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Endogenous Energy Efficiency Improvement in Housing and Cement Sectors in Switzerland

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par

Sergey ARZOYAN

Acceptée sur proposition du jury

Prof. B. Merminod, président du jury
Prof. Ph. Thalmann, directeur de thèse
Dr P. Burgherr, rapporteur
Prof. M. Farsi, rapporteur
Prof. C. Fivet, rapporteur

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Для моей семьи.

Я люблю вас больше всего на свете.

Вы моё всё.

Իմ ընտանիքի համար:

Ես ձեզ շատ եմ սիրում:

Դուք իմ ամեն ինչն եք:

Abstract

The reduction of energy consumption in the residential building stock and cement industry is a substantial component of the Swiss Energy Strategy 2050. Therefore, it is vital to identify the potential for Energy Efficiency Improvement (EEI) in these two sectors. In this study, a new methodology was developed for the acceleration of EEI via two new models. The main goal of this research is to investigate the impacts of energy and climate policies on the deep decarbonisation of the Swiss residential building stock and cement industry.

In the first paper, the Swiss building stock model is developed. The objective was to understand the future evolution of the Swiss residential building stock, taking into account the different policy measures implemented and how these measures can help to achieve deep decarbonisation of the sector. For this purpose, a two-step decision process was developed for property owners, which consists of the decision to audit and the decision to retrofit. The results of our simulations show that soft (information) and strong (economic) incentives are more effective when combined.

In the second paper, the building stock model was extended with additional features. The objective was to investigate the impact of the endogenous decision to build New Construction (NC), taking into account the introduction of restrictions on NC and the implementation of different policy measures on the Swiss residential building stock. With this intent, the choice of energy class for NC in the housing stock was endogenized, different policies were introduced and restrictions on the energy class of NC were imposed. The results show that large-scale retrofits of the existing building stock together with the introduction of different policy measures and restrictions on the energy class on NC are essential to reach deep decarbonisation targets. However, in this model, the upfront CO_2 related to the building of new constructions or the retrofitting of existing ones is not considered.

In the third paper, the energy efficiency model for the Swiss cement industry was developed. The objective of this study was to investigate how endogenous energy efficiency improvements combined with the implementation of different policy measures can help to achieve deep decarbonisation in the Swiss cement industry. The developed model is able to consider and evaluate the impact of measures on fuel and electricity consumption and CO_2 emissions, using a plant-specific bottom-up approach. The results show that to develop specific policies and programs to encourage further implementation of energy-efficient measures in the Swiss cement industry, an understanding of the existing technologies and barriers to their implementation is essential.

Overall, this research has demonstrated that it is crucial to assess the effects of different policies on EEI in the Swiss residential building stock and cement industry. In particular, a smart combination of policy measures, together with an understanding of the existing technologies and barriers to their implementation, can help to increase energy savings from EEI and achieve the goal of deep decarbonisation in both sectors, ultimately contributing to the Swiss Energy Strategy 2050 and Switzerland's long-term climate strategy.

KEYWORDS: building retrofitting, energy retrofit, endogenous energy efficiency, climate policy, policy mix, Switzerland, cement industry, emission reduction

Zusammenfassung

Die Senkung des Energieverbrauchs im Wohngebäudebestand und in der Zementindustrie ist ein wesentlicher Bestandteil der Schweizer Energiestrategie 2050. Daher ist die Identifizierung des Potenzials für Endogene Energieeffizienzsteigerung (EES) in diesen beiden Sektoren von entscheidender Bedeutung. Diese Studie entwickelt eine neue Methodik zur Beschleunigung der EES mittels zweier neuer Modelle. Das Hauptziel dieser Forschung ist es, die Auswirkungen der Energie- und Klimapolitik auf die tiefgreifende Dekarbonisierung des Schweizer Wohngebäudebestands und der Zementindustrie zu untersuchen.

In der ersten Arbeit wird das Modell für den Schweizer Gebäudebestand entwickelt. Ziel war es, die künftige Entwicklung des Schweizer Wohngebäudebestands unter Berücksichtigung der verschiedenen politischen Maßnahmen zu verstehen und herauszufinden, wie diese zu einer weitgehenden Dekarbonisierung des Sektors beitragen können. Zu diesem Zweck wurde ein zweistufiger Entscheidungsprozess für Immobilieneigentümer entwickelt: welcher aus einer Entscheidung zum Audit und einer Entscheidung zur Sanierung besteht. Unsere Simulationen zeigen, dass weiche (Information) und starke (wirtschaftliche) Anreize effektiver sind, wenn sie kombiniert werden.

In der zweiten Arbeit wurde das Gebäudebestandsmodell erweitert. Ziel war es, die Auswirkungen der endogenen Bauentscheidung unter Berücksichtigung zusätzlicher Restriktionen für Neubau und die Umsetzung verschiedener politischer Maßnahmen auf den Schweizer Wohngebäudebestand zu untersuchen. Daher wurde die Wahl der Energieklasse für Neubau im Wohnungsbestand endogenisiert, verschiedene politische Maßnahmen wurden eingeführt und Beschränkungen für Neubau-Energieklassen wurden auferlegt. Die Ergebnisse zeigen, dass groß angelegte Sanierungen des bestehenden Gebäudebestands in Verbindung mit der Einführung verschiedener politischer Maßnahmen und Beschränkungen der Energieklasse für Neubau unerlässlich sind, um die Dekarbonisierungsziele zu erreichen. In diesem Modell werden jedoch die CO_2 im Zusammenhang mit dem Bau neuer Gebäude oder der Nachrüstung bestehender Gebäude nicht berücksichtigt.

In der dritten Arbeit wurde das Energieeffizienzmodell für die Schweizer Zementindustrie entwickelt. Ziel war es, zu untersuchen, wie EES in Kombination mit der Umsetzung verschiedener politischer Maßnahmen dazu beitragen können, eine tiefe Dekarbonisierung in der Schweizer Zementindustrie zu erreichen. Das entwickelte Modell ist in der Lage, die Auswirkungen von Maßnahmen auf den Brennstoff- und Stromverbrauch sowie die $\mathrm{CO_2}$-Emissionen mit einem anlagenspezifischen Bottom-up-Ansatz abzuschätzen. Die Ergebnisse zeigen, dass für die Entwicklung spezifischer politischer Maßnahmen und Programme zur Förderung

der weiteren Umsetzung energieeffizienter Maßnahmen in der Schweizer Zementindustrie ein Verständnis der vorhandenen Technologien und der Hindernisse für deren Umsetzung unerlässlich ist.
Diese Forschung zeigt, dass die Bewertung der Auswirkungen verschiedener politischer Maßnahmen auf die EES im Schweizer Wohngebäudebestand und in der Zementindustrie entscheidend ist. Insbesondere eine optimale Kombination von politischen Maßnahmen mit einem Verständnis der bestehenden Technologien und der Hindernisse für ihre Umsetzung erhöht die Energieeinsparungen durch EES und erreicht eine tiefgreifende Dekarbonisierung in beiden Sektoren, was letztendlich zur Schweizer Energiestrategie 2050 und zur langfristigen Klimastrategie der Schweiz beiträgt.

SCHLÜSSELWÖRTER: Gebäudesanierung, energetische Sanierung, endogene Energieeffizienz, Klimapolitik, Policy-Mix, Schweiz, Zementindustrie, Emissionsminderung.

Résumé

La réduction de la consommation d'énergie dans le parc immobilier résidentiel et l'industrie du ciment est un élément important de la Stratégie énergétique suisse 2050. Il est donc essentiel d'identifier le potentiel de l'Amélioration Endogène de l'Efficacité Énergétique (AEEE) dans ces deux secteurs. Cette étude développe une nouvelle méthodologie pour l'AEEE via deux nouveaux modèles. L'objectif principal de cette recherche est d'étudier les impacts des politiques énergétiques et climatiques sur la décarbonisation profonde du parc immobilier résidentiel et de l'industrie du ciment en Suisse.

Dans le premier article, le modèle du parc immobilier suisse est développé. L'objectif est de comprendre l'évolution future du parc immobilier résidentiel suisse, en tenant compte des différentes mesures politiques mises en œuvre et de la manière dont elles peuvent contribuer à une décarbonisation profonde du secteur. Ainsi, un processus de décision en deux étapes a été développé pour les propriétaires : auditer ou non et rénover ou non. Nos simulations montrent que les incitations douces (informations) et fortes (économiques) sont plus efficaces lorsqu'elles sont combinées.

Dans le deuxième article, le modèle de parc immobilier a été étendu et élaboré. L'objectif était d'étudier l'impact de la décision endogène de construire des nouvelles constructions, compte tenu des nouvelles restrictions sur les nouvelles constructions et de la mise en œuvre de différentes mesures politiques sur le parc immobilier résidentiel suisse. Le choix de la classe énergétique des nouvelles constructions dans le parc immobilier a été endogénéisé, différentes politiques ont été introduites et des restrictions sur les classes énergétiques des nouvelles constructions ont été imposées. Les résultats montrent que les rénovations à grande échelle du parc immobilier existant ainsi que l'introduction de différentes mesures politiques et de restrictions sur la classe énergétique des nouvelles constructions sont essentielles pour atteindre les objectifs de décarbonisation profonde. Cependant, dans ce modèle, le CO_2 lié à la construction de nouvelles batiments ou à la rénovation de celles existantes n'est pas pris en compte.

Dans le troisième article, le modèle d'efficacité énergétique pour l'industrie suisse du ciment a été développé. L'objectif est d'étudier comment les améliorations endogènes de l'efficacité énergétique, combinées aux différentes mesures politiques mises en œuvre, peuvent contribuer à une décarbonisation profonde de l'industrie suisse du ciment. Le modèle développé est capable d'évaluer l'impact des mesures sur la consommation de carburant et d'électricité et sur les émissions de $\mathrm{CO_2}$, en utilisant une approche spécifique à l'usine. Les résultats montrent que pour développer des politiques et des programmes spécifiques visant à encourager la mise en œuvre de mesures d'efficacité énergétique dans l'industrie suisse du ciment, il est essentiel de comprendre les technologies existantes et les obstacles à leur mise en œuvre. Cette recherche démontre qu'il est crucial d'évaluer les effets de différentes politiques sur l'AEEE dans le parc immobilier résidentiel et l'industrie du ciment en Suisse. En particulier, des mesures politiques combinées de manière optimale avec une compréhension des technologies existantes et des obstacles à leur mise en œuvre, augmentent les économies d'énergie provenant de l'AEEE et réalisent une décarbonisation profonde dans les deux secteurs, contribuant finalement à la Stratégie énergétique suisse 2050 et à la stratégie climatique à long terme de la Suisse.

MOTS CLÉS : rénovation des bâtiments, efficacité énergétique endogène, politique climatique, combinaison de mesures économiques, Suisse, industrie du ciment, réduction des émissions

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Acronyms

A-TP Autonomous Technical Progress

ABZ Allgemeine Baugenossenschaft Zürich

ABBSM Agent-based Building Stock Model

AEEE Amélioration Endogène de l'Efficacité Énergétique

BAT Best Available Technology

BPT Best Practice Technology

BSM Building Stock Model

CCS Carbon Capture and Storage

CECB Cantonal Energy Certificate for Buildings

CES Constant Elasticity of Substitution

CO_2 Carbon Dioxide

CP Construction Period

CSC Conservation Supply Curve

CSM CO_2 Saving Measure

DR Demolition Rate

EC Energy Class

ECSC Energy Conservation Supply Curves

EEI Energy Efficiency Improvement

EEM Energy Efficiency Measure

EES Endogene Energieeffizienzsteigerung

ERA Energy Reference Area

ETS Emissions Trading System

EUP Essential Unit Process

EU European Union

MI-TP Measure-induced Technical Progress

MoPEC Modèle de Prescriptions Énergétiques des Cantons

Mt Megatons

MuKEn14 Model Regulations for Energy Use in the Cantons

NC New Construction

OT Owner Type

PEEM Pure Energy Efficiency Measures

RM Retrofit Matrix

SIA Swiss Society of Engineers and Architects

SFOE Swiss Federal Office of Energy

SCHL Société Coopérative d'Habitation Lausanne

SHD Space Heating Demand

SwissRes Swiss Residential Building Stock Model

TP Technological Progress

VAT Value-added Tax

“I love it when people say that something can’t be done. That’s when I really get motivated; I like to prove them wrong.” — Arnold Schwarzenegger

“”

“For me, life is continuously being hungry. The meaning of life is not simply to exist, to survive, but to move ahead, to go up, to achieve, to conquer. I will always stay hungry, never satisfied with current accomplishments. Have a vision, trust yourself, break some rules, ignore the naysayers, don’t be afraid to fail.” — Arnold Schwarzenegger

“”

“I started my life with a single absolute: that the world was mine to shape in the image of my highest values and never to be given up to a lesser standard, no matter how long or hard the struggle. ” - Ayn Rand, Atlas Shrugged

“”

“Certainly he must be successful with such an appearance, his wish to succeed, his native resolution, and his independence of mind.” - Guy de Maupassant, Bel-Ami

“”

“Success is the sum of small efforts, repeated day in and day out” –Robert Collier.

“”

“You think darkness is your ally? You merely adopted it; I was born in it - molded by it. I didn’t see the light until I was only a man.” - Bane

1 Introduction

1.1 Background and motivation

With the goal to promote the stepwise decarbonisation of the Swiss national energy system, the Swiss government implemented the so-called Energy Strategy 2050 [1]. This strategy predicts different scenarios that aim to decrease the final energy demand from the year 2015 until the year 2050 [1]. The main focus of the Energy Strategy is to increase energy efficiency and also promote the use of renewable energy. Indeed, the advancement and development of energy efficiencies are critical for future energy use in Switzerland. However, the Energy Efficiency Improvement (EEI) being usually exogenous in most of the analyses is a weakness of many models that are used to simulate energy pathways [2, 3, 4]. Models that are used to simulate energy and climate policies usually take into account EEI to some extent. These models are developed to respond to regulations that increase the actual price of energy, frequently by substituting other production elements, primarily capital, for energy.

Thus, the overarching aim of this thesis is to endogenise the process of energy efficiency and the improvement of this concept in residential buildings and the cement industry in Switzerland (two of the country's highest emitting sectors), which, consequently, both have considerable reduction potential.

According to the Swiss Federal Office of Energy (SFOE), the largest location of demands of the total final annual energy in Switzerland is in its building stock, accounting for 45% or 100 Terrawatthour annual [5]. Nevertheless, Switzerland's current retrofit rate is only 1% per year, which falls behind its ambitious policy targets [6]. To address this, in recent years, Switzerland made considerable efforts to implement different policy measures and introduce specific laws to support energy transition through energy retrofitting in building stock. However, it is up to each canton to make these laws binding in their regulations, which slows the process. Currently, there exist several performance certificates, standards, guidelines, and regulations such as the Swiss Cantonal Energy Certificate for Buildings (CECB), which is a performance certificate for buildings that is not mandatory in the cantons but is strongly encouraged through subsidies [7]. Additionally, there are regulations that are supposed to introduce the adoption of these regulations as a requirement of minimum energy performance for new constructions. For instance, the Model Regulations for Energy Use in the Cantons (MuKEn14) is a guideline for cantonal energy policies that include recommendations on energy performance for new constructions and newly retrofitted constructions [8]. These regulations are published on a regular basis. Moreover, the private organisation MINERGIE introduced a certification for new construction and newly retrofitted energy-efficient buildings in Switzerland [9]. These regulations are complemented by special subsidies for the efficient energy retrofitting of buildings, although these subsidies differ considerably when implementing these regulations in different regions and cantons. In Switzerland, the CO_2 levy is collected by the federal customs administration, and its revenues are redirected towards subsidies for the energy-efficient retrofitting of buildings. In many cantons, it is the responsibility of the local government to implement particular measures to control energy consumption in buildings (Programme Bâtiments [10], Modèle de Prescriptions Énergétiques des Cantons (MoPEC) [8], etc.)). Moreover, there are a number of reasons that further complicate Switzerland's energy retrofit rate, such as low energy prices [11] and high labour costs [12]. All of this makes the building stock in Switzerland a very interesting study case.

The Swiss cement industry, being a consumer of a high amount of energy as well as being a high CO_2 emitting sector, accounts for 6% [13] of the total final energy use in the Swiss economy. The Swiss cement industry production is considered to have a large and untapped potential for EEI [14]. Zuberi et Patel [14] estimated the EEI and CO_2 reduction potential of the Swiss cement industry with energy efficiency cost curves, showing an economic potential of 14% for final energy savings and an estimated 13% for the economic CO_2 abatement potential without Carbon Capture and Storage (CCS) [14]. Hence, cement producers are expected to gradually replace their equipment with more energy-efficient ones. Surely, this represents a general trend towards adopting technically advanced new equipment that is more efficient than previous units at the same cost

Nevertheless, the Swiss cement industry faces numerous barriers to EEI, such as large fluctuations in final energy prices and uncertainty about future final energy prices [14]. Moreover, these EEI potentials are very difficult to estimate, due to the unavailability of data. Estimation of energy efficiency using endogenous models, where innovation takes the form of an increasing variety of intermediate inputs, will help to identify barriers to EEI in the cement industry, as well as to develop related effective policies.

All of our models include different kinds of parameters, exogenous and endogenous variables. Particularly valued variables that are determined as endogenous are directly established in the model. Moreover, other variables that are determined as exogenous, have values that are external from the model (discount rates, construction cost, etc.). These exogenous parameters are determined by government policies and are included in the model by us. Additionally, based on scenarios or forecasts from other sources, we predict a course for these variables. Parameters in the model are similar to exogenous variables and are usually given as constants, but are represented in the form of technical production and/or consumer preferences, etc.

1.2 Objectives of the thesis

The objective of this thesis is to identify a way to endogenise the EEI of the housing and cement sector in Switzerland. We aim to implement and simulate already existing or planned regulations, assume realistic policy measures and evaluate their sensitivity to different assumptions.

In this thesis, the following research questions are addressed for the residential sector: 1) What is the future evolution of Swiss residential building stock, taking into account different policy measures implemented? 2) How will the endogenous decision of building new constructions impact the building stock? 3) What effect will it have on the overall CO_2 emissions and useful energy demand decrease, as well as how will it help to achieve the deep decarbonisation of the Swiss residential building stock? 4) What are the trade-offs of these set objectives?

Additionally, the following research questions are addressed for the cement sector: 1) How can endogenous EEI of the Swiss cement industry be modelled? 2) How will the choice of different energy-efficient measures, combined with an implementation of different policy measures, influence the reduction of CO_2 emissions and help to achieve deep decarbonisation in the Swiss cement industry? 3) How will the implementation of more energy-efficient measures influence the fossil fuel and electricity consumption of the Swiss cement industry?

In conclusion, based on the results of different retrofit strategies and the implementation of various policy measures for, both, building stock models and the cement model, potential future strategies and implications of policies are discussed.

1.3 Outline of the thesis

This thesis consists of two papers connected through the Energie – Wirtschaft – Gesellschaft (EWG) project [15] and sponsored by the SFOE. The third paper is the extension of one of the models. The first two papers refer to residential buildings and the last one to the cement sector. All three papers are based on the work I have conducted over the last four and half years.

Chapter 2 presents a paper assessing endogenous energy efficiency improvement of Swiss Building Stock. The paper is titled "A Two-Step Decision Model on Swiss Building Energy Retrofit". The earlier version of this chapter (with data up to the year 2015), published as an appendix in the final report to the SFOE, was written by Sergey Arzoyan, Quirin Oberpriller, Philippe Thalmann and Marc Vielle. The final report is available on EPFL's Infoscience platform [16].

Chapter 3 presents a paper assessing EEI improvement of Swiss Building Stock with the newly developed model for new construction (NC). This paper is an extension of Chapter 3, but not included in the SFOE report, and not published elsewhere other than in this monograph. The paper is titled "Extending Endogenous Energy Efficiency Choices to New Construction" and was written by Sergey Arzoyan.

Chapter 4 presents a paper assessing EEI improvement of the Swiss cement production. The paper is titled “Modelling Endogenous Energy Efficiency Improvement: Swiss Cement Production”. The earlier version of this chapter (with data up to the year 2015), which is published as an appendix in the final report to the SFOE, was written by Sergey Arzoyan, Quirin Oberpriller, Philippe Thalmann and Marc Vielle. The final report is available on EPFL’s Infoscience platform [16].

With the purpose of avoiding repetitions in the text, the methodology section of Chapter 3 only includes the new elements that have not already been described in Chapter 2. Additionally, there is one bibliography for the whole monograph and Chapter appendices are also at the end of the monograph in a dedicated part.

2 A Two-Step Decision Model on Swiss Building Energy Retrofit

2.1 Abstract

In standard modelling of energy and climate policies, the speed and extent of EEI are usually assumed to be unaffected even by policies designed to foster innovation. We model endogenous EEI in a model of the Swiss housing stock. The objective of this paper is to show the capabilities of our model and analyse a range of scenarios, as well as to study how Switzerland can achieve deep decarbonisation of its residential sector through retrofitting. In our framework, retrofitting results from a two-step decision model for building owners. First, they decide to conduct an energy audit, then they decide for or against retrofitting based on different factors such as the net present value (NPV) of the required investment. We use the model to simulate different policies such as a rising retrofit subsidy, a rising CO_2 tax, an information campaign, and combinations of these measures. Both of our combined scenarios achieve deep decarbonisation of the residential stock in the year 2050, with total CO_2 emissions reduced by 88% and 89% relative to 2019, and the increase of the average retrofit rates of residential stock up to 1.89% and 2.02%. In conclusion, our results show that the CO_2 tax contributes to the reduction of emissions at the smallest investment cost because it also encourages fuel switching. However, deep decarbonisation requires a substantially higher retrofit rate, which is obtained by using the revenues of the CO_2 tax to subsidise retrofitting and by adding an information campaign. The results of our simulations show that the policy instruments are much more effective when combined.

2.2 Introduction and Theoretical Background

2.2.1 Swiss context

Switzerland initiated its climate policy in 1990 [17], in close combination with an energy policy that aimed to reduce the country's dependence on imported energy (no fossil fuels are extracted in Switzerland [18]). The first goal to stabilise CO_2 emissions by 2000 at the 1990 level was achieved. The next goals were to reduce CO_2 emissions by 10% and by 20% by 2010 and 2020, respectively [19]. The first of these two goals was only achieved when foreign offsets were taken into account, and the second was missed, mostly due to a lack of reductions in the transport sector [20]. The buildings sector is on track, with CO_2 emissions from fossil energy carriers in the year 2020 being 39% lower relative to 1990 [21].

When considering EEI and fossil energy replacement in the buildings sector, it is important to keep some characteristics of this sector in mind. Between 2010 and 2017, years when there was relatively strong construction, about 1.2% of new dwellings were added to the housing stock every year [22]. Over the same period, 0.07% of dwellings on average were demolished [22]. This illustrates the housing stock's very high inertia. One-half of the existing housing stock was built before the first oil price shock in the year 1973. The second characteristic of Swiss housing is the high proportion of rental housing, at about 60% [23] - the highest share among all comparable countries.

The main existing instruments for encouraging emission reductions in the building sector are; (1) energy efficiency requirements that Switzerland's 26 local authorities (the cantons) apply when delivering a building permit for NC or substantial retrofit, (2) a CO_2 tax on heating fuels introduced in the year 2008 at the rate of 12 CHF/tCO_2 and gradually raised to 96 CHF/tCO_2 in 2018 – 2021, for the year 2022 the CO_2 tax is at 120 CHF/tCO_2 and, (3) an energy retrofit subsidy program initiated in 2010 and funded through the CO_2 tax. In August 2019, the Swiss government announced its intention to reduce greenhouse gas emissions to net-zero by 2050 [24]. The building sector is expected to be among the first to stop emitting any CO_2. It is the sector that, since 1990, has contributed the most to the reduction in greenhouse gas emissions [21].

Large integrated assessment models need to be enriched with a theoretically sound, yet numerically tractable representation of endogenous EEI so that they can better simulate energy and climate policies. This paper proposes such a representation for the Swiss residential buildings stock, where we do not differentiate between Multi-Family (MFH) and Single-Family Houses (SFH).

2.2.2 Characterisation of the Swiss residential building stock

In this study, with the goal to investigate Swiss residential building stock, we focus only on housing and do not include office and retail buildings, also we do not differentiate between single and multifamily houses. Additionally, because of data limitations, the geographical contextualisation of buildings when characterising the behaviour of decision-makers or when analysing the results of the simulation, are not taken into account. These limitations of the model can become an extension for future research. Consequently, the outcome of this model will be only representative of the residential building stock. The quantity of housing in Switzerland is measured by the total Energy Reference Area (ERA) in square meters. ERA is the sum of all areas of the heated floors of the building and is a crucial reference value to quantify the energy performance of a building [25]. The overall ERA is allocated by Construction

Table 2.1: Data Collected

City	Source	Number of dwellings	Year taken	Energy
Lausanne	SCHL	2 011(app.)	2016/2017	Heating
Zürich	ABZ	4 540 (app.)	2016/2017	Heating + Hot water
Geneva	ESTIA	18 634 (app. + buildings)	2019	Heating + Hot water
Different cities	Mobiliar	236 (buildings)	2015	Heating

Table 2.2: Derivation of the Parameter: Standardised Energy Demand, Hot Water (source: INFRAS)

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

Period (CP) and Energy Class (EC). The CP up to the year 1960 are taken in rather large time intervals, because of the lack of data in this timeframe, while from the year 1961 we have more detailed data that allows us to differentiate EC by decades. EC rank from A (best) to G (worst), following a Swiss classification described in Appendix A.2. The data on number of inhabitants per construction period and type of ownership (based on survey sent to individuals) [26] as well as the data average surface of dwellings per inhabitant (by number of rooms and construction period) [27] were collected from the Swiss Federal Statistical Office. Additionally, in order to allocate buildings within each construction period, firstly we needed to collect the data from separate surveys. The surveys, which were conducted at Société Coopérative d'Habitation Lausanne (SCHL), Allgemeine Baugenossenschaft Zürich (ABZ), Estia, and die Mobiliar (see Appendix A.3), helped us to collect data on the ERA per construction period, EC for building stock in different cities, year of construction, information on energy carriers and energy consumption of buildings. The details of the data provided are shown in Table 2.1.

Since the initial data for some surveys were provided including the energy for heating water, we needed to find a way to subtract this energy from our data. For this purpose, we used the data acquired from INFRAS, which shows how much energy for hot water is used per square meter in each apartment (see Table 2.2).

Since initially the data on heating and hot water for Zurich and Geneva was incorporated, we subtracted the energy used for hot water. For Lausanne and die Mobiliar, surveys this was not necessary. From this data, we could calculate the ERA in square meters per construction period for the year 2015 in Switzerland. The results can be seen in Figure 2.1. The thresholds of energy classes are given in Table 2.3, where they are presented as useful energy, which is the final amount of energy available to the customer after the final conversion for their use.

The allocation of ERA by CP and EC for the year 2019 in Switzerland is represented in Figure 2.1. According to the Swiss Federal Statistical Office [22] there was a total of 4.6 million dwellings in Switzerland in 2020, about 1.7 million of which were single-family houses. In the construction period before the year 1919, there remain many inefficient buildings (see Figure 2.1), whereas the buildings built from the year 1961 to the year 2000 have relatively

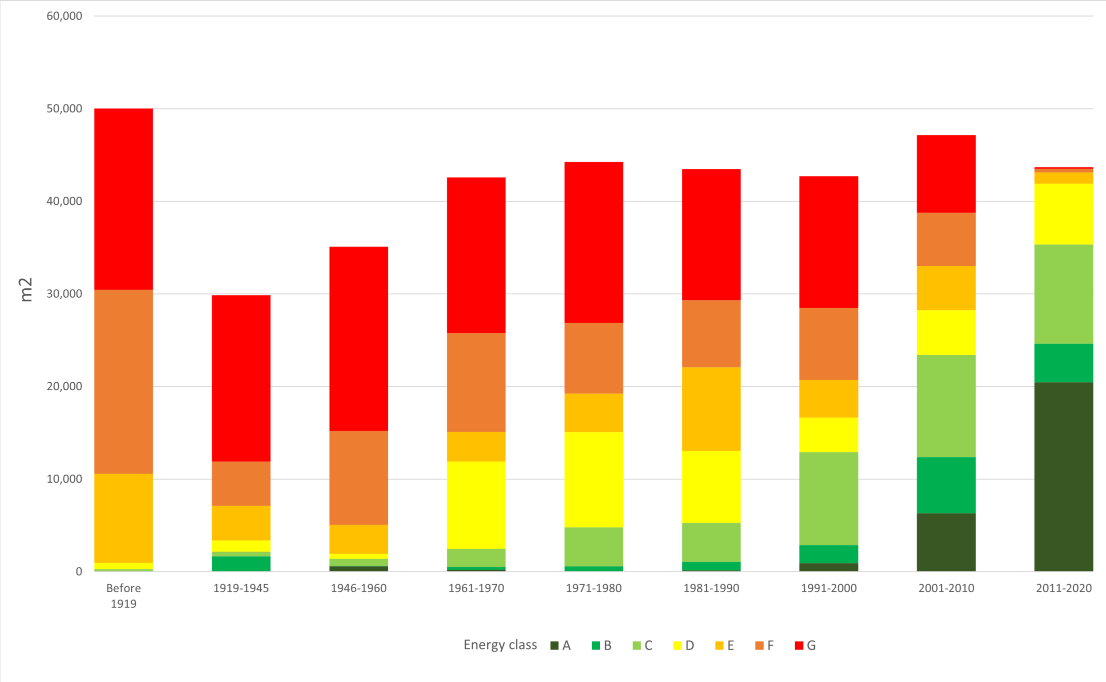

Figure 2.1: Energy reference area (ERA) in 1000 m^2 per construction period and energy class in the year 2019 (for energy thresholds, see Table 2.3); (source: our estimations, using data from the SFOE. See Appendix A.3)

Table 2.3: Thresholds of Energy Classes

Energy class	Average SHD in kWh/m^2 (Source: see Table A.2)	Our assumption of the averages in kWh/m^2
A	<20	20
B	20 – 40	30
C	40 – 60	50
D	60 – 80	70
E	80 – 100	90
F	100 – 120	110
G	>120	150

the same ratio of efficiency classes. As can be seen from Figure 2.1, the share of buildings in EC-G decreases, in EC-F remains constant, and the share of the rest of the EC increases. It is important to mention that the EC we represent are the current EC and not the EC at the time of the construction. As seen in Figure 2.1, the number of buildings with A and B energy ratings substantially increased and remained the same in the last two CPs, while buildings in EC-E and D increased and in EC-F remained constant.

