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.

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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 inhabitants 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 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

\[
SHD_{A,t} < SHD_{B,t} < ... < SHD_{F,t} < SHD_{G,t} \quad \forall t
\]

(1)

The quantity of housing in each cohort is measured by the total energy reference area ERA (m²) 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)
Table 1: CECB labels

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

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).

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

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).

\[
RG_{EC,t}^{EC'} = \sum_{t'=t}^{t+T_R} SHD_{EC,t'} \cdot PEC_{EC,t'} - SHD_{ECC,t'} \cdot PEC_{EC,t'} \cdot \frac{RC_{EC,t}^{EC'} + \psi_{t'} \cdot \tau_{RC,t} \cdot \Phi_{t}}{(1+r)^{t-t'}} \cdot (1 - \tau_{EC,t}) \cdot PI_{t} \tag{3}
\]

\[
RM_{EC,t}^{EC'} = RSE_{EC,t}^{EC'} \cdot ERR_{EC,t} \tag{4}
\]

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)

\[
RSE_{EC,t}^{EC'} = \left\{ \begin{array}{ll}
RG_{EC,t}^{EC'} > 0 & \forall EC > EC \\
RG_{EC,t}^{EC'} > RG_{EC,t}^{EC} & 0 \\
\end{array} \right.
\]

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Retrofit success is given in Eq. (5)

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RSE_{EC,t}^{EC'} = \left\{ \begin{array}{ll}
RG_{EC,t}^{EC'} > 0 & \forall EC > EC \\
RG_{EC,t}^{EC'} > RG_{EC,t}^{EC} & 0 \\
\end{array} \right.
\]
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 \(RS_{EC,t}\) multiplied on \(ERA_{EC,t}\). Then this expression is multiplied on exogenous refurbishment rate \(ERR_t\) and on the sum of \(ERA_{EC,t}\).

\[
RM_{EC,t} = \frac{ERA_{EC,t}}{\sum_{EC' EC} RE_{EC',t} \cdot RS_{EC',t} \cdot ERA_{EC,t}} \cdot ERR_t \cdot \sum_{EC} ERA_{EC,t} \text{ if } \sum_{EC} RS_{EC,t} \neq 0 \text{ and } ERA_{EC,t} \neq 0 \tag{6}
\]

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

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

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]

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

Space heating demand equals energy consumption for the base year \((\gamma_{EC})\) multiplied by heating degree day \((HDD)\) divided by an exogenous technical progress \(\mu_{EC}\) (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.

\[
\phi_{EC,t} = 0 \text{ if } EC \in \{C, D, E, F, G\} \quad \text{and} \quad \sum_{EC} \phi_{EC,t} = 1 \forall t \tag{10}
\]

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, \text{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:

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

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

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

\[
PEK_{i,t} = \lambda_{EK,i} \left(\alpha_{EK,i} \cdot (PE_{i,t})^{(1-\sigma_{EC})} + (1 - \alpha_{EK,i}) \cdot PK_{i,t}^{(1-\sigma_{EC})} \right)^{\frac{1}{1-\sigma_{EC}}} \tag{16}
\]
Table 2: CO₂ Emission Factors

<table>
<thead>
<tr>
<th>Source</th>
<th>Emission Factor (kg CO₂/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>0.078</td>
</tr>
<tr>
<td>Gas</td>
<td>0.056</td>
</tr>
<tr>
<td>Coal</td>
<td>0.093</td>
</tr>
</tbody>
</table>

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

\[ ET_{i,t} = \sum_{EC} E_{EC,i,t} \]  

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

Total investment in new building is given in Eq. 18

\[ Inv_{i}^{N} = NC_{A,t} \cdot PNC_{A,t} + NC_{B,t} \cdot PNC_{B,t} \]  

Total investment in retrofit is given in Eq. 19

\[ Inv_{i}^{R} = \sum_{EC} \sum_{EC'} RM_{EC,EC'} \cdot ERA_{EC} \cdot \frac{(RC_{EC,EC'}^{EC'} + \psi_{t})}{\tau_{RC,t}} \cdot P_{i,t} \]  

