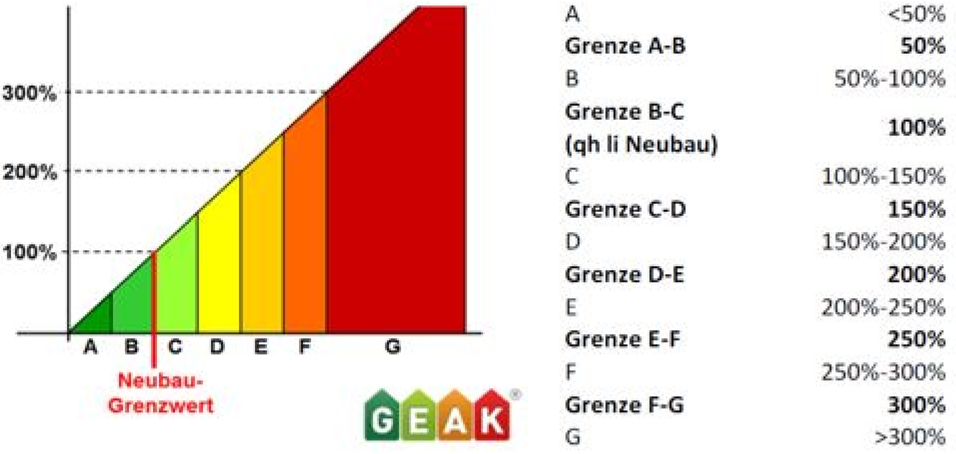

Figure 1: Graphical and numerical representation of energy classes CECB(GEAK)

3.1. *Energy reference area*

In Figure 2 we calculate the energy reference area in square meters. First of all, data on number of occupied houses per construction period for the years 2010-2016 and average surface of houses for the cohort years (before 1919,1945-1960,....2011-2016) were collected from Swiss Federal Office of Energy[6]. These two parameters are multiplied. After getting the ERA for each cohort we sum up ERAs and get the overall surface of the houses that should be heated. Thus on the Figure 2 we can see the energy reference areas in each cohort.

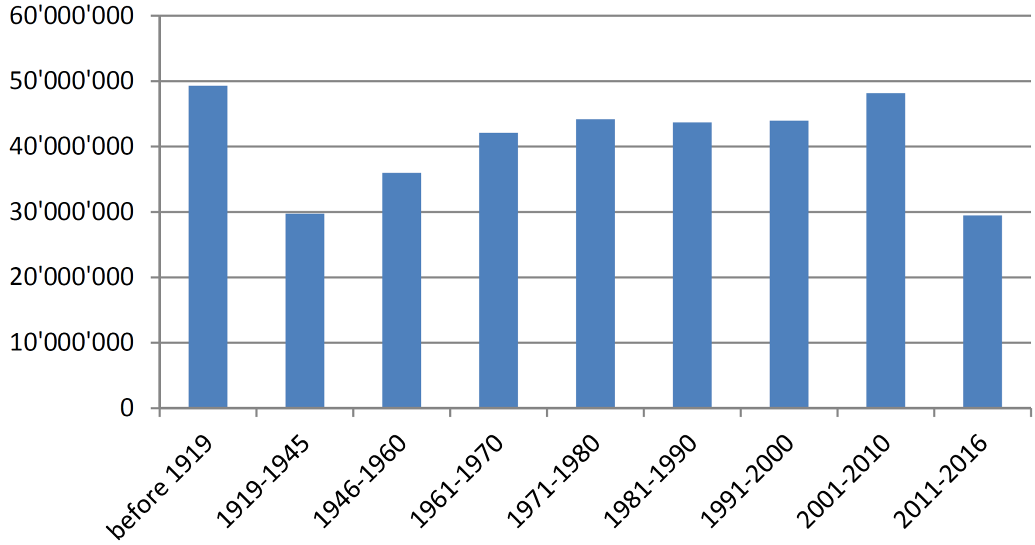

Figure 2: Energy reference area in m^2 per construction period ($ERA_{EC,t}$) year 2016

3.2. *Retrofit costs*

In order to estimate the retrofit costs that are necessary to reduce a building's SHD sufficiently for it to move to a better energy class, we use estimates from a study by SFOE [7]. 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 retrofit by the means of energy efficiency measures and subsequently satisfy the SHD 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 6 and 7, respectively. By

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

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

Table 6: Matrix for Investment Cost for SFH (in CHF/m^2 ERA)

kWh/m^2(ERA)		< 20 A	20-40 B	40-60 C	60-80 D	80-100 E	100-120 F	> 120 G
< 20	A		68	136	204	272	340	410
20-40	B			68	136	204	272	340
40-60	C				68	136	204	272
60-80	D					68	136	204
80-100	E						68	136
100-120	F							68
120	G							

Table 7: Matrix for Investment Cost for MFH (in CHF/m^2 ERA)

kWh/m^2(ERA)		< 20 A	20-40 B	40-60 C	60-80 D	80-100 E	100-120 F	> 120 G
< 20	A		41	82	123	164	205	250
20-40	B			41	82	123	164	205
40-60	C				41	82	123	164
60-80	D					41	82	123
80-100	E						41	82
100-120	F							41
120	G							

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. Table 6 and 7 display the respective retrofit costs for SFH and MFH, respectively.

In the case of SFH, for instance, 136 CHF/m^2(ERA) have to be invested in energy-efficiency retrofit measures to move a building currently classified as D to B. Similarly, 340 CHF/m^2(ERA) are needed to reduce the SHD of a F-building below 20 kWh/m^2(ERA) (i.e. turn it in a A-building). Regarding the plausibility of these estimates, one can refer to a study from a German retrofit project, which has delivered similar results (Enseling and Hinz, 2006).

3.3. Lifetime of retrofit

Lifetime of retrofit is the time till retrofit has to be repeated. Based on the Table 8 obtained from [11] we use a lifetime of 40 years.

Table 8: Lifeteme of refurbishment

Compotent	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

3.4. New construction

From Federal Statistical Office (FSO)[8] we have the data on average surface, new constructions and population from 1980-2016 by year. In order to find the overall surface of new constructions, we multiply average surface in each year by the quantity of new constructions in the corresponding year. So that new construction per capita is equal to the overall surface of new constructions (for each year) divided by the population in the corresponding year.

