Energy Efficiency in Buildings

Report

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Joint Activity Scenarios and Modelling

ENERGY EFFICIENCY IN BUILDINGS

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Chapter 1

Overview

This report describes the work done for the SCCER-FEEB+D than can be used for the simulation and modelling of the techno-economic potential of energy efficiency improvements for the JASM project.

Investment cost curves for the retrofit of the building envelope in the Swiss building stock are presented for both the CESAR and SwissRes models.

Chapter 2

Introduction

In the framework of the Energy Strategy 2050, Switzerland has set itself ambitious goals for increasing energy efficiency across all sectors (BFE, 2012, Prognos, 2012, BFE, 2013). Accounting for 44% of the Swiss final energy use in 2015, the built environment is the most important energy consumer and therefore a key area for energy efficiency improvement (Kemmler et al., 2015, 2017). Historically, space heating (mainly in the residential sector) and mobility are the end-uses with the largest share in the Swiss final energy demand (Figure 2.1). Hence, a large-scale retrofit of the existing building stock to a more energy efficient level could potentially result in considerable national energy savings.

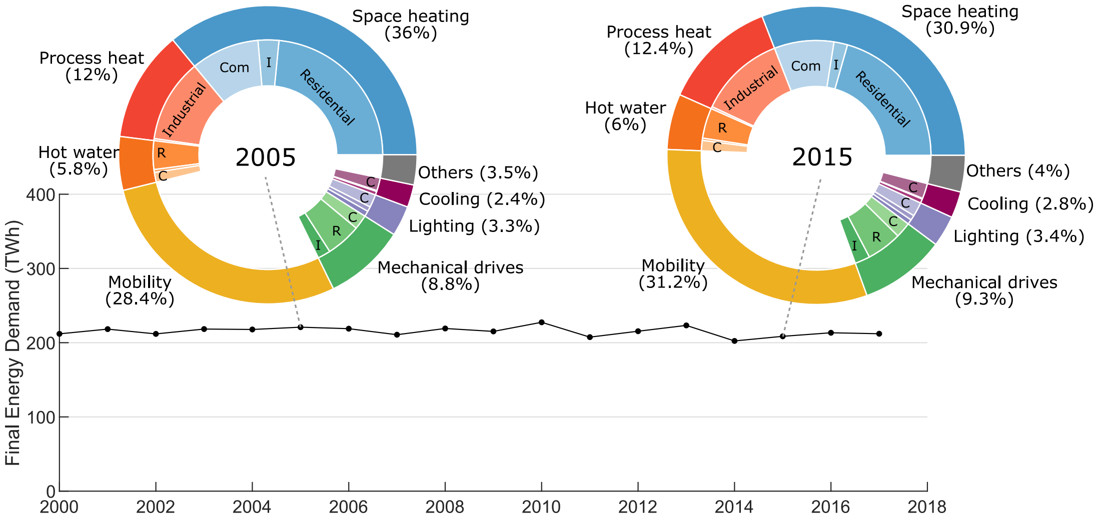


Figure 2.1: Historical Final Energy Demand. I: Industrial, R: Residential, C (or Com): Commercial. (BFE, 2018, Tables 1, 15, 21 and 24)

However, less than 1% of all buildings are retrofitted each year. In order to foster an increase in energy efficiency in Swiss buildings, the Directors of the cantonal energy authorities are working together to harmonize their energy requirements for buildings across all cantons (EnDK, 2015). On a national level, a part of the revenues from special taxes on fossil fuels are used to subsidize energy efficient retrofits for buildings (BFE, 2012).

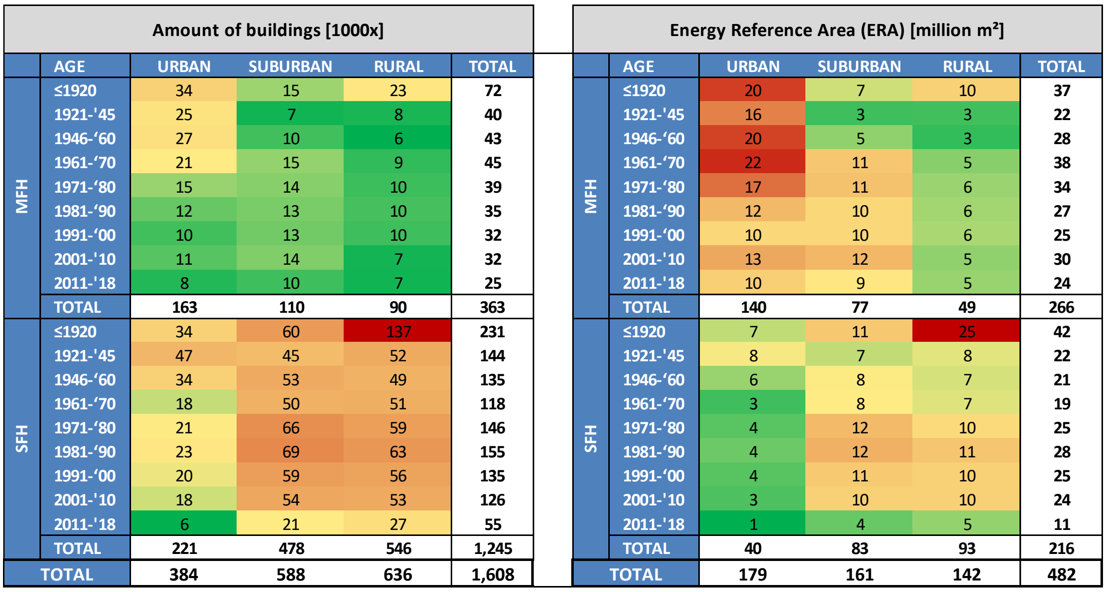
The aim of this study is to estimate the saving potential of energy retrofits and the required investment cost in the Swiss building stock. The results can then be used for the simulation of energy retrofit in full energy system models, and might therefore provide new insights on the role of energy efficiency in the Swiss energy transition, compared to a large increase in capacity of renewable energies.

2.1 Building stock statistics

To understand better the challenge of the energy retrofit in the Swiss building stock, this section provides the most important building stock characteristics for the residential building stock.

According to the official statistics, the Swiss building stock in 2019 consisted of roughly 1.8 million buildings, of which 1.6 million buildings belong to the residential building stock (BFE, 2020). The annual investment for construction is around 40 billion CHF/a, whereas only 13 billion CHF/a are currently spent on refurbishment and retrofit of the existing building stock.

Figure 2.2 presents the amount of buildings and their related Energy Reference Area[1] in the residential sector by building type, construction period and urban/rural typology. In 2016, the Swiss ERA in the residential sector accounted for 482 Mm2. This value comes from Schluck et al. (2019) that used a comprehensive data set of the Swiss buildings stock with about 30,000 buildings and 23 descriptive features including construction period, building type, typology and canton. Consistently with the Energy Statistics from the BFE (2018, p. 13), the ERA of the second homes and holiday houses is not included in the residential sector [2]. The occupancy factor (excluding second homes and holiday houses[3] from the total ERA) is 0.95, slightly higher than the 90% assumed by Jakob et al. (2016).



Amount of buildings [1000x]

	AGE	URBAN	SUBURBAN	RURAL	TOTAL
MFH	≤1920	34	15	23	72
	1921-'45	25	7	8	40
	1946-‘60	27	10	6	43
	1961-‘70	21	15	9	45
	1971-‘80	15	14	10	39
	1981-‘90	12	13	10	35
	1991-‘00	10	13	10	32
	2001-'10	11	14	7	32
	2011-'18	8	10	7	25
	TOTAL	163	110	90	363
SFH	≤1920	34	60	137	231
	1921-'45	47	45	52	144
	1946-‘60	34	53	49	135
	1961-‘70	18	50	51	118
	1971-‘80	21	66	59	146
	1981-‘90	23	69	63	155
	1991-‘00	20	59	56	135
	2001-'10	18	54	53	126
	2011-'18	6	21	27	55
	TOTAL	221	478	546	1,245
TOTAL		384	588	636	1,608

Energy Reference Area (ERA) [million m²]

	AGE	URBAN	SUBURBAN	RURAL	TOTAL
MFH	≤1920	20	7	10	37
	1921-'45	16	3	3	22
	1946-‘60	20	5	3	28
	1961-‘70	22	11	5	38
	1971-‘80	17	11	6	34
	1981-‘90	12	10	6	27
	1991-‘00	10	10	6	25
	2001-'10	13	12	5	30
	2011-'18	10	9	5	24
	TOTAL	140	77	49	266
SFH	≤1920	7	11	25	42
	1921-'45	8	7	8	22
	1946-‘60	6	8	7	21
	1961-‘70	3	8	7	19
	1971-‘80	4	12	10	25
	1981-‘90	4	12	11	28
	1991-‘00	4	11	10	25
	2001-'10	3	10	10	24
	2011-'18	1	4	5	11
	TOTAL	40	83	93	216
TOTAL		179	161	142	482

Figure 2.2: Basic building statistics of the Swiss residential building stock aggregated by main archetype categories (construction period, building type, typology). Results are presented for the amount of buildings and their related Energy Reference Area in the stock.

> Data available at https://data.sccer-jasm.ch/building-stock/

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[1] The energy reference area (ERA) is the effective heated surface of a building.

[2] All second homes are treated as holiday houses.

[3] Zweit- und Ferienwohnungen

Figure 2.2 shows that multi-family houses (MFHs) constitute 55% of the total residential ERA in Switzerland. All buildings constructed before 1980 account for roughly 60% of the total. As for the share of ERA between different typologies, the urban typology account for 37%, the rural for 30% and the remaining ERA of 33% corresponds to suburban typologies. The single archetype that accounts for the largest share of ERA (about 5%) is single-family houses (SFHs) constructed before 1920 and situated in a rural area, followed by urban MFHs constructed before 1980 (3%–4%). The Swiss residential building stock is mainly dominated by fossil-fuel based heating systems as illustrated in Figure 2.3.