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).

\[ NetTax_{i,t} = \sum_{EC} \sum_{t} E_{EC;i,t} \cdot PE_{i,t} \cdot \tau_{i,t} - \sum_{EC} \sum_{EC'} RM_{EC,EC'} \cdot ERA_{EC} \cdot \frac{(RC_{EC,EC'}^{EC'} + \psi_{t})}{\tau_{RC,t}} \cdot \tau_{EC,EC'}^{EC'} \cdot P_{i,t} \]  

CO₂ emissions from fossil fuel consumption are computed by multiplying fossil energy consumption on coefficient for particular energy carrier. Coefficients \((\xi)\) are given in Table 2

\[ CO_{2EC,i,t} = \sum_{EC} (\xi_{oil} \cdot E_{EC,oil,t} + \xi_{gas} \cdot E_{EC,gas,t} + \xi_{coal} \cdot E_{EC,coal,t}) \]  

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 energy standards), each representing a different range of space heating demand (SHD) (kWh/m²), 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/m²/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 m² 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/m²(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.

---

Table 3: Names of indices, variables and coefficients

<table>
<thead>
<tr>
<th>Indices</th>
<th>Variables</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$EC, EC', EC''$</td>
<td>Demolition rate</td>
<td>percentage</td>
</tr>
<tr>
<td>$i$</td>
<td>Energy consumption</td>
<td>joule</td>
</tr>
<tr>
<td>$t, t'$</td>
<td>Energy consumption for heating</td>
<td>joule</td>
</tr>
<tr>
<td>$ERA_{EC, t}$</td>
<td>Energy reference area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$τ_{i, t}$</td>
<td>Desired reference area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$ERR_t$</td>
<td>Exogenous retrofit rate</td>
<td>percentage</td>
</tr>
<tr>
<td>$TE_{i, t}$</td>
<td>Total heating energy</td>
<td>joule</td>
</tr>
<tr>
<td>$HDD_t$</td>
<td>Heating degree day</td>
<td></td>
</tr>
<tr>
<td>$Inv^{N}_t$</td>
<td>Total investment in new building</td>
<td>CHF</td>
</tr>
<tr>
<td>$Inv^{R}_t$</td>
<td>Total investment in retrofit</td>
<td>CHF</td>
</tr>
<tr>
<td>$NC_{EC, t}$</td>
<td>New construction</td>
<td>number</td>
</tr>
<tr>
<td>$Net Tax_t$</td>
<td>Net revenue tax</td>
<td>percentage</td>
</tr>
<tr>
<td>$PE_{i, t}$</td>
<td>Price of energy sources</td>
<td>CHF</td>
</tr>
<tr>
<td>$PEC_{EC, t}$</td>
<td>Energy price per energy cohort</td>
<td>CHF</td>
</tr>
<tr>
<td>$PI_t$</td>
<td>Price on investment</td>
<td>CHF</td>
</tr>
<tr>
<td>$PN_{CA, t}$</td>
<td>Price of new building</td>
<td>CHF</td>
</tr>
<tr>
<td>$Pop_t$</td>
<td>Population</td>
<td>number</td>
</tr>
<tr>
<td>$r$</td>
<td>Discount rate</td>
<td>percentage</td>
</tr>
<tr>
<td>$RC_{EC, t}$</td>
<td>Energy retrofit cost</td>
<td>CHF</td>
</tr>
<tr>
<td>$RG_{EC, t}$</td>
<td>Energy retrofit gain</td>
<td>CHF</td>
</tr>
<tr>
<td>$RM_{EC, t}$</td>
<td>Retrofit matrix</td>
<td></td>
</tr>
<tr>
<td>$RS_{EC, t}$</td>
<td>Retrofit success</td>
<td></td>
</tr>
<tr>
<td>$SHD_{EC, t}$</td>
<td>Space heating demand per m$^2$</td>
<td>kWh/m$^2$</td>
</tr>
<tr>
<td>$T^8$</td>
<td>Duration of retrofit</td>
<td>number</td>
</tr>
<tr>
<td>$μ_{EC}$</td>
<td>Exogenous technical progress</td>
<td>percentage</td>
</tr>
<tr>
<td>$τ_{EC, t}$</td>
<td>Tax rate on energy consumption</td>
<td>percentage</td>
</tr>
<tr>
<td>$τ^{E}_{EC, t}$</td>
<td>Subsidy on retrofit</td>
<td>percentage</td>
</tr>
<tr>
<td>$ψ_t$</td>
<td>Fixed cost of retrofit</td>
<td>percentage</td>
</tr>
<tr>
<td>$β_{EC, t}$</td>
<td>Technical progress on retrofit</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$α_{EC, i}$</td>
<td>CES share coefficient</td>
<td></td>
</tr>
<tr>
<td>$γ_{EC}$</td>
<td>Energy consumption for the base year</td>
<td></td>
</tr>
<tr>
<td>$θ_{1, t}$</td>
<td>Coefficient</td>
<td></td>
</tr>
<tr>
<td>$θ_{2, t}$</td>
<td>Coefficient</td>
<td></td>
</tr>
<tr>
<td>$λ_{EC}$</td>
<td>CES scale parameter</td>
<td></td>
</tr>
<tr>
<td>$ϕ_{EC}$</td>
<td>Share of cohort EC in construction</td>
<td></td>
</tr>
<tr>
<td>$σ_{EC}$</td>
<td>CES elasticity of substitution</td>
<td></td>
</tr>
<tr>
<td>$ξ_t$</td>
<td>Coefficient for energy carriers</td>
<td></td>
</tr>
<tr>
<td>$CO2_{EC, t}$</td>
<td>Emissions from fossil fuel consumption</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Thresholds energy classes and their SHD