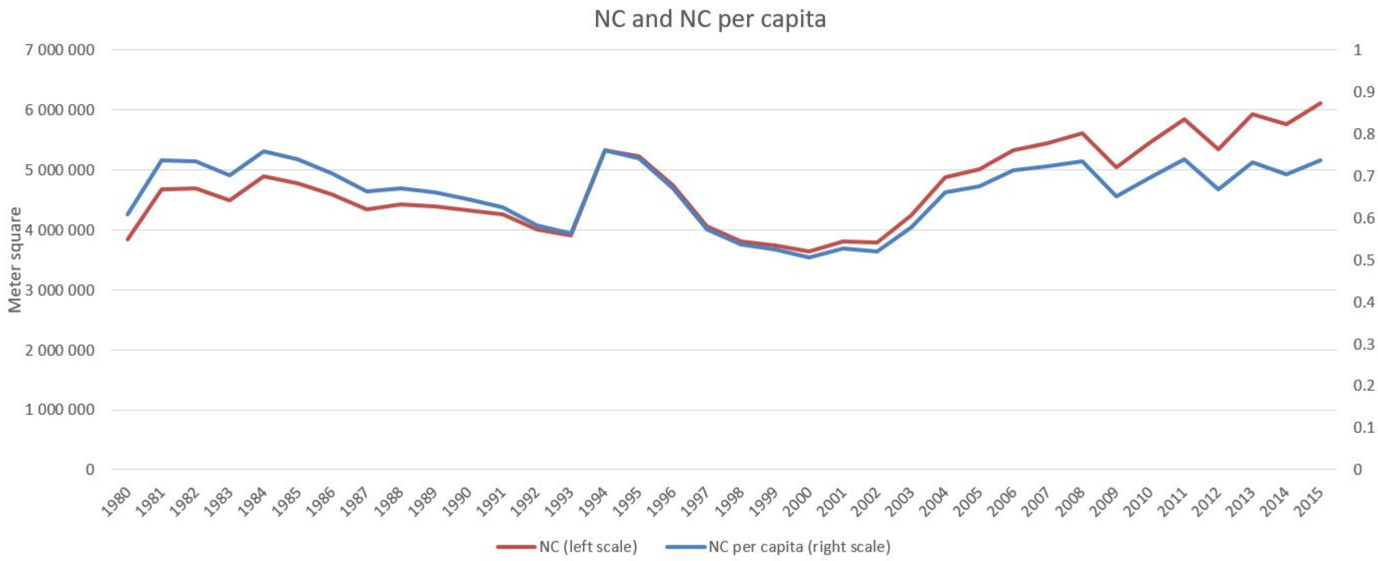

Figure 3: New construction and new construction per capita

3.5. Estimated demolition rates

To estimate demolition rates we use the statistic on occupied houses in square meters from 2010-2016 categorized by cohorts. For each construction period, we compute the decrease of occupied houses from 2016 to 2010. Some cohorts are unfortunately not represented in the statistics; for these cohorts, we interpolate the data between cohorts. Figure 5 shows the demolition rates.

3.6. Space heating demand

We know SHD for Zürich (see [6]), as can be seen in Figure 19. The canton of Zürich is taken as representative for Switzerland for all cantons. Since the construction periods in this study are only till the year of 1991-2000, after a linear approximation we added two more construction periods of 2001-2005 and 2006-2016 (see Table 9)

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

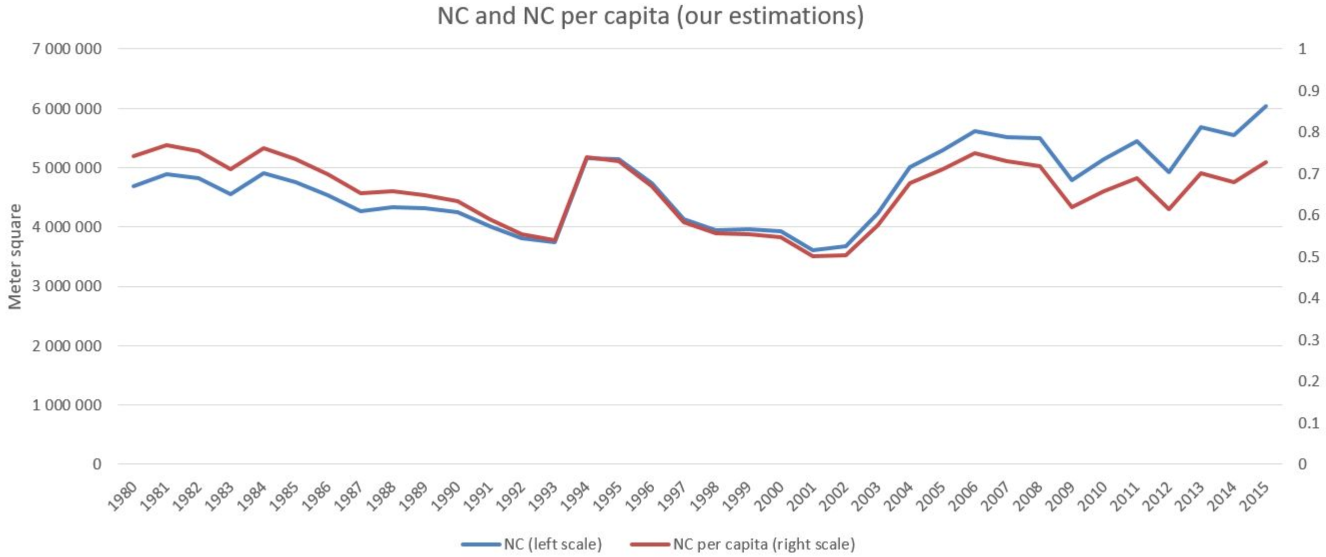

Figure 4: New construction and new construction per capita (based on our estimations)

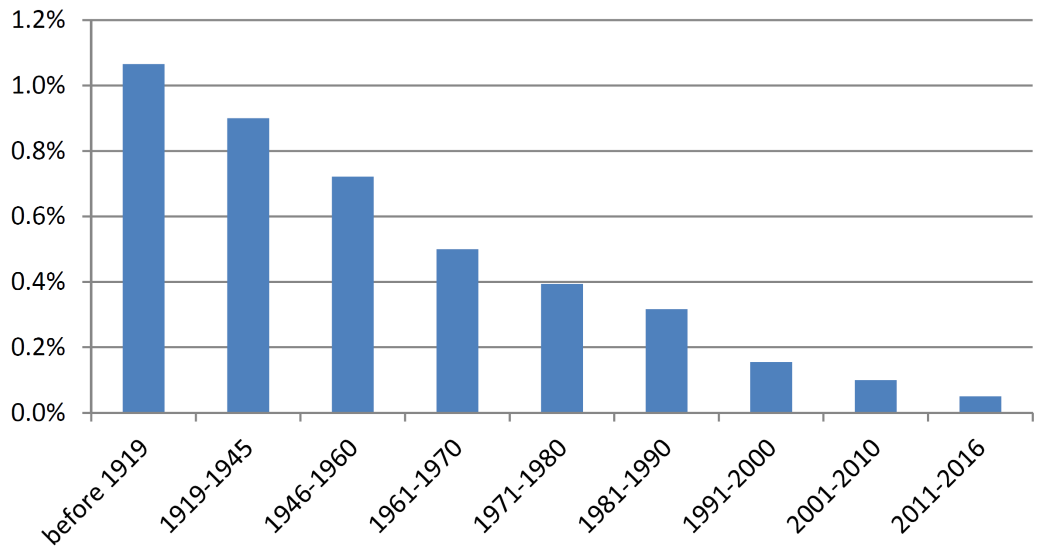

Figure 5: Estimated yearly demolition rate in % per construction period ($DR_{EC,t}$)

Table 9: SHD Zurich estimation

before 1919	135 KWh
1919-1945	170 KWh
1946-1960	170 KWh
1961-1970	165 KWh
1971-1980	165 KWh
1981-1990	123 KWh
1991-2000	90 KWh
2001-2005	75 KWh
2006-2016	70 KWh

3.6.1. 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 equation 22.

$$HDD(\theta_i, \theta_{th}) = \sum_{k=1}^{365} m_k \cdot \left(\theta_i - \theta_{e,k}\right) \tag{22}$$

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

In this equation, θ_i is the target interior 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 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 equation 22 that are commonly used for Switzerland are the following [4, 9]: $\theta_i = 20°$ 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. We compare 3 different numbers of θ_{th} of all cantons in Figure 6.

Data on HDD by cantons and their stations was collected from Meteo Swiss. We obtain HDD for each canton (see Appendix for more details).

To add, we have the number of buildings in each canton (data from SFOE) and also HDD (for 3 different θ_{th}: 8, 10 and 12°) In order to get the average HDD in Switzerland we sum up the HDD of all cantons together (for each θ_{th}) and divide the result obtained by the overall number of buildings in Switzerland. The resulting 3 numbers 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.