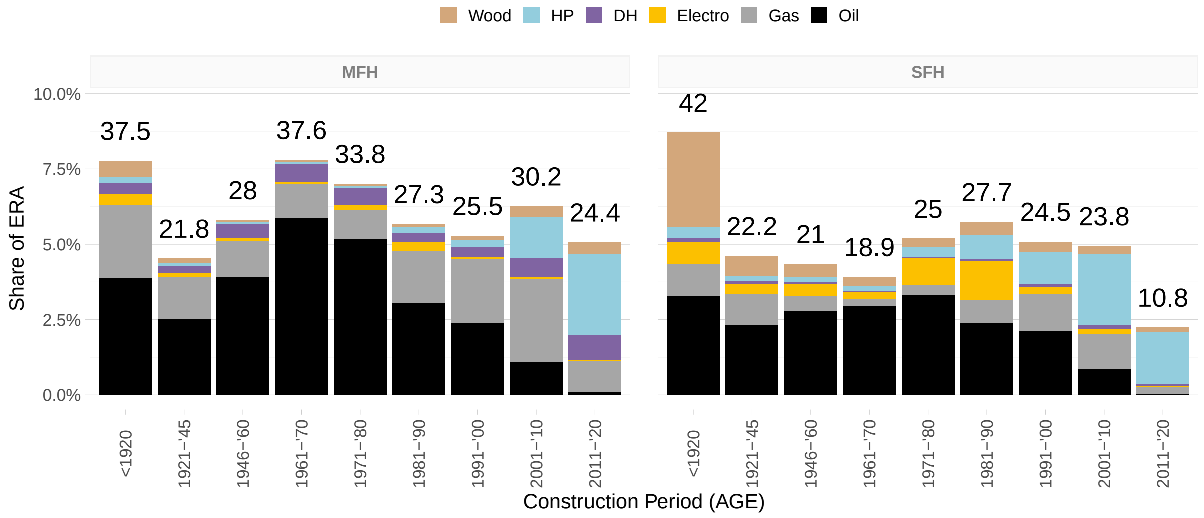

Figure 2.3: Share of heating supply technology for the total Swiss ERA by archetype category AGE and TYPE (Federal Statistical Office, 2020). The numbers on top of the bars are showing the ERA for this particular archetype in million m^2. (DH = District Heating, HP = Heat Pump)

Chapter 3

Methods

In this section we describe the methods we used to calculate the investment cost curves in the JASM project. We use two independent models from two different research groups for the simulation of envelope retrofit measures and the estimation of the investment cost: CESAR (Wang et al., 2018) and SwissRes (Streicher et al., 2018, 2019). Table 3.1 shows a comparison of the main characteristics of the two different models. We provide more details about the two models in the following sections.

Table 3.1: Main characteristics of CESAR and SwissRes models

	CESAR	**SwissRes**
Description	dynamic energy flow simulation	steady-state energy balance
Model basis	physics	physics
Dynamics	dynamic	steady-state
Time resolution	hourly	monthly
Building archetypes	500	6,700
Model complexity	complex	simple
Data requirement	high	medium

Although both models have the capability of simulating changes in the heating and ventilation system, the scope of this study is limited to envelope retrofit measures, since technology changes are already simulated in the full energy system models. In this regard, retrofitting the envelope involves additional insulation for the walls, roof or ground plates as well as the replacement of windows, which results in lower thermal losses and therefore reduced space heating demand.

Both models provide results for the energy saving potential per archetype and the required investment cost, that can be used to create an investment cost curve. Such a curve shows the cumulated investment cost as a function of the cumulated achievable energy savings ranked by their specific investment cost per energy saving.

3.1 CESAR Model (ETHZ/Empa)

We use the CESAR Tool (Wang et al., 2018) to calculate hourly heating, cooling and electricity demand profiles for a set of residential and non-residential building archetypes subject to a range of different envelope retrofitting interventions. We evaluated the following retrofitting options:

1. No retrofit
2. Roof insulation
3. Wall insulation
4. Replacement of windows
5. Floor insulation
6. Window replacement and wall insulation
7. Full retrofit (all of the above)

Table 3.2 presents the number of buildings by construction period, for both original and retrofitted constructions. The data concerning constructions preceding 1994 is from the Institut für Bauforschung (Institut für Bauforschung, 2010); data for buildings from 1994–2007 is from the Bauteilkatalog (Bundesamt fuer Energie, 2016) combined with typical insulation thickness values from Jakob (2008). We assume that all new (>2010) and retrofitted constructions comply with the minimum U-values (Grenzwerte) of the SIA380/1 norm.

Table 3.2: U-value (W/m-K) of age dependent constructions used in the CESAR tool (non-retrofitted or original constructions and constructions with insulation added during a retrofit) (Murray et al., 2019)

Construction period	**Walls**		**Roof**		**Floors**		**Windows**	
	Original	**Retrofit**	**Original**	**Retrofit**	**Original**	**Retrofit**	**Original**	**Retrofit**
<1918	1.645	0.243	0.752	0.2369	0.765	0.243	5.7778	1.06
1919–1948	1.509	0.244	0.745	0.249	0.971	0.239	5.778	1.06
1949–1978	1.259	0.233	0.856	0.248	0.778	0.254	3.126	1.06
1979–1994	0.46	0.239	0.392	0.24	0.706	0.246	1.668	1.06
1995–2001	0.268	0.215	0.289	0.22	0.336	0.248	1.652	1.06
2002–2006	0.222	0.161	0.245	0.161	0.91	0.291	1.407	1.06
2007–2009	0.211	0.155	0.206	0.161	0.252	0.18	1.3	1.06
2010–2014	0.2	0.140	0.186	0.140	0.232	0.2	1.06	0.927
>2014	0.17	0.140	0.17	0.140	0.211	0.2	0.927	0.927

To generate the investment curve from the results of CESAR, we first determined 500 representative archetype buildings using clustering techniques on various building characteristics: building area, age, energy demand, climatic region or renewable energy potential[1] (Murray et al., 2019, 2020). Second, we use the CESAR model to calculate the energy demand for each building archetype with and without retrofitting and the investment costs of the retrofitting measures. Finally, we calculated the energy efficiency cost curve using the 50 most representative archetypes, defined as those archetypes with the largest floor area. Figure 3.1 shows the percentage of the buildings attributed to each archetype. In total, the subset of the 50 most representative archetypes accounts for 27% and 78% of the area of the building stock represented by the 500 archetypes, for SFH and MFH, respectively. We assume for the up-scaling that the relative percentage of the each archetype in the subset is indicative of the archetype percentage in the up-scaled building stock. In addition to this, the subset of 50 archetypes were simulated using 53 climate files. The up-scaling assumes that each archetype has equal occurrence in each of the climatic regions.

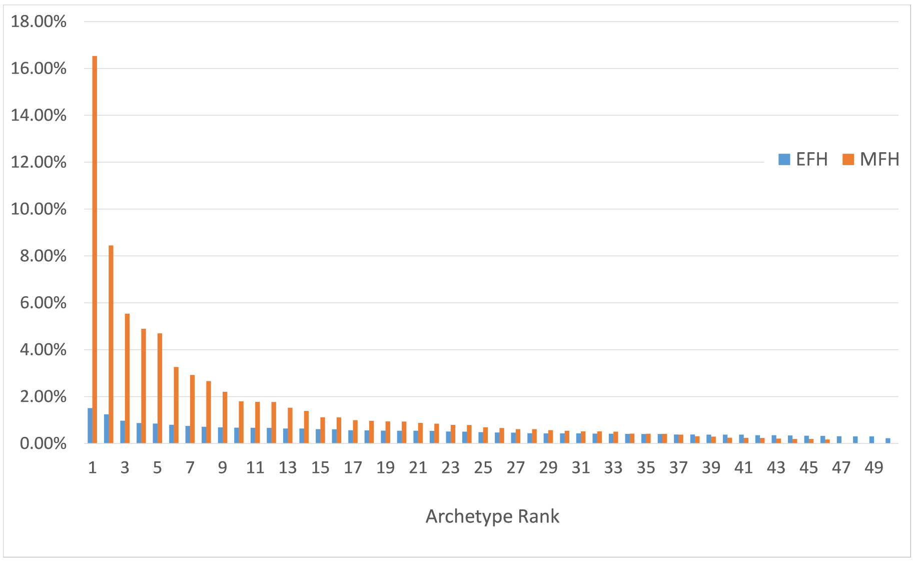

Figure 3.1: The percentage of the residential building stock, used for clustering that is represented by the subset of 50 most relevant residential archetypes (SFH = 27.1% & MFH = 77.7%).

3.2 SwissRes Model (UniGE)

The Swiss Residential Building Stock (SwissRes) Model allows to simulate the energy demand and with that the energy saving potential of energy efficiency measures for a wide range of representative archetype buildings (Table 3.3). The basic structure and input data of this bottom-up model is presented in Figure 3.2. In the first step, a statistical analysis of more than 50,000 Cantonal Building Energy Performance Certificates (CECB) by archetype category allows to recreate the physical state of the various building elements in the stock (Streicher et al., 2018). The resulting archetype configuration is complemented by other external data, such as climate time series and standardized occupant behaviour, in order to calculate the specific energy demand for space heating and domestic hot water (DHW) on a per square meter basis (Streicher et al., 2019). This specific demand can then be up-scaled to the national demand by applying the respective Energy Reference Area for each archetype.