<table>
<thead>
<tr>
<th>kWh/m$^2$(ERA)</th>
<th>&lt; 20</th>
<th>20-40</th>
<th>40-60</th>
<th>60-80</th>
<th>80-100</th>
<th>100-120</th>
<th>&gt; 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy class</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
</tr>
</tbody>
</table>

Table 5: Thresholds energy classes and their SHD

<table>
<thead>
<tr>
<th>kWh/m$^2$(ERA)</th>
<th>&lt; 31</th>
<th>63</th>
<th>94</th>
<th>126</th>
<th>157</th>
<th>189</th>
<th>&gt; 189</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy class</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
<td>G</td>
</tr>
</tbody>
</table>
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. 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.

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. 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. /m² ERA for SFH and 250 Fr./m² ERA for MFH, as is shown in the top-right cell in Table 6 and 7, 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. 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: Lifetime of refurbishment

<table>
<thead>
<tr>
<th>Component</th>
<th>Reference technical service lifetime under medium load</th>
<th>Reference technical service lifetime under heavy load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facade</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Windows, exterior doors, gates</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Roof</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Sun protection</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Heater</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Ventilation</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Air conditioning, refrigeration</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Sanitary</td>
<td>45</td>
<td>40</td>
</tr>
</tbody>
</table>

3.4. New construction

From Federal Statistical Office (FSO) 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](image)

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).

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

Figure 5: Estimated yearly demolition rate in % per construction period ($DR_{EC_j}$)
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.

\[
HDD(\theta_i, \theta_{th}) = \sum_{k=1}^{365} m_k \cdot (\theta_i - \theta_{e,k})
\]

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

In this equation, \( \theta_i \) is the target interior temperature, \( \theta_{e,k} \) is the average daily temperature for day \( k \) and \( \theta_{th} \) 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]: \( \theta_i = 20^\circ \) and \( \theta_{th} \in \{8, 10, 12^\circ\} \). 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 \( \theta_{th} \) 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 \( \theta_{th} \): 8, 10 and 12\(^\circ\)) In order to get the average HDD in Switzerland we sum up the HDD of all cantons together (for each \( \theta_{th} \)) and divide the result obtained by the overall number of buildings in Switzerland. The resulting 3 numbers with different \( \theta_{th} \) we compare with the HDD for Zurich for the same \( \theta_{th} \). The results demonstrate that our computations are close to the HDD Zurich sources’ computations.