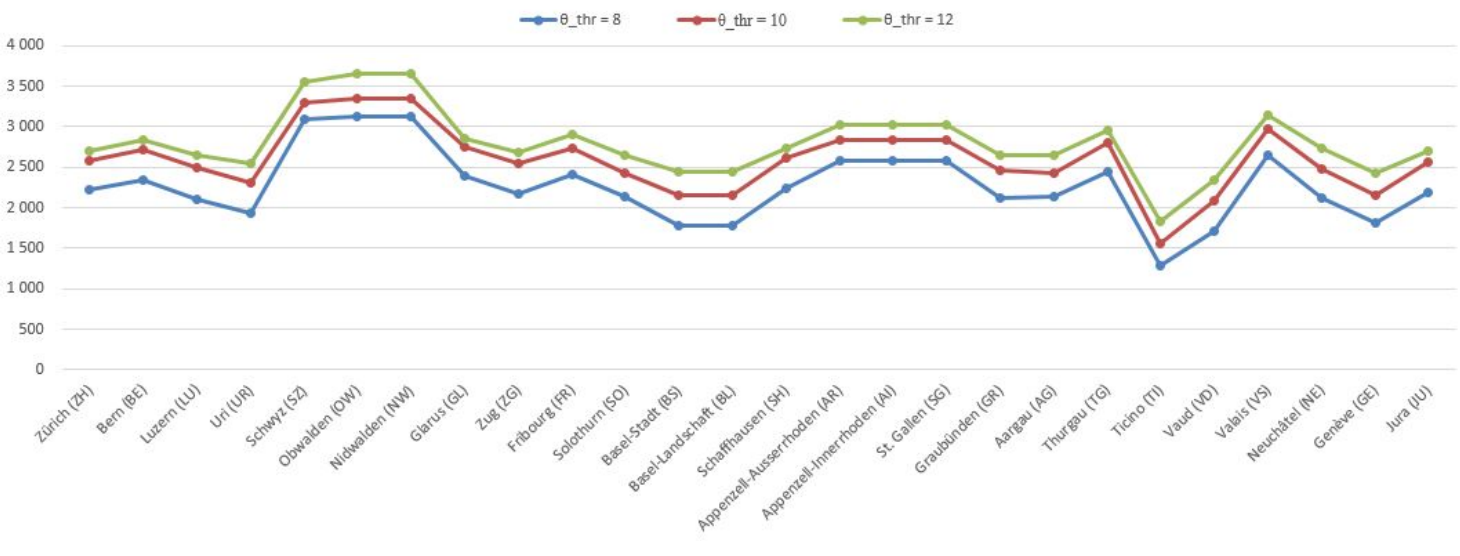

Figure 6: Heating degree days by cantons: θ_{th}=8° , θ_{th}=10°, θ_{th}=12°

Table 10: Energy consumption by energy carrier

	Our estimations	SFOE	Prognos
Oil	88 067	81 430	73 500
Coal	112	200	200
Gas	25 721	48 990	40 600
Electricity	18 120	68 680	9 300
Wood	15 561	19 060	17 700
Heat pump	16 199		5 300
Solar	415	14 810	500
Remote heat	2 909	7 540	7 000
Others	1 004		
Without heating	284		
Sum	168 393	240 710	154 100

3.7. Energy consumption by energy carrier

Energy consumption by energy carrier (oil, coal, gas, electricity and etc.) is computed for single and multi–family houses. Buildings are represented by construction periods (before 1919,1945-1960,....2006-2015). Data on energy carriers for single and multi family houses are coming from SFOE [9] in different tables (number of flats using particular energy carrier is given). Firstly, we sum up the two parameters by each energy carrier in the 2006-2015 cohort in order to get the overall number for both types of houses. After that, the resulting number is divided by the sum of the single and the sum of multi–family houses by energy carriers in order to demonstrate what is the percentage of the used energy carriers in that cohort.

The percentage is multiplied by ERA and by SHD (SHD is calculated using SHD Zürich data and our estimations) and divided by the number that will convert KWh in TJ, thus the resulting number will be in TJ. It is done, so that it is simpler for us to compare these numbers with the reference numbers that will follow.

Therefore, all the numbers for each cohort and each energy carrier are summed up, so that we have the resulting number for each energy carrier in TJ. The resulting numbers are compared with the reference data taken from SFOE and Prognos paper (see [5]) in order to understand if our estimations and calculations are reasonable (see Table 10).

As we can see, there is a big difference between electricity numbers from our estimations, Prognos paper and SFOE data. This is mainly due to the fact that in Prognos, the electricity number includes only the electricity used for the heating, when in the data from SFOE appliances are also taken into account. Difference in solar number is also due to the fact that in Prognos, number includes only the solar energy used for the heating.

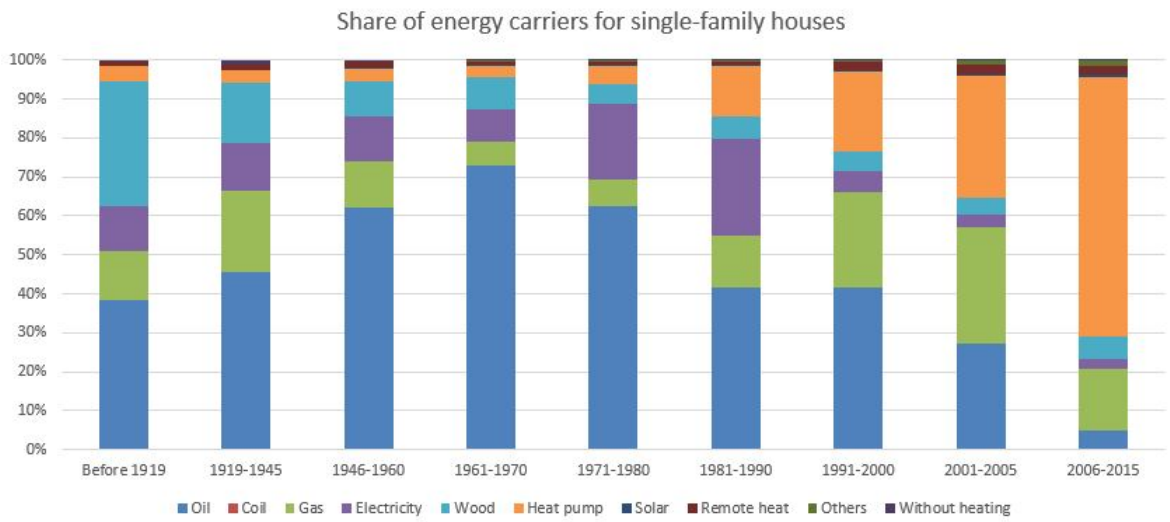

Figure 7: Share of energy carriers for single-family houses per vintage, year 2015

[9] https://www.bfs.admin.ch/bfs/fr/home/statistiques/construction-logement/batiments/domaine-energetique.assetdetail.1621740.html

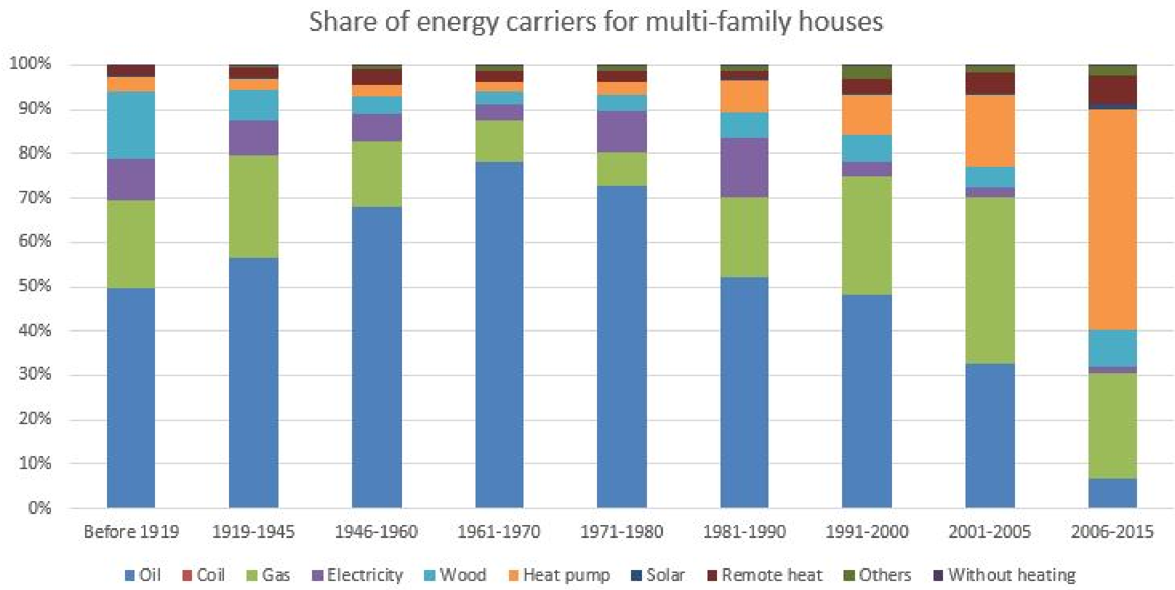

Figure 8: Share of energy carriers for multi-family houses per vintage, year 2015