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[1] We only applied the clustering technique to buildings with complete data so there is a certain probability that the archetypes do not completely represent the Swiss building stock.

Table 3.3: Overview on building archetype categories and their respective classes used in the SwissRes model.

Category	**Class**	**Description**
AGE	<1920	Construction period before 1920
	1920–‘45	Construction period 1920–1945
	1946–‘60	Construction period 1946–1960
	1961–‘70	Construction period 1961–1970
	1971–‘80	Construction period 1971–1980
	1981–‘90	Construction period 1981–1990
	1991–‘00	Construction period 1991–2000
	2001–‘05	Construction period 2001–2005
	2006–‘15	Construction period 2006–2015
TYPE	SFH	Single-Family House (1–2 residential dwellings)
	MFH	Multi-Family House (3+ dwellings)
TYPOLOGY	URBAN	1 Large center, 2 secondary center of large center, 4 Medium center
	SUBURBAN	3 Belt of large center, 5 Belt of medium center
	RURAL	6 Small center, 7 Sub-urban rural commune, 8 rural commune, 9 touristical commune

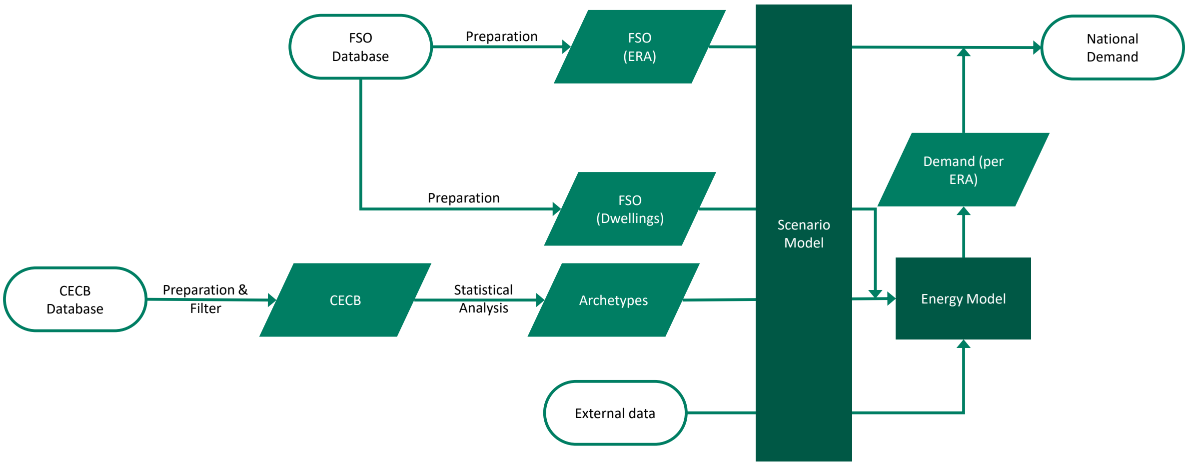


Figure 3.2: Overview on the structure of the bottom-up Swiss Residential Building Stock (SwissRes) model, with the related input data and sub models. (CECB Plus = Cantonal Building Energy Performance Certificate, FSO = Federal Statistical Office, ERA = Energy Reference Area)

The difference between the energy demand before and after applying certain energy efficiency measures allows then to estimate the related energy saving potential. If this is combined with economic input parameters, the techno-economic potential of retrofit measures can be assessed, both for different archetypes as well as for the entire stock. This also includes different economic assessment approaches representing stake holder preferences.

3.2.1 Energy model

Based on the physical properties of the building elements we can simulate the energy demand of the different archetypes. For this we use a monthly steady-state energy balance model based on the Swiss building energy demand calculation standard SIA 380/1 (Swiss Society of Engineers and Architects, 2016). Figure 3.3 shows the basic structure of the energy model and the required archetype input variables or constants.

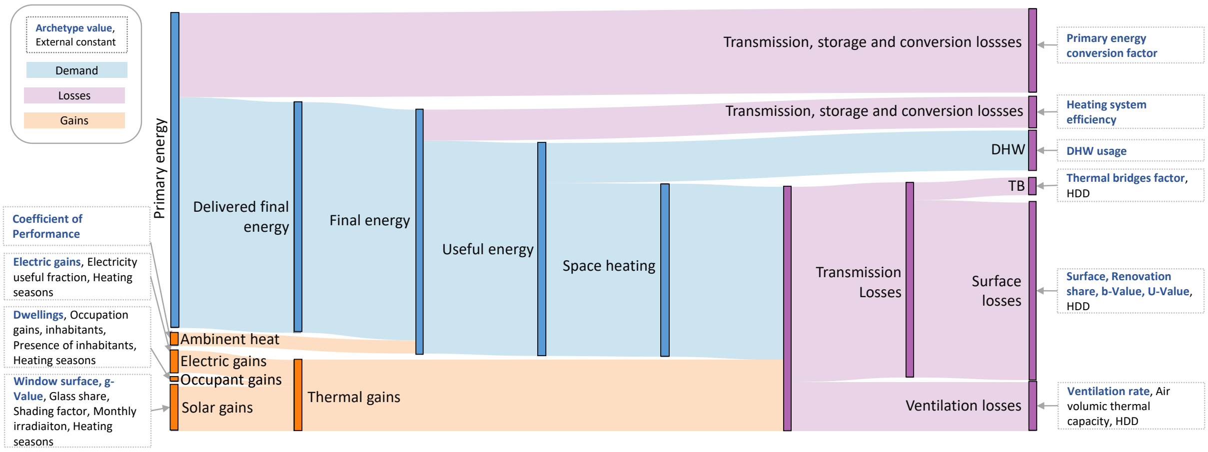


Figure 3.3: Energy balance and flows of the SwissRes energy model with its respective input variables and constants. (DHW = Domestic Hot Water, HDD = Heating Degree Day, TB = Thermal bridges)

The SwissRes model is based on the monthly balance between thermal losses and thermal gains. The gap between gains and losses leads then to the required useful space heating energy demand (Q_h) following Equation 3.1.

$$Q_h = (Q_T + Q_{TB} + Q_V) - \eta \cdot (Q_S + Q_{iP} + Q_{iEl}) \tag{3.1}$$

As for the thermal losses, these result from thermal transmission through the building elements (Q_T) and thermal bridges (Q_{TB}), together with thermal losses through ventilation of air exchange (Q_V). The magnitude of these losses depends mainly on the difference between the outdoor temperature and the desired indoor temperature, expressed as cumulated monthly Heating Degree Days (HDD), when the daily average temperature drops below 12°C (Swiss Society of Engineers and Architects, 2016).

Concerning thermal gains, the energy model accounts for internal gains from occupants (Q_{iP}) and electronic devices (Q_{iEl}) as well as for solar gains through the windows (Q_S). For the latter, we aggregated the average monthly irradiation per cardinal direction (north, east, south, west) by canton (Federal Office of Metrology and Climatology MeteoSwiss, 2020). We combined this with the share of windows by direction derived from the CECB, to calculate the solar gains per archetype. It should be noted, that only the gains occurring during a heating day are taken into account for the energy balance.

The final energy demand is calculated from the useful energy demand and the heating system efficiency (η_{es}) as a function of the age (Age_h) of the heating system following Equation 3.2.

$$E_h = \frac{Q_h}{\eta_{es}(Age_h)} \tag{3.2}$$

More details of the energy balance model are provided in Streicher et al. (2019).

The results of the SwissRes energy model had a significant deviation between the modelled energy demand and the measured consumption (Streicher et al., 2019). We addressed this energy performance gap (EPG) issue by adjusting the assumed indoor temperature. This ensures a realistic estimation of the energy saving potential of retrofit measures. To calculate the corrected internal temperature we used the comparison of the SwissRes demand in Figure 3.4 with measured data from Schneider et al. (2016). Furthermore, we assumed that the buildings will be heated to 22°C after the retrofit.

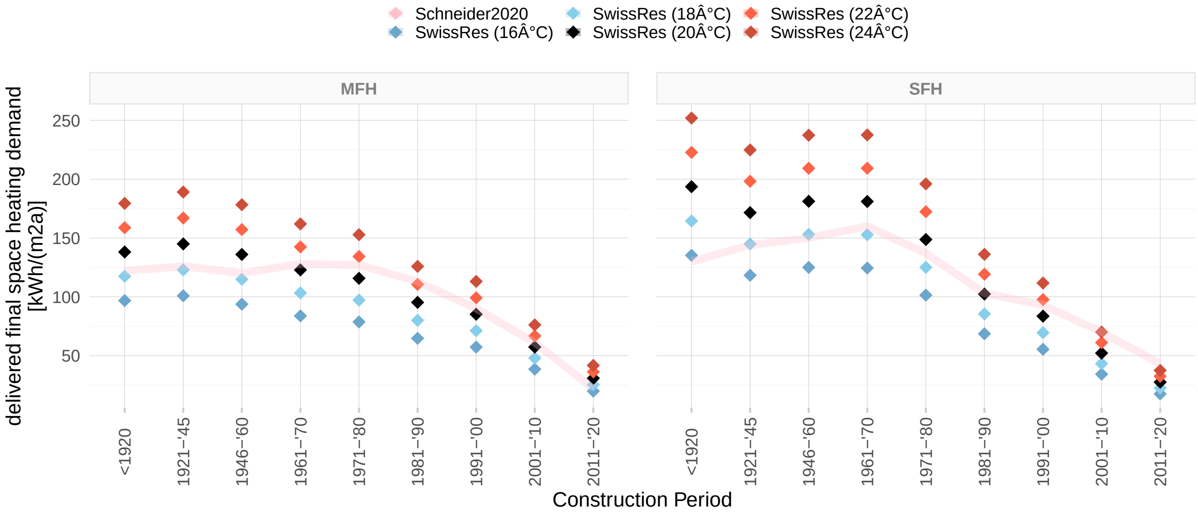


Figure 3.4: Comparison of SwissRes model results for the average final energy space heating demand as a function of the indoor temperature with measured consumption by building type (Schneider et al., 2016). The diamonds represent the results of the SwissRes model for different internal temperatures, which are used to define the factor for the EPG correction.