Figure 6: Heating degree days by cantons: \( \theta_{th}=8^\circ \), \( \theta_{th}=10^\circ \), \( \theta_{th}=12^\circ \)
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

---

Table 10: Energy consumption by energy carrier

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

---

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.

\[
EFW_t = \frac{EF_{electricity}}{400\%}
\]

Table 11: Expense of energy per KWh

<table>
<thead>
<tr>
<th>Price KWh</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.201</td>
</tr>
<tr>
<td>Gas</td>
<td>0.093</td>
</tr>
<tr>
<td>Oil</td>
<td>0.079</td>
</tr>
<tr>
<td>Wood</td>
<td>0.059</td>
</tr>
<tr>
<td>Heatpump</td>
<td>0.050</td>
</tr>
<tr>
<td>Solar</td>
<td>0.001</td>
</tr>
<tr>
<td>District heating</td>
<td>0.085</td>
</tr>
<tr>
<td>Others</td>
<td>0.201</td>
</tr>
</tbody>
</table>

We also calculate the prices of energy carriers from the city of Zürich\footnote{https://www.stadt-zuerich.ch/gud/de/index/beratungen_bewilligungen/ugz/Liegenschaftsbesitzende/energie-coaching/faktenblaetter.html} (see Table\ref{table:energy_prices}). In the table we can see the Energy carriers and their capital cost and maintenance cost in.

\begin{table}[h]
\centering
\begin{tabular}{lcc}
\hline
Energy Carrier & Capital cost CHF/year & Maintenance cost CHF/year \\
\hline
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 \\
\hline
\end{tabular}
\caption{Price of energy 2015}
\end{table}

4. Numerical implementations

We report in this section preliminary experiments with the model presented in section\ref{section:overview}. 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\ref{table:label_to_vintage}.

\begin{table}[h]
\centering
\begin{tabular}{lc}
\hline
EC & Vintage \\
\hline
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 \\
\hline
\end{tabular}
\caption{Correspondence between label and vintage}
\end{table}

4.1. Reference scenario

The Table\ref{table:reference_scenario} shows the value of the parameters used in the reference scenario (See Figures\ref{figure:reference_scenario} and\ref{figure:reference_scenario_2}).

4.2. Subsidy on retrofit

In this scenario we assume that the government implements a 25\% subsidy on the retrofit cost (See Figures\ref{figure:subsidy_on_retrofit} and\ref{figure:subsidy_on_retrofit_2}). 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.
Table 14: Value of parameter in the reference scenario

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of retrofit</td>
<td>$T^R$</td>
</tr>
<tr>
<td>Exogenous retrofit rate</td>
<td>ERR</td>
</tr>
<tr>
<td>Discount rate</td>
<td>$r$</td>
</tr>
<tr>
<td>CES elasticity of substitution</td>
<td>$\sigma_{EC}$</td>
</tr>
<tr>
<td>Technical progress on retrofit</td>
<td>$\tau_{RC}$</td>
</tr>
<tr>
<td>Subsidy on retrofit</td>
<td>$\tau^t_{EC}$</td>
</tr>
<tr>
<td>Tax rate on energy consumption</td>
<td>$\tau_{it}$</td>
</tr>
<tr>
<td>Demolition rate</td>
<td>$DR_{EC}$</td>
</tr>
<tr>
<td>Share of cohort EC in construction</td>
<td>$\phi_A$</td>
</tr>
<tr>
<td>Share of cohort EC in construction</td>
<td>$\phi_B$</td>
</tr>
</tbody>
</table>

Table 15: Value of parameter in the reference scenario

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of retrofit</td>
<td>40</td>
</tr>
<tr>
<td>Exogenous retrofit rate</td>
<td>0.01</td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.03</td>
</tr>
<tr>
<td>CES elasticity of substitution</td>
<td>0.25</td>
</tr>
<tr>
<td>Technical progress on retrofit</td>
<td>0.01</td>
</tr>
<tr>
<td>Subsidy on retrofit</td>
<td>0</td>
</tr>
<tr>
<td>Tax rate on energy consumption</td>
<td>0</td>
</tr>
<tr>
<td>Demolition rate</td>
<td>0.005</td>
</tr>
</tbody>
</table>