2.3 Literature Review

2.3.1 Barriers to energy efficiency improvements

Many studies have indicated that building retrofitting is a potential investment opportunity. Homeowners can save significant amounts of energy by investing in energy efficiency retrofits, and the value of these savings can be greater than the upfront investment [28, 29]. Many homeowners do not undertake home retrofitting due to a lack of expertise in retrofitting, not knowing how to improve energy efficiency, or having concerns about the cost. Amstalden et al. used a discounted cash flow approach to assess the profitability of energy efficiency retrofit investments in buildings in Switzerland [30]. The results showed that, if the energy prices remain at 2005 levels in the future, energy efficiency retrofit investments would be almost profitable even without policy instruments such as subsidies, income tax deductions, and carbon taxes. Furthermore, if energy prices rise, retrofit investments in buildings would be a promising investment opportunity. Yet, for a variety of reasons, homeowners have not responded enthusiastically to building retrofitting. The renovation rate in Switzerland, with respect to the existing building stock, is only about 1% per year. Despite cost-effectiveness, EEI is often not implemented, which is regularly referred to as the energy efficiency gap, or energy paradox [31].

Information problems are a major barrier to investment in energy efficiency, that is, information barriers are a major reason for the energy efficiency gap. In his study, Louis-Gaëtan Giraude [32] reviewed the information barriers to energy efficiency in buildings, positing that energy efficiency has the nature of a credence good, i.e. its value is never revealed to the buyer, even long after the purchase is made.

The split incentive phenomenon is another major barrier inhibiting energy efficiency retrofits. The building owner must pay to investment in energy efficiency retrofits, while the tenants reap the benefits through lower energy costs. This incentive mismatch between building owners and tenants is often referred to as the "split incentive" problem. In such circumstances, there is an absence of motive for the building owner to undertake energy efficiency retrofits. A study by Giraudet et al. [33] shows that, in order to achieve the energy-saving targets set by the government in France, the rental housing problem must be better addressed.

Other important barriers also exist, which do not fall under the scope of this research. The following barriers can be implemented in future research: (i) difficult access to funds and mortgage necessary to start the renovation works, (ii) late age of the owners who are not willing to invest into something they will not benefit from, (iii) investment strategies from big building owners (i.e. pension funds) that favour demolition/reconstruction dynamics over renovation, (iv) heritage building protection that make energy-retrofit hard to implement or performance levels hard to reach because of the impact of renovation techniques on the cultural value of the façade, (v) difficulty of applying retrofits without decreasing the square footage of the dwelling, (vi) high urban pressure that would call for a full demolition rather than an energy-retrofit.

2.3.2 Energy audit

Besides the energy disclosure mentioned above, energy audits are also often considered to help overcome information barriers. Energy audits involve inspecting and assessing a building's energy use and giving recommendations for reducing it, while maintaining the same or better levels of energy services [29]. Common approaches for energy audits include blower door tests, infrared imaging, checking the construction drawings, visiting the building to estimate the thickness of insulation in the walls, etc. An energy audit can provide homeowners with information on the current state of their building's energy use and potential opportunities for EEI, as well as providing information on the costs and benefits of energy retrofits. Requiring mandatory energy audits for all buildings is unrealistic, as audits would place a monetary and time burden on homeowners, especially for those with smaller buildings, as well as incurring significant regulatory costs. The primary challenge for energy audits is thus the willingness of homeowners to undertake the audits. Despite the proactive promotion of government and utility, the market for energy audits is currently small. Palmer et al. [29] speculated on the reasons for this in a study: Firstly, a lack of information, amongst many homeowners who do not even know about the existence of energy audits or what information the audits can provide; another more critical reason is cost, with homeowners' concerns about the cost of retrofitting deterring them from undertaking audits. Conclusions on this issue are currently inconsistent [34, 35, 29]. Firstly, homeowners do not always follow the recommendations they receive for energy improvements after an energy audit. Secondly, the lack of follow-up on post-retrofit energy use makes the salience of energy audits on EEI dubious [29]. In a study on the impact of energy audits on private owners' investments in EEMs in the Netherlands, the results showed that a large proportion of audit recommendations were ignored, with only 19% of audit recipients who adopted EEMs indicating that the audit ratings or recommendations influenced their decisions [35].

2.3.3 Policy measures for energy efficiency improvement

Policy instruments are an important tool for achieving carbon mitigation targets, which take various forms: regulatory, financial, and informative [33]. Among these, financial policies are considered to be the most effective, with the most common examples including carbon taxes and subsidies. Although there is no uniform carbon tax in the European Union (EU), several countries such as Sweden, France, Finland, and Ireland have enacted or introduced carbon taxes. Switzerland also introduced a carbon tax in the year 2008, with the rate gradually increasing from 12 CHF/tCO_2 in the year 2008 to 96 CHF/tCO_2 in 2018-2021 and to 120 CHF/tCO_2 in the year 2022. The effect of carbon taxes on energy efficiency has been extensively studied [36, 33, 37, 38]. However, a well-designed carbon tax faces many challenges, particularly determining the effectiveness, which depends on how well policymakers address the following three issues: setting the tax rate, collecting the tax, and using the resulting revenue [39]. There are two mainstream approaches to setting carbon tax rates; the Pigouvian Approach, whereby the optimal carbon tax should be equal to the marginal social cost of carbon emissions, and the second approach, whereby the carbon tax should be calibrated to achieve a set future reduction target. The setting of the carbon tax rate will affect its effect on mitigation [37]. The uses of carbon tax revenues are varied and may be used as subsidies for energy efficiency projects [36], offsetting tax reductions, reducing future deficits, or providing transitional assistance to those particularly hard hit by the carbon tax [39]. The destination of the revenue from the carbon tax will affect the effect of this policy on energy savings and carbon emission reduction. A study of the use of carbon tax revenues in France reveals that recycling the revenue of the French carbon tax as an energy efficiency subsidy will achieve more energy savings compared to lump-sum recycling [40].

Subsidy programs are available in various forms such as tax credits, zero-interest loans, reduced Value-added Tax (VAT) and so on. Their potential for energy saving and mitigation has been extensively studied [33]. Switzerland has introduced various subsidies, usually in the form of tax credits or deductions.

Giraudet et al. [33] conducted simulations and evaluations of a range of subsidy programs and carbon tax policies in France using Res-IRF, an energy-economy model of energy demand for space heating in France. Their evaluation criteria focused on cost-effectiveness, leverage, and distributional impacts, and the results showed that the carbon tax was most effective when there was no specification of revenue recycling [33].

2.3.4 Building stock models

Buildings' energy consumption has long been recognised as a problem that deserves serious attention. To improve it, it is important to understand the building stock's long-term dynamics. This will help us to gain a more profound understanding of the flow that drives the system's activities, and could be integrated as a stipulation to attain a more reliable way to address advancements of building stock's current and future energy demands [41].

There exist many models and tools to evaluate the energy consumption of the building stock. There are two studies [42, 43] that provide highly valued reviews of the existing Building Stock Model (BSM) and represent the difference between the top-down and bottom-up approaches in building stock level energy consumption modelling, as shown in Figure 2.2. It is important to note that the "archetype" and "sample" approaches demonstrated in Figure 2.2 are often combined with statistical (e.g. regression) approaches to allow for the bottom-up effects. Thus, it is not really a case of two different bottom-up approaches, but rather two parts of the same approach. Our housing stock model falls under the description of a bottom-up approach in this typology. Both reviews discuss the disadvantages of each type. The top-down approach models the housing stock at an aggregate level and mostly relies on statistical relationships between total energy consumption and its driving factors, such as gross domestic product, energy price, and so on. The bottom-up approach models buildings at the individual level, where energy consumption is estimated for individuals or groups of buildings, and then aggregated to obtain the total energy consumption. In the case of limited access to data, pure top-down models are a suitable way of describing building stock. Since top-down models cannot explicitly take into account the system's components, they are in reality incapable of exploring the effect of particular technologies or measures [42, 43].

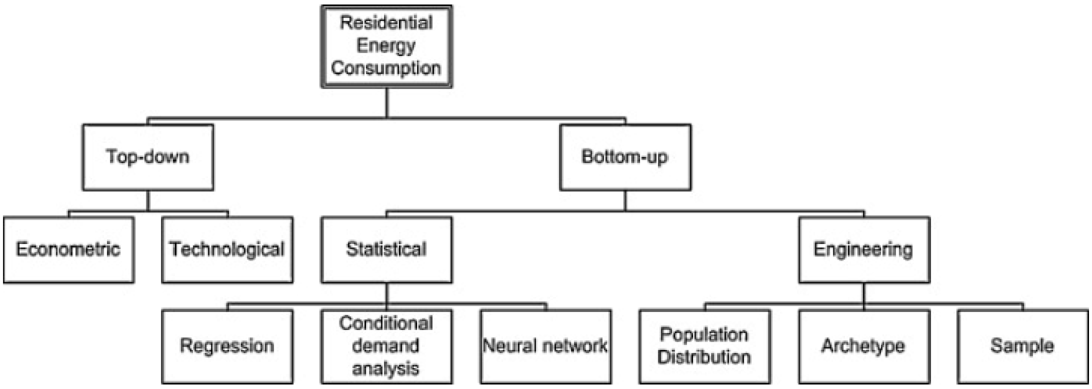

Figure 2.2: The classification of existing building stock models (source [43], Fig. 2)

Numerous bottom-up models are used to conduct energy and carbon analyses on building stocks [44, 45, 46, 47, 48, 49]. Many studies [50, 51] applied bottom-up models to European countries. The advantage of bottom-up models compared to top-down ones is their ability to model in detail the energy demand of end-users and technologies.

The Swiss Residential Building Stock Model (SwissRes) [52] can estimate the theoretical energy savings from a large-scale renovation program, calculate the new annual final energy Space Heating Demand (SHD) for the renovated building stock for all the archetype buildings and heating supply systems. This model uses an archetype approach, which calculates the cost supply curves for 48 archetype categories in the residential sector. The 48 archetype categories allow differentiating between 8 construction periods, 2 building types (Multi-Family (MFH) and Single-Family Houses (SFH)) in terms of techno-economic potential, and 3 spatial categories. Whereas in our building stock model, we introduce 9 construction periods and do not differentiate between Multi- and Single-Family Houses.

Our model proposes focusing on the decision of housing owners doing the retrofit. Firstly, it computes the percentage of owners who conduct an audit. Secondly, the owners who conducted the energy audit calculate the retrofit gain. The model computes the economic gain, which is the NPV of the retrofit measure after changing from one EC to another EC after the retrofit. The model also demonstrates the transition between EC.

Similar to our building stock model, the Agent-based Building Stock Model (ABBSM) [2, 53] is a decision model that is able to simulate a building owner's investment decisions under an economic and policy framework. Both BSM and ABBSM can assess the energy and CO_2 emissions of the building stock over time. Additionally, our model as well as ABBSM, are capable of studying the effects of different policy scenarios on the long-term transformation of the building stock. Both models take into account drivers such as technological change and building stock growth, whereas ABBSM is also able to consider the tradeoffs between investment in energy efficiency and renewable energy supply measures when it comes to reducing the CO_2 emissions of the building stock and calculating the effect of policy on the diffusion of technology (in terms of the rate of adoption) and to quantify the effect in terms of energy or emissions saved. Our building stock model is able to, considering the different policy measures introduced, examine the tradeoffs between investment in energy efficient retrofitting, demonstrate the effect of different policies on overall retrofit rate, as well as calculate the CO_2 emissions and energy demand decrease of the building stock. In later versions of ABBSM, agent types like tenants and households are added to the model. In our model, we differentiate between owner occupiers (tenants) and building owners. The ABBSM differentiates between three different decision types: (i) new building heating system, (ii) heating system replacement and (iii) building envelope retrofit, while in our building stock model we focus on the decision of homeowners to undergo building envelope retrofitting, which will affect the overall consumption of energy and decrease CO_2 emissions.

Furthermore, scientists recognised just how important it was to collect building stock data for building stock modelling and when assessing its potential for energy consumption improvement in the future.

Aiming to improve the behavioural realism often lacking in bottom-up models, Giraudet et al. [45] developed Res-IRF, a model of the French residential SHD, in 2009. It incorporates some barriers to the "energy efficiency gap", such as the non-energy attributes of home energy retrofits, the rebound effect. Barriers such as difficulties of community decision-making, and split incentive phenomenon, incorporated in the Res-IRF model were included in our building stock model. The accuracy and stability of the Res-IRF model have been tested in a performed global sensitivity analysis [54]. The Res-IRF model has been updated in a recent study [33] to include segmentation of households by income category.

Overall, bottom-up building stock models are a powerful tool for estimating energy consumption, taking into consideration occupant behaviour dynamics, and assessing energy and climate policies. However, in most models, the representation of barriers to EEI such as information gaps, split incentives, etc., is lacking. In order to capture the barriers to EEI and occupant behaviour in the building stock models, in this study, we develop a two-step decision model for Swiss energy retrofitting buildings. In the model, two barriers to EEI are considered: Information gaps and split incentives. The consideration of split incentives in the housing stock model is of interest, specifically to Switzerland, given the fact that around two-thirds of Swiss dwellings are rentals.

We use the two-step decision model to investigate the effectiveness of climate policies, with the aim to explore the question: What policies should Switzerland implement to reduce carbon emissions from the residential building sector to meet its ambitious carbon reduction targets?

2.4 Methodology

The objective of this research is to demonstrate the capabilities of our model, analyse a range of scenarios, as well as to study how Switzerland can achieve deep decarbonisation of its residential sector through retrofitting. A two-step decision model for energy retrofitting buildings is developed in this study, which incorporates consideration of energy efficiency barriers, such as incomplete information and the split incentive phenomenon. In the first step, owners decide whether or not they will conduct an energy audit of their building, based on their perception that retrofitting could be profitable. If owners decide to conduct an energy audit, then, in the second stage, they calculate the NPV and if it is positive they carry out a retrofit. In the first step, we calculate the proportion of owners who conduct the energy audit. This implies that only a certain share of owners will undertake an energy audit, while the rest will not consider undertaking an energy audit and subsequent energy retrofit, even if it is profitable. This step reflects the barriers of incomplete information. In the second step, for owners who decided to conduct an energy audit, the NPV is calculated. In the model, EC and owner types are considered, which are classified according to the characteristics of the owners (owner-occupied/rented out, young/old, poor/rich, profit-based/non-profit-based). Based on this classification, the model introduces different discount rates (r) and split incentive parameters (χ). The conceptual framework of the two-step decision model for retrofitting is shown in Figure 2.3.

The equations used in the model and the specific variables and parameters are described in the following sections.

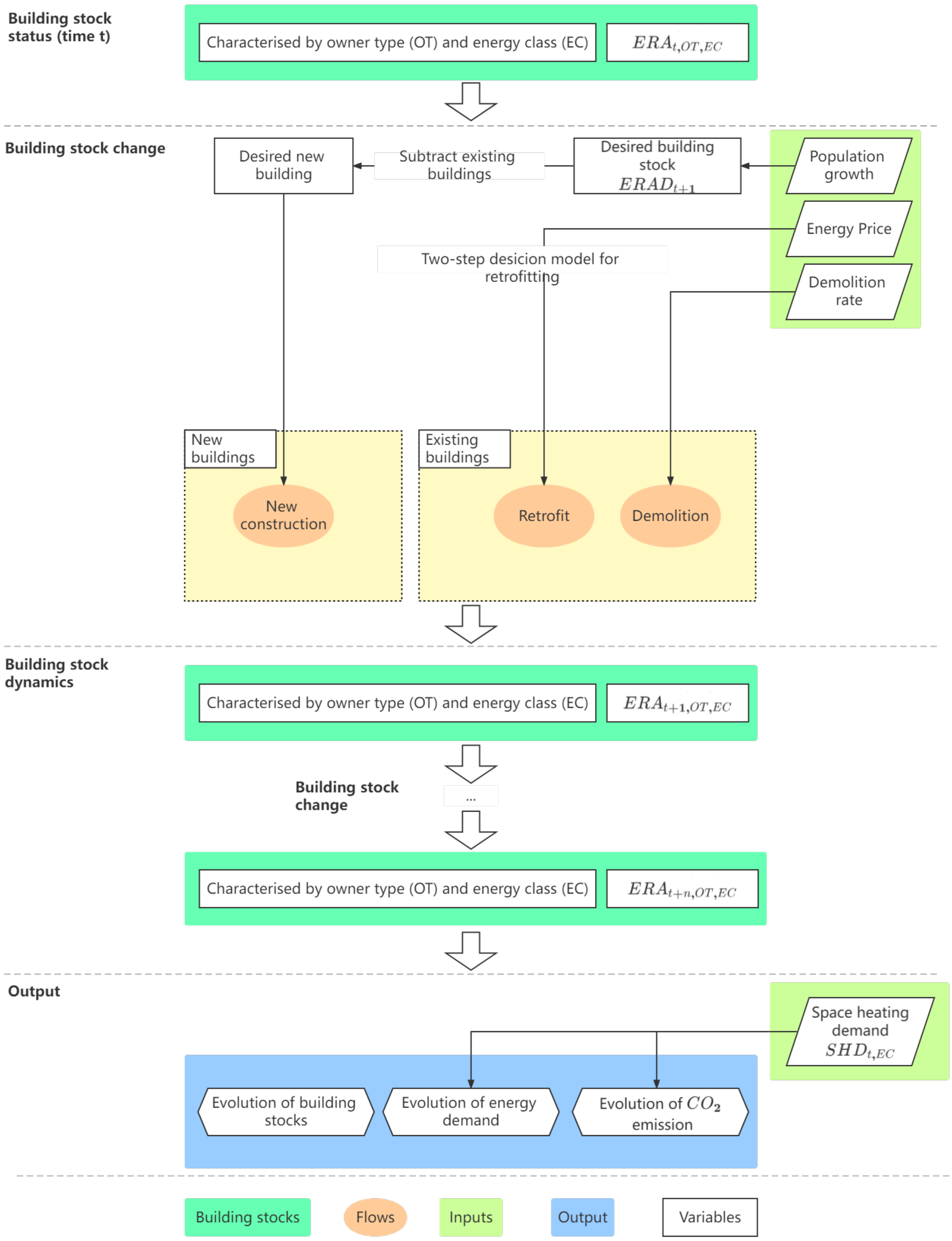

Figure 2.3: Conceptual framework of the extended building stock model

2.4.1 Energy reference area

Our model's main variable is the ERA, which, in combination with the structure's EC and climate, determines the heating needs for the Swiss residential sector. As shown in Figure 2.1, a building is characterised by its year of construction (CP), and its EC. We add another dimension that represents the property Owner Type (OT) of the house/flat. Indeed, energy retrofitting decisions very much depend on the characteristics of the owners represented in our model through different discount rates (r) and split incentive parameters (χ). We do not model individual buildings. Instead, we assume that all property owners within an energy class conduct an identical cost-benefit analysis regarding retrofitting decisions. This could lead to unrealistic results, as all owners within an EC would retrofit at the same time, leading to a spike in the retrofit rate at certain time periods. To smooth retrofit rates, we have to introduce further heterogeneity into the model (apart from the six energy classes). Therefore, we include the following two features. Firstly, we apply a two-step model, where in the first step only a certain proportion of owners is triggered to conduct the cost-benefit analysis (see Chapter 2.4.4). The remaining owners do not consider retrofits, even if they were profitable. This reflects the barrier that owners have incomplete information or do not pay much attention to the energy efficiency of their buildings (lack of salience). Secondly, we introduce owner types, which differ with respect to the discount rate and whether they inhabit the dwelling themselves or rent it (see Table 2.4). What is important for discount rates is that they change from one owner type to another, which adds a diversity amongst owner types. These discount rates are illustrative, which were chosen to bring heterogeneity into the model. Important to mention that we introduced the heterogeneity of owners and not simply the heterogeneity of housing stock, because in this case, we would see for example that all buildings in energy class G are retrofitted to energy class D buildings. Thus, we would see one big wave of buildings of one energy class being transferred to another energy class, which is not realistic.

2.4.2 Housing owners

We distinguish between six owner types whose characteristics are shown in Table 2.4. There are owner-occupied and rental properties (40% and 60% of dwellings, respectively, based on the data from the Swiss Federal Statistical Office [22]). In the case of owner-occupied properties, the owner of the property is simultaneously the occupier. In the case of rental property, the building owner is not the occupier of the property.

Owner-occupiers of properties can be further categorised by the characteristics of age (young, middle-aged, old) and degree of wealth (poor, wealthy). Based on internal discussions and best estimates we assigned different owner types: "Old or poor", "Middle-aged" and "Young and wealthy". Depending on these characteristics, the discount rates change, because for some owner-occupiers retrofitting is less profitable in the long-term, they have less access to funding and a limited time horizon (elderly owner-occupants). For example, for an old or poor owner, access to retrofitting is limited because the owner has a high discount rate due to the

Table 2.4: Owner Types, Shares and Their Discount Rates

Share of total ERA that is owner-occupied/rental	Type	Share of ERA	Owner type	Discount rate	Split incentive
40%	1	20%	Young and wealthy (Owner-occupier)	2%	1
	2	60%	Middle-aged (Owner-occupier)	4%	1
	3	20%	Old or poor (Owner-occupier)	6%	1
60%	4	10%	Non-Profit-based (Building owners)	2%	0.5
	5	30%	Profit-based (Building owners)	4%	0.5
	6	60%	Private (Building owners)	6%	0.5

short horizon and less access to funding. In contrast, the young and wealthy owner, who has a low discount rate and easier access to funding, is more likely to find a retrofit profitable (see Table 2.4). We assume that all owner types have the same distribution of buildings according to energy classes. Since we do not have any information to distinguish between different owner types and their share of ERA, we guesstimated the share of the ERA after a consultation with experts (consultancy company in Zurich) in the field (see Table 2.4).

The owners of a rental property are cooperatives (non profit-based), municipalities (non profit-based), investment corporations (profit-based), pension funds (profit-based), and individuals (people). Here, the discount rate changes too, depending on the owner's characteristics. For example, non-profit owners typically expect a small or no return on their investment because their goal is to satisfy the needs of their tenants.

Private individual owners of rental housing generally seek a return on their investment, often for retirement purposes. Moreover, profit-based institutional building owners (group 5) hold diversified portfolios, while individual building owners (group 6) often own a single building. Hence, the former is content with a lower expected return from a particular building (see Table 2.4).

Split incentives are one of the most salient barriers to energy efficiency retrofits in buildings. This barrier arises only for rental dwellings. In this situation, the building owner is responsible for investing capital into retrofits, whereas the tenants benefit as their energy bill is reduced. The costs and the benefits of retrofits thus do not directly accrue to the same actor - the incentives are split. The building owner has the option of raising the rent to recover his/her investment. In our model, we introduce a split incentive parameter, which lowers the benefits for building owners. In the case of building owners, we fix the split incentive parameter (χ) to 0.5 (instead of 1 for the other owner type). Thereby, we assume that the building owners can only recover 50% of the monetary energy saving by increasing the rent. The values of this parameter for all types of owners are given in Table 2.4.

2.4.3 Evolution of the housing stock

The law of motion of the ERA is given in Eq.(2.1). The ERA changes from one construction period to the next, since a proportion of housing is demolished (Demolition Rate (DR)), or through NC, and by transfers between classes due to a Retrofit Matrix (RM) (see Eq. 2.4). In Eq.(2.1), t is a year from 2019 to the year 2050, A and G are energy classes, EC is the energy class of a building before retrofit and EC' is the energy class of a building after the retrofit.

$$\begin{aligned} ERA_{t+1,OT,EC} &= (1-DR_t)\cdot ERA_{t,OT,EC} + NC_{t,OT,EC} \\ &- \sum_{A}^{EC'<EC} RM_{t,OT,EC,EC'} + \sum_{EC'>EC}^{G} RM_{t,OT,EC',EC} \end{aligned} \tag{2.1}$$

There will be a retrofit from EC to EC' if both of the following conditions hold true:

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.

NC are computed from the desired reference area that is linked to population growth, which we assume follow the central scenario of the population forecasts of the Swiss Federal Statistical Office [55].

Increasingly demanding building regulations imply that new constructions are only built-in energy classes A, B, and C, the proportions of which change over time as the contributions of the most efficient energy classes increase.

2.4.4 The retrofitting decision

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

- First step: energy audit.

  We assume that, prior to an energy audit of their building, owners are unaware of the costs and benefits of a retrofit. A certain proportion of owners can be triggered each year to commission an energy audit by rising energy prices or an information campaign.

- Second step: retrofitting decision.

  The triggered owners decide on whether to perform a retrofit, depending on the result of the energy audit, which is basically a cost-benefit analysis.

First step: energy audit

The percentage of owners who conduct an audit (Γ) is represented by Eq. 2.2, where SHD is the representative heating demand per m^2 for each EC (see Table 2.3), energy price (PEC), Θ is the sensitivity of the audit rate to the preious year's variation of energy spending, and θ is the response of the audit rate to the level of energy prices. Here, the percentage of owners who conduct an audit (Γ) is not dependent on owner type for the sake of simplification. This can be considered as improvement for future work, where this probability can be derived as a function of owner type.

The renovation rate of energy classes will be sensitive to the probability of owners conducting an energy audit, as well as to the increase in information level and energy prices, which are weighted by SHD.

Based on a dwelling's current energy class, there is a certain baseline probability (Π) that the owner will conduct the audit. Since we do not have any information on the baseline probability, based on expert consultation from INFRAS, we decided to increase the probability in a straight line by 0.5% per energy class: in EC A it is 0% and in EC G it is 3%.

The probability increases with the owner's information level (Inf): {1; 2; 3; 4}. For example, a standard information campaign would raise the owner's information level from 1 to 2; a targeted personalised message to an owner would raise it to 3, and direct contact by an energy specialist, possibly with the offer to pay all or part of the energy audit costs, would raise their information level to 4.

$$\Gamma_{t,EC} = \Bigg(1 + \Theta \cdot \Big(\frac{(PEC_{t,EC} \cdot SHD_{t,EC}) - (PEC_{t-1,EC} \cdot SHD_{t-1,EC})}{PEC_{2014,EC} \cdot SHD_{2014,EC}}\Big) + \theta \cdot \frac{PEC_{t,EC} \cdot SHD_{t,EC}}{PEC_{2014,A} \cdot SHD_{2014,A}}\Bigg) \cdot \Pi_{EC} \cdot Inf_t \tag{2.2}$$

Second step: retrofitting decision

In the second step, those owners who commissioned an energy audit calculate the highest economic balance of retrofitting their building, i.e. retrofit gain (RG). The retrofit gain is the NPV of the retrofit measure from energy class EC to EC', i.e. discounting all future energy-saving gains over the investment horizon (T). This retrofit gain is given in Eq.(2.3), where (RC) is the retrofit cost, τ is a subsidy on retrofit and (PI) is the price of investment. In the case of the building owner (owner types 4 to 6), we fix the split incentive parameter (χ) to 0.5 (instead of 1 for the other owner types). Thereby, because of the absence of information, we assume that the building owner can only recover 50% of the monetary energy saving by increasing the rent.

$$RG_{t,OT,EC,EC'} = \chi_{OT} \sum_{t'=t}^{t+T} \frac{SHD_{t,EC} \cdot PEC_{t',EC} - SHD_{t,EC'} \cdot PEC_{t',EC'}}{(1+r_{OT})^{t'-t}} - \\ - RC_{t,EC,EC'} \cdot (1-\tau_{t,EC,EC'}) \cdot PI_t \tag{2.3}$$

Retrofit matrix

Transitions between energy classes are represented by RM. The RM given in Eq. 2.4 is one element of the retrofit matrix, measuring the ERA of one owner type that is retrofitted from EC to EC' in year t. This RM is calculated by multiplying the probability of conducting the audit (Γ) by the probability of performing the retrofit (Ω) (see Eq. 2.5) and by the Energy Reference Area (ERA).

$$RM_{t,OT,EC,EC'} = \Gamma_{t,EC} \cdot \Omega_{t,OT,EC,EC'} \cdot ERA_{t,OT,EC} \tag{2.4}$$

$$\Omega_{t,OT,EC,EC'} = 1 \text{ if} \begin{cases} RG_{t,OT,EC,EC'} > 0 \quad and \\ RG_{t,OT,EC,EC'} > RG_{t,OT,EC,EC^*} \quad \forall\ EC^* \neq EC' \end{cases} ;0 \text{ otherwise} \tag{2.5}$$

2.4.5 Energy consumption and CO_2 emissions

To compute total heating energy demand, we add up the demands of the seven ECs. In each EC, it is computed by multiplying the SHD of that class by the corresponding ERA. The mix of energy carriers (oil, natural gas, district heating, heat pump, direct electricity, and wood) is specific to each EC. The substitution possibilities are represented by a Constant Elasticity of Substitution (CES) function of the total energy demand in each EC. This implies that buildings retrofitted from one EC to another adopt a mix of energy carriers of their new class. It implies that the mix of energy carriers, and hence the CO_2 intensity of heat production, can change within each EC in response to changing relative prices of energy carriers. This does not require any specific investment, nor does it count as retrofitting. Only the transfer of buildings from one EC to a better one does. For the sake of simplicity we assume that, in the base year (i.e. 2019), the energy mix is the same for all construction periods and owner types within a specific energy class. The price of each energy carrier includes the fuel price and the cost of the heating equipment (boiler, heat pump, etc.).