The SwissRes model provides the monthly values for all energy flows in Figure 3.3 and all archetypes in Table 3.3, which results in roughly 100,000 rows for each of the 12 output variables (e.g., surface losses, solar gains or primary energy demand). We can then aggregate this vast amount of data to annual values or to any combination of archetype categories by weighting all archetypes with their respective share of ERA in the stock.

3.2.2 Retrofit measures

Table 3.4 shows the selected retrofit measures for the different building elements and their required U-Values after retrofit. These measures are based on the harmonized energy retrofit packages (system solutions) provided by the private energy label MINERGIE for a passive house retrofit (MINERGIE, 2018). For the JASM project, we bundled these measures into one complete retrofit package that can ensure a high thermal performance while avoiding damages to the building (Streicher et al., 2020).

We applied the following procedure to simulate the retrofit of the building envelope in the SwissRes model:

Table 3.4: Thermal requirements and related costs for retrofit measures. Cost are presented in [CHF/m2 element]. (SFH = Single Family House, MFH = Multifamily House)

Building element	**Ground**	**Wall**	**Roof**	**Window**	**Window**
Retrofit measure	Interior insulation	Exterior insulation	Exterior insulation		
Building type	SFH & MFH	SFH & MFH	SFH & MFH	SFH	MFH
U-Value required [W/(m2K)]	0.25	0.2	0.17	1	1
Full cost fixed	2.6	4.65	4.72	926	847
Full cost add.	91.1	254	163	0	0
Improvement cost fixed	2.6	3.98	4.72	334	301
Improvement cost add	91.1	19	33.2	0	0

1. Check which buildings need to improve the U-Values of certain elements to reach the requirements, thereby considering an additional 10% margin for already retrofitted elements (i.e., retrofitted building elements can have a 10% higher U-Value than the requirements).
2. Calculate required U-Value of additional insulation ($U_{insulation}$).
3. Calculate thickness t of additional insulation with an equivalent λ of 0.0035 W/(m K), thus,

   $$t = \frac{\lambda}{U_{insulation}} = \lambda \cdot \left(\frac{1}{U_{required}} + \frac{1}{U_{current}} \right),$$

   based on the current ($U_{current}$) and required ($U_{required}$) U-Values.
4. Ensure that the thickness of the new insulation is not below 3cm (minimum requirement).

Windows are an exception to the presented method, since their retrofit usually entails the replacement of the whole window. Therefore, the U-Value of the new window equals to the U-Value after retrofit.

After simulating energy demand for each archetype and retrofit option with the SwissRes model, we can estimate the energy saving potential as the difference between final energy demand before and after retrofit.

Figure 3.5 shows the distribution of the delivered final energy demand before and after retrofit for the main archetype categories.

3.2.3 Investment cost

We derive the investment cost for retrofitting the envelope from cost regression functions for building elements estimated by the German Institute for Buildings and Environment (Hinz, 2015). We convert the Euro prices of 2015 to the Swiss context using the average annual exchange rate to Swiss Franc of 1.07 for this year (Statista, 2018) and a surcharge of 60% according to a market survey of international construction prices (Turner & Townsend, 2017). Table 3.4 presents the resulting investment cost for additional insulation (I_{add}) and fixed cost (I_{fixed}) per square meter element surface. We convert the

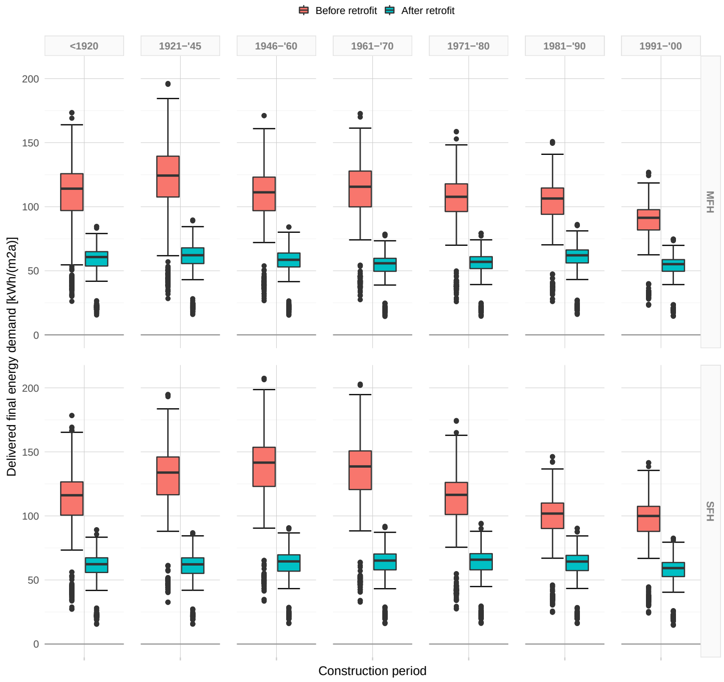


Figure 3.5: Distribution of delivered final energy demand before and after retrofit by building type and construction period.

investment cost of the element surface to investment cost per square meter ERA using the relative surfaces for building elements (A) from the SwissRes model. With all this input data we can then calculate the specific investment cost per square meter ERA for each of the four elements (el) according to Equation 3.3

$$I_{m2} = \sum_{el=1}^{4} \left((t_{el} \cdot I_{add,el} + I_{fixed,el}) \cdot A_{el} \right) \cdot ERA \tag{3.3}$$

Similar to the energy demand, we upscale the specific investment cost to the entire stock with the ERA of each archetype.

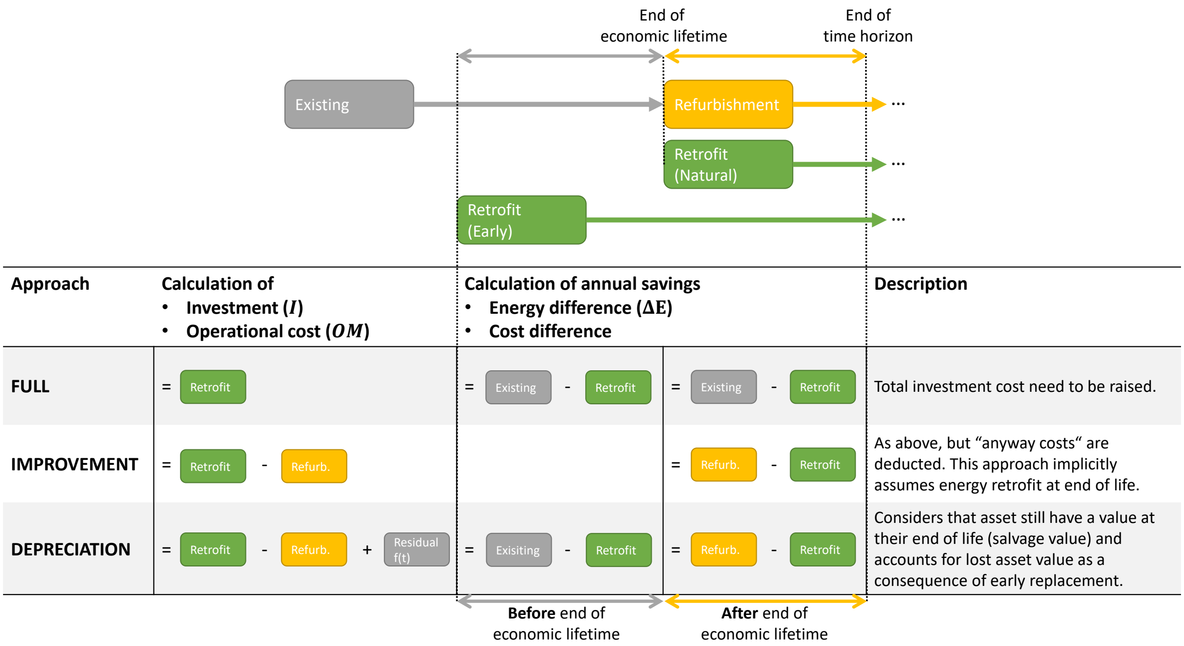
3.2.4 Economic assessment

The economic assessment of the building retrofit measures is based on the cost-effectiveness assessment procedure developed in Streicher et al. (2020). In the case of buildings, three different retrofit cases for an existing element need to be taken into account, as illustrated in the top part of Figure 3.6:

1. Refurbishment: Having reached the end of its economic lifetime, the existing element can be refurbished. Depending on the context, a refurbishment according to conventional practice may entail a simple repair and paint works on the envelope, as well as possibly the renewal of the existing heating system with the same technology as already installed. This usually implies that the energy efficiency does not improve significantly.
2. Retrofit (natural): The existing element is replaced by a more efficient technology at the end of

its economic lifetime or refurbishment cycle. This case is referred to as natural energy retrofit, since the retrofit is in line with the natural refurbishment cycles of building elements.

3. Retrofit (early): The existing element is replaced by a more efficient technology before reaching the end of its economic lifetime.