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 Figures 15 and 16). 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 m² - Scenario subsidy

Figure 14: Retrofit in m² - Scenario subsidy (negative numbers building that are subtracted, positive numbers building that are added)
Figure 15: Energy reference area in m² - Scenario fossil energy tax

Figure 16: Retrofit in m² - 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).

![Diagram of coupling framework]

Figure 22: Coupling framework

6. Further improvements

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

- Obtain data on building stock by energy label,
- Endogenization $D_{EC,t}$, 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 $\phi_{EC,t}$,

---

23
• Take into account barriers in housing retrofit (Eq.(3)) which will limit renovation decisions [12].

• Better modeling of equation $ERA_t$.

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 ECs 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


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
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
SHAREFERFUR(EC,T) Share refurbishment
PHI(EC,T) Share of cohort EC in construction
THO(EC,ECP,T) Subsidies on refurbishment
PI(T) Price of investment
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
FNC(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
T R duration of refurbishment
FLAG test parameter
Tau_RC technical progress on refurbishment cost
$include Data
TJKWh=277777.7778;
TR=40;
R=0.03;

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") = 8822000/1000;
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;


Sigma(EC) = 0.25 ;
Alpha(EC,I)=(E0(EC,I,"2016")*PE(I,"2016")**Sigma(EC))/(SUM(IP,E0(EC,IP,"2016")**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;

DR("A",T)=0.0005;
DR("B",T)=0.001;
DR(\text{"C"}, T) = 0.0016;

DR(\text{"D"}, T) = 0.0032;

DR(\text{"E"}, T) = 0.0039;

DR(\text{"F"}, T) = 0.005;

DR(\text{"G"}, T) = 0.0072;

DR(\text{"H"}, T) = 0.009;

DR(\text{"I"}, T) = 0.01;

DR(\text{EC}, T) = 0.005;

* From SHD zurich

SHD(\text{"I"}, T) = 135;

SHD(\text{"H"}, T) = 170;

SHD(\text{"G"}, T) = 170;

SHD(\text{"F"}, T) = 165;

SHD(\text{"E"}, T) = 165;

SHD(\text{"D"}, T) = 123;

SHD(\text{"C"}, T) = 90;

SHD(\text{"B"}, T) = 70;

SHD(\text{"A"}, T) = 60;

RC(\text{EC}, \text{ECP}, T) = \max(0, (\text{SHD(\text{EC}, T) - SHD(\text{ECP}, T)}) \times 41/20) / ((1 + \text{Tau}_{\text{RC}})^{2-\text{Ord}(T)});

display RC;

ERA(\text{EC}, T) = ERA_{0}(\text{EC}, T) / 1000;

display PEC;

loop (T$(\text{ord}(T) gt 1) ,

POP(T+1) = POP(T) \times (1 - 0.009224349);

ERAD(T) = \Theta_{\text{one}}(T) \times POP(T+1);

X(T) = \text{SUM(\text{ECP} \times (1 - DR(\text{ECP}, T)) \times \text{ERA(\text{ECP}, T)});

NC(\text{EC}, T) = PHI(\text{EC}, T) \times \text{SUM(\text{ECP} \times (1 - DR(\text{ECP}, T)) \times \text{ERA(\text{ECP}, T)});

NC(\text{EC}, T) \times NC(\text{EC}, T) \times NC(\text{EC}, T) \times (\text{ord}(T) \times 1 - 0);

RG(\text{EC}, \text{ECP}, T) = (\text{SHD(\text{EC}, T+1) \times PEC(\text{EC}, T+1) - SHD(\text{ECP}, T+1) \times PEC(\text{ECP}, T+1)}) / (1 + R);