2.4.6 Calibration of the model

Numerous research was conducted on the discount rate in the field of energy efficiency investments. In 2013, Alberini et al. [56] conducted a survey of 473 Swiss homeowners asking about their preferences for energy retrofits and concluded on discount rates from 1.5% to 3%. Additionally, Braungardt et al. [57] suggested that discount rates for private investors range from 4% to 6% and from 10% to 12% and are justified for both developed and developing countries, respectively, while Steinbach and Staniaszek [58] demonstrated the outcomes of discount rates from 4% to 9.5% implemented in energy scenarios for Germany. In the SwissRes model, used to estimate the energy savings of retrofitting in Swiss residential buildings, discount rates of 3% and 6% were applied to different scenarios [52]. Additionally, an agent-based building stock model was developed for the Swiss residential building sector, and a discount rate of 2% was determined based on a parameter calibration [2]. Furthermore, the profitability of energy efficiency retrofit investments in the Swiss residential building sector is based on the discounted cash flow approach was explored, taking a discount rate of 3.5%, which was derived from the Swiss Society of Engineers and Architects (SIA) recommended discount rate range of 3% to 3.5% for Swiss building investments [30]. To conclude, taking into account the above-mentioned studies, we assumed different discount rates for our 6 owner types ranging from 2% (mean value of the Swiss studies) to 6% (high value for private investors in developed countries).

To estimate the demolition rate (DR) for each construction period, we compute the decrease of the ERA from the year 2019 to the year 2010 (see Table A.1 in Appendix A.1). We base our calculation on the evolution of the ERA from 2010 to 2019 in Switzerland, categorised by energy classes [59].

After a consultation with our colleagues from INFRAS, the share of new constructions in 2019 in energy classes A, B, and C was set to 20%, 35%, and 45%, respectively. It was also suggested to assume that the share of NC in energy classes A and B will increase. The share of buildings in energy class C will decrease by 2.5% per year and, consequently, disappear in 2033. Over that period, it will be replaced by buildings in energy class B. After 2033, we assume that the share of B will also decrease by 2% per year, and all new constructions will be built in energy class A. Additionally, the values of retrofit cost and their calculation are described in Appendix A.4 (see Table A.8).

Swiss official statistics [60] provide the surface of occupied dwellings per construction period in square meters. Unfortunately, they do not provide any information about the average energy consumption or the allocation of dwellings per energy class for the different construction periods. With the help of four different surveys, the distribution of dwellings by energy carriers for each energy class was computed. The details of these surveys can be found in Appendix A.3. The overall energy consumption by all construction periods is allocated by energy carriers and energy classes. Since 95.6% of the ERA in all surveys is represented only by the Geneva survey, we used the weighted average method and calculated adjustment factors to properly account for all four surveys. Additionally, since we do not have data on the description of the Swiss housing stock over several years (time series of energy classes and retrofits), we can not check whether the model is able to replicate past observations.

2.5 Scenario simulations

In this section, we simulate several scenarios with our building stock model (for the overview of policy scenarios see Table 2.5). By applying our model, we aim to evaluate the various policy scenarios on the long-term development of the Swiss building stock. The scenarios are designed to illustrate the role of endogenous EEI, and to demonstrate our model's capabilities in analysing a range of scenarios, and to study how Switzerland can achieve deep decarbonisation of its residential sector. In the study conducted by Linton et al. [61], deep decarbonisation was defined as pursuing 80–100% total net reduction in CO_2 emissions by the year 2050 or sooner. In our study we will consider the same values for deep decarbonisation. Additionally, we want to explore how far each of the scenarios can go in the direction of a deep decarbonisation pathway.

Table 2.5: Policy Scenarios

Scenarios	**Subsidy**	**CO_2 tax (CHF/tCO_2)**	**Information level**
Baseline scenario	30%	2019-2021: 96 2022-2050: 120	1
P1: A subsidy increase scenario	+1%/year	2019-2021: 96 2022-2050: 120	1
P2: A Moderate CO_2 tax increase scenario	30%	2019-2021: 96 2022: 120 2023-2050: +9 CHF/year	1
P3: A High CO_2 tax increase scenario	30%	2019-2021: 96 2022: 120 2023-2050: +26 CHF/year	1
P4: An information level increase scenario	30%	2019-2021: 96 2022-2050: 120	2019-2023: 1 2024-2028: 2 2029-2033: 3 2034-2050: 4
P5: A first combination scenario	+1%/year	2019-2021: 96 2022: 120 2023-2050: +9 CHF/year	2019-2023: 1 2024-2028: 2 2029-2033: 3 2034-2050: 4
P6: A second combination scenario	+1%/year	2019-2021: 96 2022: 120 2023-2050: +26 CHF/year	2019-2023: 1 2024-2028: 2 2029-2033: 3 2034-2050: 4

Similar to our research, the study conducted by Nägeli et al. [53] and which applies an agent-based building stock model (ABBSM) introduced policies to speed up the decarbonisation of the Swiss building stock. These policies demonstrated their effect on 3 scenarios conducted: reference, incentive and regulation. In the reference scenario, CO_2 tax remains at the level of 96 CHF, as do the subsidies on retrofit. The same was done in our Baseline scenario. In incentive and regulation scenarios conducted, the results demonstrate that the CO_2 emissions decrease by 85% and by 89% relative to the reference scenario. In these scenarios, CO_2 tax is increased stepwise. The increased revenue from CO_2 tax is used to finance and expand current subsidy schemes. In our building stock model we decided to introduce similar scenarios, where in the first one we increase only subsidies, and in the other two we focus on increasing CO_2 tax in a different manner (Moderate and High CO_2 tax scenarios). The regulation scenario, which is mainly focused on policies to ban direct electric systems, is reinforced by CO_2 emissions limitations of 20 kg CO_2/m^2 in the year 2030 and reduced stepwise every five years down to 0 kg CO_2/m^2 a year. Similar to this regulation scenario, we introduced the information level policy scenario where the information level is increased stepwise every 5 years up to level 4 in the year 2050. In addition to these scenarios, we decided to introduce two additional ones. We merged different scenarios to see how the combination of different policies would impact the reduction of CO_2 emissions. Thus, similar to the study conducted by Nägeli et al. [53], we combined a standard NPV calculation and, as we will see in the next sections, generated similar results for CO_2 emissions reductions.

We will first run a Baseline scenario from 2019 to 2050, which is described in the next subsection. Then, we will simulate six policy scenarios, as follows:

1. *A subsidy increase scenario*: the government increases the existing subsidy on retrofit investments by 1 percentage point every year.
2. *A Moderate CO_2 tax increase scenario*: the government increases the existing CO_2 tax each year by 9 Swiss franc (CHF).
3. *A High CO_2 tax increase scenario*: the annual CO_2 tax increase is equal to CHF 26 in this scenario.
4. *An information level increase scenario*: we assume the government campaigns for retrofit investment, which we capture through an increase in the information level.
5. *A first combination scenario*: this scenario combines measures of scenarios 1, 2 and 4.
6. *A second combination scenario*: this scenario combines measures of scenarios 1, 3 and 4.

The following parameters will remain unchanged throughout all the above-mentioned scenarios: ERA, population growth, and energy prices. The ERA is presented in Chapter 2.2.2. The population growth is based on the population forecasts of the Swiss Federal Statistical

Office [55]. Energy prices are derived from the World Energy Outlook 2018; we will use the current *policies scenario* [62]. It is also important to mention that the scope of application of this model is limited to Switzerland. However, this model can be used for other countries as well if key input parameters are changed. Additionally, the list of assumptions of our model is as follows:

1. It is assumed that owner groups are uniformly distributed over all building construction periods and over all building energy classes, which may not be the case in real life.
2. It is assumed that the rate of construction of new dwellings will be equivalent to the rate of population increase in the next 30 years.
3. It is assumed that the rates of owner-occupier vs rental owners will remain unchanged.
4. It is assumed that all renovation works are related to an energy-retrofit motivated by financial (and environmental) reasons (and not by other reasons, e.g. wear and tear, acoustic or aesthetic reasons).

2.5.1 Baseline scenario

In the Baseline scenario, the retrofit subsidy and CO_2 tax are equal to the current values in Switzerland. The subsidy on retrofit ($\tau^t_{EC,EC'}$) is defined at the cantonal level. On average, it pays 30% of the energy retrofit investment [63]. The CO_2 tax on heating fuel equals CHF 96 from the year 2019 to the year 2021 and is constant from the year 2022 and equals CHF 120 [64]. The information level (Inf) is equal to 1.

Figure 2.4 shows the evolution of the ERA from the year 2019 to the year 2050 and Figure 2.5 shows the percentage of the ERA per energy class by owner groups in the year 2050. The results demonstrated in Figure 2.5 are based on the assumption that, at the beginning, all owner types have the same distribution of buildings according to energy classes. The average retrofit rate is equal to 0.75%. The proportion of buildings in energy class A increases from 7.5% to 30%, whereas the share of buildings in classes E, F, and G combined decreases from 65% to 25%. This result is driven by retrofitting (from G, F, E and D to C, B, and A) and new constructions that are built in classes A, B, and C. From 2019 to 2050. As previously mentioned, because of the lack of data on the description of the Swiss housing stock, we are not able to check whether the model is able to replicate past observations. In 2050, the average energy consumption is 58 kWh/m^2 and total CO_2 emissions decrease by 66% relative to 2019 (see Table 2.7). The CO_2 emissions provide information about the buildings' energy efficiency and the energy mix, and additional ERA.

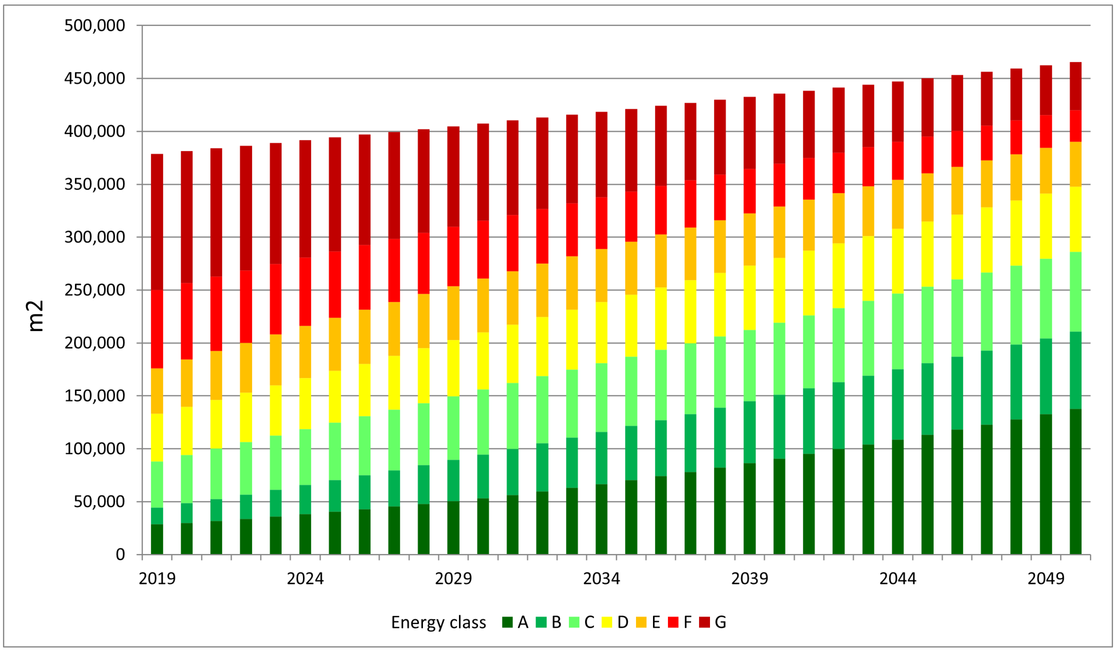

Figure 2.4: Total Energy Reference Area (ERA) per energy class in 1000 m^2 - Baseline scenario

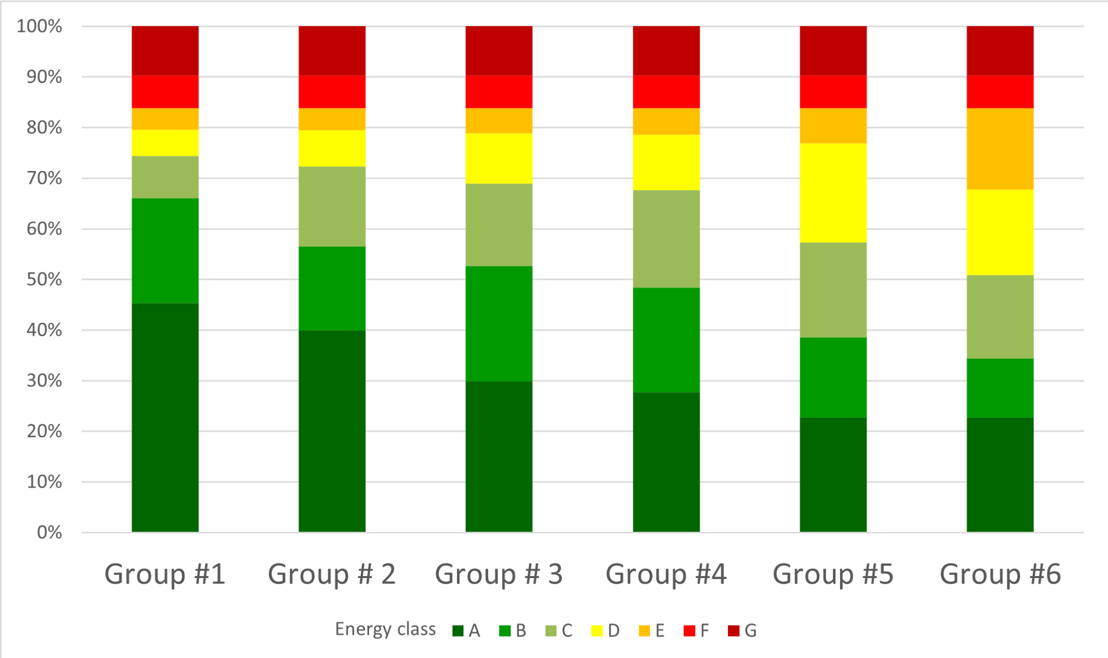

Figure 2.5: Energy Reference Area (ERA) in % per energy class by owner groups (2050) - Baseline scenario

2.5.2 Subsidy increase scenario

We assume that the government will increase the current subsidy by 1 percentage point per year until the year 2050. The subsidy rate will reach 61% in the year 2050, since the initial subsidy is 30% in the year 2019. If instead of a 1 percentage point increase per year, we use another higher value, the subsidy increase becomes very high. It might overshoot and achieve 100% of subsidies in the year 2050. Thus, it was decided to use a 1 percentage point increase. The government will pay subsidies from the general budget. More retrofit investments become profitable and the average retrofit rate will rise to 1%. The proportion of buildings in energy class A increases to 33.5%, while the share of buildings in classes E, F, and G combined decreases to 23%. The average energy consumption in 2050 will decrease to 55 kWh/m^2 and the CO_2 emissions will decrease by 68% relative to 2019 (see Table 2.7). Figure 2.6 demonstrates the evolution of the ERA from the year 2019 to the year 2050.

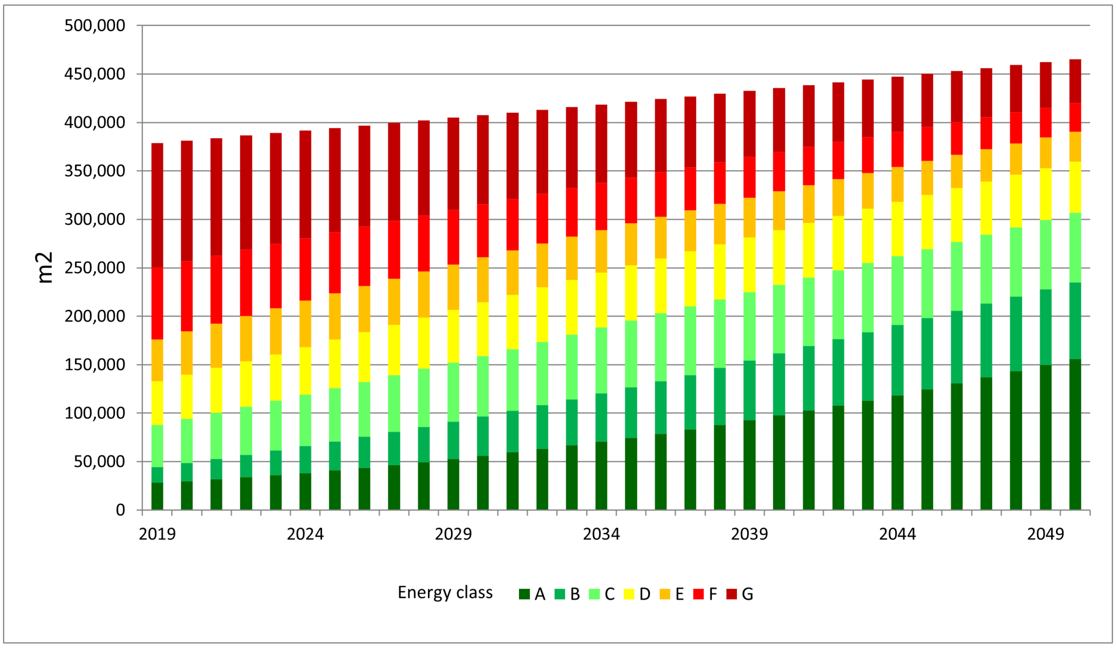

Figure 2.6: Total Energy Reference Area (ERA) per energy class in 1000 m^2 – Subsidy scenario

2.5.3 CO_2 tax increase scenarios

In the tax increase scenarios, we assume that the government raises the CO_2 tax from the year 2019 onwards to above its level in the Baseline scenario, as shown in Table 2.6. In these scenarios, we did not want to overshoot above certain values (400 CHF/tonne and 900 CHF/tonne). Thus, we used the values demonstrated in Table 2.6. Figures 2.7 and 2.8 display the evolution of the ERA from the year 2019 to the year 2050.

Neither of the tax scenarios triggers much retrofitting. The average retrofit rate increases slightly to 0.76% and 0.78%. The proportion of buildings in energy class A rises to 30% and

Table 2.6: CO_2 Tax on Emissions (CHF/tonne)

Year	Baseline	Moderate tax increase	High tax increase
2019	96	96	96
2020	96	96	96
2021	96	96	96
2022	120	120	120
2023 to 2049	120	+9/year	+26/year
2050	120	372	848

32%, while the share of buildings in classes E, F and G combined decreases to 23% and 21%, respectively. The average energy consumption per square meter decreases slightly more than in the Baseline scenario, to 56.5 kWh/m^2 and 54.4 kWh/m^2 in 2050. Nonetheless, the CO_2 emissions decrease by 67% and 69% relative to the year 2019.

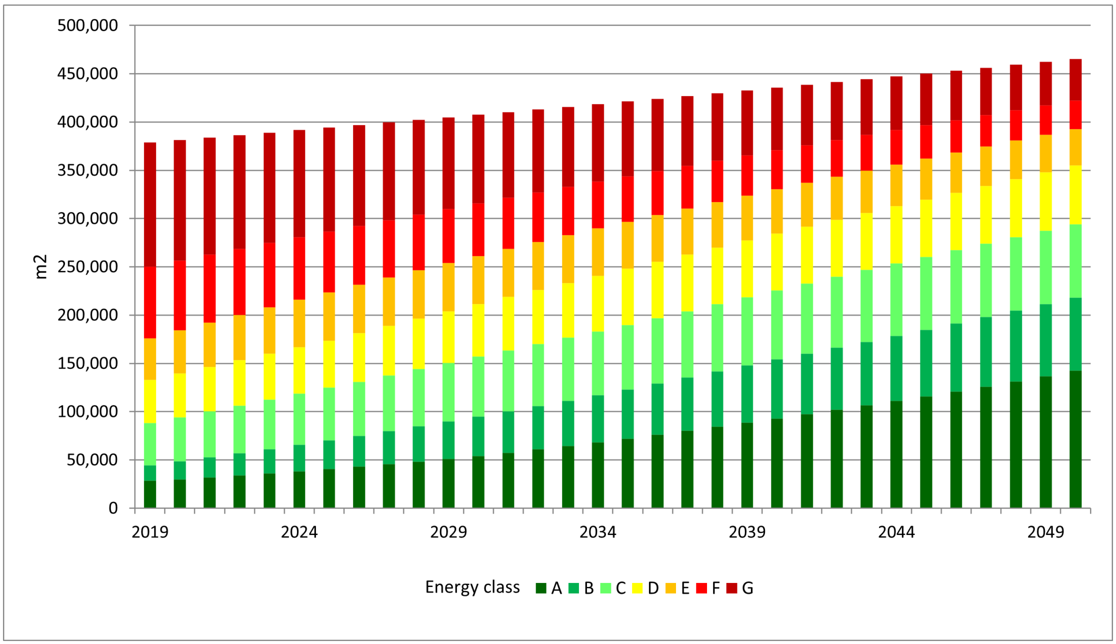

Figure 2.7: Total Energy Reference Area (ERA) per energy class in 1000 m^2 - Moderate CO_2 tax increase scenario

It is particularly interesting to compare the tax increase scenario with the subsidy increase scenario. The high tax increase triggers about as much additional retrofit investment cost, cumulated from the year 2019 to 2050, as the subsidy increase, namely about 27% more than in the Baseline scenario (see Table 2.7.). However, it obtains a larger decrease in CO_2 emissions, namely 69% in 2050 relative to the year 2019, compared to 68% in the subsidy increase scenario. This latter reduction is obtained by the moderate tax increase scenario with a much smaller increase in retrofit investment. This is due to the fact that the CO_2 tax leads to fuel switching from oil and natural gas to electricity (heat pumps) and wood, which a subsidy on retrofitting does not.

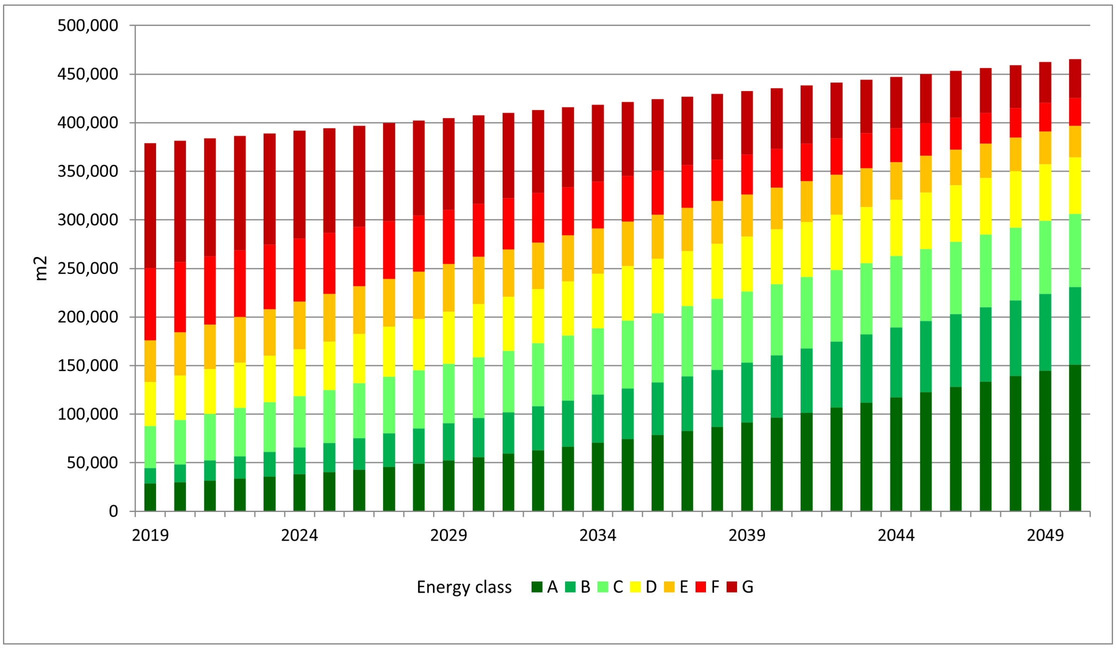

Figure 2.8: Total Energy Reference Area (ERA) per energy class in 1000 m^2 - High CO_2 tax increase scenario

2.5.4 Information level increase scenario

In the information level increase scenario, we ran the model with an increase in the information level every five years up to information level 4. This means that from the year 2034 to 2050, the information level remains constant. In this scenario, the average retrofit rate rises to 1.18% and the share of buildings in energy class A rises to 34%, while the proportion of buildings in classes E, F and G combined decreases to 11.5%. The total CO_2 emissions declines by 83% relative to the year 2019. This shows that solely increasing the information level is sufficient for a deep decarbonisation pathway. In Figure 2.9 the evolution of the ERA from the year 2019 to the year 2050 can be seen. The result comparisons for all the scenarios are displayed in Table 2.7.

A positive outcome of comparing the Baseline scenario with the information level scenario is a rise in retrofit rate, from 0.75% to 1.18%. The reason for this is that more owners are going through step 1 (energy audit) and, as a result, the useful energy demand decreases to 43% compared to 27% in the Baseline scenario (see Table 2.7). This is mainly due to the fact that all the buildings become more energy-efficient and the CO_2 emissions decrease even further relative to the Baseline scenario (an 83% drop compared to 66% in the Baseline scenario), because there is also a little more substitution (away from fossil energy) within the context of retrofitting. Not surprisingly, this comes at a high cost in terms of retrofit investment, higher than in the tax increase scenarios, which can also count on fuel switching to reduce CO_2 emissions.

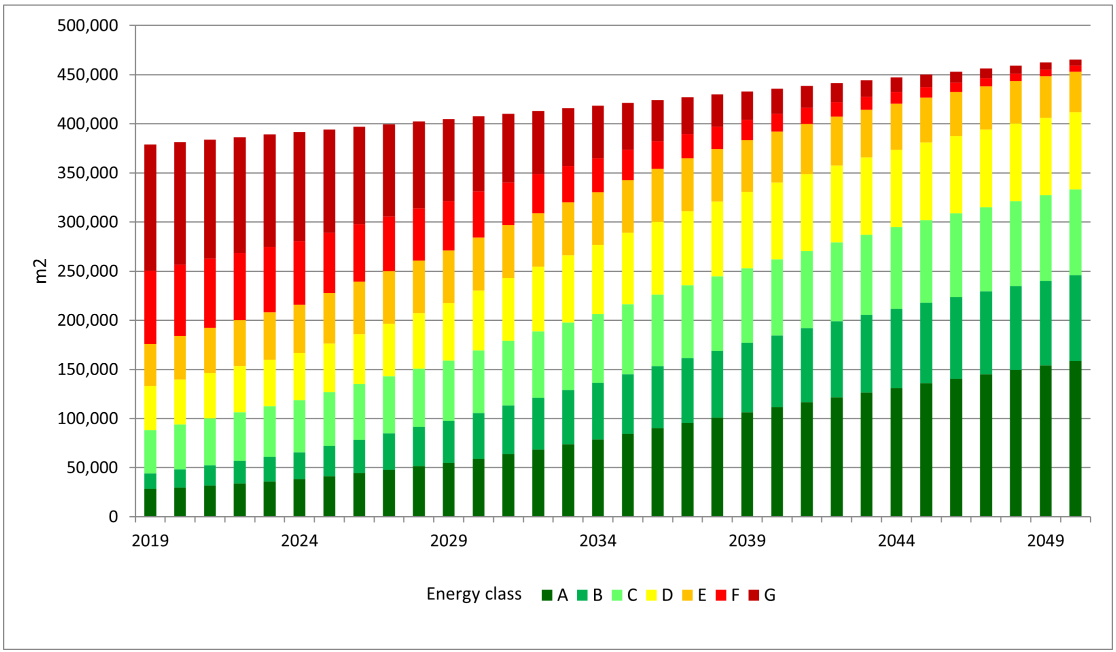

Figure 2.9: Total Energy Reference Area (ERA) per energy class in 1000 m^2 - Information level scenario

2.5.5 Combination scenarios

The first combination scenario combines the Moderate CO_2 tax increase scenario (see Table 2.5) with a 1 percentage point subsidy increase per year, as well as with an information level increase (as in the information level scenario). In this scenario, the subsidy reaches 63% in the year 2050. By increasing the subsidy, we achieve equality between the cumulated cost of the subsidy and the cumulated revenues of the CO_2 tax between the years 2019 and 2050 (see Figure 2.10). In the second combination scenario, we used a 1 percentage point subsidy increase per year and the High CO_2 tax increase scenario instead of the Moderate CO_2 tax increase scenario (see Table 2.5). In this scenario, the subsidy reaches 63% in the year 2050. Here, we obtain that the sum of the cost of the subsidy and the sum of revenues of the CO_2 tax between the year 2019 and 2050 are nearly equal (see Figure 2.11).