3.8. *Price of energy*

We obtain the prices of energy carriers from different sources (see Table 11). The prices of electricity, gas and oil are coming from SFOE. According to [11] the price of pellets for 6600 kg is around 2000 CHF. So that we calculate and get the price of one tonne of pellets around 300 CHF. Also we know that one tonne of pellets is 5106 KWh of energy. Thus, dividing the price of one tonne of pellets by the energy of one tonne of it we get the price of 1 KWh energy. Heat pump price is one quarter of the electricity price according to the equation 23 take from see [14]. For solar price we assume to be its marginal price which is close to zero. Price of remote heat according to IWB [10] is equal to 0.0835-0.0856 CHF/KWh and according to Energie 360 [11] it is equal to 0.86 CHF/KWh. We deciding to use the price of 0.085 CHF/KWh in our model.

$$EFW_t = \frac{EF_{electricity}}{400\%} \tag{23}$$

Table 11: Expense of energy per KWh

Price KWh	2016
Electricity	0.201
Gas	0.093
Oil	0.079
Wood	0.059
Heatpump	0.050
Solar	0.001
District heating	0.085
Others	0.201

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

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

We also calculate the prices of energy carriers from the city of Zürich [12] (see Table 12). In the table we can see the Energy carriers and their capital cost and maintenance cost in.

Table 12: Price of energy 2015

Energy Carrier	Capital cost CHF/year	Maintenance cost CHF/year
Oil	0.048	0.021
Coil	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. Numerical implementations

We report in this section preliminary experiments with the model presented in section 2. Several simplifications are required mainly due to data availability. First, it was impossible to find statistic on the Swiss building stock by energy label (EC). We decided in a first step to replace the energy label by vintage (i.e. date of construction) and in this section the indices EC correspond to the vintage as given in Table 13.

Table 13: Correspondence between label and vintage

EC	Vintage
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

4.1. Reference scenario

The Table 15 shows the value of the parameters used in the reference scenario (See Figures 9 and 10).

4.2. Subsidy on retrofit

In this scenario we assume that the government implements a 25% subsidy on the retrofit cost (See Figures 13 and 14). In comparison to the energy reference area the amount of buildings in Label A increases when the amount of buildings in Label B decreases. That shows us that the buildings previously in label B switched to the label A (the most expensive label). Nonetheless, since we have subsidies for label A, it is still profitable to do the retrofit. For the case of retrofit in sqm. we see that the amount of the buildings renovated is the same, but since we have additional 25% of subsidy, the buildings are retrofitted till Label A, by taking the big amount of buildings of Label B. It means that previously renovated houses till Label B, are now renovated till Label A due to the subsidies.

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

Table 14: Value of parameter in the reference scenario

Duration of retrofit	T^R	40
Exogenous retrofit rate	ERR	0.01
Discount rate	r	0.03
CES elasticity of substitution	σ_{EC}	0.25
Technical progress on retrofit	τ_{RC}	0.01
Subsidy on retrofit	$\tau_{EC,t}^{EC'}$	0
Tax rate on energy consumption	$\tau_{i,t}$	0
Demolition rate	DR_EC	0.005
Share of cohort EC in construction	ϕ_A	0.7
Share of cohort EC in construction	ϕ_B	0.3

Table 15: Value of parameter in the reference scenario

Duration of retrofit	40
Exogenous retrofit rate	0.01
Discount rate	0.03
CES elasticity of substitution	0.25
Technical progress on retrofit	0.01
Subsidy on retrofit	0
Tax rate on energy consumption	0
Demolition rate	0.005

4.3. *Tax on fossil energy*

In this simulation, we assume that the government puts a tax on fossil energy of 50% (for oil, coal and natural gas)(See Figures15 and16). This scenario also fosters retrofit. Since 20% of tax was introduced, more buildings are renovated till Label A. If we compare with the case when we introduce 25% of subsidies, we see the tax of energy gives slightly more incentives to retrofit. Thus, more buildings are renovated till the highest level. Additionally, the retrofit is sqm. is higher than in the reference and subsidy scenarios. All the buildings are retrofitted till Label A since it is not economically profitable to renovate only till label B.

4.4. *Exogenous retrofit rate*

In this Scenario we change the Exogenous retrofit rate (ERR) from 1% to 1.5% (See Figures 17 and 18).

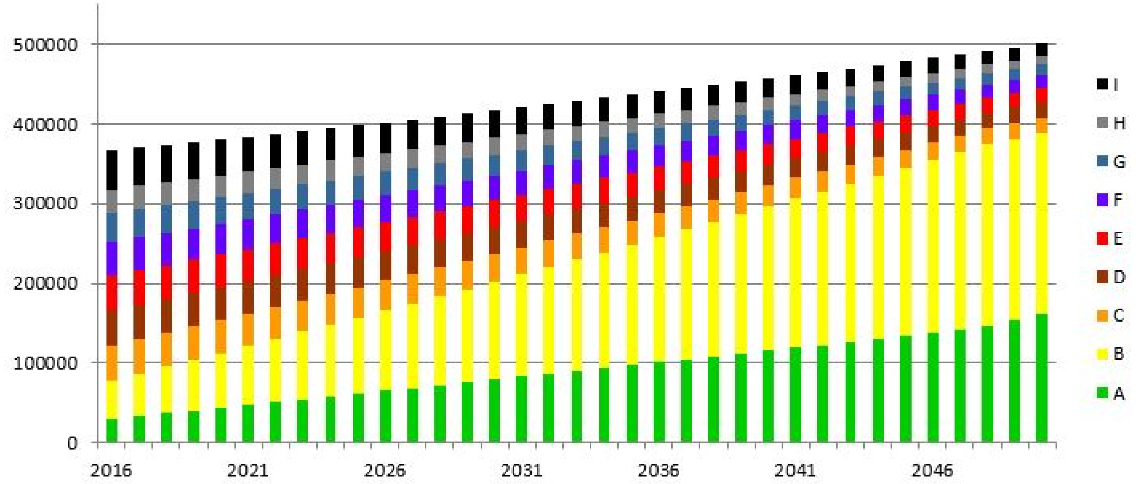

Figure 9: Energy reference area in m^2 - Reference scenario

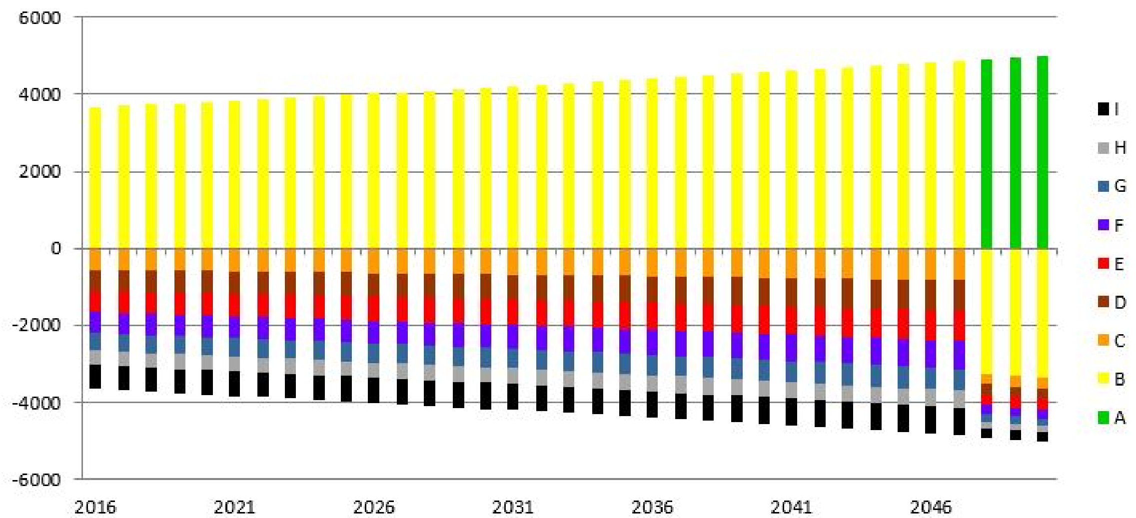

Figure 10: Retrofit in m^2 - Reference scenario (negative numbers are buildings that are subtracted, positive numbers are buildings that are added to an energy cohort)