Approach	Calculation of • Investment (I) • Operational cost (OM)	Calculation of annual savings • Energy difference (ΔE) • Cost difference **Before** end of economic lifetime	**After** end of economic lifetime	Description
FULL	= Retrofit	= Existing - Retrofit	= Existing - Retrofit	Total investment cost need to be raised.
IMPROVEMENT	= Retrofit - Refurb.		= Refurb. - Retrofit	As above, but “anyway costs“ are deducted. This approach implicitly assumes energy retrofit at end of life.
DEPRECIATION	= Retrofit - Refurb. + Residual f(t)	= Exisiting - Retrofit	= Refurb. - Retrofit	Considers that asset still have a value at their end of life (salvage value) and accounts for lost asset value as a consequence of early replacement.

Figure 3.6: Overview on alternative energy retrofit cases (top) and related economic assessment approaches for the cost-benefit analysis of retrofit measures (table below). Adopted from (European Union, 2012, Pielli, 2008, EuroPHit, 2016)

The different retrofit cases are coupled with three different economic assessment approaches that represent different stakeholder preferences, based on the recommendations by Pielli (2008):

1. FULL takes into account the full cost and full savings of the retrofit.
2. IMPROVEMENT (IMP), in contrast, takes into account only the cost and respective savings related to the improvement of energy efficiency. This approach is also referred to as energy related cost, since it deducts the cost of the non-energy related refurbishment.
3. DEPRECIATION (DEP), based on deprecation patterns, adds the residual value of the existing element to the IMP cost.

The bottom part of Figure 3.6 shows in more detail the differences between the economic assessment options when it comes to the calculation of investment cost and savings. In the FULL approach, the investment cost are simply the full retrofit cost, while the savings correspond to the difference between the existing technology and the new or retrofitted technology. This approach does not account for any differences in function of the timing of the retrofit.

In the IMP approach, we deduct the cost of the refurbishment from the full retrofit cost, while the savings are the difference between the refurbished element and the new or retrofitted element. To avoid large biases, this approach should only be used for retrofit of elements that are very close to the end of the economic lifetime and accordingly should be restricted to the natural refurbishment cycles.

In the DEP approach, we also deduct the refurbishment costs from the full retrofit cost, but we add the residual value of the existing building element as a function of the age of the building element. This approach therefore accounts both for natural as well as early refurbishment, but ensures a (economic) barrier for early retrofit. We consider two time spans for the energy savings in the DEP approach: before and after the end of the economic lifetime of the existing element. In the period before the end of the economic lifetime, we calculate the energy savings as the differences between the retrofit and the existing element. In the period after the end of the economic lifetime, the energy savings are the difference between the retrofit and the refurbishment (which would have to be done by then). We use a linear depreciation pattern to calculate the residual value the building elements. We estimate the value of the asset at a given point in time multiplying the initial investment cost by a residual factor, thus,

$$1-\left(\frac{Age(t)}{L}\right)\cdot(1-slv),$$

where (Age) is the age of the building element at the given point in time, L is the economic lifetime of the respective building element, and slv is the salvage value ratio, which represents the ratio of the absolute value at end of lifetime relative to the initial investment costs. For the SwissRes model, we assume a salvage value of 20%, which is considered as a standard value for real estate assets (Böhm et al., 2002).

The current age of the different building elements is based on the distribution of building elements in their original state or already retrofitted in current decades. Based on the statistical analysis in Streicher et al. (2018), we divide the building elements of the stock into Typical Thermal Performance Classes (TTPC) that represent a certain range of U-Values applied in a given retrofit period (Figure 3.7). We use the TTPCs as proxies for the distribution of the age of the building elements in the stock.

Figure 3.8 shows the resulting average specific investment cost for envelope retrofit for the different economic assessment approaches.

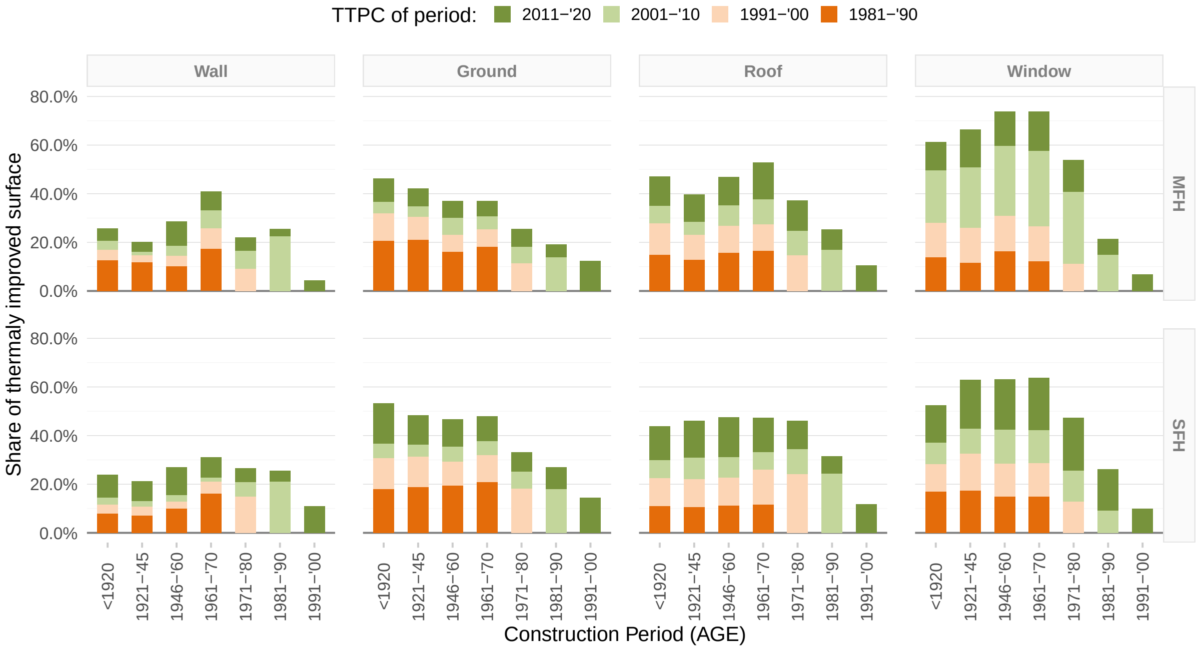


Figure 3.7: Total share of surfaces by Typical Thermal Performance Class (TTPC) for walls, ground plates, roofs and windows in the Swiss residential building stock as a function of type of building (TYPE, i.e. MFH and SFH) and construction period (AGE).

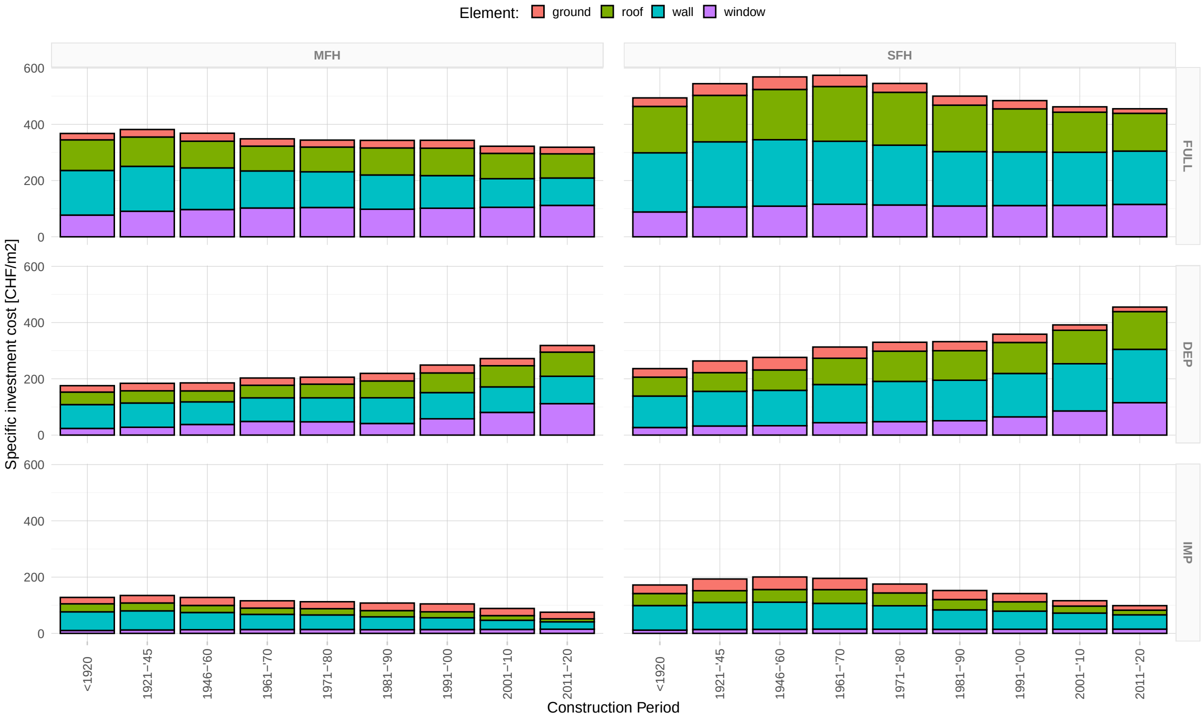


Figure 3.8: Average specific investment cost for complete envelope retrofit by building element and archetype categories building type and construction period.