Both scenarios achieve deep decarbonisation in the year 2050, with total CO_2 emissions reducing by 88% and 89% relative to the year 2019. Here, there is a significant increase in the percentage of buildings in the highest energy class A with 42% in the first scenario and 44.5% in the second scenario. Additionally, buildings in classes E, F, and G combined shrink to 4.5% and 3.5%, respectively. Table 2.7 shows that the average retrofit rates are 0.91% and 1.26%. Additionally, Figures 2.12 and 2.13 demonstrate the evolution of the ERA from the year 2019 to 2050. In this section, we introduced two combination scenarios. The first combination scenario with the moderate CO_2 tax increase achieved the goal of deep decarbonisation. The goal was to capture the response of the combination scenario to increasing CO_2 tax and to see how it would affect the results of the model. Hence, we introduced the second combination scenario where we increased the CO_2 tax according to the scenario High CO_2 tax increase.

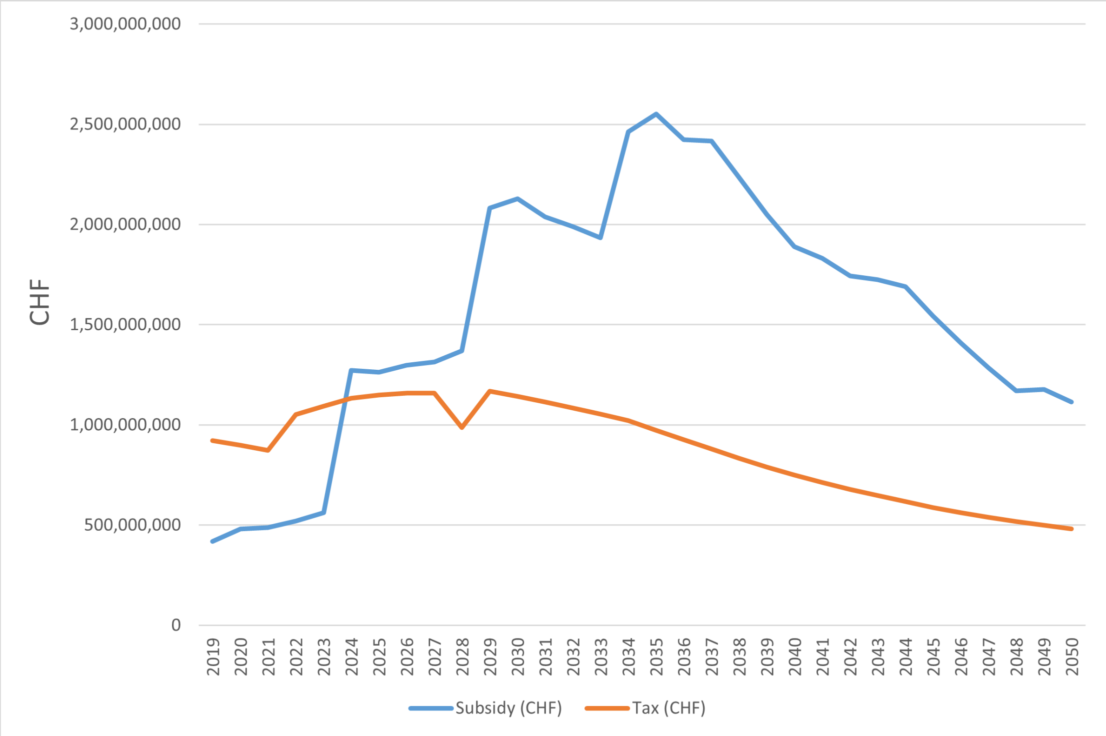

Figure 2.10: The cost of the subsidy and the revenues of CO_2 tax (in CHF) between 2019 and 2050 for the 1st combination scenario

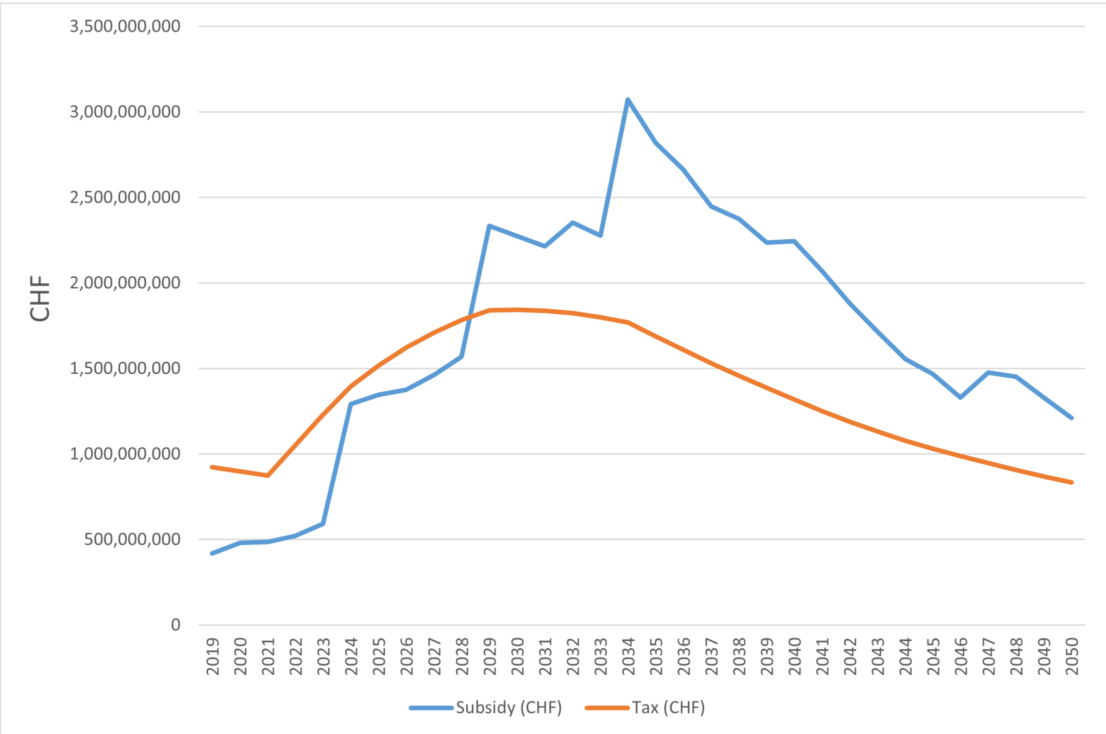

Figure 2.11: The cost of the subsidy and the revenues of CO_2 tax (in CHF) between the year 2019 and 2050 for the 2nd combination scenario.

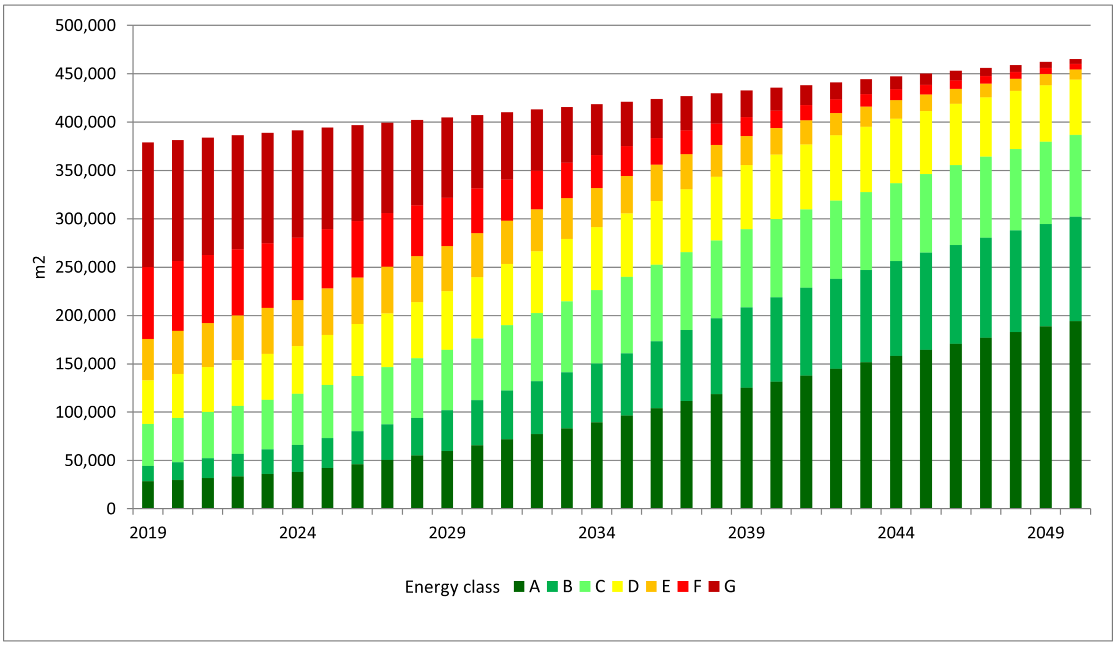

Figure 2.12: Total Energy Reference Area (ERA) per energy class in 1000 m^2 - 1st combination scenario

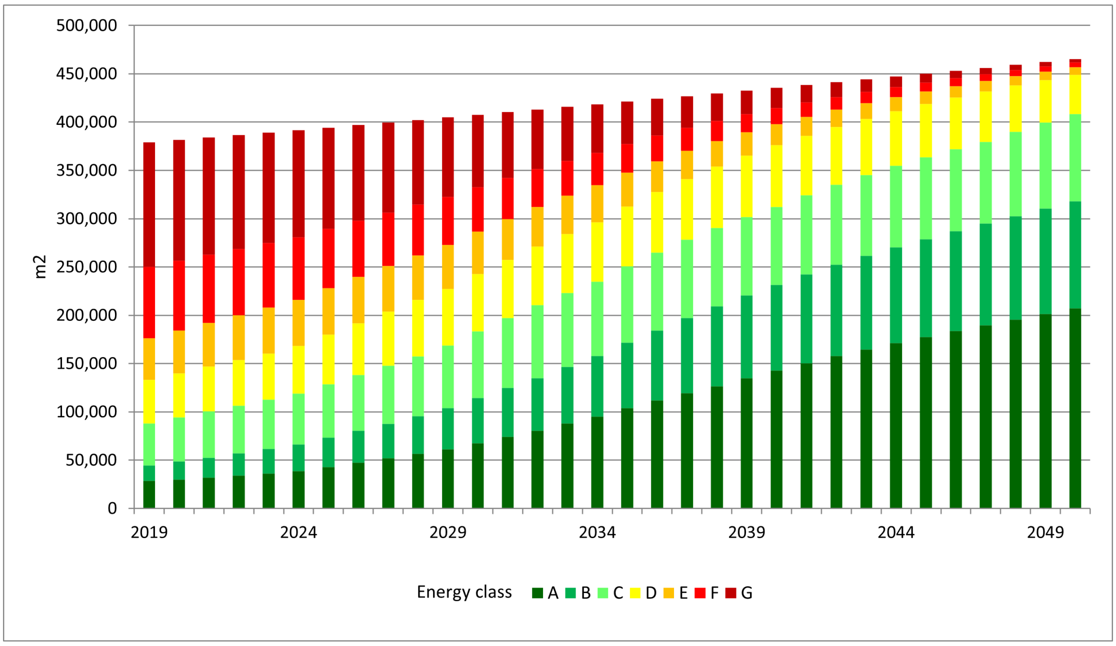

Figure 2.13: Total Energy Reference Area (ERA) per energy class in 1000 m^2 - 2nd combination scenario

2.5.6 Comparison of all scenarios

All the scenarios are compared in Table 2.7, Figure 2.15 and Figure 2.14. Comparing the two CO_2 tax increase scenarios reveals that useful energy demand does not significantly decrease in the low-tax scenario (down by 28% relative to the year 2019, compared to 31% in the high-tax scenario). The same is true for total CO_2 emissions (down by 67% and 69%, respectively). A striking difference between these two scenarios concerns retrofit investment costs, which increase by 27% relative to the baseline in the high-tax scenario, compared to only 10% in the low-tax scenario. This, as we saw, did not generate many additional benefits. This illustrates the rapidly rising marginal costs.

When we compare the Moderate CO_2 tax increase scenario with the subsidy increase scenario, we notice the almost identical total CO_2 emissions decrease of 67% and 68% relative to the year 2019, a very similar drop in useful energy demand of 28% and 30% relative to 2019 and the slight variance between retrofit rates. As a result, we can conclude that, when the outcome of both scenarios is almost identical, it would be coherent to implement the scenario with lower investment costs. Thus, it is worth implementing the moderate tax increase scenario, relative to the Baseline scenario, the investment costs only increase by 10% in the moderate tax increase scenario, whereas in the subsidy increase scenario the investment costs grow by 28%. This is due to the fact that the higher CO_2 tax encourages investors to replace fossil fuels as the source of energy, while the subsidy only encourages energy saving.

Comparing the information level increase scenario with the High CO_2 tax increase scenario, we see that they are down by 83% and 69% relative to 2019. Additionally, even though we have a significant difference in retrofit rates (0.78% and 1.18%), the outcome indicates a slightly stronger useful energy demand drop: by 57% and 49% relative to 2019. This can be explained by the fact that the CO_2 tax does not trigger many more stage 1 energy audits. It is interesting to note that, compared to the High CO_2 tax scenario, we can achieve almost identical results with the information level scenario in terms of reduction in CO_2 emissions and, additionally, very similar useful energy demand. Obviously, when the results are almost identical, it makes sense to choose the option with lower investment costs. Therefore, when comparing these two scenarios, we can see that it would be cheaper to implement the High CO_2 tax increase scenario because it cuts CO_2 emissions with less investment, namely by 27% (High CO_2 tax scenario) compared to 68% (information level scenario) investment cost increase relative to the Baseline scenario.

Moreover, it is not surprising that the greatest reductions in energy use and CO_2 emissions are obtained with the two combination scenarios. The second combination scenario, with the much higher CO_2 tax, induces the increase of retrofit investment costs by 153% compared to the baseline, when the low tax only induces a retrofit investment cost by 132%. The decrease of CO_2 emissions is not much greater, namely 89% compared to 88%. This demonstrates that it is very costly to eliminate the last remaining CO_2 emissions from buildings.

Table 2.7: Comparison of Scenarios

Scenarios	year 2019	Baseline	Subsidy increase	Moderate CO_2 tax increase	High CO_2 tax increase	Inf. level increase	Combination 1st	Combination 2nd
Average value for 2020-2050 (except column '2019')								
Annual audit rate per energy class, average	1.88%	1.82%	1.83%	1.85%	1.91%	5.19%	5.12%	5.20%
Annual retrofit rate per owner type, average	1.23%	0.75%	0.81%	0.76%	0.78%	1.18%	0.91%	1.26%
Annual retrofit rate, owner type 1 ('best')	1.74%	0.81%	0.81%	0.83%	0.87%	0.73%	0.71%	0.67%
Annual retrofit rate, owner type 6 ('worst')	1.18%	0.85%	0.71%	0.83%	0.82%	2.18%	0.66%	1.90%
Annual retrofit rate, energy class C	0.11%	0.06%	0.44%	0.06%	0.06%	0.08%	1.02%	0.90%
Annual retrofit rate, energy class D	0.13%	0.29%	0.85%	0.38%	0.46%	0.38%	1.82%	7.60%
Annual retrofit rate, energy class E	0.14%	2.19%	2.19%	2.29%	2.46%	8.76%	9.16%	9.86%
Annual retrofit rate, energy class F	2.09%	2.60%	2.60%	2.72%	2.92%	10.39%	10.87%	11.69%
Annual retrofit rate, energy class G	2.28%	3.42%	3.42%	3.72%	4.26%	13.67%	14.86%	17.03%
Sum 2020-2050, variation relative to baseline scenario								
Retrofit investment			28%	10%	27%	68%	132%	153%
2050 compared to 2019								
Useful energy demand per m^2		-46%	-49%	-47%	-49%	-57%	-64%	-66%
Useful energy demand total		-27%	-30%	-28%	-31%	-43%	-52%	-55%
CO2 emissions per m^2		-69%	-71%	-72%	-76%	-84%	-89%	-92%
CO2 emissions total		-66%	-68%	-67%	-69%	-83%	-88%	-89%

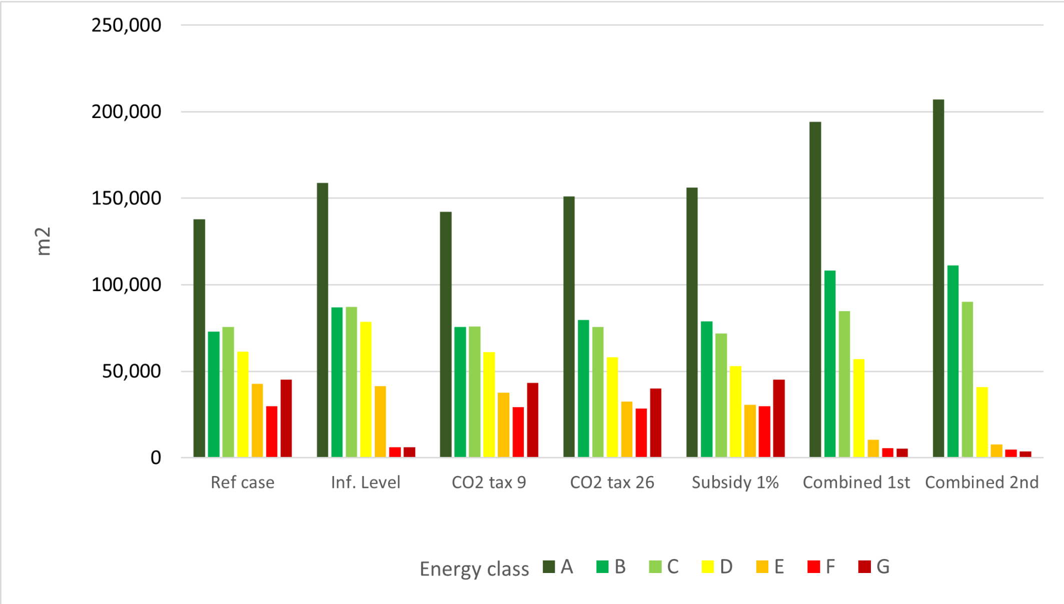

Figure 2.14: Surfaces (m^2) of energy classes in the year 2050 for all scenarios

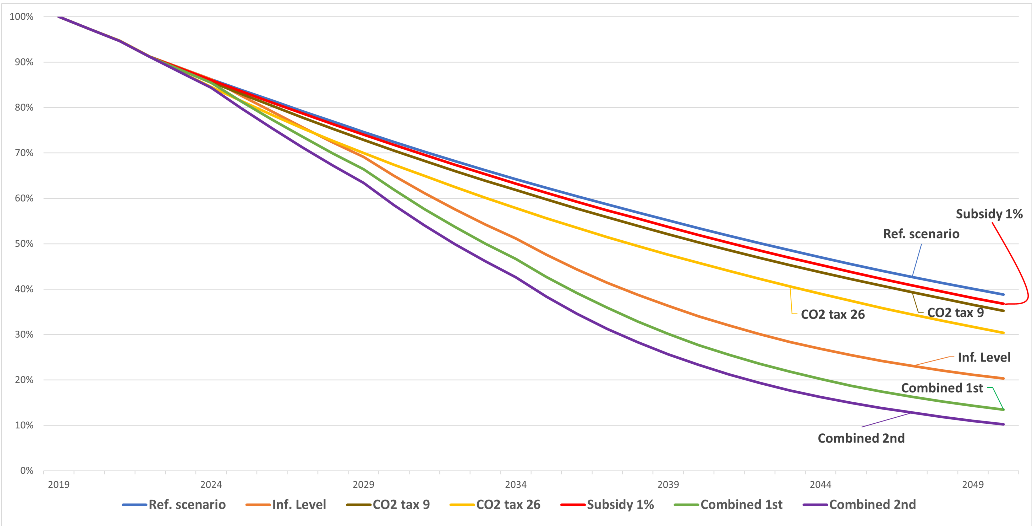

Figure 2.15: CO_2 emissions for all scenarios from the year 2019 to 2050

2.6 Conclusions and policy implications

In our simulations, we find that an information campaign and other policies inducing building owners to undertake an energy audit are quite effective in increasing the rate of retrofitting. The model shows us that the average retrofit rate for 2019-2050 increases from 0.75% in the Baseline scenario to 1.18% in the information scenario, and 68% more is spent on retrofitting. Nevertheless, the reduction in CO_2 emissions is only somewhat larger than in the Baseline scenario, namely 66% in the Baseline scenario compared to 83% in the information level scenario. In other words, an information campaign is costly and results in minimal benefit.

In our model, increasing subsidies for retrofitting increases the retrofit rate and the retrofit investment substantially, with little gain in terms of CO_2 emissions reduction compared to the baseline. The retrofit rate does not have a significant impact on the change of energy carrier mix, i.e. on CO_2 emissions reduction, because the building stock continues to use fossil fuel energy, even if they are using it less.

When looking at the results of the model, we can see that moderately stepping up the existing CO_2 tax on heating fuels is about as effective as the rising retrofit subsidy in terms of CO_2 emissions reduction, but the outcome is achieved at a substantially lower cost in terms of retrofit investment. In the model, the higher CO_2 tax encourages fuel switching, which the other policies do not. Nevertheless, the results demonstrate that even a very high CO_2 tax (848 CHF per tonne in the year 2050) only lowers CO_2 emissions by 69% in the year 2050 relative to the year 2019, not enough for deep decarbonisation. This is because owners still need to go through the first step of energy auditing their building. Owners do so at an increasing rate as their heating bill goes up, but not at a substantially sufficient rate, because the increase is very gradual and because 70% of the ERA in Switzerland belongs to building owners, who do not pay the heating bill.

Our simulations show that economic instruments are much more effective when combined with policies to raise owners' awareness of energy retrofitting, because the economic instruments influence owners only after they have opted to energy audit their building. It is worth repeatedly providing comprehensive information about these price signals to obtain more CO_2 abatement. Our most ambitious scenario combining the CO_2 tax increase and retrofit subsidy with an information campaign raises the average retrofit rate up to 1.26%. Retrofit investment increases by 153%. As a result, useful energy demand per square meter decreases by 66% and CO_2 emissions by 89%. This can be a strong argument for combining soft (information) and strong (economic) incentives. In this case, the rebound effect, which can affect the resulting useful energy demand, is not taken into account.

In our model, we combined a standard NPV calculation with a first stage probability calculation. The modelling of this first stage is challenging. We tried to use a relatively simple and plausible representation, which is sensitive to price changes. Clearly, more research is needed on this important first stage of the owners' decision to invest in energy retrofitting.

In this model, with the parametrisation we have chosen, we see that, for example, the information level has a strong impact on CO_2 emissions. More attention to this should be given and it deserves further examination than is common in other studies, where other barriers such as financing, rent regulation etc. are emphasised.

3 Extending Endogenous Energy Efficiency Choices to New Construction

3.1 Abstract

The retrofitting of existing buildings and the construction of new ones is an essential element in the process of meeting CO_2 emission goals. Existing energy and climate policies aim to increase energy-efficient retrofitting and the construction of energy-efficient buildings. Our objective is to propose a methodology that incorporates a two-step building-stock decision model together with a novel endogenised model for the building of new constructions, where they will be sensitive to different policy regulations (e.g. subsidies), taking into account both investment decisions at the building retrofit level and the expansion of existing constructions. The developed optimisation model takes into account a long-term time horizon with various investment alternatives, which allows economic and technological advances to be represented over the model's time horizon. It integrates a multi-objective approach, taking into account the decision-related trade-offs between investments in different energy classes. The results show that, with a flexible combination of subsidies, the restriction rules for new constructions, an ambitious information campaign, and a CO_2 tax, the Swiss residential building sector can finally achieve the 2050 target set, namely a reduction in useful energy demand by 50%. However, the achievement requires increasing investment costs. Therefore, the model's findings demonstrate that, in order to meet the target, it is essential to encourage homeowners by offering a combination of different economic instruments to undertake retrofits of the building stock and build new energy efficient constructions.

3.2 Introduction

In Switzerland, there are three main energy and climate policies related to the building sector: the CO_2 tax introduced in 2008 [64]; the building's program that subsidises building energy-efficient renovations [65]; and the Cantonal building regulations that introduce energy efficiency standards and heating system regulations for existing and new constructions [66]. Important to notice that there are no regulations for existing buildings, until the owner applies for a building permit to renovate or retrofit them. The energy-saving potential of retrofits has received widespread attention and recognition [52], however, the impact of NC on building energy efficiency is often overlooked in research. The building stock model is a powerful tool for estimating energy consumption in the building sector. Our previously developed two-step decision model focuses on modeling retrofits, while NC, and their allocation to different energy classes are not within this focus. However, NC also contribute to energy use and CO_2 emissions. In addition, in Switzerland, in many cases NC are built on previously demolished building sites. These demolitions also have a CO_2 impact, and they represent a loss of CO_2 investment. Thus, we wanted to find a better approach to introduce innovation to the model by allocating NC to different classes, which may be done endogenously.

Therefore, the purpose of this study is to complement and extend the previously developed building stock model (See Chapter 2) by changing the allocation of NC to different EC from the previous exogenous modeling to endogenous modeling. In addition, we will test the effect of this extension using multiple scenario simulations. This new version of the model will enhance our understanding of the role of endogenous allocation of NC in achieving emission reduction targets and contribute to the CO_2 emission abatement maximisation in the housing sector.

3.3 Literature review

There exist numerous building stock models that have been developed to evaluate energy consumption and GHG emissions in the building sector, which may be at different scales, applied to different regions, and with different input data requirements. Building stock models can be static or dynamic. Generally, static models estimate building stocks at a defined moment in time (a single month or a year) [67, 68, 69, 70]. Dynamic building stock models typically model the demolition and renovation of existing constructions, as well as the building of NC, to project the future energy demand and GHG emissions of buildings [3, 71]. The Res-IRF, developed by Giraudet et al. [45] designed to explore the energy-saving potential of French households, simulated the dynamic changes in building stock through NC, building demolition, energy retrofitting and fuel switching. Sandberg et al. [72] analysed the Norwegian dwelling stock energy consumption for 2016-2050 using a dynamic, stock-driven (construction, demolition, and renovation-driven), segmented dwelling stock model. The agent-based building stock model for Switzerland developed by Nägeli et al. [2] modeled the stock dynamics through the processes of NC, demolition, as well as retrofit and replacement in existing buildings. Compared to static models, dynamic building stock models reflect the evolution of the building stock and its energy consumption over time, facilitate the observation of the interaction between drivers and changes, and therefore are preferred for modeling future scenarios and making medium- to long-term projections [2, 3]. However, most studies have used static modeling and have focused relatively little attention on the dynamic changes in the building stock [3, 4]. To add, most dynamic modeling of the building stock is based on simple exogenous assumptions, i.e., assuming fixed rates for building demolition, renovation, and NC through expert judgment or historical trends [2, 3, 4]. In Chapter 2 the NC are endogenously assigned to a certain share in energy classes A, B and C. This study's contribution assigns an endogenous element to the shares of energy classes A, B and C, i.e. they respond to different policy regulations (e.g. subsidies).

It is meaningful to simulate NC in the building stock model using an endogenous model, which will allow us to analyse the impact of changes in environmental factors such as energy prices, CO_2 taxes, etc., on homeowners' decisions. However, modeling the dynamics of NC in the building stock with specialised endogenous models, rather than exogenous assumptions, is relatively rare in studies. A few cases have applied discrete choice models to determine the market share of NC with different energy efficiencies: In the building stock model Res-IRF [45], the total housing demand is first determined by population and household income growth, and the demand for new housing is further identified by subtracting the existing housing stock. Their NC is then divided into three categories, each with different energy efficiency. The share of NC in each category is determined by life-cycle costs. The life-cycle costs include construction costs, operating energy expenditures, and intangible costs. Mastrucci et al. [73] used discrete choice models to specifically identify household decisions about NC in their simulations of the global evolution of building stock, energy demand, and CO_2 emissions from space heating and cooling. The results revealed that the simulated scenarios differed significantly in terms of energy efficiency for NC and renovation [73].