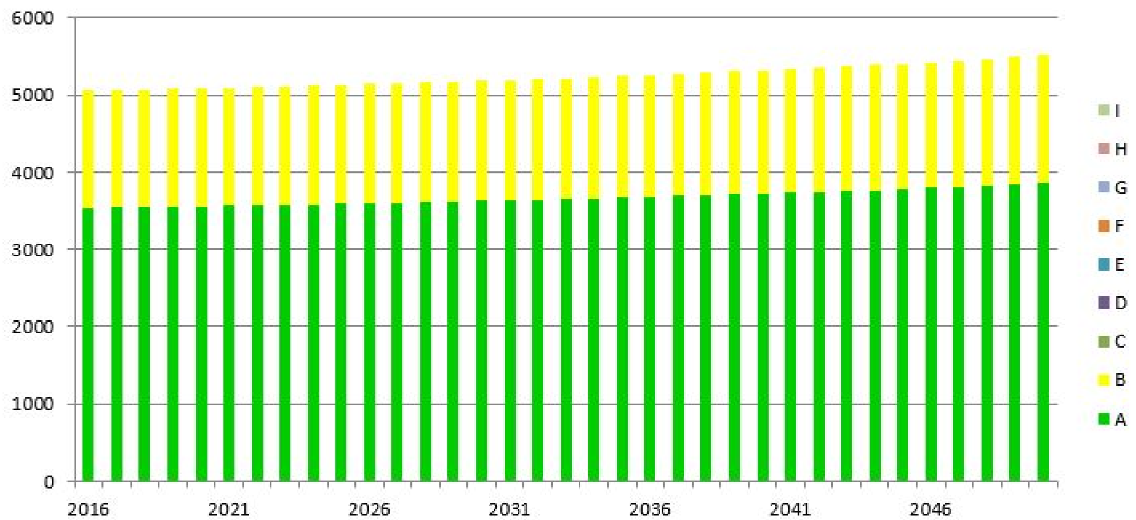

Figure 11: New construction in m^2 - Reference scenario

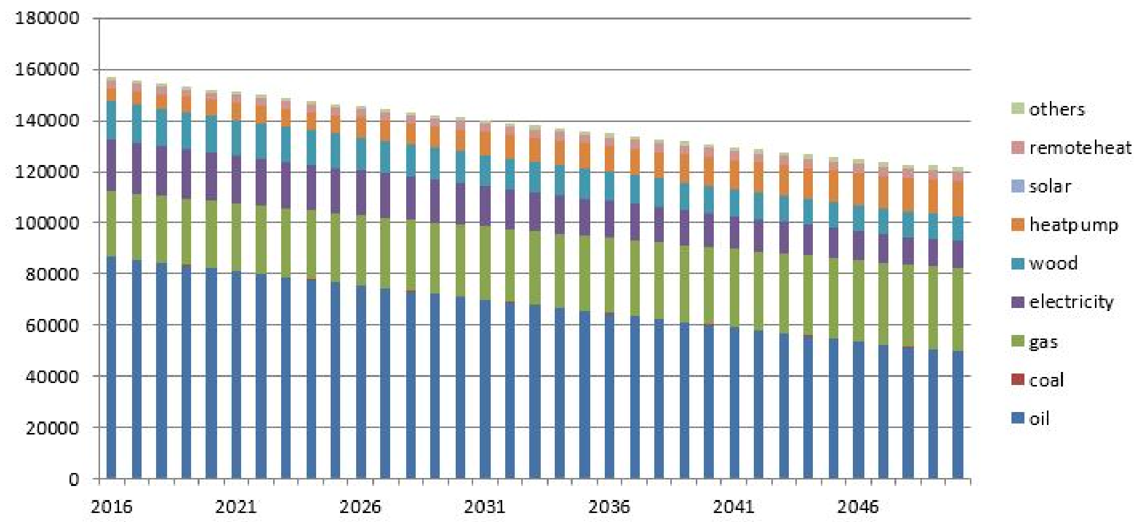

Figure 12: Energy consumption by energy carriers in TJ - Reference scenario

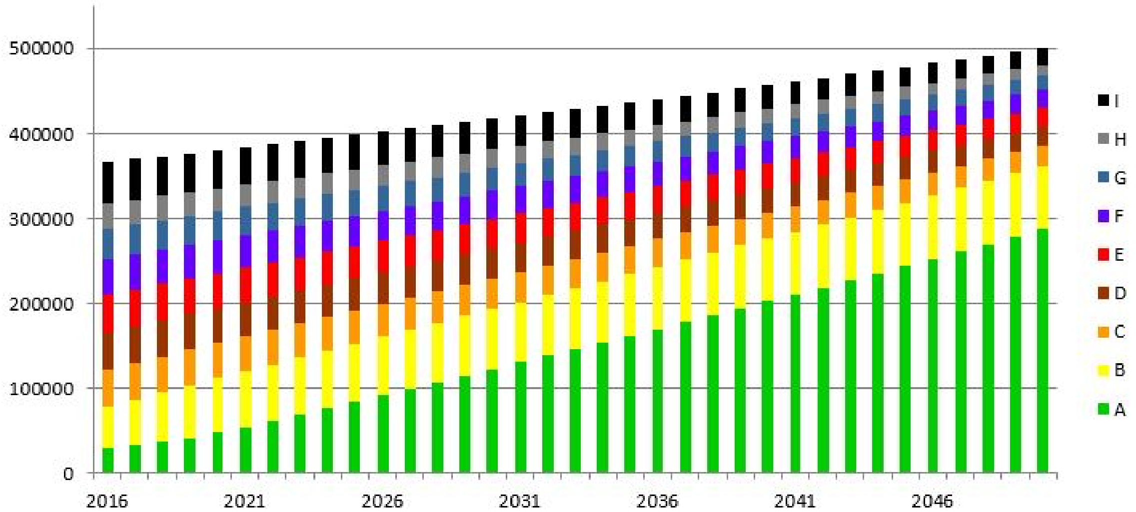

Figure 13: Energy reference area in m^2 - Scenario subsidy

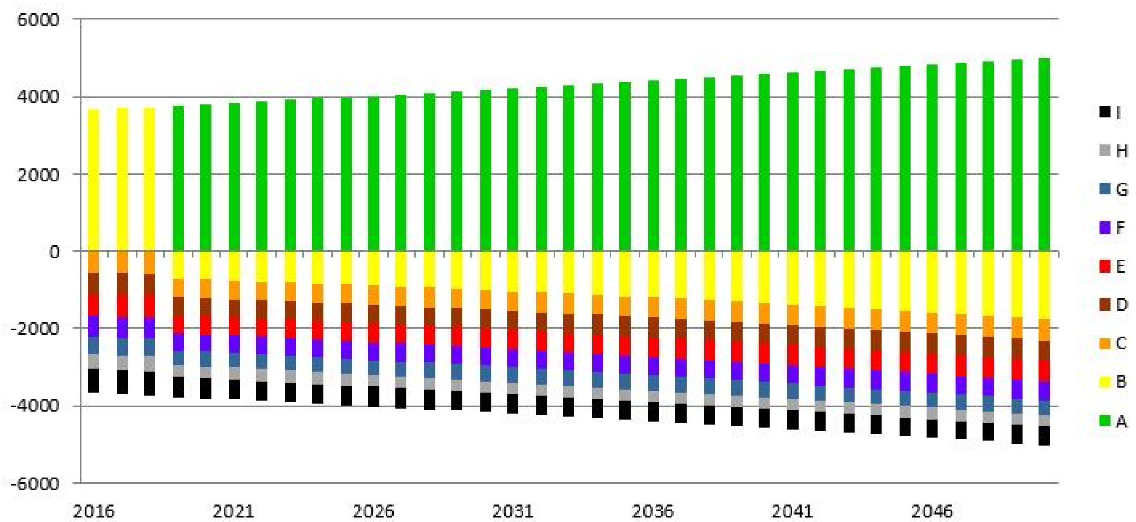