Chapter 4

Results

4.1 Residential buildings

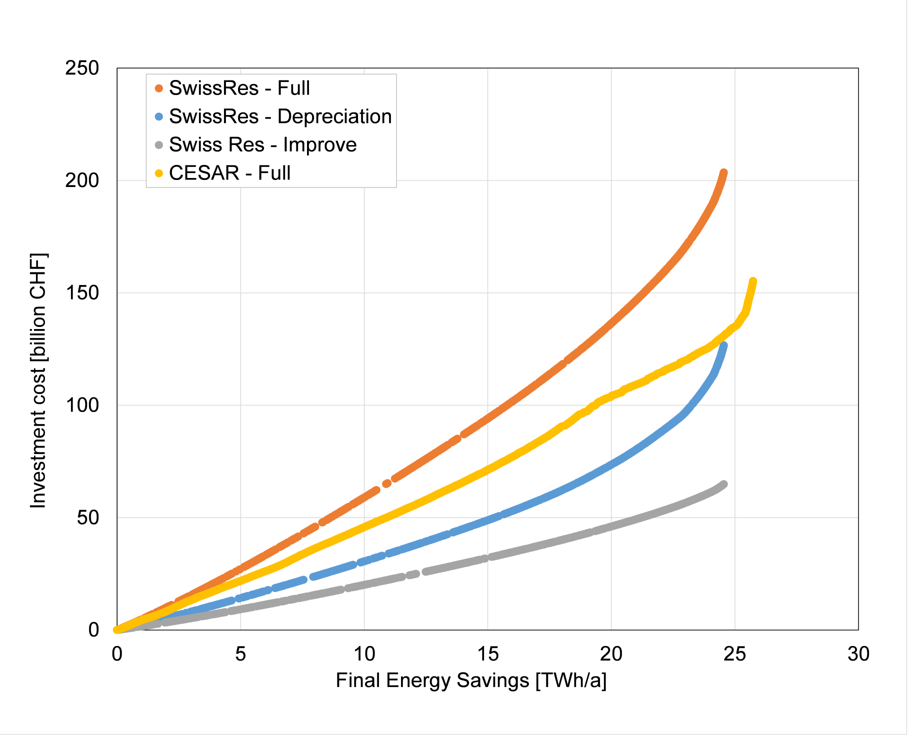
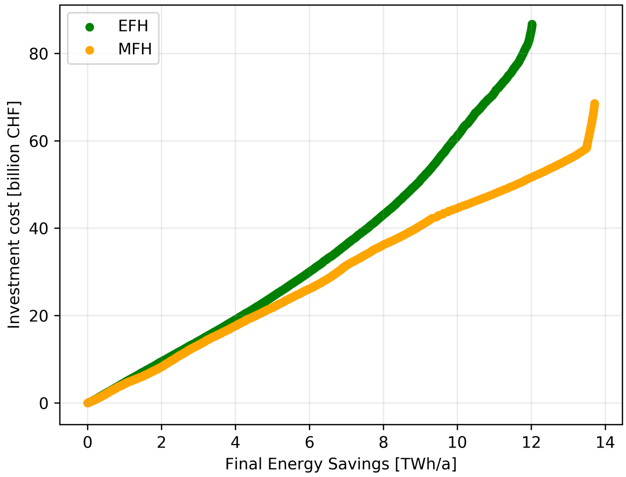


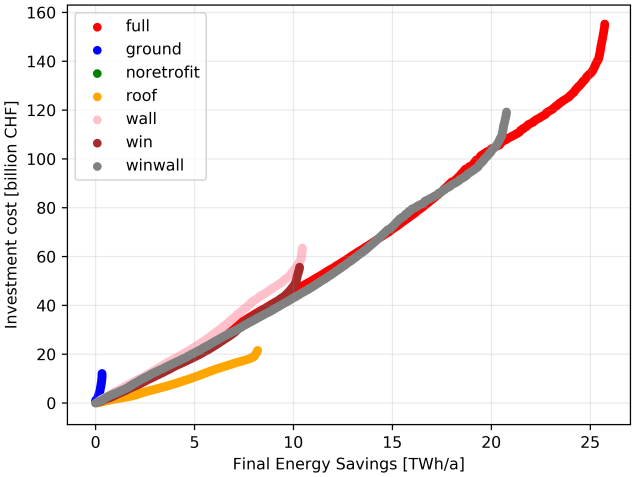
Figure 4.1: Comparison of the investment cost curve for residential buildings.

Figure 4.1 compares the resulting energy efficiency curves investment curves for the up-scaled CESAR results (full-retrofit) and the scenarios of the SwissRes simulations. The CESAR full retrofit is equivalent to the Swiss-Res full scenario. Both models find similar total saving potentials of around 25 TWh for the current residential building stock. However, the results from CESAR indicate have lower investment costs. It is known that CESAR has a tendency to over-estimate the performance (under-estimate the demand) of new and fully retrofitted buildings, so this could explain this trend. The reason for this is not fully understood but it has been suggested that it could be partly explained by unrealistically low ventilation/infiltration rates that are assumed for new buildings. This can also be due to uncertainty on the interaction between the occupant and the building, e.g. opening of doors and windows.

4.1.1 CESAR



(a) Investment curve curve for the different residential building types.



(b) Investment cost curve for different retrofit solutions.

Figure 4.2: Energy efficiency curves from the CESAR model by building type and retrofit strategy.

> Data available at https://data.sccer-jasm.ch/retrofit-savings-cesar/

We split the investment curve of the CESAR model for MFH and SFH (Figure 4.2a). These results indicate lower investment costs and higher energy saving potentials for the MFHs. Furthermore, we split the energy efficiency curve into retrofit options to identify the effectiveness of each retrofit solution (Figure 4.2b). Ground retrofits have the highest cost but the lowest energy savings potentials; whereas roof retrofits are the most cost effective strategy. The replacement of windows and walls accounts for the greatest part of energy savings of the full retrofit but also for the largest part of the costs.

4.1.2 SwissRes

To get a better understanding of the cost-effectiveness of envelope retrofit as provided in the SwissRes model, Figure 4.3 shows the investment curve with specific investment cost per saved energy. The results clearly indicate that the specific investment cost are relatively stable until around 20 TWh annual savings.

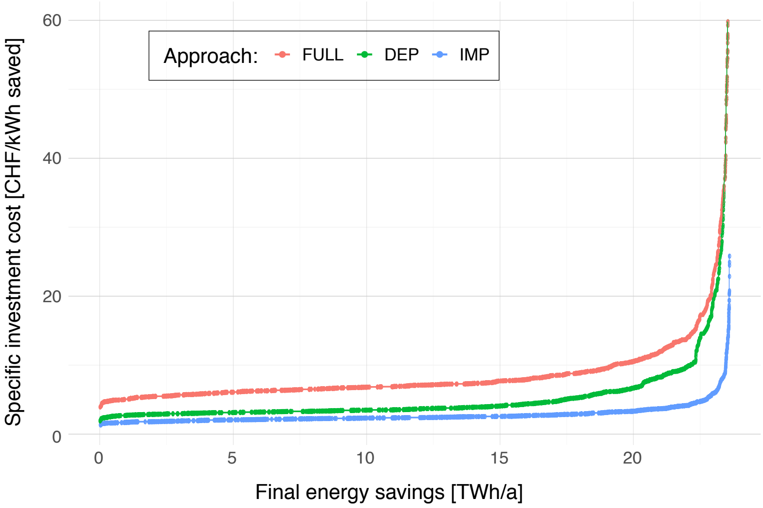


Figure 4.3: Specific investment cost curve by economic assessment approach for the SwissRes model.

> Data available at https://data.sccer-jasm.ch/energy-efficiency-residential-swissres/

Given the archetype structure of the SwissRes model, the results can be further disaggregated. Figure 4.4 shows the investment cost curve for each combination of building type and construction period individually for the three economic assessment approaches. In general, we see that the age of building has a very strong influence on the investment cost-effectiveness, with new buildings requiring very high investment cost and no measurable effect on the energy savings. In more detail, the results indicate that very old SFHs have a very high saving potential of almost 3 TWh/a. MFHs constructed between 1960 and 1980 feature also a high saving potential in the range of 2.5 TWh/a and show the highest investment cost-effectiveness of all archetypes. This result is consistent with the findings with the CESAR model presented in the Section 4.1.1.

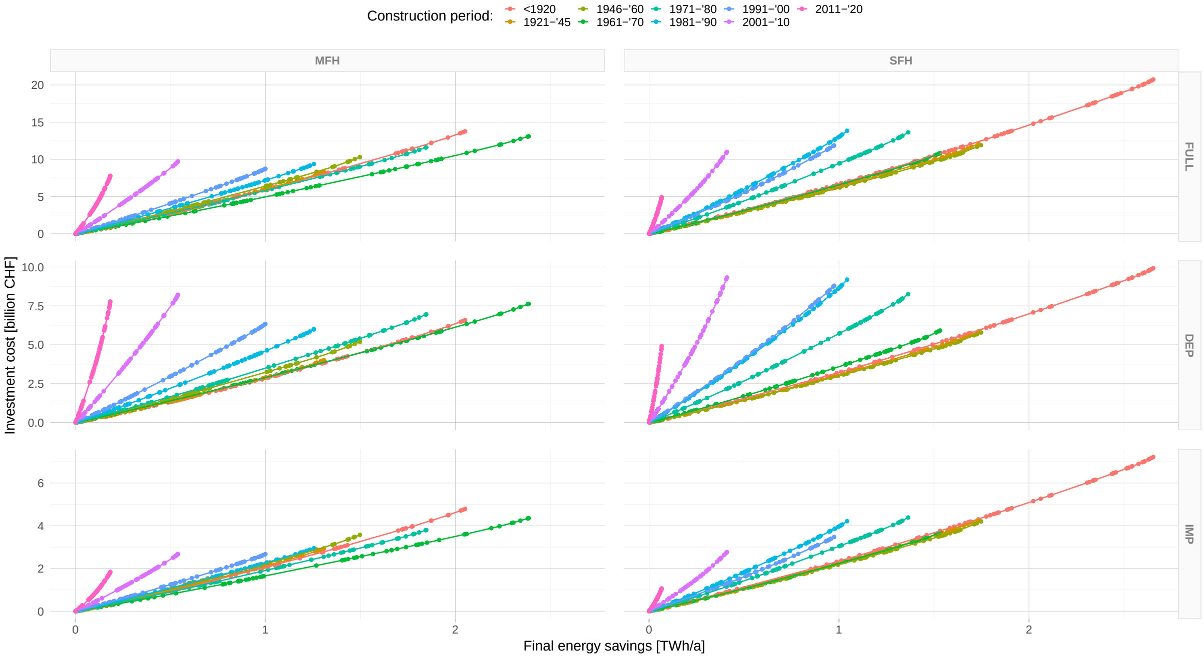


Figure 4.4: Investment cost curve by economic assessment approach and archetype categories construction period and building type for the SwissRes model.