While the two studies above [45, 73] have endogenously modeled NC, they have not taken into account heterogeneity as in the renovation modeling. However, they have taken into account economic (e.g., energy prices, disposable income) factors, but have not addressed environmental factors such as possible tightening of building energy efficiency standards.

Studies analysing energy efficiency in the residential sector reveal that setting stricter requirements for NC is necessary to achieve the set GHG emission reduction targets. Nägeli et al. [53] evaluated the impact of climate policy on GHG emissions in the Swiss residential sector through an agent-based building stock model, and the results showed that the current climate policy is insufficient to achieve GHG emission targets and that stricter requirements are needed for both existing constructions and NC. However, the implementation of these regulatory measures is difficult, and their advancement is slow, so the increase in standards for energy efficiency in NC should be made gradually. Jakob and Madlener [74] used the experience curve concept to analyse the energy-efficient building envelopes in Switzerland over the past 30 years. The results showed that the establishment of building codes and standards and the active promotion of labels and standards have driven technological advances in building energy efficiency and energy conservation measures. In this study, Jakob and Madlener also provided policy recommendations for the implementation, effective control, and periodic revision of building standards, which would effectively reduce the energy demand of buildings.

Switzerland's energy and climate regulations are tending towards becoming increasingly stringent [75, 76, 77]. In 2014, the energy efficiency standard MuKEn14 for buildings was adopted, which sets a standard of 35 kWh/m^2 for NC (for both single-family houses and multifamily houses). The MuKEn14 standard was implemented in all regions by 2018, with an in-force date of 2020. In addition, the revised CO_2 Act requires cantons to set building standards for NC to ensure that total building emissions are 50% lower than 1990 levels by 2026/27. It also states that fossil fuel heating systems will be banned in NC starting in 2023. Although the revised CO_2 Act was not approved in the referendum in June 2021, it still implies that energy efficiency requirements for NC will become stricter.

Considering the policy recommendations of previous studies [53, 74] to set stricter energy efficiency standards for NC and the trend towards their incorporation into the regulatory system, it would be valuable to explore the impacts of introducing energy efficiency restrictions on the energy consumption for NC.

3.4 Methodology

3.4.1 Endogenous modeling of new construction

In this study, as was done in Chapter 2, with the goal to investigate Swiss residential building stock, we focus only on housing and do not include office and retail buildings. The results of this model will only represent the residential building stock. In our first model (see Chapter 2), we computed the NC taking into account the desired reference area linked to population growth. In this chapter, we develop a NC model that is added as a novel element to the model described in Chapter 2, which led to this model's development. The high demand for buildings, requirements for energy-efficient buildings, and policy regulations imply that NC in the future will only be built within energy classes A, B, and C [66] criteria and standards. Thus, the objective of the new version of the model is to endogenise the process of allocation of energy classes for NC and make them sensitive to the introduction of different policy measures, contrary to the exogenous allocation that has been done in the first model. In the first model, the share of NC in 2015 in energy classes A, B, and C was set exogenously by us (at 20%, 35%, and 45%, respectively). Additionally, we assumed that the proportion of NC in energy classes A and B will increase with time. We considered that the proportion of buildings in energy class C will decrease by 2.5% per year and consequently disappear in 2033. After that, these buildings will be replaced by buildings in energy class B, which we assume will decrease by 2% per year, and eventually, all NC will be built in energy class A.

3.4.2 Novel model for new construction

The newly developed model for NC will be incorporated with the previous two-step decision model for retrofitting, with the conceptual framework shown in Figure 2.3. The major difference of the framework for this chapter is that now the movement from the desired new building to NC is an endogenous decision making process. In this model, the NC, just like the demolition rate, are a certain proportion of the housing stock and are given endogenously.

What is endogenous now is the allocation of buildings across energy classes A, B and C. The dynamics of the building stock are captured through the demolition and renovation of existing constructions and the building of NC (see Eq. 2.1). The retrofitting is calculated through the model described in Chapter 2, which will not be repeated here. The limitation of the model is that the CO_2 embodied in NC is not considered. Buildings of energy classes A and B embody more CO_2 than less energy-efficient buildings, so there is a trade-off between embodied CO_2 (or energy) and utilised CO_2 (or energy).

The calculation of NC is based on the decision by homeowners to invest in their building. The extent of investment depends on which EC the NC will belong. Nowadays, because of increasingly strict policies implied in building regulations towards homeowners and investors, NC will only be built in energy classes A, B and C [66]. The homeowners and investors will base their decisions on a cost-benefit analysis. The construction cost (CC, CHF/m^2) that relates to the cost-benefit analysis differs between various energy classes. Despite the fact that the higher the EC, the more expensive the construction cost, numerous homeowners prefer to invest in high-EC buildings.

We make an assumption that tenants are sensitive to the possibility to rent an apartment in a building of higher EC and of higher energy efficiency. The tenants want to know how much they can save on heating costs in a more efficient building. There is rental housing where we assume that a better EC means fewer energy costs, which also means that tenants are willing to pay more rent because they need to pay less for heating. We assume that they can pay more for rent, which covers the extra costs for the owner.

The benefit, which also relates to cost-benefit analysis, refers to the returns gained by homeowners. The meaning of benefit differs for rental and owner-occupied housing. While in the case of the rental property the return is the rental income, for owner-occupiers it is an implicit income. The implicit income demonstrates the housing expenses, which are in this case eliminated for the owner, since, if they did not live in their house, they would need to pay rent for another place.

The EC and the characteristics of the building are often decided by developers. The developer is not going to construct buildings of EC-C if nobody is going to buy these buildings. Thus, the choices of the developer reflect the preference of the investors. In our model, we have owners: investors, people who hold buildings over a long period in order to obtain income. It is true that many buildings are built by developers, but they are built with investors in mind, because developers know that eventually they will want to sell it to investors and therefore their choices reflect the preferences of investors, just as if investors build for themselves. This is also valid for NC.

Taking into account that the NC will only be built within energy classes A, B, and C, in our model we take EC-C as the base class (the profit made by a building within C class is assumed to be zero). The rental income (RI, CHF/m^2 per year) of EC C is calculated based on Eq. 3.1, where CCM is the construction cost per meter square, T is the expected service life of buildings, MC

is the maintenance cost (CHF/m^2 per year), which equals 1% of the construction cost and r_{OT} is the discount rate of owner type. Eq. 3.2 shows how CCM is calculated for EC-C buildings, where the CC is the construction cost and SA (m^2) is the building surface.

$$RI_{t,OT,C} = \frac{CCM_{t,OT,C} \cdot r_{OT}}{(1 - \frac{1}{1+r_{OT}})^T} + MC_{OT,C} \tag{3.1}$$

$$CCM_{t,OT,C} = \frac{CC_{t,OT,C}}{SA_{EC,OT}} \tag{3.2}$$

ES represents the energy savings relative to EC-C, which is given in Eq. 3.3, where DEC (kWh/m^2 per year, see Table 3.1) is the difference in energy consumption between energy classes, SA is the building surface, PEC (CHF/kWh) is the energy price.

Table 3.1: Difference in Energy Consumption Between Energy Classes

Energy classes (EC)	DEC in kWh/m^2 per year
A and C	30
B and C	20

$$ES_{t,EC,OT,CP} = DEC_{EC,OT} \cdot SA_{EC,OT} \cdot PEC_{t,EC,OT,CP} \tag{3.3}$$

MP is the market price of rental (CHF/m^2 per year), given in Eq. 3.4. For energy class C, the MP is equal to its RI. Our assumption for energy class A and B buildings is that their MP is equal to RI, which is related to RI of EC-C buildings, plus the energy savings relative to energy classes A and B.

$$MP_{t,OT,EC} = RI_{t,OT,C} + ES_{t,EC,OT,CP} = \left(\frac{CCM_{t,OT,C} \cdot r_{OT}}{(1 - \frac{1}{1+r_{OT}})^T} + MC_{OT,C}\right) + \\ + \left(DEC_{EC,OT} \cdot SA_{EC,OT} \cdot PEC_{t,EC,OT,CP}\right) \tag{3.4}$$

The benefit to the homeowner is expressed in terms of the present value of net income ($PVNI$, CHF/m^2), which is calculated in Eq. 3.5. PR is the relative profit compared to NC with the C energy class, which is the difference between the $PVNI$ and the construction cost per meter square (CCM, in CHF/m^2), as shown in Eq. 3.6.

$$PVNI_{t,OT,EC} = \frac{MP_{t,OT,EC} - MC_{OT,EC}}{r_{OT}} \cdot (1 - \frac{1}{1 + r_{OT}})^T \tag{3.5}$$

$$PR_{t,OT,EC} = PVNI_{t,OT,EC} - CCM_{t,EC,OT} \tag{3.6}$$

In this study, model variables such as rental income (RI) and energy savings (ES) of EC-A and B are affected by policy variables such as subsidy rate (SR) and CO_2 tax (TX).

In the case of the introduction of subsidies on EC-A and B buildings, the CCM for these energy classes will change according to Eq. 3.7, where CC is the construction cost of EC-A or B, ΔCC is the difference in construction cost between EC relative to EC-C buildings, and SR is the subsidy rate. The results of Eq. 3.7 will affect the PR of energy class A and B buildings.

$$CCM_{t,OT,EC} = \frac{CC_{t,OT,EC} - \Delta CC_{t,OT,EC} \cdot SR_T}{SA_{EC,OT}} \tag{3.7}$$

The energy price PEC is determined by Eq. 3.8, where PF is the fuel price and TX is the CO_2 tax. When introducing the CO_2 tax, the results of Eq. 3.8 will affect the ES for EC-A and B buildings.

$$PEC_{t,EC} = PF_{t,EC} + TX_{t,EC} \tag{3.8}$$

The profits vary according to EC and owner types, and owners will choose the most profitable EC for their NC. The share of NC in each EC will change over time based on the share of owner types and their corresponding investment decisions.

3.5 Model variables and parameters

3.5.1 Owner types for existing and new constructions

In the first building stock model, 6 owner types were introduced (see Table 3.2). In the *NC* model, we differentiate between five owner types (see Table 3.3). We consider that, in the future, young and wealthy, middle-aged, profit-based, and private owner types will be able to realise NC projects. These owner types differ from those in the energy retrofit model. Each owner type is given the same share of *NC* as its share in the housing stock in the reference year, with one exception: in this model, we assume that a larger share of young and wealthy will build *NC* in the future and old or poor owner types will not. Thus, after internal discussion, we decided to transfer the share of the "Old or poor" owner type to the "Young and wealthy" owner type.

As mentioned above, we do not consider the characteristics of owner-occupied/rental in the *NC* model. Additionally, we assigned various discount rates to different owner types (see Table 3.2). As already described in Chapter 2, we assume that all owner types have the same distribution of buildings according to EC and, since we do not have any information to distinguish between different owner types and their share of ERA, after consultation with experts in the field (consultancy company in Zurich), we guesstimated the share of the ERA (see Table 3.2).

In rental housing, the split incentive problem is that the owner invests in energy retrofit, which lowers the cost for the tenant. In this case, we assume that the owner only receives half of the energy savings. In this study, for new rental construction, the split incentive problem disappears because the owner sets the rent at the level justified by low energy cost. If the flat has a low energy cost, the owner can charge more for rent, because the tenant is willing to pay more rent for new energy-efficient construction.

Table 3.2: Owner Types, Shares and Their Discount Rates for Retrofits (discussed in section 3.5.2)

Share of total *ERA* that is owner-occupied/rental	Type	Share of *ERA*	Owner type	Discount rate	Sincent incentive
40%	1	20%	Young and wealthy (Owner-occupier)	2%	1
	2	60%	Middle-aged (Owner-occupier)	4%	1
	3	20%	Old or poor (Owner-occupier)	6%	1
60%	4	10%	Non-Profit-based (Building owners)	2%	0.5
	5	30%	Profit-based (Building owners)	4%	0.5
	6	60%	Private (Building owners)	6%	0.5

Table 3.3: Owner Types, Shares and Their Discount Rates for New Constructions (discussed in section 3.5.2)

Type	Share of *ERA*	Owner type	Discount rate
1	16%	Young and wealthy	1%
2	24%	Middle-aged	2%
3	6%	Non-Profit-based	3%
4	18%	Profit-based	4%
5	36%	Private	5%

3.5.2 Discount rates for retrofitting

The discount rates applied in studies related to energy retrofits in the Swiss residential sector are concentrated in the range of 2%-6% (see Table 3.2).

The discount rate for NC is usually the same as, or close to, that for renovation in the existing relevant studies. In the Res-IRF model, for the evolution of retrofitting, different discount rates (ranging from 7% to 40%) were assigned to buildings with different characteristics (Owner-occupied/Rented; Detached house/Collective dwelling), while for the evolution of NC, a uniform discount rate of 7% was applied [45]. In the MESSAGEix-Buildings model, to evaluate changes in the global building stock and its energy demand, NC are assigned a discount rate of 7% for Single-Family and 10% for Multi-Family buildings [73].

In regards to the NC model, investment decisions are extremely dependent on the characteristics of the homeowner, therefore we captured these differences between homeowners through the discount rate (r). In this model, the decision was made to apply a slightly lower discount rate compared to those used in the first BSM model: ranging from 1% to 5% (see Table 3.2). The reason for choosing these discount rates in contrast to discount rates chosen for Chapter 2, is that if we used the same discount rates as in Chapter 2, then energy class A buildings would never become profitable.

3.5.3 Discussion on construction costs

According to open sources [78], one of the countries with the highest construction costs is Switzerland. There exist official statistics on construction costs in Switzerland: for the construction price index of the city of Zurich or the Construction price index of the Swiss Federal Statistical Office. However, they do not distinguish costs by energy class, they are only for one representative residential building. The results of the study conducted by Dwaikat and Ali [79] in the USA, UK, Australia, and New Zealand show the comparison of different empirical studies and conclude that the majority of green buildings cost more to construct than similar non-green buildings. Additionally, there are few studies that state the contrary. We made assumptions represented in Table 3.4. These are representative construction costs assuming there is an extra cost for the higher energy class of 750 CHF/m^2. The actual construction costs depend on the absolute number of square meters constructed, but in this study we do not take into account economy of scale. After a consultation with experts (consultancy company in Zurich), they confirmed that the representative construction costs indexed in Table 3.4 meet their experience. Table 3.5 summarises all the indices, variables, and parameters involved in the model.

Table 3.4: Construction Costs (CC) for Different Energy Classes

Energy classes	CC in CHF/m^2	Additional cost in CHF/m^2	% increase between neighboring energy classes
C	4,500		
B	5,250	750	22.2%
A	6,000	750	18.2%

Table 3.5: Summary of All Indices, Variables and Parameters

	Meaning	Unit	Values	Sources/Description
Indices				
t, t'	Time period			
OT	Owner type		For retrofitting: see Table 2.4	See Section 3.5.2
EC, EC'	Energy class		{A; B; C; D; E; F; G}	Energy classes according to CECB, see Table A.2 in Appendix A.2
Variables				
CP	Construction period	year	{before 1919; 1919-1945; 1946-1960; 1961-1970; 1971-1980; 1981-1990; 1991-2000; 2011-2020}	
$NC_{t,OT,EC}$	New construction	m^2		
$PR_{t,OT,EC}$	Profit of new construction	CHF/m^2		
$PVNI_{t,OT,EC}$	Present value of the net income of NC	CHF/m^2		
$MP_{t,OT,EC}$	Market price of rental	CHF/m^2		
MC_{EC}	Maintenance cost	CHF/m^2	Equal to 1% of construction cost	
$RI_{OT,C}$	Rental income	CHF/m^2		
$ES_{t,C,EC}$	Energy saving compared to energy class C	CHF/m^2		
SA	Building surface	m^2	100	
Parameters				
CC_{EC}	Construction cost	CHF/m^2	See Table 3.4	See Section 3.5.3

Continuation of Table 3.5

	Meaning	Unit	Values	Sources/Description
$DEC_{C,EC}$	Difference in energy consumption between energy classes	kWh/m^2	For energy class B and C: 20; For energy class A and C: 30	
$PEC_{t,EC}$	Energy price	CHF/kWh		Derived from the World Energy Outlook 2021 (the *Stated Policies* will be used); WEO2018
r	Discount rate		For existing dwellings: {2%; 4%; 6%; 2%; 4%; 6%}; For new construction: {1%; 2%; 3%; 4%; 5%}	See Section 3.5.2
Inf	Information level		{1; 2; 3; 4}	
T	Expected service life of buildings	Year	For existing dwellings: 40; For new construction: 60	
τ	Subsidy rate on retrofitting		30%	Equal to the current values in Switzerland

3.6 Scenario simulations

Under the Paris Agreement on Climate Change, Switzerland aims to achieve zero GHG emissions by 2050 [24]. Energy efficiency is also a key component of Switzerland's Energy Strategy 2050, which includes additional ambitious energy use reduction targets for households and industrial production [80].

Deep decarbonisation of the building sector depends heavily on a significant reduction of energy consumption, which consequently leads to reduced CO_2 emissions. One feature of the model is that even if the building stock did solely consist of buildings only in energy class A, these constructions will continue to emit. In our model, most buildings in energy class A do not emit CO_2, because the little energy they need is provided by heat-pumps. However, it is true that not all buildings can be equipped with heat pumps or connected to district heating. This is why the average CO_2 emissions per kWh heating energy demand is very low for energy class A buildings in the model. The emissions of such a highly efficient building stock will be significantly less than in building stock consisting of energy-inefficient buildings in other energy classes.

In order to demonstrate the future evolution of the Swiss building stock due to retrofitting, NC, and demolition activities, and to explore the energy-saving potential of the building sector, we simulate a number of different policy scenarios. The outcome of these scenarios contributes to answering the question of how effective some policy measures need to be in order to achieve significant reductions in energy demand and CO_2 emissions in the Swiss residential building sector.

In this study, we decided to set scenario targets to a 50% reduction in useful energy demand for all buildings by the year 2050. We achieved 50% reduction in useful energy demand in Chapter 2 for the best combination scenarios, and we wanted to investigate which scenarios would achieve the same best results when introducing endogenising NC in the model. The dynamics of the building stock allow us to observe the impact of each policy tool on energy consumption. The 2050 target can be potentially reached in different ways. Thus, we defined three scenarios, and for each of them we varied specific parameters, while the others were kept constant. The objective was to demonstrate that, by changing selected parameters (subsidies, information level, restrictions) in the scenarios, it is possible to achieve the 2050 target. Another objective was to show the effectiveness of endogenising NC. In all the following scenarios, we have achieved the envisaged 2050 target.

3.6.1 Scenario horizon

The Baseline scenario is identical to the one in Chapter 2 (see table 2.5).

1. The subsidy on retrofit ($\tau^t_{EC,EC'}$) pays 30% of the energy retrofit investment.
2. The information level (Inf) is equal to 1.
3. The CO_2 tax on heating fuel equals CHF 96 from the year 2019 to the year 2021 and is constant from the year 2022 and equals CHF 120.

It was chosen to use the same Baseline scenario in this chapter as in Chapter 2, in order to have the same starting point for both models, which will provide a better overview of recommendations when comparing the results of both models.

The focus of the three new scenarios is on achieving the 2050 target. All three scenarios have a fast increase in the information level (see Table 3.6). The CO_2 Change scenario has a constant 30% subsidy both on refurbishment and on the cost difference of NC, no restrictions on NC and 59.5 CHF tax increase per year from 2023 to 2050. In this scenario the tax increase of 59.5 CHF per year lets us achieve the set 2050 target. The Subsidy scenario has a 1% subsidy increase from the year 2020 to 2050, both on refurbishment and on cost difference of NC, no restrictions on NC as well as a 12.5 CHF tax increase per year from 2023 to 2050. In the Subsidy scenario, in order to achieve the set 2050 target, the 12.5 CHF tax increase per year is required. The Restrictions scenario has a constant 30% subsidy both on refurbishment and on cost difference of NC, restrictions of energy class C buildings from the year 2025 and of energy class B building from the year 2035 as well as 47 CHF tax increase a year from 2023 to 2050. In this scenario, the set 2050 target can be achieved when a 47 CHF tax increase per year is introduced.

Table 3.6: Policy Scenarios

Scenarios	Subsidy on retrofit	Subsidy on cost difference (NC)	Information level	Restriction	CO_2 tax (CHF/tCO_2)
Baseline Scenario	2019-2050: 30%		2019-2050: 1		2019-2021: 96 2022-2050: 120 2050: 120
CO_2 tax	2019-2050: 30%	2019-2050: 30%	2019: 1 2020: 2 2021: 3 2022-2050: 4		2019-2021: 96 2022: 120 2023-2050: +59.5 CHF/year 2050: 1786
Subsidy	2019: 30% 2020-2050: + 1% year 2050: 61%	2019: 30% 2020-2050: + 1% year 2050: 61%	2019: 1 2020: 2 2021: 3 2022-2050: 4		2019-2021: 96 2022: 120 2023-2050: +12.5 CHF/year 2050: 470
Restrictions	2019-2050: 30%	2019-2050: 30%	2019: 1 2020: 2 2021: 3 2022-2050: 4	C from year 2025 B from year 2035	2019-2021: 96 2022: 120 2023-2050: +47 CHF/year 2050: 1436

3.6.2 Comparison of all scenarios

The initial objective of the present study was to show the effectiveness of endogenising NC and to identify policy scenarios that achieve the useful energy demand reduction target of 50% by the year 2050. We have set a goal, and fixed variables and parameters in our scenarios. We ran the model with a reasonable CO_2 tax, but then it was necessary to adjust different parameters to reach the 2050 target.

The results of this study indicate that all three scenarios achieve the 2050 target of decreasing energy demand by 50% as well as achieving deep decarbonisation (decrease of CO_2 emissions by 87%, 90%, and 91%, respectively). There are particular differences in how the scenarios reach this target, even if they are small. The comparison of all scenarios can be seen in Table 3.7. The most obvious finding to emerge from the analysis is that the Subsidy scenario has the highest retrofit rate and highest retrofit investment. In our model, the CO_2 tax encourages fuel substitution by replacing the CO_2-intensive energy carriers with less CO_2-intensive options. In the scenarios where the fuel substitution is triggered by the CO_2 tax, it contributes to reducing useful energy demand with fewer retrofit investments compared to the Subsidy scenario. In the Subsidy scenario, despite the fact that the increasing subsidy does not directly affect the energy substitution, it still triggers the energy mix change in different energy classes with a corresponding investment increase. Thus, in the Subsidy scenario, the energy mix change in energy classes triggered by rising subsidies as well as lower CO_2 tax than in the other two scenarios, leads to an increase in the retrofit investments which aids in achieving the set targets.

Table 3.7: Comparison of All Simulations

Scenarios	**Year 2019**	**Baseline**	**CO_2 tax**	**Subsidy**	**Restrictions**
Average value for 2020-2050 (except column '2019')					
Annual retrofit rate per owner type, average	1.27%	0.89%	2.08%	2.13%	2.04%
Annual retrofit rate, owner type 1 ('best')	1.74%	1.23%	2.41%	2.36%	2.41%
Annual retrofit rate, owner type 6 ('worst')	1.18%	0.74%	2.05%	2.04%	2.07%
Sum 2020-2050 compared to Baseline scenario					
Retrofit investment			116%	122%	108%
last year class C buildings are built (NC model)			2024	2023	2025
last year class B buildings are built (NC model)			-	-	2035
2050 compared to 2019					
Useful energy demand per m^2		-37.4%	-60.3%	-60.4%	-60.4%
Useful energy demand total		-21.1%	-50.0%	-50.0%	-50.0%
CO_2 emissions per m^2		-59.0%	-93.1%	-89.8%	-92.3%
CO_2 emissions total		-48.2%	-91.3%	-87.2%	-90.3%

According to the model, in the Subsidy scenario, the subsidy starts at 30% and by the year 2050 reaches 61%, compared to the other two scenarios where the subsidies are constant at 30% until the year 2050. The important relevant finding was that the sole subsidy increase was insufficient to achieve the 2050 target. Since a moderate CO_2 tax increase is preferable over a very high subsidy rate increase, an additional CO_2 tax was required to achieve the set goal. Consequently, we increased the CO_2 tax by 12.5 CHF per year, which let us achieve our 2050 target in the Subsidy scenario. In the Subsidy scenario, the last year when energy class C buildings are built (referring to the NC model) is the year 2023, while in the CO_2 tax scenario it is the year 2024. These results suggest that, by increasing subsidies in the Subsidy scenario, energy class B buildings become profitable after the year 2023 and hence more attractive for building owners than energy class C buildings.

The findings of the CO_2 tax scenario demonstrate that energy class B buildings become profitable and hence attractive for building owners after the year 2024. The results of the study indicate that, in order to achieve the set 2050 target with a constant subsidy for both refurbishment and cost difference of NC, it is necessary to significantly increase the CO_2 tax (+59.5 CHF/year). In this case, it will shift the year when energy class C buildings are no longer built by one year later. These are interesting results and the explanation for this is that building owners prefer to acquire moderate subsidies introduced together with the moderate CO_2 tax increase, as in the Subsidy scenario, rather than the introduction of constant subsidies and high CO_2 tax increase, every year as in the CO_2 tax scenario. The outcomes of both scenarios show that the Subsidy scenario is 6% more expensive than the CO_2 tax scenario due to the increasing subsidy rate, has a higher retrofit rate, and eliminates energy class C building one year earlier than in the CO_2 Change scenario.

The lowest retrofit rate with the lowest investment costs are in the Restrictions scenario. There are two causes for the differences between this and other scenarios. In this scenario the setup of the subsidy rate is exactly the same as in the CO_2 tax scenario, however, the subsidies do not continue further in time because of the nature of the scenario, where the building of Ec-C NC are restricted from the year 2025 and for EC-B constructions from the year 2035. Hence, the budget used to subsidise NC is lower than in the first two scenarios. In contrast to earlier findings, (CO_2 tax increase by 59.5 CHF/year and 12.5 CHF/year, respectively), in the Restrictions scenarios, an increase of 47 CHF/year CO_2 tax is enough to achieve the 2050 target. The results showed that, in order to achieve the 2050 target, it is necessary, together with restrictions, to introduce a 47 CHF/year CO_2 tax, which is lower than in the first scenario and higher than in the second scenario. This suggests that the introduction of restrictions can both decrease the investment costs and the required CO_2 tax to achieve the set goal. In the third scenario, the subsidy rate is the same, but the time horizon to apply these subsidies is shorter, thus less money is spent to further support the construction of these buildings. Consequently, the investments are 8% lower than in the CO_2 Change scenario and 14% lower than in the Subsidy scenario. When comparing the three scenarios, we conclude that, despite the slightly lower annual retrofit rate in the Restrictions scenario, this scenario is preferable, because it reaches the 50% reduction in useful energy demand target set, applies a lower CO_2

tax than in the Subsidy scenario, requires the least investment and has only energy class A buildings constructed from the year 2035.

In conclusion, the use of different scenarios introduced in this study is to evaluate how different policies (or combinations) can be used to achieve the 2050 target. Results showed that increasing the subsidy rate plays an important role in achieving the goal, although it is difficult to achieve the set 2050 target solely by increasing subsidies. It could also be possible to reach the 2050 target with subsidies alone, but they would probably be extremely high, although increasing the subsidy rate too high or too fast is not preferable. The same applies for the restrictions: Results demonstrated that it is difficult to achieve the set 2050 target solely using restrictions and thus, the introduction of a moderate CO_2 tax increase was mandatory. The process of forbidding the construction of buildings of particular EC can take a significant amount of time and effort. Thus, we assume that even the restriction years applied in the scenario are optimistic. The CO_2 tax plays an important role in two scenarios and facilitates two out of three scenarios to achieve the set goal. In the CO_2 tax scenario, by solely increasing the tax, it was possible to achieve the set goal. This shows that a high increase of CO_2 tax can help to achieve the set goal, but increasing the CO_2 tax too high or too fast is not preferable.

To conclude, future research should consider the potential effects of different economic instruments in more detail, for example how the more rapidly increasing subsidy rate on both refurbishments and the cost difference of NC can affect the results. In future work, investigating high CO_2 taxes might prove important, because, as was demonstrated in the scenarios, the increase of CO_2 tax can significantly affect the results. Looking forward, future studies could investigate the association and combinations of high CO_2 tax, faster subsidy increase, and different years of restrictions. Future research should be devoted to the development of scenarios that can be used in future by policy developers and governmental entities. Indeed, future investigations are necessary to validate the kinds of conclusions that can be drawn from this study, while this study provides a good starting point for discussion and further research.

3.7 Conclusion and policy implications

In summary, we developed a decision model for NC that is integrated with the previously developed two-step decision model for retrofitting, to predict the evolution of the residential building stock in Switzerland. This decision model for NC is based on a cost-benefit analysis of the owner's investment in NC with different energy classes. Although household decisions about building energy-efficient constructions are influenced by many factors such as age, income, and personal preferences, the cost is often considered a more important factor in energy efficiency investments, and it has become a common driver in energy decision models. In this model, the owners are divided into five categories in order to introduce heterogeneity. The consideration that energy efficiency requirements for NC will become increasingly stringent in the future are taken into account.