+ (\text{SHD(\text{EC}, T+2) \times PEC(\text{EC}, T+2) - SHD(\text{ECP}, T+2) \times PEC(\text{ECP}, T+2)}) / (1 + R)^{2} + (\text{SHD(\text{EC}, T+3) \times PEC(\text{EC}, T+3) - SHD(\text{ECP}, T+3) \times PEC(\text{ECP}, T+3)}) / (1 + R)^{3} + (\text{SHD(\text{EC}, T+4) \times PEC(\text{EC}, T+4) - SHD(\text{ECP}, T+4) \times PEC(\text{ECP}, T+4)}) / (1 + R)^{4} + (\text{SHD(\text{EC}, T+5) \times PEC(\text{EC}, T+5) - SHD(\text{ECP}, T+5) \times PEC(\text{ECP}, T+5)}) / (1 + R)^{5} + (\text{SHD(\text{EC}, T+6) \times PEC(\text{EC}, T+6) - SHD(\text{ECP}, T+6) \times PEC(\text{ECP}, T+6)}) / (1 + R)^{6} + (\text{SHD(\text{EC}, T+7) \times PEC(\text{EC}, T+7) - SHD(\text{ECP}, T+7) \times PEC(\text{ECP}, T+7)}) / (1 + R)^{7} + (\text{SHD(\text{EC}, T+8) \times PEC(\text{EC}, T+8) - SHD(\text{ECP}, T+8) \times PEC(\text{ECP}, T+8)}) / (1 + R)^{8} + (\text{SHD(\text{EC}, T+9) \times PEC(\text{EC}, T+9) - SHD(\text{ECP}, T+9) \times PEC(\text{ECP}, T+9)}) / (1 + R)^{9} + (\text{SHD(\text{EC}, T+10) \times PEC(\text{EC}, T+10) - SHD(\text{ECP}, T+10) \times PEC(\text{ECP}, T+10)}) / (1 + R)^{10} + (\text{SHD(\text{EC}, T+11) \times PEC(\text{EC}, T+11) - SHD(\text{ECP}, T+11) \times PEC(\text{ECP}, T+11)}) / (1 + R)^{11} + (\text{SHD(\text{EC}, T+12) \times PEC(\text{EC}, T+12) - SHD(\text{ECP}, T+12) \times PEC(\text{ECP}, T+12)}) / (1 + R)^{12} + (\text{SHD(\text{EC}, T+13) \times PEC(\text{EC}, T+13) - SHD(\text{ECP}, T+13) \times PEC(\text{ECP}, T+13)}) / (1 + R)^{13} + (\text{SHD(\text{EC}, T+14) \times PEC(\text{EC}, T+14) - SHD(\text{ECP}, T+14) \times PEC(\text{ECP}, T+14)}) / (1 + R)^{14} + (\text{SHD(\text{EC}, T+15) \times PEC(\text{EC}, T+15) - SHD(\text{ECP}, T+15) \times PEC(\text{ECP}, T+15)}) / (1 + R)^{15} + (\text{SHD(\text{EC}, T+16) \times PEC(\text{EC}, T+16) - SHD(\text{ECP}, T+16) \times PEC(\text{ECP}, T+16)}) / (1 + R)^{16} + (\text{SHD(\text{EC}, T+17) \times PEC(\text{EC}, T+17) - SHD(\text{ECP}, T+17) \times PEC(\text{ECP}, T+17)}) / (1 + R)^{17} + (\text{SHD(\text{EC}, T+18) \times PEC(\text{EC}, T+18) - SHD(\text{ECP}, T+18) \times PEC(\text{ECP}, T+18)}) / (1 + R)^{18} + (\text{SHD(\text{EC}, T+19) \times PEC(\text{EC}, T+19) - SHD(\text{ECP}, T+19) \times PEC(\text{ECP}, T+19)}) / (1 + R)^{19} + (\text{SHD(\text{EC}, T+20) \times PEC(\text{EC}, T+20) - SHD(\text{ECP}, T+20) \times PEC(\text{ECP}, T+20)}) / (1 + R)^{20} + (\text{SHD(\text{EC}, T+21) \times PEC(\text{EC}, T+21) - SHD(\text{ECP}, T+21) \times PEC(\text{ECP}, T+21)}) / (1 + R)^{21} + (\text{SHD(\text{EC}, T+22) \times PEC(\text{EC}, T+22) - SHD(\text{ECP}, T+22) \times PEC(\text{ECP}, T+22)}) / (1 + R)^{22} + (\text{SHD(\text{EC}, T+23) \times PEC(\text{EC}, T+23) - SHD(\text{ECP}, T+23) \times PEC(\text{ECP}, T+23)}) / (1 + R)^{23} + (\text{SHD(\text{EC}, T+24) \times PEC(\text{EC}, T+24) - SHD(\text{ECP}, T+24) \times PEC(\text{ECP}, T+24)}) / (1 + R)^{24} + (\text{SHD(\text{EC}, T+25) \times PEC(\text{EC}, T+25) - SHD(\text{ECP}, T+25) \times PEC(\text{ECP}, T+25)}) / (1 + R)^{25} + (\text{SHD(\text{EC}, T+26) \times PEC(\text{EC}, T+26) - SHD(\text{ECP}, T+26) \times PEC(\text{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+37) * PEC(EC, T+37) - SHD(ECP, T+37) * PEC(ECP, T+37)) / (1+R)**37
+ (SHD(EC, T+38) * PEC(EC, T+38) - SHD(ECP, T+38) * PEC(ECP, T+38)) / (1+R)**38
+ (SHD(EC, T+39) * 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("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("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(ECB, ECD, 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(ECB, RM(EC, ECP, 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 / TJWh;