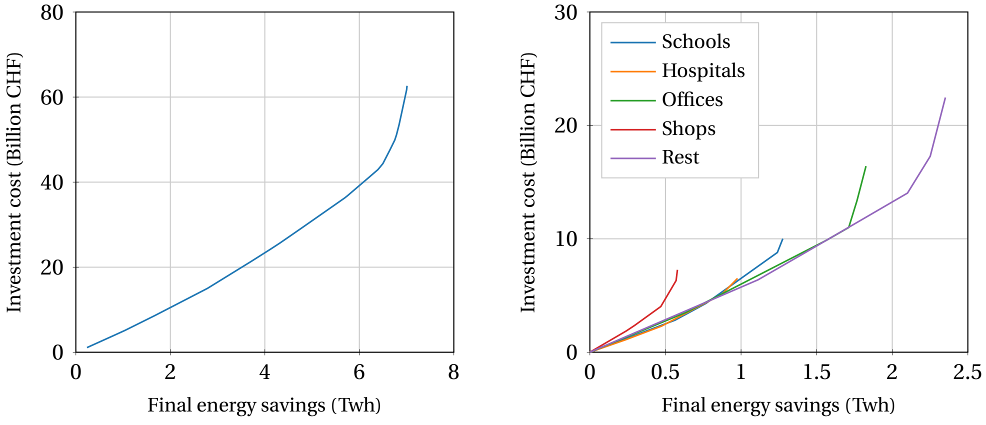
> Data available at https://data.sccer-jasm.ch/energy-efficiency-residential-swissres/

4.2 Commercial buildings

We use the CESAR model to estimate saving potentials and the corresponding investment costs for hospitals, offices, schools and shops. The estimation includes nine archetypes for each building type.

To get the energy efficiency curve for the whole commercial sector we upscale, for each building type, the estimation from the nine archetypes to the full building stock. We take the ERA for the full building stock from the ERA by building type published by Wüest Partner (2019) and the distribution by age classes from Jakob et al. (2019, p. 68). We then match each archetype to an age class and upscale the energy savings and the investment costs, assuming constant savings per ERA (in kWh/m2) and investment costs per energy saved (in CHF/kWh). The buildings covered by the CESAR model account for 66% of the total ERA in 2013. The remaining ERA corresponds to restaurants, hotels, agriculture buildings, transport buildings and other commercial buildings. We assume that these other categories have savings potentials per area (in kWh/m2) and investment costs per energy saved (in CHF/kWh) that correspond to the average of the rest of the buildings. Finally, we added the temporarily used buildings, whose ERA we know from the BFE (2018), and we assume that the distribution into age classes corresponds to that in the residential sector.

Figure 4.5a shows the energy efficiency investment curve for commercial buildings. An investment of 40 billion CHF achieves an estimated saving of 6 TWh. Figure 4.5b depicts a further breakdown of the non-residential investment curve by building type. This graph shows that retrofitting office buildings account for most of the savings, i.e. 1.75 TWh of savings for ca. 10 billion CHF. The retrofitting of the other categories is less attractive in terms of cost effectiveness, particularly shops where the maximum energy saving potential is ca. 0.6 TWh for nearly 10 billion CHF.



(a) Full building stock

(b) By building type

Figure 4.5: Energy efficiency cost curve for the Swiss commercial sector

> Data available at https://data.sccer-jasm.ch/retrofit-savings-cesar/

Chapter 5

Discussion

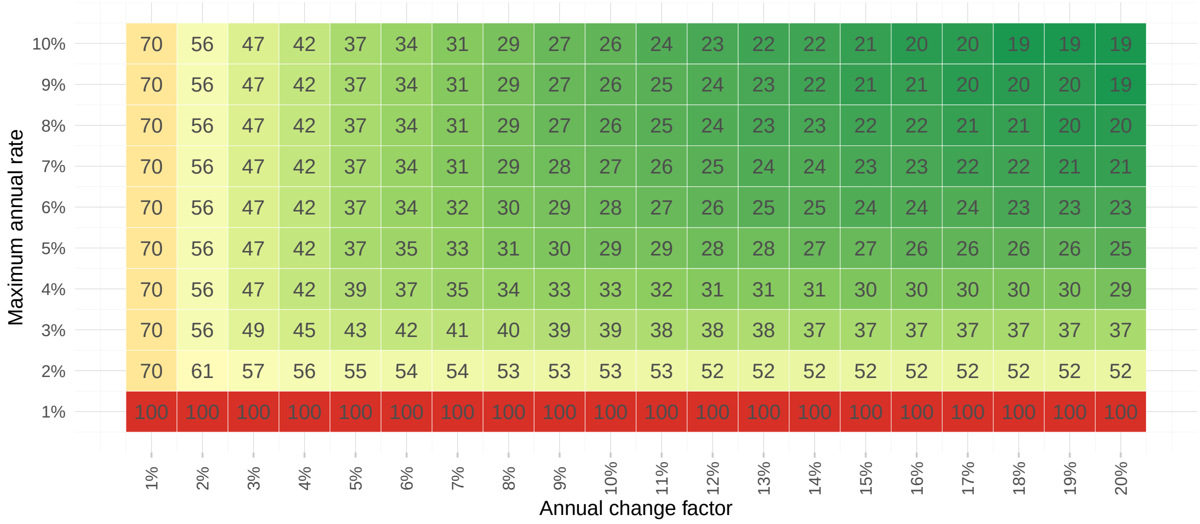
This section discusses the potential of envelope retrofit in the Swiss building stock based on the results; as well as the major modelling limitations and their implications for the results are discussed.

5.1 Potential of envelope retrofit

The results indicate a maximum final energy saving potential of envelope retrofit in the range of 25 TWh/a for the residential building stock (Figure 4.1), and 6 TWh/a for the non-residential building stock (Figure 4.5a). This leads to a combined technical reduction potential of approximately 32 TWh/a or 40 kWh/m2/a. The final energy demand for space heating in 2015 was 62 TWh/a (Figure 2.1). This saving potential therefore accounts for roughly a 50% demand reduction and could decrease the specific final space heating demand of today's building stock down to 43 kWh/m2/a (compared to around 130 kWh/m2/a currently). This high technical saving potential is confirmed by other Swiss studies, which estimated a relative saving potential of 60–67% for envelope retrofit (Siller et al., 2007, Amstalden et al., 2007, Kannan and Turton, 2014). These differences can be traced back to a substantially higher demand before retrofit in these studies, which results in a specific demand of roughly 50 kWh/m2/a after retrofit and is close to the results of this study.

While this study could confirm a high technical potential of envelope retrofit in the Swiss building stock, it is important to consider that such a large-scale retrofit of the entire stock would take decades to be achieved if we continue at the very low current retrofit rate of 1% per year. Figure 5.1 presents the time in years needed to achieve a complete retrofit of the Swiss building stock depending on the (achievable) maximum annual retrofit rate (y-axis) and the annual percentage change of the current retrofit rate of 1%/a (x-axis). A full retrofit by 2050 (30 years in the plot) requires an increase in the current annual rate to at least 4%/a. However, this will work only if the current retrofit rate of 1%/a increases significantly and constantly in the next decades. According to Figure 5.1, the current rate of 1%/a needs to increase by an annual factor of +15% (1.15) to achieve a retrofit of the entire stock in approximately 30 years. Alternatively, for a slower transition with annual change rates below 10%, a complete retrofit of the stock in 30 years could only be achieved if the annual retrofit rate increases beyond 4%/a. It is therefore very likely that despite the high technical potential of envelope retrofit, this potential could only be partially implemented by 2050.