This research studies a range of policy simulations that help to achieve energy retrofit and a decrease in useful energy demand in Swiss residential building stock. In this research, the rebound effect, which can affect resulting useful energy demand, is not taken into account. When introducing a mix of different policy scenarios, a forced replacement of older and less energy-efficient buildings with new and more efficient ones takes place. This results in a significant useful energy demand reduction by 50% in the year 2050. Nevertheless, in order to achieve the set goal, higher investment costs are required due to the introduction of generous subsidy schemes already in place. Hence, in order to achieve the goal set in the model, sufficient subsidies together with strict restriction rules when building NC, mixed with ambitious information campaigns and high CO_2 taxes are essential. The results suggest that, in order to achieve the 2050 reduction target of useful energy demand, it is essential to increase the level of retrofitting activity as well as to restrict the construction of inefficient buildings, which could be beneficial in terms of long-term gains. In our model, imposing restrictions on the energy class of NC can quickly improve the energy efficiency of the NC stock.

In conclusion, it will be indispensable to address barriers and find solutions for buildings with higher investment (e.g. construction costs). Since under current policies these buildings cannot benefit from an economically feasible retrofit, it is crucial to adopt suitable policies in order to improve the economic potential of retrofitting. Therefore, suitable policies that include the potential economic incentives for owners coupled with the introduction of energy-efficient technologies will give them additional incentives to undertake retrofits and build NC. What can be learned from the simulations, is that an impactful reduction in energy use requires strong and immediate policies, in particular, the introduction of subsidies coupled with a CO_2 tax escalating more rapidly than in the past, more active information campaigns, and restrictions on the energy classes of NC. The results of the model show that large-scale retrofits of the whole existing building stock together with the introduction of particular policy measures for building NC are essential to reach our targets. The outcome of the model also demonstrates that the retrofits and building of NC will result in a synergy between cost savings and long-lasting and energy-efficient buildings in the stock.

4 Endogenous Energy Efficiency Improvement in the Swiss Cement Industry

4.1 Abstract

Currently, six cement plants exist in Switzerland, which produce approximately 94% of their clinker in rotary dry kilns and the rest in semi-dry kilns. The Swiss cement industry, with a total production of about 5 million tonnes of cement per year, is one of the three highest industrial energy consumers in the country and therefore has great potential for Energy Efficiency Improvement (EEI) and CO_2 abatement. Our objective was to develop a better representation of EEI triggered by energy and climate policies. We illustrate this by assessing the impacts of a set of realistic policies on the diffusion and adoption of technologies associated with energy consumption and energy use or CO_2 emissions reduction, as well as structural changes in the Swiss cement industry. The model we developed for six Swiss cement plants implements these measures based on a cost-benefit analysis in combination with other rules related to the replacement of inefficient equipment at the end of its lifetime. This research intends to give useful indicators, such as prices of energy efficiency solutions, to help better grasp both theoretical and final energy and CO_2 savings potentials. In this study Energy Efficiency Measure (EEM) are classified into three categories: 1) Implementing Essential Unit Process (EUP) measures means replacing inefficient equipment with a more efficient option, thereby directly making the process more efficient (e.g. replacing a mill with a more efficient one), 2) Implementing Pure Energy Efficiency Measures (PEEM) measures means adding a piece of equipment. PEEM is not part of the manufacturing process, but only serves to improve the overall energy efficiency of the plant (e.g. waste heat recovery). 3) CO_2 Saving Measure (CSM) (e.g. CO_2 capture using MEA scrubbing). In two scenarios where Carbon Capture and Storage (CCS) is implemented, CO_2 emissions decrease by 96%, while fuel and electricity consumption increase drastically. In the CCS scenarios, the cumulative CO_2 emissions over the calculation period 2015-2050 decrease by 26% and 44%. To conclude, implementing CCS is a choice faced by each cement plant, comparing the discounted costs of CCS, including the costs of the additional fuel and electricity use, with the price of the emission certificates that the plants could sell or would not need to buy after implementing CCS.

4.2 Introduction

4.2.1 World context

According to the Intergovernmental Panel on Climate Change [81], the four main industries (power plants, iron and steel production, cement manufacturing and (petro-)chemicals) are accountable for almost 34% of global CO_2 emissions. The major part of CO_2 emissions in the industrial sector is defined by the intensity that it combusts fossil fuels. Moreover, production processes such as iron, steel, and cement production chemically produce CO_2 as a waste gas [82].

Generally, most cement produced in a country is consumed in the construction sector, the trade of cement is generally limited to the country of production and the process of cement manufacturing is common to all existing cement plants. The production of cement is an energy-intensive process that includes considerable thermal energy in order to decarbonise the primary raw material (limestone) into clinker, which is the principal component of cement [83]. Since the cement industry has a high level of process emissions, this industry is the third top CO_2 emitter globally, responsible for 5% of global CO_2 emissions [82]. Cement is considered a key construction material that is used in the construction of buildings and different infrastructures. In cement production, energy accounts for nearly 30-40% of production costs. The main challenges for this industry are the conservation of energy and material resources, as well as the goal of reducing CO_2 emissions caused by cement production and distribution processes.

4.2.2 Swiss context

The objective of this research was to endogenise the energy efficiency process and to implement this concept in the cement industry in Switzerland. The process to endogenise the EEI of Swiss building stock was demonstrated in chapters 2 and 3. In this study, the endogenisation is the process where innovation takes the form of an increasing variety of intermediate inputs.

The data relating to CO_2 emissions and energy usage is not widely accessible. The reasons for this can be the fact that the cement industry is of a comparatively small size and highly competitive. Thus, it might be complicated to acquire related specific information regarding Switzerland's cement plants. Due to this lack of data, complications can occur when trying to evaluate the potential for EEI and to understand what are the hurdles to limit the implementation of the best technologies in cement production. Thus, it is indispensable to be able to identify the challenges and to find energy efficiency indicators that will help to design effective policies in the Swiss context. We used the available data in order to calibrate the model. The main contribution of this study is thus, not to provide exact numbers, but rather insights. Our model demonstrates a coherent approach to investigating these aspects and makes explicit assumptions and approaches.

4.3 Literature review

There have already been studies conducted researching the energy efficiency of cement-making and EEI measures for the cement industry [84, 85]. The information on cement production and energy comes from various studies and statistics. In the study [84], the authors used benchmarking to compare the individual performance of plants with the most energy-efficient cement making process. The results showed the value of benchmarking as a basis for potential estimation improvements. Additionally, it demonstrated information on the energy use of the global cement industry. Energy benchmarking supplies highly valuable information about the energy efficiency potentials of cement industries.

Further, many studies looked at the potential reductions in emissions and energy use in cement plants in the U.S. [86] and in Europe [87]. For example, Worrell et al. [86] studied the energy intensity and energy use trends of the US cement industry (from 1970 to 1999). Consequently, they calculated and demonstrated the baseline energy consumption by cement production processes in the US in 1999. This study determines EEMs and computes investment costs, energy savings, operations, and maintenance costs for each of the EEMs. In addition, another paper studied the energy-saving potential of 16 plants in China [88]. The data on plants was collected and was further used to benchmark the energy efficiency of individual Chinese plants and international best practices. They used the Benchmarking and Energy Saving Tool for Cement (BEST-Cement) [89]. As a result, 32 EEMs that could be potentially suitable for the 16 Chinese cement plants were established. Additionally, the potential for energy efficiency was evaluated for the year 2008.

Moreover, possible EEI waiting to be captured were shown in an exhaustive review of European cement facilities [90]. The authors of this study identified in their list of possible EEI possibilities that would not be profitable by standard capital investment decision criteria. In the study by Worell et al [91], only the improvement margins in the operating costs (acquired through technological improvements) were covered. Additionally, in this case, the possible related productivity improvements were not taken into account. The result showed that the financial tools used by companies have a secondary role when there is a process of investment making decisions. Conversely, these tools are rather used as communication tools that give weight to the strategic nature of the investment [92].

Wang et al. [93] conducted their research on exergy analyses and parametric optimisations for power plants in the cement industry. The outcome exhibited the exergy losses in the condenser, turbine, and heat recovery steam generator. These exergy losses were considerably large. Thus, by reducing these exergy losses, it will be possible to significantly ameliorate the co-generation system's performance.

The main source used in our research was the study conducted by Zuberi and Patel [14]. This study adopted a bottom-up analysis to investigate the EEI of technologies and CO_2 emission reduction potentials in the Swiss cement industry by means of energy efficiency cost curves. Additionally, a number of EEMs with relatively long payback periods (4–8 years) have been identified. Zuberi and Patel [14] used economic data to analyse the cost-effectiveness of the implemented measures. They also focused on techno-economic barriers that limit best practice implementations in Swiss cement plants. The outcome of this research displayed the energy efficiency gap in the cement sector. In this study we are going to examine how policies can close this energy efficiency gap.

4.3.1 Models

The development of the Conservation Supply Curve (CSC) started to evolve at the beginning of the 1980s in order to evaluate cost-effective EEMs [94]. The CSC is related to energy savings achieved by implementing a particular efficiency measure, set off against that measure's "cost of conserved energy" [95] and is thus able to identify the potential energy savings, as well as to rank different EEMs against each other. CSC has been used in many industries such as ammonia, cement, iron, and steel industries. Additionally, with the help of CSC, it is also possible to calculate the cost of conserving specific energy fuels (steam [96] or electricity [97]). To add, Fleiter et al. [98] used CSC to evaluate CO_2 abatement.

Furthermore, Energy Conservation Supply Curves (ECSC) have been used in several studies on energy efficiency in several energy-related industrial sectors. In the study by Kong et al. [99], the authors designed ECSCs for fuel and electricity for the pulp and paper industry in China. The result of this study demonstrated cost-effective conservation potentials of 27% for fuels and 4% for electricity. Cost-effective measures related to inefficient recovery in the iron and steel sector in China were studied by Zhang et al. [100].

Additionally, the Chinese ammonia industry [101] created electricity and fuel conservation curves. It was demonstrated that it is possible to achieve a 14% reduction in electricity and fuel consumption when using a 30% discount rate. While Xu et al. [102] determined that, with the help of CSC and with cost-effective efficiency potentials, it is possible to achieve a 25% reduction in final energy consumption for the pulp and paper industry in the US. Similarly, the study conducted by Sathitbun-anan et al. [96] determined 17 steam conservation measures. Sathitbun-anan et al. [96] based their study on five leading Thai sugar mills, which succeeded in developing steam conservation curves for nine sugar mills in Thailand. While McKane and Hasanbeigi [103] conducted their research on four countries in Europe and Brazil on the cost-effectiveness of electricity efficient potentials of industrial motor systems for these countries.

Indeed, CSCs are able to identify cost-effective EEMs in different industries. Nevertheless, there still exists a need to defeat barriers to the implementation of EEMs. In their study, Sorrell and Schleich [104] gave an explanation of barriers and, in 2013, Cagno et al. [105] introduced further developments. This was studied by Trianni and Cagno [106] for non-energy intensive manufacturing SMEs (Small and Medium Sized companies) as well as for the foundry industry by Rohdin et al. [107]. Additionally, Fleiter et al. [108] conducted a study on barriers to energy efficiency bottom-up energy-demand models, while Tesema and Worrell [109] in their study for the cement industry calculated CSCs, where they highlighted the high importance of overcoming barriers in order to be able to apply EEMs.

Tesema and Worrell [109] in their study used data from eight operational plants and twelve plants under construction in Ethiopia in order to develop fuel and electricity CSCs for the cement industry. In the same way, Hasanbeigi et al. [110] developed fuel and electricity CSSs for the cement industry in China (2010-2030) and assessed the potential of adopting 23 energy efficiency technologies, while Hasanbeigi et al. [111] and Therdyothin et al. [97] estimated 47 EEM and their cost-effectiveness in the cement industry in Thailand.

Models that focus on the cement industry include cement production models that center on the production of dry kilns for clinker and roller (or ball) mills for grinding. Furthermore, some of these models take into account different types of cement; fly ash, Portland cement, blast furnace slug, for example [112]. In all cement industry models, different types of cement, as well as different production technologies, compete for market share on the basis of their production costs. Another important point to mention is that recycling is not taken into account for cement, mainly due to the reason that the demolition waste is used as gravel for infrastructures and roads. The amount of models that include retrofit measures for EEI is scarce [113]. A limited amount of large-scale models consider material efficiency improvements through material substitution or product life extension [114]. This is the same situation for models that account for reducing losses in production processes [115]. Nevertheless, the number of studies on clinker substituting alternative materials in the cement industry has increased [116, 112]. To conclude, only a few models account for the potential of carbon capture and storage (CCS) technology [87, 117].

Few models have modules with bottom-up details that focus on the cement industry. The globally integrated asset model (IMAGE) has a specific integrated module targeted to the cement industry. The model analyses future projections on GHG emissions [118]. This model takes into account global and regional cement and clinker production and demand. Additionally, it also considers the trade of technologies, materials energy use, GHG emissions, and stock turnover. Another such example is POLES, this model has the ability to project CO_2 emissions and energy use. Furthermore, this model also takes into account retrofitting, technologies, and stock turnover [83]. Bottom-up methods quantify all the influencing factors that lead to the dispersion of measurement results and build models for mathematical synthesis. Numerous bottom-up studies have assessed energy-saving potentials based on using the Best Available Technology (BAT) or Best Practice Technology (BPT) techniques. Thus, previously, energy-saving potential was assessed under the idea that BAT and BPT were applied to the industrial process itself. This approach was used in a variety of industries in order to simulate EEI potentials [119, 120]. Nevertheless, the studies that use the BAT approach did not take into account the effect of technology diffusion on energy-saving potential. Thus, they did not take into account the development over time and were not able to give a conclusion on the timescale required in order to liberate this potential.

Additionally, some developed bottom-up models have considered the technology diffusion influence [98, 121, 122, 112, 123]. The main advantage of these models is the transparency of the technology's development, which allows projecting a clear and realistic development path. However, in these kinds of models it is important that, prior to modeling, some essential parameters should be exogenously forecasted, which are usually acquired from different statistical methods. Nonetheless, these statistical models might lack fidelity, mainly due to the reason that they are based on historical data and are unable to catch specific factors or changes in a dynamic environment.

Our model differs from other models demonstrated above in several ways. In our model, we created scenarios for the implementation of EEM and we indicate these measures will be implemented based on a cost-benefit analysis and how this can be influenced through different policies. We simulated several scenarios where we wanted to demonstrate the capabilities of our model when analysing various ranges of scenarios and we aim to study how Switzerland can achieve deep decarbonisation of its cement sector. Our model was constructed for the Swiss cement industry to estimate the EEI and the potential of decreasing CO_2 emissions by taking into account the costs, lifetime, and energy savings of different technologies and measures. With our model, we estimated the potential energy consumption reduction and CO_2 emissions abatement potential for the Swiss cement industry from the year 2015 to the year 2050. More research is needed to deal with the remaining issues connected to cement-related modeling, such as understanding the existing technologies and barriers to their implementation, development of effective programs and policies to overcome the barriers to adoption, development of the resources to gather information on energy efficiency, as well as to develop effective models to address these challenges for the world of tomorrow.

4.4 Methodology

4.4.1 Swiss context

Currently, in Switzerland there exist six cement plants, belonging to 3 companies, which produce approximately 94% of the clinker in rotary dry kilns and the rest in semi-dry kilns. Throughout the year, Switzerland produces about 5 million tonnes of cement in total [14]. The specific energy use for Switzerland in 2019 is 3.54 GJ/t-c. It is below the maximum BAT value (4 GJ/t-cl), but approximately 7% above the minimum BAT value (3.3 GJ/t-cl) [124]. This demonstrates that Switzerland still has energy efficiency potential. In our model, we used the data on average share of fuels of the total fuel energy demand by the Swiss cement sector in the year 2014 (see Table 4.1) derived from the study conducted by Zuberi and Patel [14]. In their study Zuberi and Patel calculated the CO_2 abatement potential of each technology measure as the product of fuel energy savings and emission factor of coal, which is a weighted average of bituminous coal, lignite and petroleum coke. The contributions made by blending cement, which abates mineral CO_2 in addition to fossil-fuel related CO_2 emissions, are taken into account in the results for CO_2 abatement.

Table 4.1: Average Share of Fuels in Total Fuel Energy Demand by the Swiss Cement Sector

Energy Carrier	Share (wt. %)
Light fuel oil	0.57
Heavy fuel oil	0.44
Natural gas	0.28
Coal, coke	42.92
Alternative fuels	55.79
Total	100

We "backward engineered" the data given in the paper by Zuberi and Patel [14] to determine a hypothetical plant without any measures (using only old equipment). From this starting point, we derived the plant-specific energy consumption and CO_2 emissions, considering the initially implemented measures. The resulting sum over all plants matched the estimates coming from the study conducted by Zuberi and Patel [14] of overall current energy consumption and CO_2 emissions. The study by Zuberi and Patel [14] does not indicate which Swiss plants adopted which energy-efficient measures, but only provides overall adoption rates. In this study, we assume that these adoption rates are weighted by the six plants' clinker production. Thus, they show the affected share of total clinker production by each measure.

There are many reasons to select the cement sector as a candidate for exemplifying EEI in the industry: its product is quite homogeneous and it has a high energy intensity.

Following the study conducted by Zuberi and Patel [14], we distinguish between EUP measures and PEEM. An EUP is an essential part of the manufacturing process. Therefore, implementing such a measure means replacing inefficient equipment with an efficient alternative, thereby directly making the process more efficient (e.g. replacing a mill with a more efficient one). A PEEM, on the other hand, is not part of the manufacturing process, but only serves to improve the overall energy efficiency of the plant (e.g. waste heat recovery). Implementing a PPEM means adding a piece of equipment. It is important to distinguish between EUP and PEEM measures because, according to initial allocation, each plant has in place a specific mix of inefficient EUP-equipment, efficient EUP-equipment, and PEEM. In our model to increase energy efficiency, plant specific measures are implemented or reimplemented. Most measures (all EUP and most PEEM) are already implemented, so that further improvements occur at reimplementation.

We model approximately 15 measures based on the thorough analysis of the study conducted by Zuberi and Patel [14], who provide a list of energy efficiency and CO_2 mitigation measures that are applicable to Swiss cement plants. This list also includes investment costs, fuel savings, electricity savings, CO_2 abatement potential, lifetimes, as well as adoption rates. Examples of measures are mill or grinder replacement, changes in the kiln, or replacing a pneumatic with a mechanical transport system. The abbreviation and the list of technology measures are given in Table 4.2.

Table 4.2: Technology Measures (source Zuberi and Patel [14])

Abbreviation	Measure category	Technology measure
RM1	EUP	Replacing a ball mill with vertical roller mill
RM2	EUP	Replacing pneumatic with mechanical transport system
RM3	EUP	Gravity-type homogenising silo
RM4	EUP	High efficiency classifiers/separators raw material grinding
CP1	EUP	Changing from lepol kilns to kilns with cyclone preheaters and precalciner
CP2	PEEM	Upgrading preheater kiln to a preheater/precalciner kiln
CP3	EUP	Retrofitting of cyclones with lower pressure drop
CP5	EUP	Modernisation of grate coolers
CP6	PEEM	ORC for low temperature waste energy recovery
CG1	EUP	Replacing ball mills with vertical roller mills
CG2	EUP	High efficiency classifiers for finish grinding
CG3	PEEM	High pressure roller press as pre-grinding to ball mill in final grinding
CG4	EUP	Improved grinding media for ball mills modernisation
CG5a	PEEM	Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag)
CG5b	PEEM	Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag)
FR1	CSM	Using alternative fuels
FR2	CSM	Replacing coal demand by natural gas
I1	PEEM	Optimisation of the overall process control system
I2	EUP	Celitement
I3	EUP	Fluidised bed advanced cement kiln systems
I4	CSM	CO_2 capture using MEA scrubbing

4.4.2 Description of the model

In order to build the model, the equations given in the study conducted by Zuberi and Patel [14] were used. In our study, the specific cost, which is also referred to as the levelised cost of each of the energy measures, is calculated in Eq. 4.1. The specific cost is applicable depending on the relevant sectoral potential for final energy savings. In the equation 4.1, I_y is the initial investment (CHF) of each measure 'y', ANF is the Annuity factor (see Eq. 4.2), $O\&M_y$ is the operation and maintenance cost (CHF) and B_y is the annual benefits of the measure (CHF) (the annual final energy cost savings over the lifetime to be achieved from the first year onwards after implementation) calculated in Eq. 4.3. In Eq. 4.3. EIS_y is the electricity savings potential, FIS_y is the fuel savings potential, CA_y is the CO_2 abatement potential, P is the price of electricity 'e' (CHF/GJ), price of fuel 'f' (CHF/GJ) and of CO_2 (CHF/t-CO_2 emitted).

$$C_{spec,y} = \frac{(I_y * ANF + O\&M_y - B_y)}{ES_y} \tag{4.1}$$

$$ANF = \frac{(1+r)^L \times r}{(1+r)^L - 1} \tag{4.2}$$

$$B_y = \Big((EIS_y \times P_e) + (FIS_y \times P_f) + (CA_y \times P_{CO2}) \Big) \times PR_y \tag{4.3}$$

The net present value (NPV) for each measure 'y' for the base year 2016 will be calculated using Eq. 4.4, where CF_t is the annual cash flow for the year 't', determined in Eq. 4.5, r is the average discount rate and L_y is a measure of the lifetime. In Eq. 4.5, $I_{y,t}$ is equal to zero after the year of investment.

$$NPV_y = \sum_{t=2016}^{L_y} CF_t \times (1+r)^{-t+2016} \tag{4.4}$$

$$CF_t = I_{y,t} + O\&M_{y,t} - B_{y,t} \tag{4.5}$$

The first step is to build a model for all six existing Swiss cement plants, replicate the investment decision of plant owners, model the efficiency improvement, and describe the production processes of these plants, in particular, which EEMs they have already implemented. Starting from an initial allocation of already implemented efficiency measures, plants become more energy efficient by implementing additional measures. We model the implementation of these measures based on whether the NPV in Eq. 4.4 is positive or not in combination with other rules related to the replacement of inefficient equipment at the end of the lifetime.

The EEI for each of the six Swiss cement plants are modeled. Plants become more energy efficient by implementing efficiency measures. The model starts with an initial allocation of plant-specific measures. Zuberi and Patel [14] do not indicate which plants adopted which measures, only overall adoption rates. The shares of total clinker production by each plant are given in Table 4.3. We assume that these adoption rates are weighted by the six plants' clinker production, so they indicate what share of total clinker production is affected by each measure. Using the data on the plants' clinker production, we are able to determine an initial allocation that replicates the adoption rate from the study done by Zuberi and Patel [14] (see Table 4.4). As we did not verify whether our assumed initial allocation corresponds to reality, we labeled the plants from A to F, so that no conclusions drawn are associated with a specific plant.

We do not have data regarding the age of the efficient equipment already in place. We thus assume that the age depends on the number of plants that already adopted the respective measure. For example, if a measure is implemented in 5 out of 6 plants, the age in each plant is 5/6 of the lifetime. The idea behind this is that measures that have been implemented in most plants are more likely to be "usual practice" in the industry and thus already older.

Table 4.3: Share of Total Clinker Production in 2015 (source Zuberi and Patel [14])

Plants	Share of total clinker production in Megatons (Mt) per year (Mt/y)
A	16%
B	19%
C	20%
D	17%
E	6%
F	21%

Table 4.4: Initial Allocation of Measures and Calculation of Rate of Adoption in 2015 (based on adoption rate of Zuberi and Patel [14])

Share of total clinker production (Mt/y)	16%	19%	20%	17%	6%	21%	Rate of adoption
Plant	A	B	C	D	E	F	
RM1	YES	YES	YES	YES		YES	94%
RM2	YES	YES		YES	YES	YES	80%
RM3	YES	YES			YES	YES	63%
RM4	YES						16%
CP1	YES	YES	YES	YES		YES	94%
CP2	YES	YES		YES	YES		58%
CP3			YES	YES			37%
CP5	YES	YES	YES	YES		YES	94%
CP6	YES			YES			33%
CG1			YES				20%
CG2			YES		YES		27%
CG3		YES		YES	YES		42%
CG4					YES	YES	28%
CG5a	YES	YES	YES	YES	YES	YES	100%
CG5b							0%
FR1	YES	YES	YES	YES			72%
FR2							0%
I1	YES	YES	YES	YES			72%
I2							0%
I3							0%

Additionally, the gain of currently installed measures is determined with the help of the data on the initial allocation of measures (given in Table 6 in Zuberi and Patel [14]) and Energy savings by each measure. Moreover, the initial allocation of measures (see Table 4.4) (YES = implemented) is calculated taking into account the remaining diffusion rates taken from Table 2 of Zuberi and Patel [14]. In the year 2050, all measures are implemented in all plants, except for those that are competing with other measures: CG1, CG3, CG4, FR1, I2 and I3. This is the same in all scenarios. The measures indicating the largest reductions in fuel and electricity are I4, CP3, CG3 and CG4.

Zuberi and Patel [14] estimate that the current average energy consumption for the six plants per ton of produced clinker is 3.5 GJ (fuel) (see Table 4.5) and 0.5 GJ/t-cl (electricity) (see Table 4.6), respectively. Using these averages and the saving potential of the measures (see Table B.9 in Appendix B.2) implemented in the initial allocation allows us to calculate the current fuel and electricity consumption for each plant with the measures currently installed (see Table 4.5 and Table 4.6). Based on the study conducted by Zuberi and Patel [14] and confirmed by a representative of the cement industry, the current best-available technology would need 3.0 GJ/t-cl fuel energy and 0.4 GJ/t-cl electricity.

Table 4.5: Fuel Consumption by Plant (GJ/t-cl)

Fuel Consumption w/o measures (GJ/t-cl)	5.85	
Plants	Gain Measures (GJ/t-cl)	Fuel consumption with measures (GJ/t-cl)
A	1.41	4.44
B	3.18	2.67
C	2.75	3.10
D	1.41	4.44
E	2.20	3.65
F	2.70	3.15
Av. fuel consumption (GJ/t-cl)		3.5

Table 4.6: Electricity Consumption by Plant (GJ/t-cl)

Elec. Consumption w/o measures (GJ/t-cl)	0.64	
Plants	Gain Measures (GJ/t-cl)	Elec. Consumption with measures (GJ/t-cl)
A	0.13	0.51
B	0.15	0.49
C	0.16	0.48
D	0.20	0.44
E	0.13	0.51
F	0.08	0.56
Av. Elec consumption (GJ/t-cl)		0.5

4.4.3 Energy efficiency improvement

Starting from this initial allocation, the energy efficiency of the plants improves along two pathways:

- Measure-induced Technical Progress (MI-TP): Inefficient equipment is replaced by more efficient equipment that fulfills the same function but is of another type (e.g., a ball mill is replaced by a vertical roller mill). Or a PEEM is introduced (e.g. waste heat recovery). We refer to this process as an implementation of a measure. The magnitude of the MI-TP is measure-specific.
- Autonomous Technical Progress (A-TP): Efficient equipment that was state-of-the-art at the time of its implementation, but has become somewhat outdated by the end of its lifetime. This outdated equipment is replaced by the same type, yet of an improved variant (e.g., a vertical roller mill version 1 is replaced by a vertical roller mill version 2; or waste heat recovery version 1 is replaced by waste heat recovery version 2). We refer to this process as a reimplementation of the measure. We assume that A-TP yields an improvement of the saving potential of 1% per year and that investment costs are not affected by Technological Progress (TP). We do not further endogenise this part of the TP within our model.

In reality, the distinction between these two pathways may be blurred in some cases. In the model, we nevertheless strictly separate them.

According to the initial allocation, each plant has a specific mix of inefficient EUP-equipment, efficient EUP-equipment, and PEEM in place. To increase energy efficiency, plant-specific measures are implemented or reimplemented according to the following rules:

1. An inefficient EUP-equipment is replaced by efficient EUP-equipment, at the latest when the lifetime of the inefficient EUP-equipment is over.
2. An inefficient EUP-equipment may be replaced by an efficient EUP-equipment earlier, if and when the NPV of this replacement becomes positive (see below).
3. If a PEEM is not implemented in the initial allocation, it is implemented as soon as its NPV turns positive for a given year. A PEEM may thus never be implemented if its NPV remains negative over the modeling period.
4. Once EUP measures or PEEM are in place, they are always reimplemented at the end of their lifetime using state-of-the-art technology. They are never reimplemented before the end of their lifetime.

Table 4.7: Model Parameters

Parameters		
r	Average discount rate	11%
P_e	Price of electricity	trajectory of prices (CHF/GJ)
P_f	Price of fuel	trajectory of prices (CHF/GJ)
P_{CO_2}	price of CO_2 emitted	trajectory of prices (CHF/GJ)
EF	Emission factor of coal	93.15 tCO_2/GJ
L_y	Measure lifetime	depends on the technology (see Table B.9 in Appendix B.2)
EIS_y	Electricity savings	depends on the technology (see Table B.9 in Appendix B.2)
FIS_y	Fuel savings potential	depends on the technology (see Table B.9 in Appendix B.2)
CA_y	Abatement potential for each measure, CO_2 savings	depends on the technology (see Table B.9 in Appendix B.2)
I_y	Initial investment	depends on the technology (see Table B.9 in Appendix B.2)
$O\&M$	Operation and maintenance cost	depends on the technology (see Table B.9 in Appendix B.2)
B_y	Annual benefits of the measure	depends on the technology (see Table B.9 in Appendix B.2)
ES_y	Annual final energy savings potential of the measure	depends on the technology (see Table B.9 in Appendix B.2)
$C_{spec,y}$	Specific cost	
ANF	Annuity factor	
NPV_y	Net present value	
CF_t	Cash flow	
PR_y	Clinker or cement production to which measure is applicable	

The NPV is thus only relevant for the implementation of measures (definition see above), including the replacement of inefficient by efficient EUP-equipment, unless the measure is already in place (in which case it is simply always reimplemented at the end of its lifetime). If relevant, we calculate the NPV yearly, based on the investment costs of the measure (difference of investment costs of inefficient and efficient equipment) as compared to the energy savings (including CO_2 price). The future energy savings are improved at a rate of 11%, which is close to the value that was used in the study conducted by Zuberi and Patel [14]. The parameters of the model are demonstrated in Table 4.7.