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

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

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

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

312
313}
314 );
315
316
317 display SHAREREFUR, RS, RM, RG, RC, ERAD, NC, X, DR, RC;
318
319 $include Sortie
Appendix B  Meteo stations for each canton

In Table 16 we can see the cantons with the corresponding stations’ names, locations, longitudes, latitudes, coordinates, altitudes and corresponding numbers of $\theta_{th}$.

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>
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<tr>
<th>Canton</th>
<th>Name</th>
<th>Location</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Altitude</th>
<th>$\theta_{h}=8$</th>
<th>$\theta_{h}=10$</th>
<th>$\theta_{h}=12$</th>
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<tr>
<td>Aargau (AG)</td>
<td>BIL</td>
<td>Biel/Bienne</td>
<td>715</td>
<td>4707</td>
<td>433</td>
<td>2'130</td>
<td>2'435</td>
<td>2'642</td>
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<tr>
<td>Appenzell-Ausserrhoden (AR)</td>
<td>STG</td>
<td>St. Gallen</td>
<td>923</td>
<td>4725</td>
<td>775</td>
<td>2'581</td>
<td>2'834</td>
<td>3'029</td>
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<td>Appenzell-Innerrhoden (AI)</td>
<td>STG</td>
<td>St. Gallen</td>
<td>923</td>
<td>4725</td>
<td>775</td>
<td>2'581</td>
<td>2'834</td>
<td>3'029</td>
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<tr>
<td>Basel-Landschaft (BL)</td>
<td>BAS</td>
<td>Basel / Binningen</td>
<td>735</td>
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<td>1'773</td>
<td>2'159</td>
<td>2'450</td>
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<tr>
<td>Basel-Stadt (BS)</td>
<td>BAS</td>
<td>Basel / Binningen</td>
<td>735</td>
<td>4732</td>
<td>316</td>
<td>1'773</td>
<td>2'159</td>
<td>2'450</td>
</tr>
<tr>
<td>Bern (BE)</td>
<td>BER</td>
<td>Bern / Zollikofen</td>
<td>727</td>
<td>4659</td>
<td>552</td>
<td>2'349</td>
<td>2'711</td>
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<tr>
<td>Fribourg (FR)</td>
<td>GRA</td>
<td>Fribourg / Posieux</td>
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<td>Genève-Cointrin</td>
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<td>Glarus</td>
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<td>3'123</td>
<td>3'352</td>
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