Figure 14: Retrofit in m^2 - Scenario subsidy (negative numbers building that are subtracted, positive numbers building that are added)

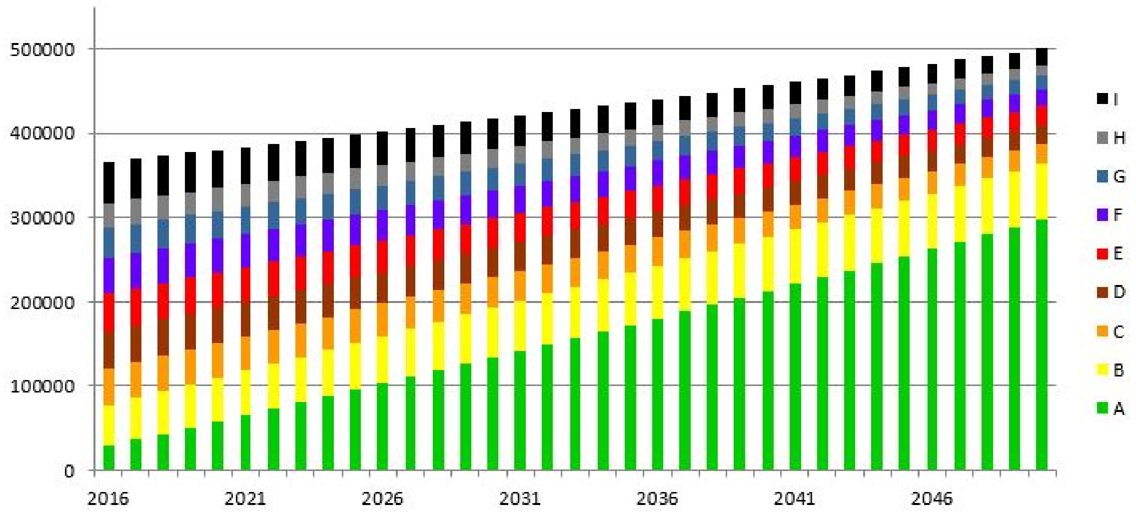

Figure 15: Energy reference area in m^2 - Scenario fossil energy tax

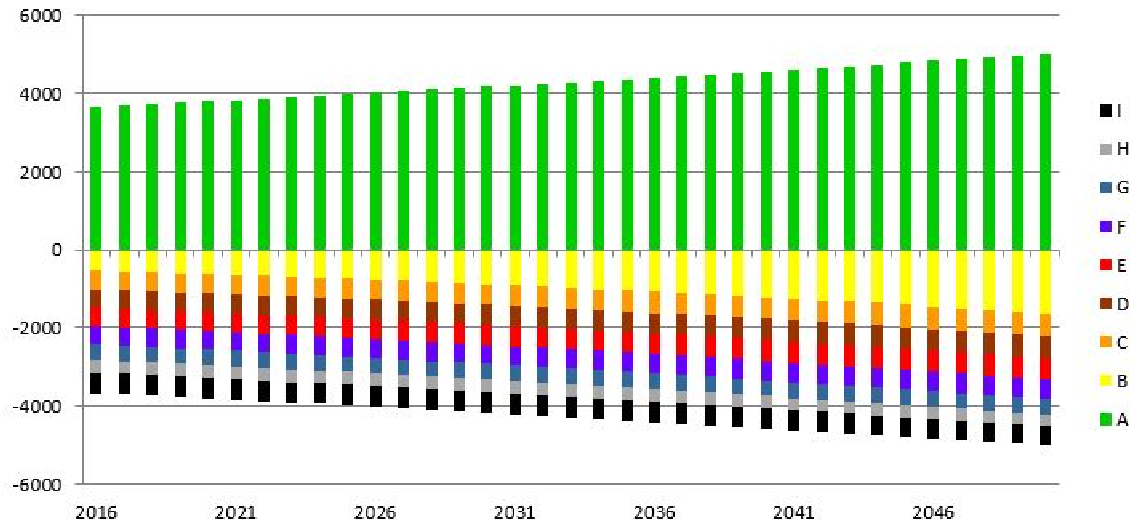

Figure 16: Retrofit in m^2 - Scenario fossil energy tax (negative numbers are buildings that are subtracted, positive numbers are buildings that are added to an energy cohort)