Regarding rule 2, inefficient EUP-equipment can be replaced before the end of its lifetime if the NPV justifies this, i.e. if the anticipated replacement by an efficient EUP-equipment is compensated by the energy savings obtained in comparison with the replaced equipment over the latter's remaining lifetime. The anticipated cost of equipment replacement is assumed to equal a fraction of the replacement measure, this fraction is equal to the fraction of the lifetime of the existing equipment prior to being decommissioned and replaced. Consider for instance an EUP-equipment with a lifetime of 20 years. Replacing it after 15 years, i.e. 5 years before its end of life, costs 5/20 of the replacement measure's cost and is justified if the present value of the energy savings that this replacement makes possible over the 5 years remaining exceeds, in their discounted sum, this early replacement cost. Investment costs are thus linearly depreciated (e.g. if the age of the inefficient equipment is three-quarters of its lifetime, then the NPV-relevant investment cost is cut by three-quarters). At the same time, benefits are considered for the rest of the inefficient equipment's lifetime as well.

Rule 1 follows from this logic that, at the end of the lifetime, the replacement costs of a measure are zero. It implies that inefficient EUP-equipment is never replaced by inefficient EUP-equipment. And once efficient EUP-equipment is in place, it is always replaced by efficient EUP-equipment.

The NPV of measures changes with time, due to:

- technical progress: we assume a plausible improvement value of the energy-saving potential of 2% per year.
- changes in fuel prices (including the CO_2 price), and
- linear depreciation of investment costs for EUP-measures only.

Finally, note that rules 1. to 3. are related to MI-TP, whereas rule 4 yields A-TP.

4.4.4 Limitations of the model

We took into account competing measures (see Table 4.8), that is, some measures cannot be implemented simultaneously (e.g., there are several measures related to cement grinding). In addition, we allow carbon capture and storage in special scenarios only: one scenario where CCS can be implemented as soon as it is profitable ("High Emissions Trading System (ETS) price with CCS") and one scenario where CCS is only available from 2040 due to technical and legal barriers ("High ETS price with CCS 2040").

Table 4.8: Competing Measures (=measures are in competition) (source: own Table based on [14])

	CP1	CP2	CP3	CP5	CP6	CG1	CG3	CG4	FR1	FR2	I2	I3
CP1											X	X
CP2												
CP3												
CP5												
CP6												
CG1							X	X				
CG3						X						
CG4						X						
FR1										X		
FR2									X			
I2	X	X	X	X	X							X
I3	X	X	X	X	X							

Regarding the impact on fuel and electricity consumption of CCS, we use Zuberi and Patel's [14] data and assume that CCS acts as an "end-of-pipe". That is, emissions are first reduced by all other measures and remaining emissions are subsequently reduced by 95% with CCS. We assume that this percentage is not affected by TP.

Other improvements one may implement in the next version of the model are:

- According to the representative of the cement industry, old equipment is often repaired rather than replaced and thus used much longer than its technological lifetime (often, the repair is considered environmentally beneficial, but in the case of products that use a lot of energy during the consumption phase (e.g. refrigerator), replacement is often better than repair.
- Include non-financial constraints (building permits).
- The efficiency potential depends on how many measures are already implemented (some measures save a fraction of the total energy consumption and not an absolute value).

4.5 Numerical implementation: deep decarbonisation of the Swiss cement sector

In our model, we use the equations provided by Zuberi and Patel [14] to create the scenarios for the implementation of EEM. We show when these measures will be implemented based on cost-benefit analysis and how this can be influenced through different policies. In this section, we simulate several scenarios with our cement model. The target of these simulations is twofold. First, we want to demonstrate the analysing capabilities of our model over a various range of scenarios. Second, we aim to study how Switzerland can achieve deep decarbonisation (more than 88% of total CO_2 emissions decrease compared to the year 2015) of its cement sector. The main climate policy applicable to the cement industry is its required participation in the Swiss emission trading system (ETS). The Swiss ETS has been linked with the EU ETS since 2020. Swiss cement plants thus receive an allotted emissions allowance under the Swiss cap, but they may trade allowances on the EU ETS market. The price of emission allowances (the "ETS price") is determined at the European level and presumably minimally affected by the activities of Swiss participants. Therefore, this price is not a parameter for Swiss climate policy. The ETS price is highly uncertain, as it will depend on the future emission caps decided by the European Union, the development of the European economy, and how the participants in the ETS respond to the price signal. To account for this uncertainty, we shall simulate a scenario where the ETS price remains relatively low and another scenario where it rises sharply. We use the scenarios derived from the Current Energy Policy Scenario and the Zero Basis Scenario respectively of the Energy perspectives 2050+ (see Table 4.9). We extrapolate the 2050 ETS price at a constant value up to the year 2080, because this is needed for the NPV calculation. One relevant lever for Swiss climate policy concerns carbon capture and storage (CCS). Today, technical, economic, and legal barriers hinder cement plants from implementing CCS. We shall assume that the technical and legal barriers are lifted in 2040 for cement plants, following [1]. Based on these considerations, we simulate four scenarios. In each case, the model runs from 2015 to 2050.

Table 4.9: Energy and CO_2 Prices

	Current Energy Policy			Zero Basis		
	Coal	Electricity	CO_2	Coal	Electricity	CO_2
2015	3.29	33	7	3.29	33	7
2016	3.10	37	7	3.10	37	7
2017	3.29	34	7	3.29	34	7
2018	3.97	33	18	3.97	33	18
2019	3.56	39	28	3.56	37	28
2020	3.38	38	28	3.27	37	28
2021	3.43	37	29	3.21	35	29
2022	3.44	41	29	3.15	38	29
2023	3.45	41	30	3.10	38	30
2024	3.46	44	30	3.05	38	30
2025	3.48	43	31	3.00	39	31
2026	3.51	42	31	2.97	39	31
2027	3.54	43	31	2.94	37	31
2028	3.56	42	32	2.92	36	32
2029	3.57	43	32	2.89	38	32
2030	3.59	43	33	2.88	38	33
2031	3.60	44	34	2.86	41	43
2032	3.61	43	35	2.86	44	54
2033	3.62	45	36	2.86	46	65
2034	3.63	48	37	2.86	54	76
2035	3.64	50	38	2.86	54	86
2036	3.65	50	39	2.86	58	97
2037	3.66	53	40	2.86	60	108
2038	3.66	48	41	2.87	63	119
2039	3.67	52	42	2.87	60	129
2040	3.68	53	43	2.87	63	140
2041	3.70	55	45	2.78	73	166
2042	3.71	54	46	2.70	85	191
2043	3.73	59	47	2.61	87	217
2044	3.74	58	48	2.52	97	243
2045	3.76	62	49	2.43	95	268
2046	3.78	58	50	2.34	99	294
2047	3.79	58	51	2.26	104	320
2048	3.81	53	52	2.17	104	345
2049	3.83	49	53	2.08	100	371
2050	3.84	54	54	1.99	106	397

1. *Baseline scenario*: low CO_2 (ETS) price.

2. *High CO_2 price scenario*: high (ETS) price.

3. *High CO_2 price with CCS constrained 2040*: high (ETS) price + CCS measure available in 2040.

4. *High CO_2 price with CCS unconstrained*: high (ETS) price + CCS measure available as soon as it becomes profitable.

4.5.1 Baseline scenario

We guesstimated that in the Baseline scenario, the technical improvement equals 1%. Technological improvement means that fuel and electricity savings improve, but not the investment costs. Additionally, the Discount rate = 11%, the CO_2 price is derived from the Current Energy

Policy Scenario of the Energy perspectives 2050+ (see Table 4.9). Measure CG5 plays an important role in our model. We treated a measure CG5 (derived from the study conducted by Zuberi and Patel [14]) in a special way. This measure concerns the blending of cement, which refers to mixing cement with additives other than clinker. This reduces the demand for clinker and, consequently, energy consumption and CO_2 emissions. Zuberi and Patel [14] assume a fixed fraction of 35% additives by mass of cement for measure CG5, implicitly assuming that either there is blending in a plant at this scale or none at all. As in reality blending can occur on a continuous scale, we use a slightly more realistic assumption and split CG5 into two parts: CG5a is 2/3 of CG5 in terms of costs and savings, and it is part of the initial allocation of each plant. This allows us to match the adoption rate of 33% from their study [14]. CG5b (which is 1/3 of CG5 in terms of costs and savings) is in no plant's initial allocation and subsequently treated as a standard PEEM.

In Figure 4.1 and in Figure 4.3 we can see a drop in fuel consumption and CO_2 emissions in year 2035 and year 2044 at the time of the cement blending measure (CG5), which has a significantly positive impact on CO_2 and fuel savings (due to the technical progress it is more efficient than in the year 2015). Additionally, in the case of the implementation of the CG5 measure, the electricity consumption increases only slightly. This is the reason we cannot see a significant decrease in electricity consumption in Figure 4.2. In the initial allocation, the measure CG5a is already in place for all the plants, which has a lifetime of 20 years.

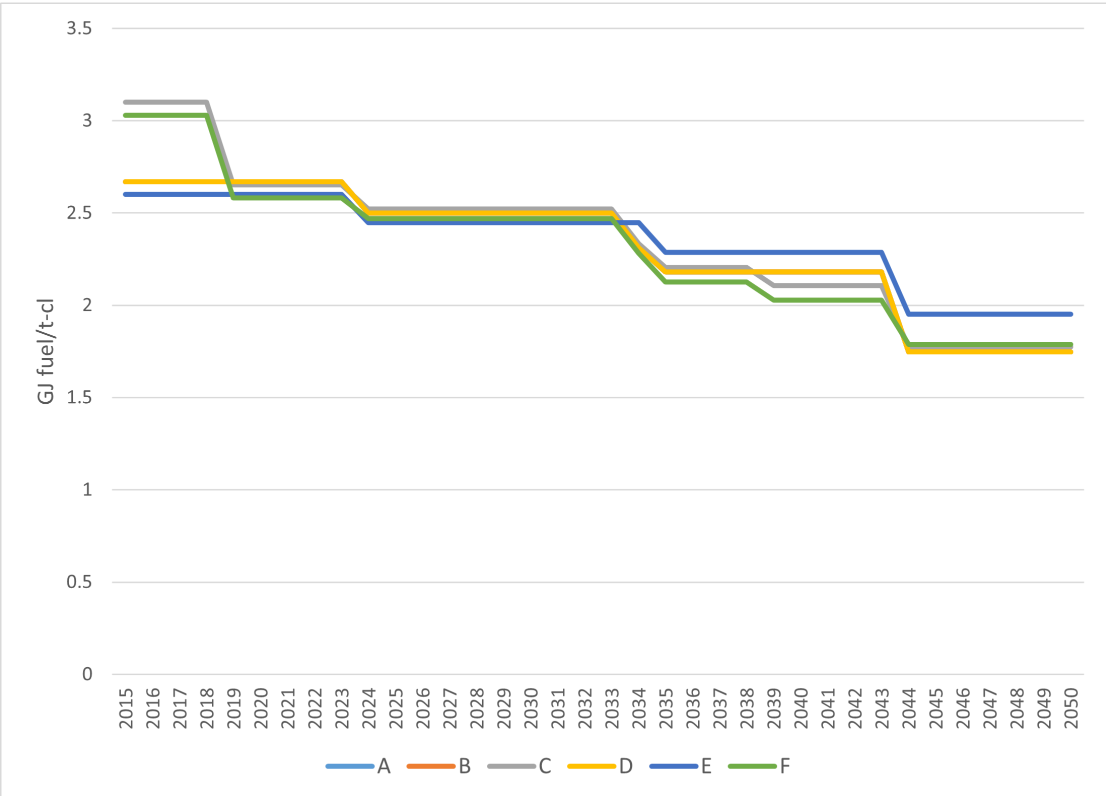

Figure 4.1: Fuel consumption by cement plant. Baseline scenario

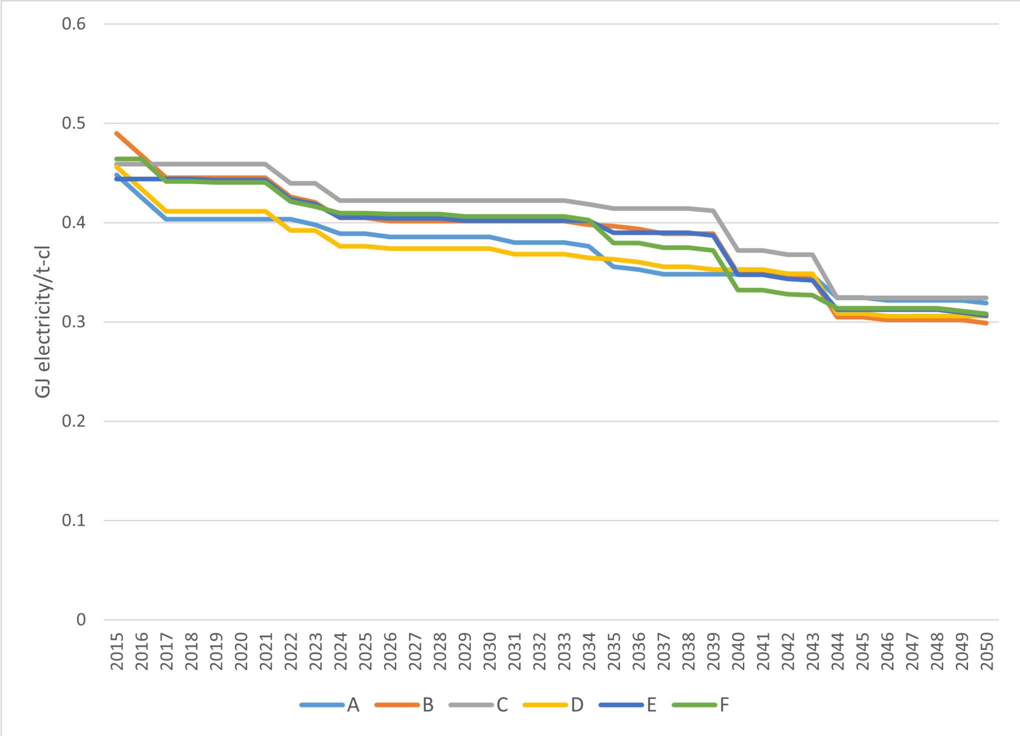

Figure 4.2: Electricity consumption by cement plant. Baseline scenario

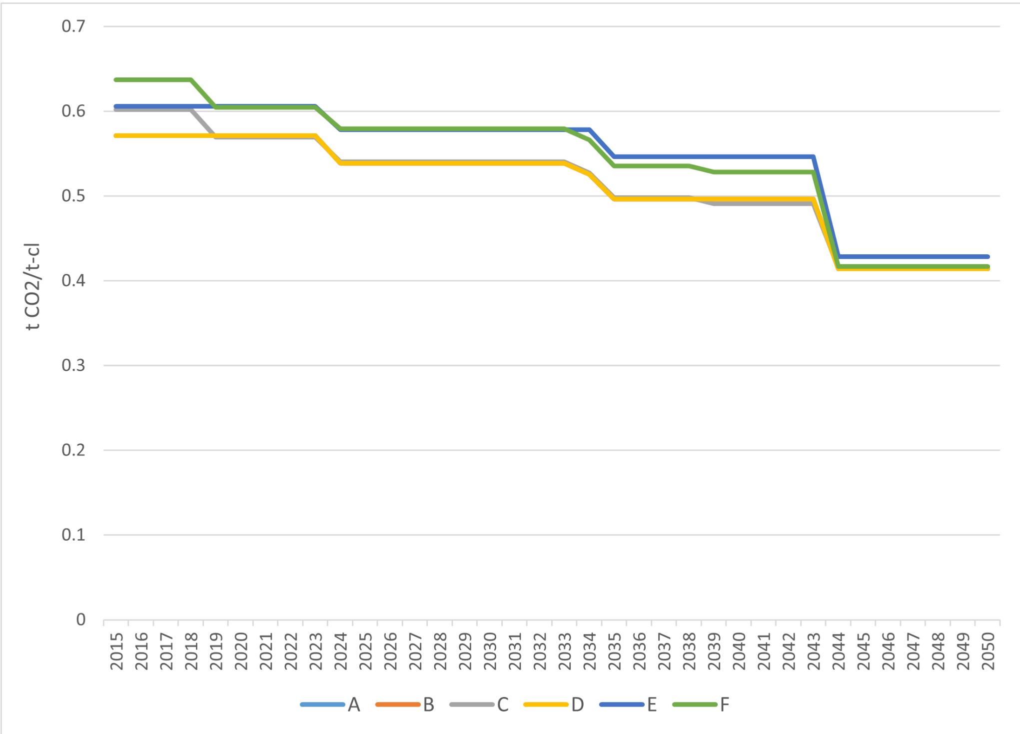

Figure 4.3: CO_2 emissions by cement plant. Baseline scenario

4.5.2 High CO_2 price scenario

The one difference between the High CO_2 price scenario and the Baseline scenario is the low CO_2 price change to the High CO_2 price. In Figure 4.6 we notice that the drop during the year 2024 is much less than in 2044. The reason for this is the technical progress. Thus, each year, the measure increases the efficiency by 1%.

In this scenario, the slow implementation of measures evolve until they are automatically replaced just prior to the year 2050. This occurs at the end of the lifetime of the measures (independent of the CO_2 price) (see Figure 4.6). Moreover, the drop in CO_2 emissions occurs during the year 2044 just as many of the measures are being replaced at the end of their lifetime. This is because we have the first round of measure replacements during 2024 and then the second round during 2044 (we consider that the measures are already 10 years old by the year 2015).

The only impact that the CO_2 price has is to promt some plants to replace their measures as soon as possible. We can assume the NPV calculation, where the ETS price plays a role, however, there is also an automatic replacement at the end of the lifetime where the CO_2 price does not play a role. We can see two declines occurring during the year 2044 for fuel and electricity consumption (see Figures 4.4 and 4.5). If we compare the Baseline scenario with the High CO_2 price scenario, we notice that the impact of the CO_2 price on fuel and electricity consumption is low.

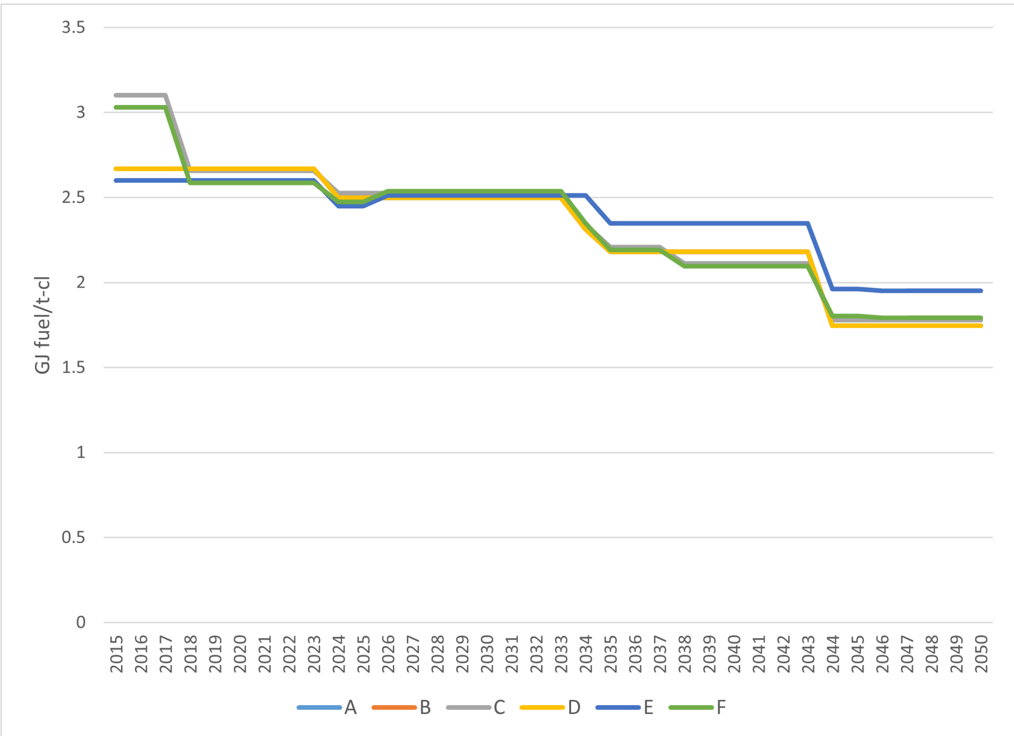

Figure 4.4: Fuel consumption by cement plant. High CO_2 price scenario.

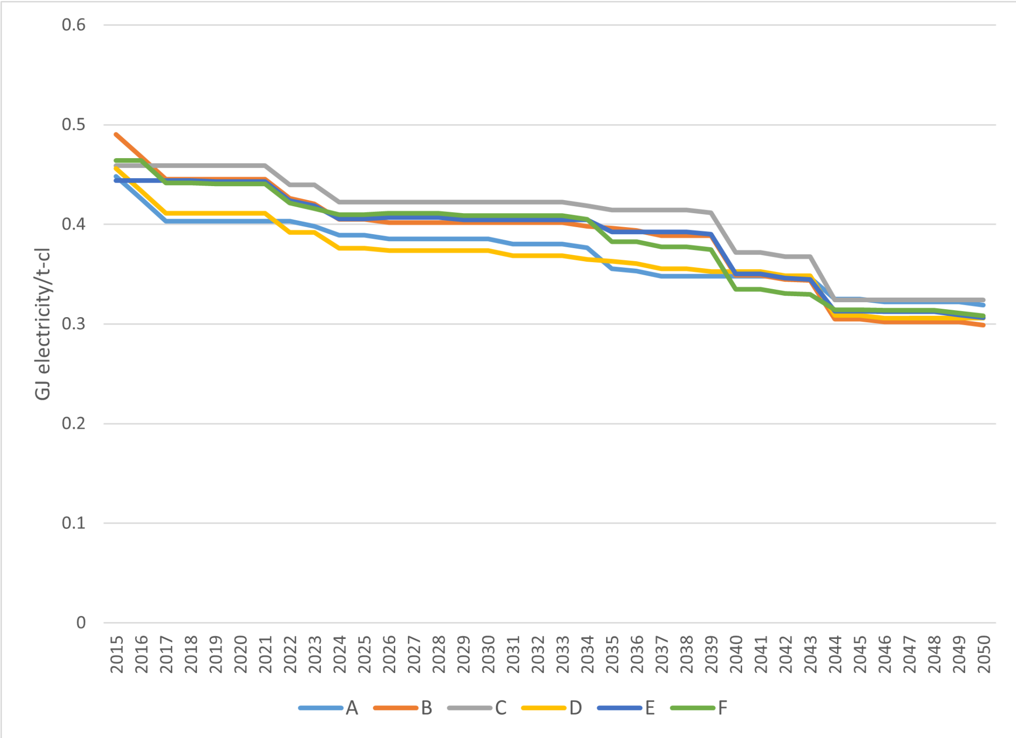

Figure 4.5: Electricity consumption by cement plant. High CO_2 price scenario.

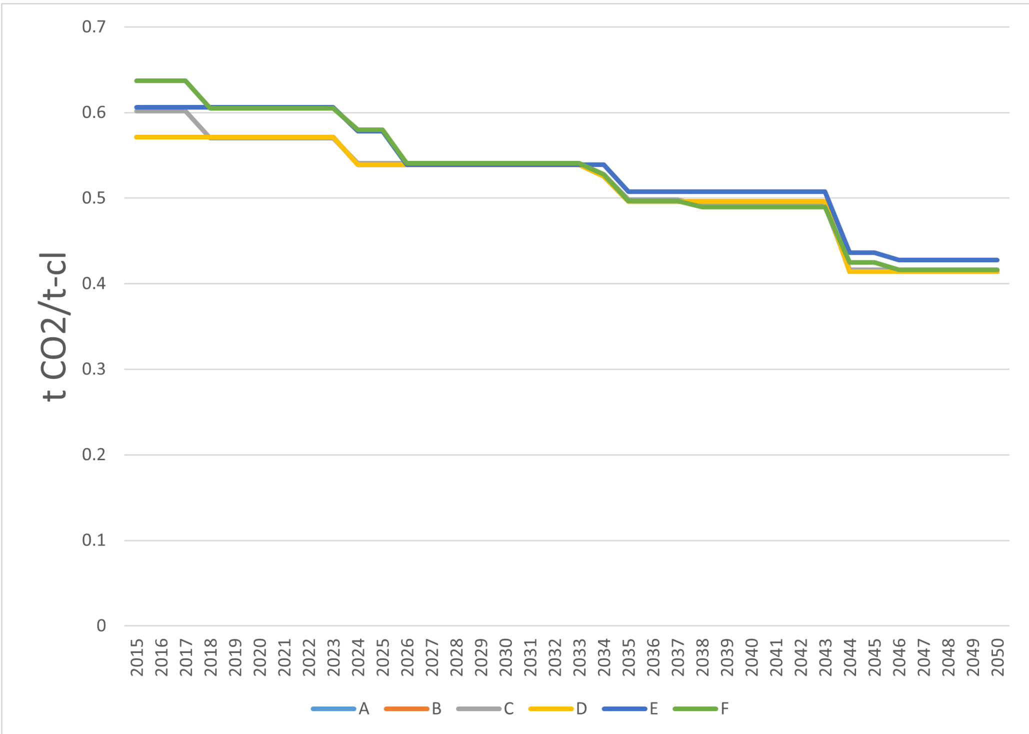

Figure 4.6: CO_2 emissions by cement plant. High CO_2 price scenario.

4.5.3 High CO_2 price with CCS constrained 2040

In this scenario, we introduced CCS measures at the plant level. It is possible to implement CCS from the year 2040 on, but it is only implemented by plants that find it profitable. Due to the High ETS price, CCS is profitable, so it is implemented by all plants as soon as possible. CCS technology needs CO_2 transportation and permanent storage solutions, and we assume that these solutions are in place by the year 2040. In this scenario, we use the high CO_2 price. The rest of the parameters are the same as in the Baseline scenario.

The measure CCS is a CO_2 capture measure that provides significant CO_2 abatements. At the same time, we can see in Figure 4.7 and Figure 4.8 that the fuel and electricity consumption spike in the year 2040 as soon as the CCS measure becomes available. This is explained by the fact that the measure CCS requires additional energy. Thus, as soon as the CCS measure becomes available in 2040 the fuel and electricity consumption increases. In Figure 4.9 we can see that, as soon as the CCS measure is introduced in the year 2040, we have a noticeable drop in CO_2 emissions after sequestration.

We have undertaken the plausibility check and compared the numbers given in the study conducted by Zuberi and Patel [14] for fuel and electricity consumption for the CCS measure (e.g I4) with numbers given in the study done by Gardarsdottir et al. [125]. We can conclude that Zuberi and Patel's assumption is plausible for both electricity and fuel.

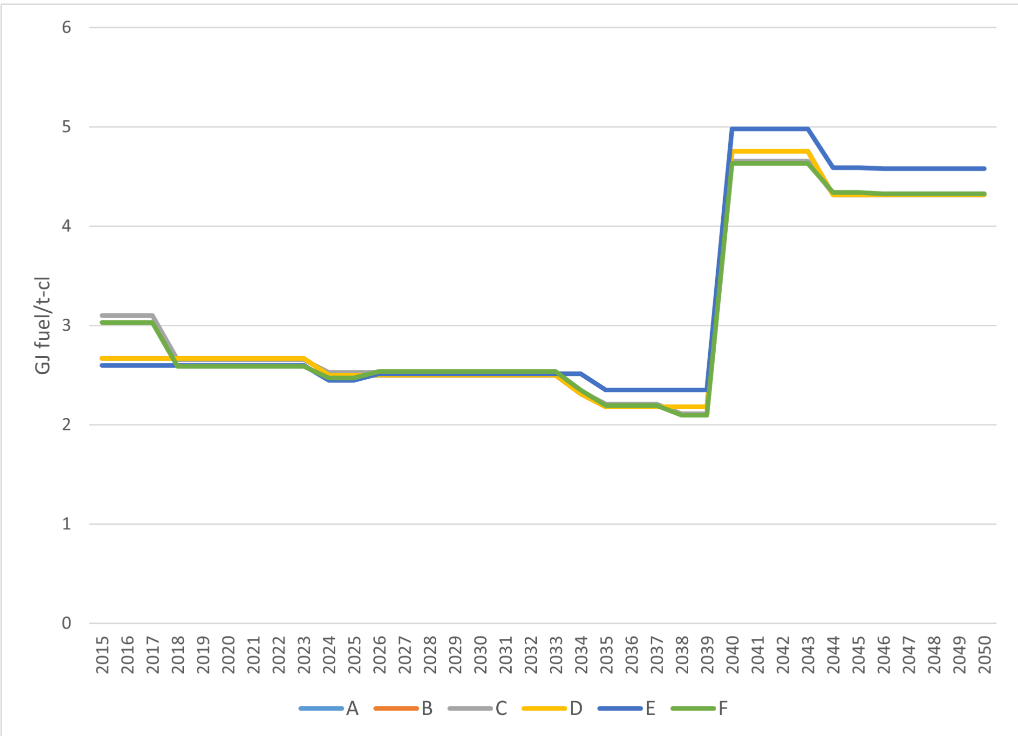

Figure 4.7: Fuel consumption by cement plant. The CCS measure available in 2040 scenario.