The high upfront investment costs that house owners face when retrofitting their homes is one of the main barrier to realize the high energy saving potentials in buildings. According to the results of this



Maximum annual rate	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%	16%	17%	18%	19%	20%
10%	70	56	47	42	37	34	31	29	27	26	24	23	22	22	21	20	20	19	19	19
9%	70	56	47	42	37	34	31	29	27	26	25	24	23	22	21	21	20	20	20	19
8%	70	56	47	42	37	34	31	29	27	26	25	24	23	23	22	22	21	21	20	20
7%	70	56	47	42	37	34	31	29	28	27	26	25	24	24	23	23	22	22	21	21
6%	70	56	47	42	37	34	32	30	29	28	27	26	25	25	24	24	24	23	23	23
5%	70	56	47	42	37	35	33	31	30	29	29	28	28	27	27	26	26	26	26	25
4%	70	56	47	42	39	37	35	34	33	33	32	31	31	31	30	30	30	30	30	29
3%	70	56	49	45	43	42	41	40	39	39	38	38	38	37	37	37	37	37	37	37
2%	70	61	57	56	55	54	54	53	53	53	53	52	52	52	52	52	52	52	52	52
1%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Figure 5.1: Time requirement (in years) for retrofitting an entire building stock, as a function of the maximum annual retrofit rate and the annual change factor of the current retrofit rate of 1% (Streicher et al., Forthcoming 2020)

study, the implementation of the complete technical potential of envelope retrofit would require very high FULL investment costs in the range of 150–200 billion CHF for the residential (Figure 4.1) and up to 30 billion CHF for the non-residential building stock (Figure 4.5a). This means that until 2050, approximately 6–8 billion CHF/a would have to be covered on average. These values can be put into perspective by comparison with the budget volume of the federal building programme (Gebäudeprogramm) which amounts to 360 million CHF annually (sourced from the CO2 tax) (BFE, 2020). Together with the current cantonal contributions of 80 million CHF/a on average (BFE, 2020), these subsidies compensate roughly 5-7% of the required average annual investment cost for retrofitting the entire building stock until 2050. However, the results also showed a non-linear relationship between cumulated energy savings and cumulated investment cost, with higher levels of savings requiring higher specific investment cost per saved energy (Figure 4.3). This concerns in particular newer buildings, whose U-values are already close to the efficiency requirements and have therefore low energy saving potentials with high investment costs (Figure 4.4). Therefore, if we limit retrofitting measures to a maximum specific cost of 10 CHF/kWh, the total investment costs are almost halved. In this case, the government subsidies account for 9–11% of the investment cost. Notably, by limiting the retrofit costs to 10 CHF/kWh we only reduce the total energy saving potential by 25%, to 24 TWh/a per year. It is therefore crucial to consider the trade-offs between very high total savings and the significantly more expensive implementation. Energy system models that analyze the whole system can shed light in this aspect. They compare building retrofitting to other changes in the energy system and determine the optimal level of energy savings that are needed to achieve certain climate change mitigation goals.

In terms of the economic considerations for envelope retrofit, estimates show that investments on refurbishment (and partial retrofit) of the Swiss building stock are roughly 13 billion CHF/a (BFE, 2020). This means that the annual spending on maintaining the building stock surpasses the investments of 6-8 billion CHF/a required to retrofit all the envelope building elements in the stock until 2050. The methodology presented in Section 3.2.4, accounts for these already occurring cost in the calculation of the investment requirements. The results show investment requirements of 60 or 125 billion CHF for the IMP and DEP approaches, respectively (Figure 4.1). These total costs correspond to an average investment cost of 2 billion CHF/a and 4 billion CHF/a, compared to the 6-8 billion CHF/a when excluding the investments on refurbishment. Exiting subsidies could additionally reduce these costs by 11–22%. This illustrates well the strong effect on the economic considerations of the assumed stakeholder perspective and subsequently the economic assessment approach.

The FULL approach is nowadays the most widely applied and it represents the most conservative valuation method since it requires that the energy savings alone will have to payback all the energy retrofit investments (Pielli, 2008). Such an approach results in very high investment cost. This shows that an exclusively profit-oriented strategy of the market represented by external investors conflicts with attainability of the goals of the energy transition and of deep decarbonisation.

In contrast, the IMP approach implies the strategy to wait for the right point in time for the energy retrofit, i.e. to separately retrofit building elements once their respective lifetime has been reached. Therefore, it only considers the cost related to the energy efficiency improvement. This approach stands for a sensible strategy, but its systematically implementation is unlikely due to a wide range of barriers (e.g. lack of capital when a measure is due, lacking of alignment with family plans, age of owners or occupants, perceived asset value differing from assumed value according to the method, etc.). Moreover, due to different lifetimes of the building elements, their related refurbishment cycles will in most cases not overlap, leading to a constant need of improvement, which cannot benefit from the (economic) synergies of a complete energy retrofit. This restriction leads to a slower transition, which implies a larger amount of cumulated impacts.

For all these reasons and in order to accelerate the energy transition, the DEP approach allows to capture early energy retrofit strategies and the intrinsic asset value of building elements. Opposite to the two extreme approaches which are either completely including (FULL) or completely excluding (IMP) the refurbishment costs, the DEP approach represents a better balance between environmental/energy and economic aspects by not considering the full investment cost while still factoring in the remaining value of the existing building elements (Pielli, 2008). Hence, the DEP approach is able to represents the inertia of energy retrofitting while identifying the most appropriate point in time for an early retrofit, based on the trade-off between high environmental impacts and the replacement of still functional elements. From this point of view, the DEP approach can be considered as a method that indicates the potential of implementing deep energy retrofitting as complete packages (i.e., not element-wise) in a more sustainable manner (covering the energy/environmental and the economic dimensions of sustainability).

5.2 Model limitations

The results of this study have highlighted some priority areas to direct investments for the retrofitting of buildings; however there are a large number of assumptions that have been made that could have large impacts on the accuracy of the results.

For the CESAR model, this is particularly highlighted in the comparison with SwissRes. As mentioned before, the CESAR model can over-estimate the performance of new and retrofitted buildings. Another source of uncertainty arises from the limited number of archetypes used to represent the building stock. In this study the subset of SFH archetypes represented less than 30% of the area represented by the 500 set. In the case of MFHs, the representative archetypes account for 80% of the total area, but the first 5 accounted for the most of this area. Any inaccuracies in the simulation of these 5 buildings would have large implications for the up-scaled results. For these reasons it is stressed to be cautious when using the values from CESAR. High-level observations are acceptable; however more detailed investigation is required to fully understand the reasoning behind the differences. In the future, data-driven approaches will be investigated to better understand these results.

As for the SwissRes model, one of the main uncertainties is that the investment cost estimation is based on a conversion from German to Swiss prices. However, the investment cost estimations for Switzerland with SwissRes are in a similar range of other related studies in Streicher et al. (2020) and the CESAR model that. As for the main input data of the SwissRes model, the CECB is the largest publicly available source for building element data in Switzerland. However, compared to the residential building stock, the CECB is only a small sample (3%) and any analysis based on this source can therefore only be an approximation of the current state of the real building stock. The CECB data covers all archetype categories and matches the national statistic (Streicher et al., 2018). However, the literature review indicate that data from energy certificates can be biased towards well performing buildings (Loga and Diefenbach, 2009). Requests for a CECB are indeed primarily driven by proactive owners, unless they are legally required by the local cantonal policy. Additionally, the building specific data such as U-Values are expert based assumptions, which do not require any physical measurements. However, the SwissRes model uses the CECB PLUS certificate, which implies a systematic input of all individual building elements and should therefore provide a more diverse dataset of the building (element) properties (Conférence des directeurs cantonaux de l'énergie, 2018). Furthermore, the comparison with related studies using questionnaires as main data source, has shown a very good match for the estimated U-Value ranges and shares of retrofitted element, which indicates that the CECB data is indeed providing a good representation of the Swiss residential building stock (Streicher et al., 2018).

As for the differences in economic assessment approaches, results for the IMP and DEP approach are currently only available for the residential building stock. While the non-residential building stock is only accounting for about 20% of the total savings and 13–16% of the total investments, it would be very beneficial to investigate the IMP and DEP potential of the non-residential building stock in future studies.

Besides a variation of input parameters, the investment cost of both models could also be influenced by technical or social constraints which are outside the scope of this study, e.g. economies of scale can reduce costs while local environmental conditions such as space or noise restrictions or specific architecture could make retrofit more challenging and subsequently more costly. Furthermore, this study does not consider the indirect impact of retrofit actions on people actually living in the building. This concerns discomfort or even relocation during retrofitting as well as an assessment of the rent increase in MFHs and whether this could be kept at a socially acceptable level (Lang and Lanz, 2018). Additionally, most of the techno-economic studies on the building stock (including this study) neglect the ownership of the building, mostly due to data limitation on this often confidential information. However, given this mismatch, more research to account for the ownership of the building when assessing the potential of energy retrofit is recommended.

Next to these challenges, it should also be considered that energy retrofit can lead to additional economic benefits originating from "improved durability, reduced maintenance, greater comfort, increased habitable space, increased productivity, and improved health and safety" after retrofit, as stated by the International Energy Agency (IEA, 2015).

Chapter 6

Conclusion

The results of both the CESAR and the SwissRes model show that an energy retrofit of the building elements could lead to a reduction of roughly 50% (32 TWh/a) of the total final energy demand of space heating. This study could hence confirm the high technical energy saving potential of envelope retrofit measures in the Swiss building stock. The results in this study can be used by energy-system models to assess the optimal energy saving levels and investment costs needed to achieve different CO2 emissions targets in Switzerland. Our analysis shows that implementing the total technical potential is not possible at the current retrofit rate of 1% per year.

The potential of the envelope retrofit is furthermore restricted by the very high investment cost that are leading to average investment cost in the range of 6-8 billion CHF/a until 2050. According to this study, about 5–7% of these investment cost could be covered by the current budget allocated to retrofit subsidies. The results indicate a non-linear relationship between the cumulated savings and the cumulated investment cost, in particular beyond a total savings potential of 24 TWh/a. This means that the maximum technical saving potential features a very high trade-off for the required investment cost. The results indicate that already 75% of the technical saving potential could be reached with almost half the investment volume. If we consider the very high annual maintenance expenses of the building stock (that are actually higher than the annual investment cost requirements for the envelope retrofit), the total investment cost are in the range of 2-4 billion CHF/a.

As for further research, data-driven analysis could allow to better understand the differences between the CESAR and SwissRes model. Furthermore, the different cost valuation approaches could be extended also to the none residential building stock. A more detailed analysis of the social restrictions of energy retrofit in the Swiss building stock, as well as the consideration of additional benefits for the owner and occupants of the building would complement the holistic analysis of the potential of envelope retrofit for the Swiss Energy Strategy 2050.

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