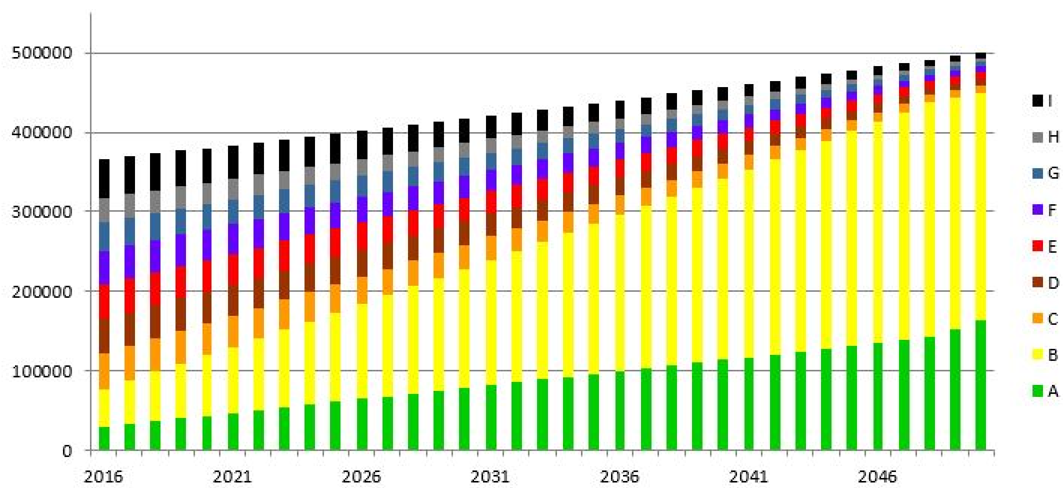

Figure 17: Energy reference area in sqm - Scenario exogenous retrofit rate

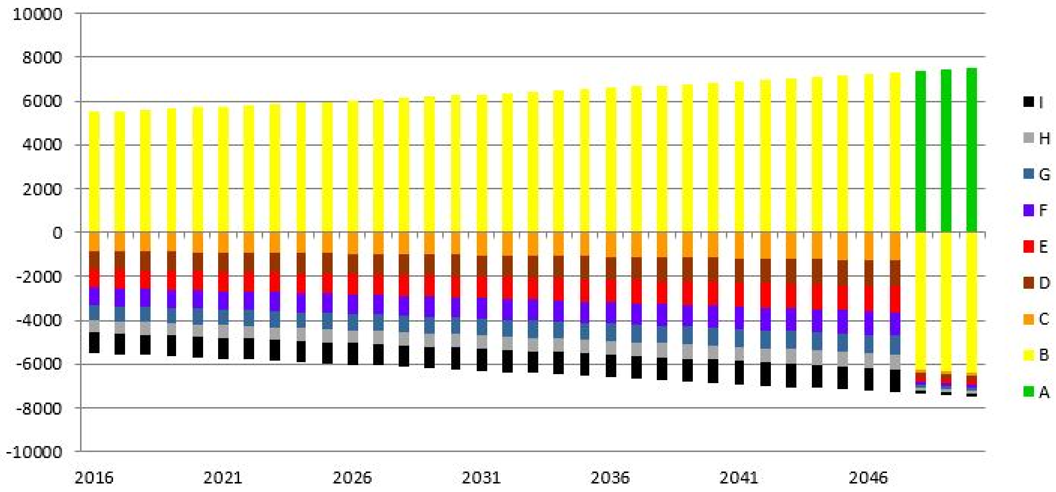

Figure 18: Retrofit in sqm - Scenario exogenous retrofit rate

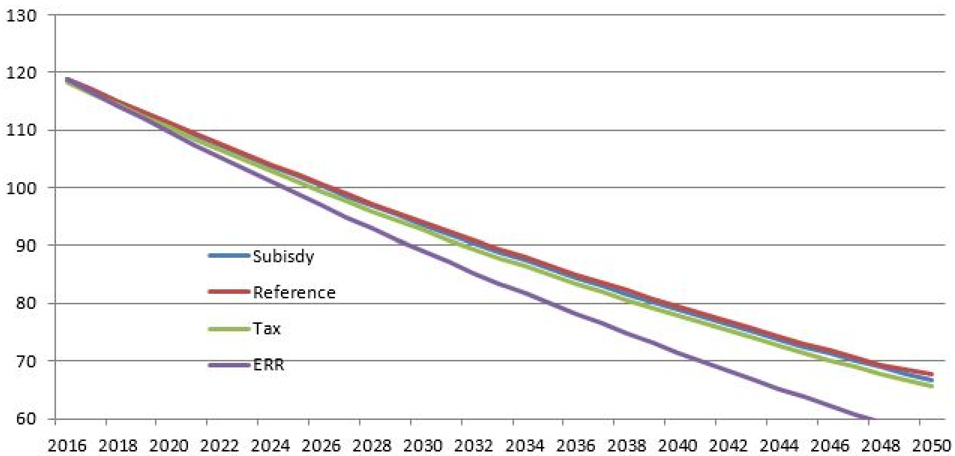

Figure 19: SHD in KWh/m^2

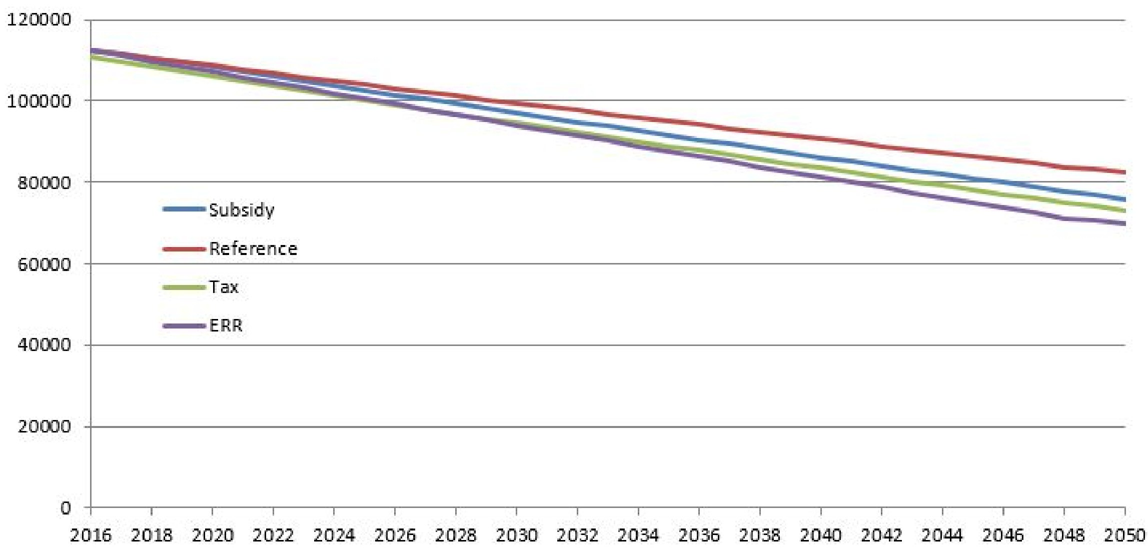

Figure 20: Fossil energy consumption in TJ

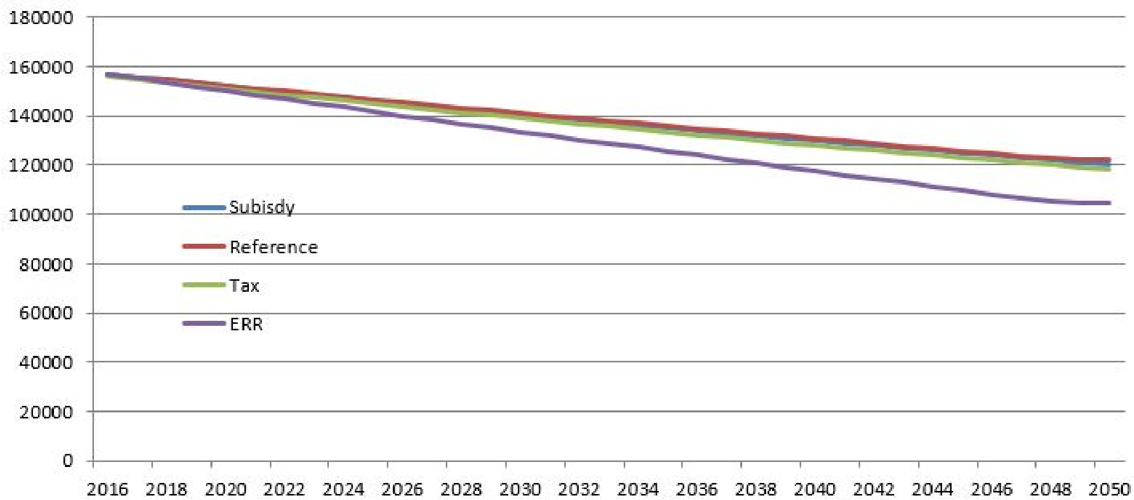

Figure 21: Energy consumption in TJ

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 22. GEMINI-E3 will provide 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 the 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 defined based on the scenario definitions (i.e. policy design).

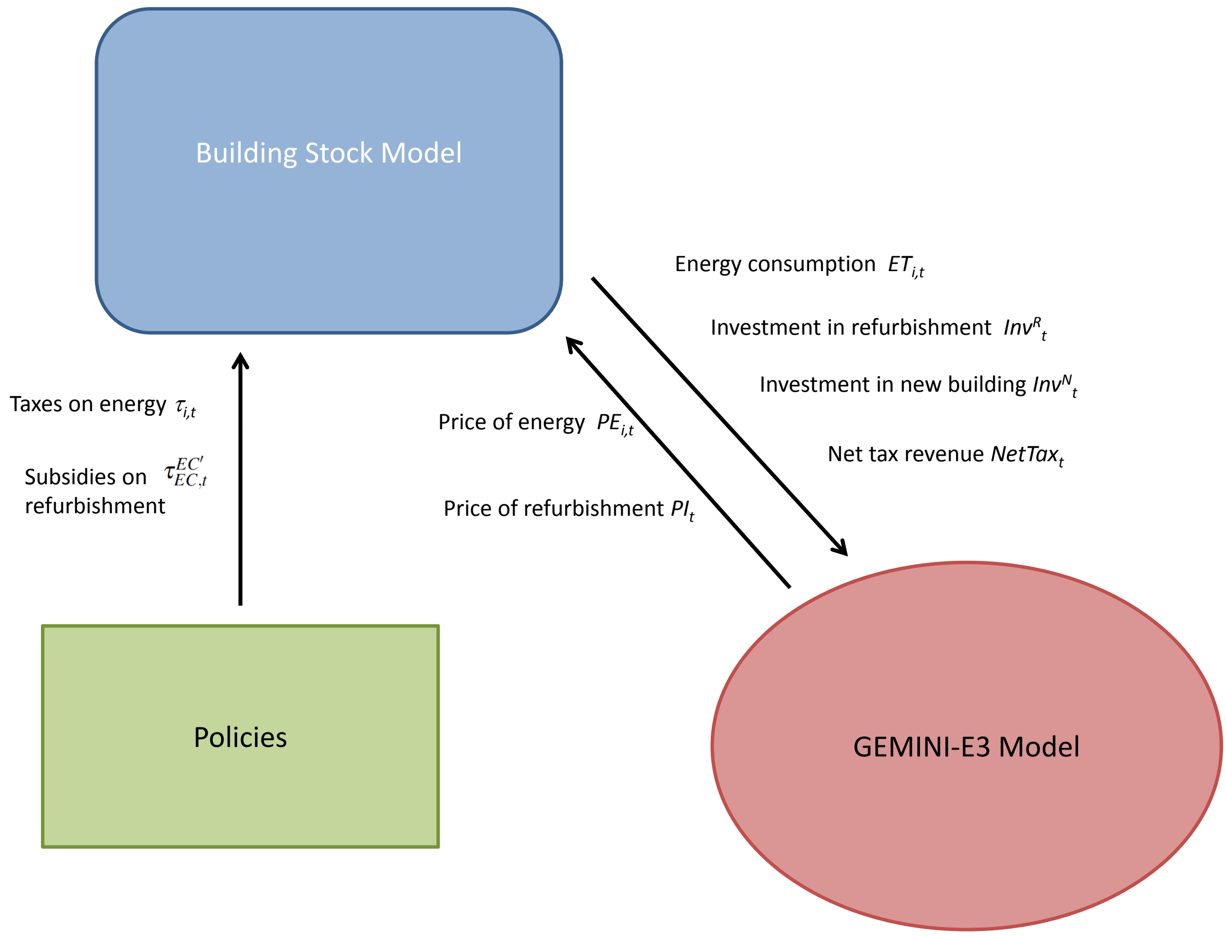

Figure 22: Coupling framework

6. Further improvements

Several improvements can be implemented in our building stock model. We give hereafter a tentative list that focusses mainly on coefficients that are exogenous in this first version:

- Obtain data on building stock by energy label,
- Endogenization $DR_{EC,t}$, Jakob et al. [7] used a log-logistic function calibrated with real data from the city of Zürich to estimate the demolition probability for each EC.
- Endogenization ERR_t,
- Endogenization $\phi_{EC,t}$,

- Take into account barriers in housing retrofit (Eq.(3)) which will limit renovation decisions [12],
- Better modeling of equation $\overline{ERA_t}$.

6.1. Endogenization of the retrofit rate

The most challenging part of the model is to determine retrofit rate for a given energy cohort and at a given time. The rates must be such that in the initial year ("initial problem") as well as in following years ("time shift problem") an appropriate retrofit rate results. We shall do so using the micro-economic decision model as outlined above.

First Step: determine pure economic costs of layer one

In both versions - Histograms or Discrete Choice - we would first determine the pure economic costs (first layer) bottom up.

Second Step: Overlay with additional structure due to further idiosyncratic characteristics

- in the Version Histogram, we would need to generate histograms until they fit the observed real refurbishment rate results:
  - Such histograms must be constructed for all *EC*s and within the *EC* for all possible retrofit successes;
  - If several *RG* have net benefits above zero within a *EC*, the *RG* with the greatest net benefit is obtained (as we do not model individual buildings, this is not straightforward. Yet, there should be a work-around to that problem).
- in the Version Discrete Choice, we would need to define /estimate the DC function and the inputs until the replicate the real retrofit rate results:
  - The discrete choice model should also determine which *RG* an owner chooses, if any (multi-dimensional choice);
  - Advantage of this version are that it may be easier to solve the time shift problem and we account for the unobservable facts in a more sophisticated way using a DC-model than merely shifting histograms;
  - One the other hand, estimating a DC model properly may be not feasible which means that we include yet another black box.

7. References

[1] K. J. Arrow, H. B. Chenery, B. S. Minhas, and R. M. Solow. Capital-Labor Substitution and Economic Efficiency. *The Review of Economics and Statistics*, 43(3):225–250, 1961.

[2] Frédéric Babonneau, Philippe Thalmann, and Marc Vielle. Defining deep decarbonization pathways for Switzerland: an economic evaluation. *Climate Policy*, 18(1):1–13, 2018.

[3] Alain Bernard and Marc Vielle. GEMINI-E3, a general equilibrium model of international–national interactions between economy, energy and the environment. *Computational Management Science*, 5(3): 173–206, 2008.

[4] M. Christenson, H. Manz, and D. Gyalistras. Climate warming impact on degree-days and building energy demand in Switzerland. *Energy Conversion and Management*, 47:671–686, 2006.

[5] Bundesamt für Energie and BFE. Eidgenössisches departement für umwelt, verkehr, energie und kommunikation uvek. 2012.

[6] Energie in Wohnbauten. Kanton Zürich Baudirektion. Amt für Abfall, Wasser, Energie und Luft. 2014.

[7] Martin Jakob, Gregor Martius, Giacomo Catenazzi, and Heike Berleth. Energetische Erneuerungsraten im Gebäudebereich - Synthesebericht zu Gebäudehlle und Heizanlagen. Swiss Federal Office of Energy, 2014.

[8] Martin Jakob, Giacomo Catenazzi, Remo Forster, Thomas Egli, Thorsten Kaiser, Raphael Looser, Marc Melliger, Claudio Nägeli, Ulrich Reiter, Martin Soini, and Benjamin Sunarjo. Erweiterung des gebäudeparkmodells gemäss sia-effizienzpfad energie. Swiss Federal Office of Energy, 2016.

[9] Almut Kirchner, Andreas Kemmler, Peter Hofer, Mario Keller, Martin Jakob, and Giacomo Catenazzi. Analyse des schweizerischen Energieverbrauchs 2000–2009 nach Verwendungszwecken. Technical report, Bundesamt für Energie BFE, 2010.

[10] Claudio Nägeli, Martin Jakob, Benjamin Sunarjo, and Giacomo Catenazzi. A building specific , economic building stock model to evaluate energy efficiency and renewable energy. *Cisbat*, pages 877–882, 2015.

[11] Swiss Federal office of Energy. Co2 tax exemption without emissions trading. 2013.

[12] Jenny Palm and Katharina Reindl. Understanding barriers to energy-efficiency renovations of multifamily dwellings. *Energy Efficiency*, 11(1):53–65, Jan 2018.

[13] Kai Nino Streicher, David Parra, Meinrad C. Bruerer, and Marin K. Patel. Techno-economic potential of large-scale energy retrofit in the Swiss residential building stock. *Energy Procedia*, 122:121–126, 2017.

[14] Umwelt, Verkehr, and Energie und Kommunikation UVEK. Eidgenssisches departement fr. 3003.

[15] Wüest Partner. Immo-monitoring 2017/2, 2017.

Acknowledgements

The research leading to these results has received funding from the Swiss Federal Office of Energy. Also, we are enormously thankful to Philippe Thalmann and Rolf Iten for their help as well as their wise remarks.

Appendix A 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")**Sigm»
a(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 B Meteo stations for each canton

In Table 16 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 16: 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