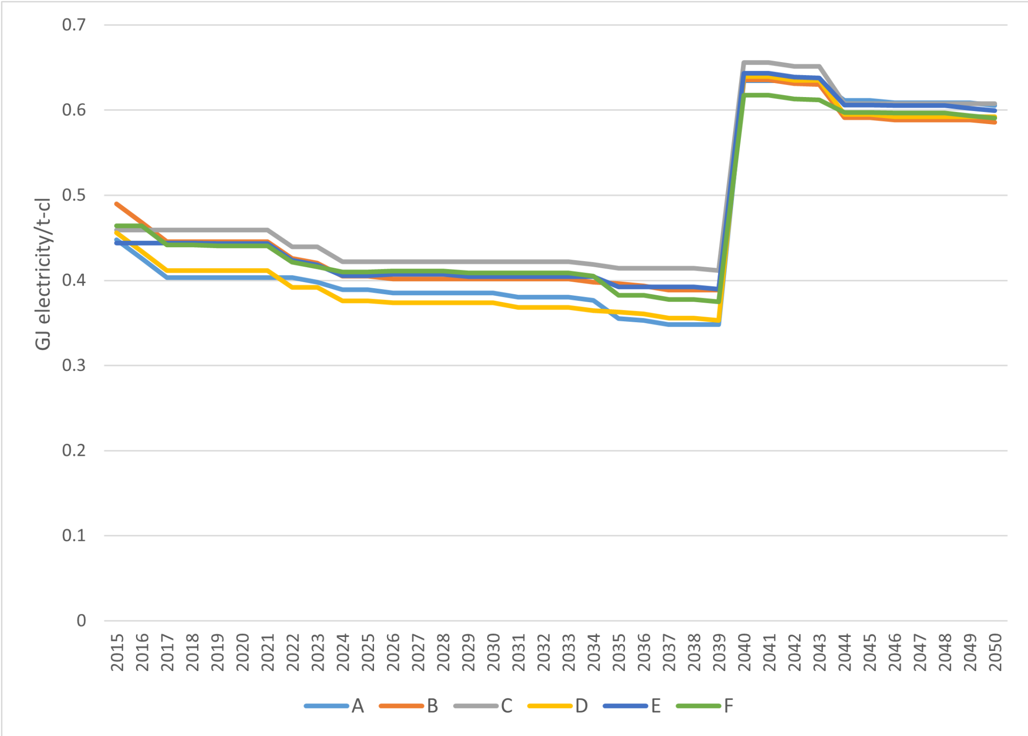

Figure 4.8: Electricity consumption by cement plant. The CCS measure available in 2040 scenario.

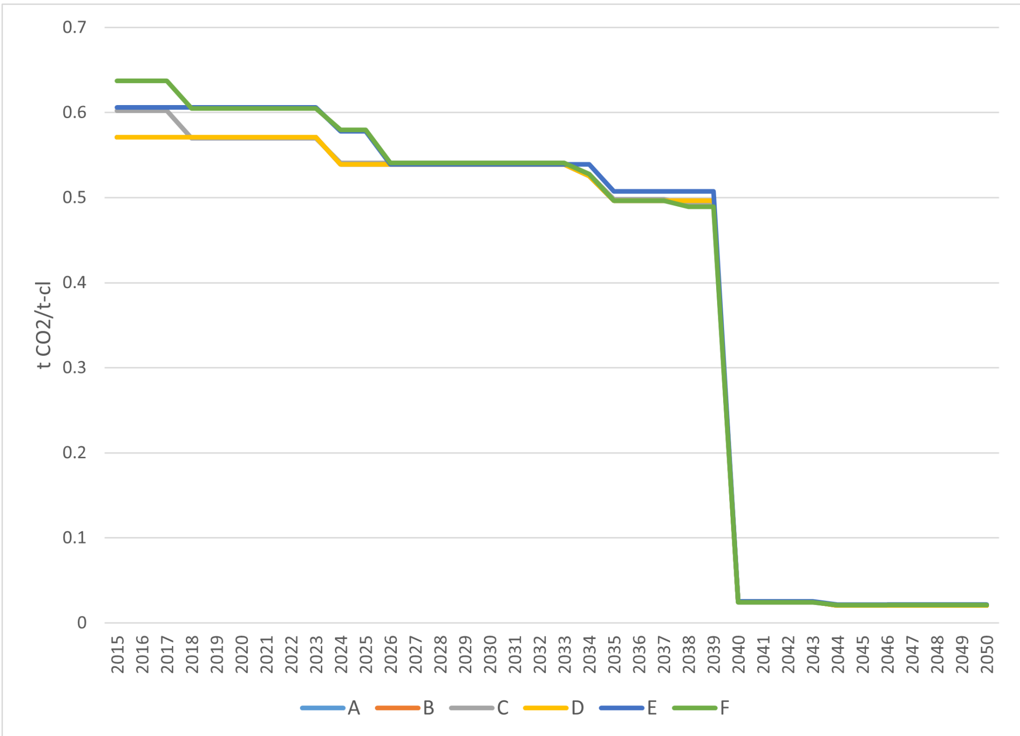

Figure 4.9: CO_2 emissions by cement plant after sequestration. The CCS measure available in 2040 scenario.

4.5.4 High CO_2 price with unconstrained CCS

In this scenario, the CCS measure is implemented as soon as it becomes profitable. Here we also use the high CO_2 price and we make an assumption that the whole system needed for the CCS measure becomes available as soon as it becomes profitable. The other parameters stay the same as in the Baseline scenario, in which the CCS measure never becomes profitable and, therefore, is never implemented.

In Figure 4.12 we can see that the CCS measure has a profitable impact and thus is implemented in the year 2033. This is the reason why we have a noticeable drop in CO_2 emissions after sequestration in 2033. The reason is similar to the scenario where the CCS measure is allowed to be implemented in the year 2040. Since the CCS measure is a CO_2 capture measure that provides a significant CO_2 abatement, we can see also a noticeable drop in the year 2033. The same story relates to the fuel and electricity consumption: we see the spikes in the year 2033 (see Figure 4.10 and Figure 4.11).

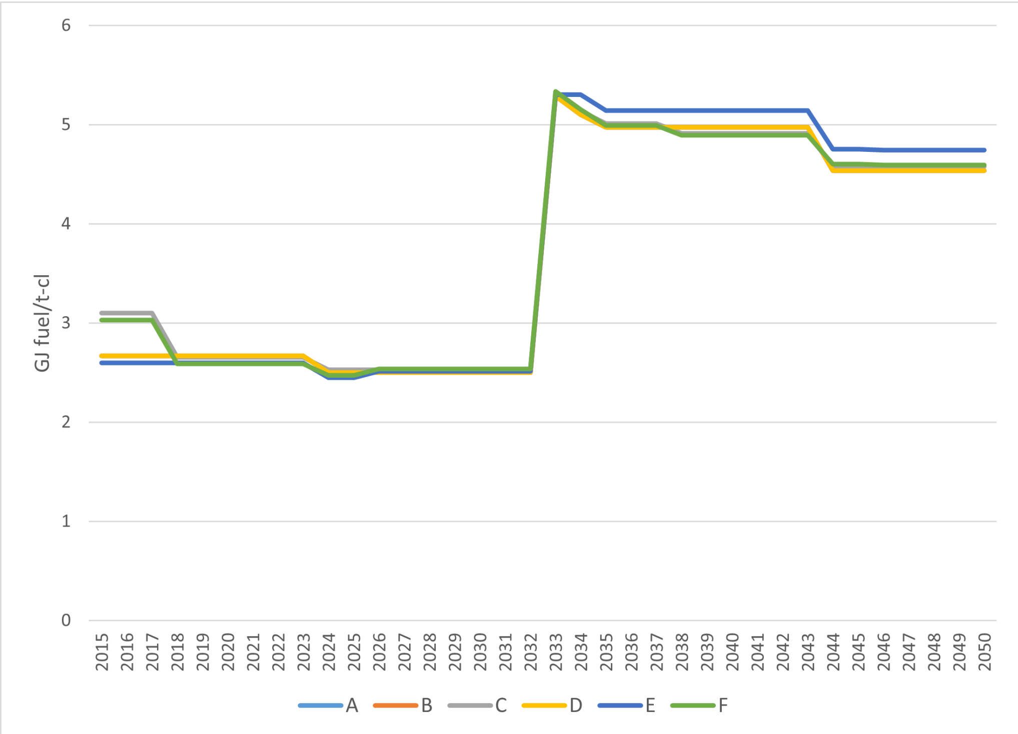

Figure 4.10: Fuel consumption by cement plant. The CCS measure available when profitable scenario.

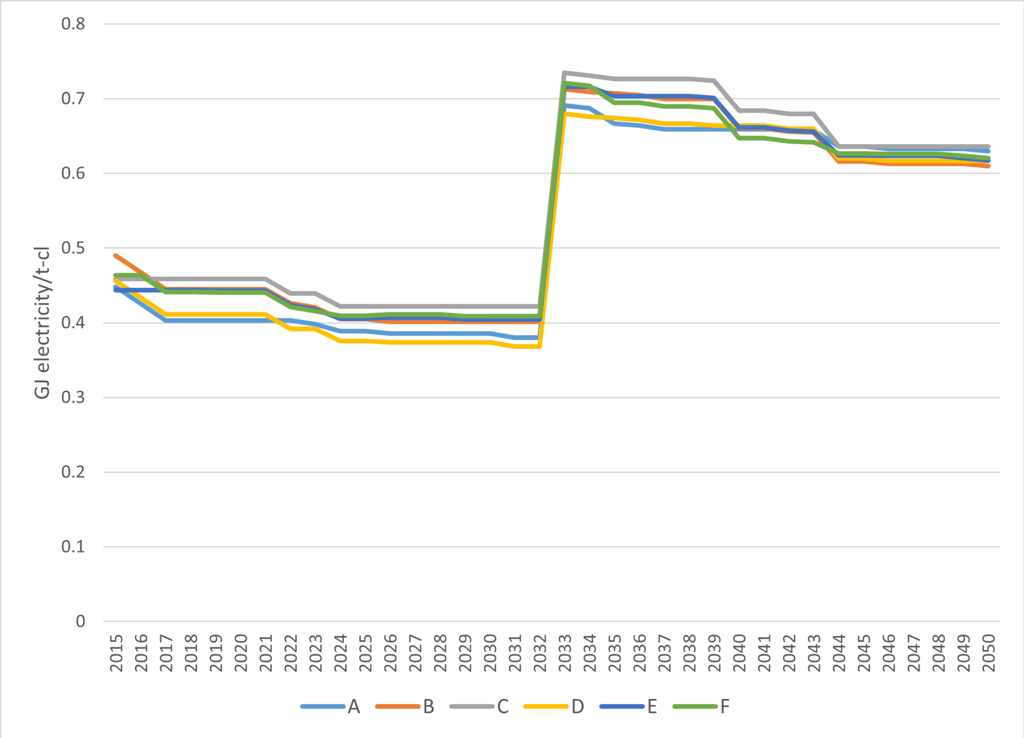

Figure 4.11: Electricity consumption by cement plant. The CCS measure available when profitable scenario.

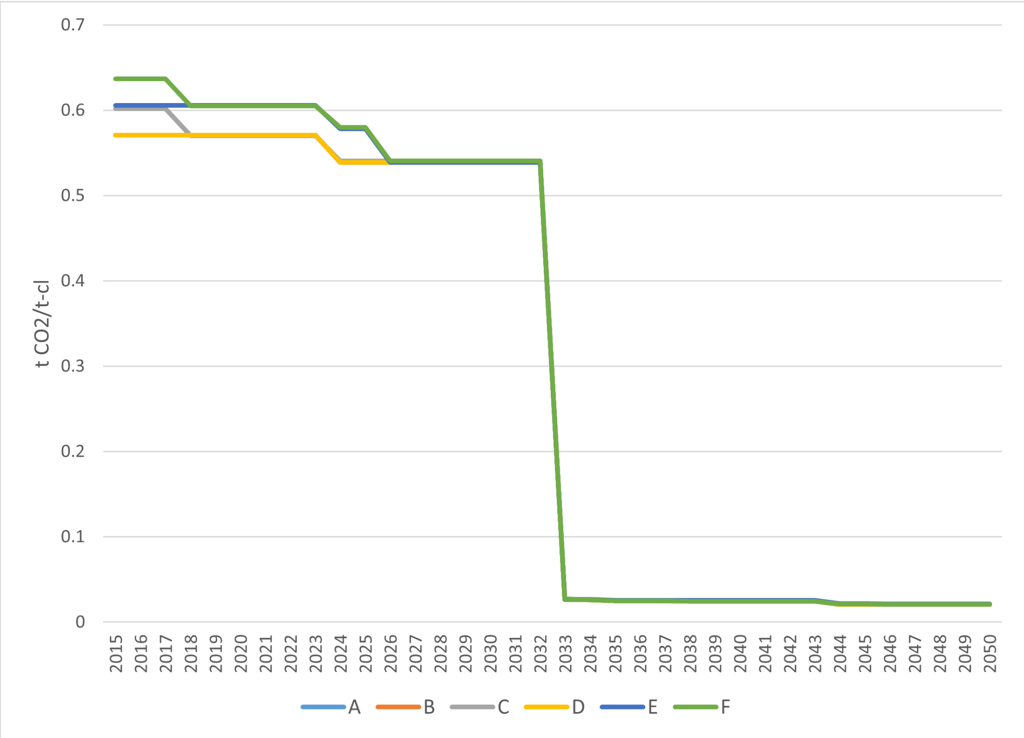

Figure 4.12: CO_2 emissions by cement plant after sequestration. The CCS measure available when profitable scenario.

4.5.5 Comparison of scenarios

In the Baseline scenario, the CO_2 emissions decrease for all six plants from the year 2015 to 2050 by around 29.7% (see Table 4.10). In the High CO_2 price scenario, the High CO_2 price with CCS constrained in year 2040 scenario, and the CCS unconstrained scenarios, the difference in CO_2 emissions decrease from the year 2015 to 2050 by 29.7%, 96.5% and 96.5%, respectively. For the third and fourth scenarios we take into account the CO_2 emissions after sequestration when the CCS measure is already in place.

Table 4.10: Comparison of Results

Comparison 2050 to 2015	Low ETS price	High ETS price	High ETS price with CCS 2040	High ETS price with CCS
Change in fuels consumption	– 36%	– 36%	+ 56%	+ 64%
Change in electricity consumption	– 33%	– 33%	+30%	+35%
Change in CO_2 emissions	– 30%	– 30%	-96%	-96%
Cumulative CO_2 emissions 2015-2050 relative to scenario “Low ETS price"	–	-1.3%	-26%	-44%

Moreover, the fuel consumption in the Baseline scenario decreases for all six plants from the year 2015 to 2050 by around 35.7%, we can also observe the same decrease in the second scenario (see Table 4.10). For the rest of the scenarios, due to the implementation of the CCS measure in the year 2040 and 2033, the fuel consumption from the year 2015 to 2050 increases by 56.4% and 64.4%, respectively. Furthermore, we observe the electricity consumption decrease in the first two scenarios. The results show that, in the Baseline and High CO_2 price scenarios, the electricity consumption from the year 2015 to 2050 decreases by 32.55% in both cases, while in the third and fourth scenarios the consumption increases by 29.7% and 35.1%, respectively (see Table 4.10). Similarly, in this case, the CCS measure has an additional energy demand, which greatly affects electricity consumption.

The overview in Table 4.10 shows that, between the years 2015 and 2050, fuel and electricity consumption, as well as CO_2 emissions, drop by about 30% to 35% in the scenarios without CCS. As can be seen from the results, the first two scenarios do not have a substantial CO_2 emissions reduction because the measure that has a significant CO_2 abatement potential is not implemented in either of these two scenarios. Thus, there is no significant difference between the low and High CO_2 price scenarios. The reason is that in each case, the latter phase is dominated by autonomous technical progress. The autonomous technical progress builds up for the slower measure-induced technical progress in earlier phases of the Low tax scenario. Over the years from 2015 to 2050, the cumulative total CO_2 emissions relative to the Low tax scenario are about 1.3% lower in the High CO_2 price scenario and between 26% and 44% lower in the scenarios with CCS. In the scenarios with CCS, CO_2 emissions drop by 96% mainly resulting from our assumption that CCS reduces emissions by 95%.

The implementation of CCS leads to a strong increase in fuel and electricity consumption, while they decrease in the Baseline scenario due to the various EEMs. This increase is higher the earlier CCS is implemented, because earlier implementation means that the technology is less advanced and more energy-intensive. As a result, the energy consumption is higher in the year 2049 than in the other CCS scenarios, but the energy consumption in the year 2050 is lower. This shows the importance of early implementation of this technology for the cement industry, even if it means more energy consumption. Additionally, the last row of Table 4.10 is based on total CO_2 emissions, not per ton clinker. The CO_2 emissions and energy consumption are calculated per ton of clinker produced. Thus, when changes in clinker production occur, they can positively or negatively affect the results. According to the assumption done by SFOE [1], the total clinker production in Switzerland will increase by 3.4% in the year 2050 than in the year 2015. Thus, the CO_2 emissions and energy savings in the cement industry would be marginally less.

4.6 Conclusion

The key contributions of this study compared to other studies in this field are: (1) It is focused on the Swiss cement industry. The model replicates the investment decision of plant owners, introduces the EEI, and describes the production processes of cement plants in Switzerland. (2) This model distinguishes between EUP measures and PEEM. Additionally, it takes into account competing measures (see Table 4.8). (3) The model functions with approximately 20 measures based on a list of energy efficiency and CO_2 mitigation measures that are applicable for Swiss cement plants. (4) Three different policy scenarios for 2050 CO_2 emissions, fuel, and electricity consumption are investigated, by combining fuel prices, discount rate, and availability of CCS measures in the future to evaluate the effects of such policies on the promotion of energy-saving technologies. The key contributions of our study, relative to the study by Zuberi and Patel [14], is that our model created scenarios for the implementation of EEMs, we show when these measures will be implemented based on cost-benefit analysis and how this can be influenced through different policies. Given the importance of the cement industry in Switzerland as one of the highest energy-consuming and CO_2-emitting industries, the goal of our study was to understand the potential for EEI and CO_2 emission reductions. The purpose of the paper was also to show how endogenous EEI could be modeled. Specifically, our model was constructed for the Swiss cement industry to estimate the EEI and the potential reduction of CO_2 emissions by taking into account the costs, lifetime, and energy savings of different technologies and measures.

We analysed the effects of around 20 energy efficiency technologies and measures for the cement industry. Using our model, we estimated the potential energy consumption reduction and CO_2 emissions abatement potential for the Swiss cement industry from the year 2015 to 2050. We also developed two scenarios with CCS technology.

In the first scenario, we assume that the CCS measure becomes an available technology in the year 2040. In the second scenario, we allow the CCS to be implemented as soon as this technology becomes profitable (in the year 2033). We calculated and compared the fuel and electricity consumption increase as well as CO_2 emissions after the sequestration for both scenarios from the year 2015 to 2050.

We recommended to undertaken further research related to the implementation barriers for the identified cost-effective technologies and measures. An understanding of the existing technologies and barriers to their implementation is an important first step that will lead to developing specific policies and programs to encourage further implementation of energy-efficiency opportunities. Once the barriers to the implementation of new technologies have been identified, it is crucial to develop effective programs and policies to overcome the barriers to adoption. These kinds of programs and policies might include, but are not limited to, the development of the resources to gather information on energy efficiency and particular technological assistance that will help to identify and implement energy-efficiency measures.

When looking at our model and trying to interpret the results, one should pay attention to the method and formulas used in the development of the model. Energy-saving potentials and the cost of energy-efficiency measures and technologies will vary according to country and cement plant-specific conditions. Additionally, one can use the refinements of the model in future simulations. These refinements might include TP with a constant improvement with time, taxes, subsidies on investment, the efficiency potential depending on how many measures are already implemented as well as the implementation of only one measure per period.

5 Overall Conclusions and Future Research

5.1 Conclusions

This study was conducted with the purpose of finding a trackable way to represent endogenous EEI in the Swiss residential building stock and cement industry. Models developed for Swiss residential building stock and cement industry are able to respond to different policies that will directly affect EEI. Based on our models' outcomes, proactive measures can be taken and property owners can respond to suitable incentives.

In the first model for the Swiss residential building stock, simulations show that the policy instruments are much more effective when combined. This provides a strong argument for combining soft (information) and strong (economic) incentives. The results of this model demonstrate that the information level has a strong impact on CO_2 emissions, and therefore deserves further examination in future studies, and should be given more attention in the literature. In the second model, we demonstrated that a sufficiently high CO_2 tax (with corresponding annual increases) together with high information level is one way to achieve the decarbonisation target. Another way to achieve the target is to increase subsidies, although a moderate CO_2 tax increase is still required. The Restriction scenario also achieves the target, although with a lower CO_2 tax than in the CO_2 tax scenario.

The results also suggest that it is important to increase the level of retrofitting activity, as well as to restrict the construction of inefficient buildings. This model contributes to the CO_2 emission abatement maximisation in the housing sector, and it also enhanced our understanding of the role of endogenous allocation of new constructions in achieving emission and energy demand reduction targets. In our model, imposing restrictions on the energy class of new constructions can quickly improve the energy efficiency of the building stock.

Our model, developed for the Swiss cement industry, estimates the energy efficiency improvements and the potential reduction of CO_2 emissions by taking into account the costs, lifetime, and energy savings of different technologies and measures. The results of this model indicate that an understanding of the existing technologies and their barriers is a vital step that will lead to creating particular policies to stimulate the application of energy-efficiency opportunities.

We performed a number of different policy scenario simulations with both sectoral models to see the impact of various energy policies on energy efficiency. The results of these simulations demonstrated that it is extremely important to consider more than economic (e.g. subsidies and taxes) or solely soft policies (e.g. information campaigns). In conclusion, the simulations also showed that, in order to achieve deep decarbonisation targets in both sectors with minimal expenditure, an intelligent and effective combination of different monetary and soft policies together with the availability of different energy-efficient technologies is crucial.

To conclude, the research carried out in this PhD, can provide interesting insights for Swiss energy policies. Firstly, it makes sense to pay more attention to endogenous energy efficiency within the Swiss residential building stock and cement industry, as they have the potential to considerably reduce their contribution towards $\mathrm{CO_2}$ emissions in the country. Secondly, the potential EEI in both sectors and implementation of different policy scenarios, especially their smart combination, which would help achieve the goal of deep decarbonisation, should be taken more seriously when tackling goals to reduce the Swiss national energy consumption.

We conclude with an answer to the question posed at the beginning of this study: The EEI in the Swiss residential building stock and cement industry is an important issue that needs to be addressed urgently and can help increase energy savings as well as achieve the goal of deep decarbonisation in both sectors, ultimately contributing to the Swiss Energy Strategy 2050 and Switzerland's long-term climate strategy.

5.2 Limitations and Future research

The future work on these two models can potentially pursue several extensions and developments. It will be indispensable to acquire more realistic and expanded data in order to further calibrate the parameters of the models. In order to have another opportunity to make the models more robust and extensive, several features could be added. For example, particular constraints, myopia, or uncertainty in cost-saving when changing energy carriers and uncertainty in authorisations when undergoing retrofits. Further studies are necessary to determine appropriate policy instruments that would provide the most cost-effective transformation.

For instance, for the housing model it would be essential to obtain the data on the investment cost function and measures that will increase the share of buildings that will be energy-audited as well as an improved presentation of costs and benefits in the model. This would also be true for the cement industry model.

There are certain limitations to the housing model that can be addressed in the future research. One key limitation is that upfront CO_2 related to the building of new constructions or the retrofitting of existing ones is not considered in the model. Additionally, since data on energy audits is currently unavailable, we endogenised the decision of housing owners doing the retrofit. Thus, the energy audit decision itself firmly depends on the parameters introduced in the model. Future research could investigate the impact of the audit probability based on data to validate the model, improve the calibration of the model and also simulate more policy scenarios. In our models, since the data we have on Swiss residential building stock is sourced from different cooperatives and companies, we only have a snapshot of information about the complete stock. Hence, this data may not be entirely representative for the Swiss residential building stock. It would be very interesting for the future research that more complete data on Swiss residential building stock would be available.

Soft policies are particularly of interest for owners of buildings who might be excluded from obtaining complete information about the advantages of retrofitting a construction. Thus, they are, unfortunately, not capable of calculating and estimating monetary savings that an energy retrofit could bring. In conclusion, to show strict quantitative results and give reliable recommendations, it would be necessary to use more accurate and comprehensive data to formally calibrate and validate the model.

Indeed, there are also limitations to the cement model. In future research it is worth addressing these limitations. It would be interesting to investigate the implementation of Carbon Capture and Storage (CCS) in more detail, by, for example, taking into account additional barriers and not only the cost. It would also be important to collect data on efficiency and abatement measures that are not yet considered in the model. For the cement industry, the energy efficiency potential, energy efficiency measures, and technology costs of cement plants will vary depending on the country and plant-specific conditions. However, their energy efficiency gaps are still present, mainly because the identified policy and technology measures to improve energy efficiency have not yet been adopted. Therefore, a better understanding of the identified cost-effective technologies and measures as well as their barriers to implementation is very important. This should be followed closely by the development of appropriate and effective policies to overcome barriers to the adoption of these technologies.

Moreover, the cement model is limited by the fact that non-financial constraints (building permits) and fixed costs of implementing the measures are not considered. Additionally, in our model, the efficiency potential depends on how many measures are already implemented. Furthermore, in reality, old plant equipment is often repaired rather than replaced and thus used much longer than its technological lifetime, however, this is not taken into account in our model.

In the future, in the case of having better data, these models would be of significant use for real policy simulations. The only issue is that we do not have very good data yet, especially in regards to calibration assumptions about discount rates, construction costs, elasticity of retrofit to information, etc. These parameters are calibrated in the models in an ad-hoc manner. The parametrisation of the models serves to illustrate and demonstrate the modeling frameworks of the two models developed, and their applicability to the housing and cement sectors. Therefore, it is important to analyse the policy simulations and their implications carefully. Policy conclusions should not go beyond the reported findings and/or models' prediction capacity. The goal of the entire research was to develop a useful model that depicts tractable representation of endogenous EEI at the sectoral level that would be appropriate for inclusion in a more comprehensive general equilibrium economic model.

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A Appendix

A.1 Indices, variables and coefficients

Table A.1: Indices, Variables and Coefficients

Indices		Values	Units
$EC, EC', \overline{EC}$		Energy class according to CECB ∈ {A, B, C, D, E, F, G} see Table A.2	
i	Energy carrier	{oil, coal, gas, electricity, wood, heat pump, solar, remote heat, others}	
t, t'	Time period		
CP	Construction Period	{before 1919; 1919-1945; 1946-1960; 1961-1970; 1971-1980; 1981-1990; 1991-2000; 2001-2010; 2011-2020}	
OT	Owner types	{owner-occupant, building owner}	
$Parameter$			
Θ	Elasticity	1	
r^{OT}	Discount rate	{2; 4; 6; 2; 4; 6}	%
DR^t	Demolition rate	{1; 0.9; 0.72; 0.5; 0.39; 0.32; 0.16; 0.1; 0.05; 0; 0; 0; 0}	
$\overline{PEC_{EC}}$	Price of energy per energy class, base year		CHF
θ	Impact price level	0.2	
$SHD_{EC}^{t'}$	Representative heating demand per m^2 for each EC	{150; 110; 90; 70; 50; 30; 20}	kWh/m^2
$\tau_{EC,EC'}^t$	Subsidy rate on retrofit (baseline case)	30	%
$RC_{EC,EC'}^t$	Energy retrofit cost		CHF
NC_{CEC}^{Ht}	New construction		number
Inf	Information level {1; 2; 3; 4}		number
$\Pi_{t,EC}$	Baseline probability that owner conducts an audit	{0; 0.5; 1; 1.5; 2; 2.5; 3}	%
χ	Split incentive	{1; 1; 1; 0.5; 0.5; 0.5}	
$Variables$			
$ERA_{EC}^{OT,t}$	Energy reference area		m^2
CO_2	CO_2 emissions		per tonne
$RG_{EC,EC'}^{OT,t}$	Energy retrofit gain		CHF
PI_t	Price of investment in retrofit per kWh		CHF
PEC_{EC}^t	Energy price per kWh		CHF
$RM_{EC,EC'}^{OT,t}$	Retrofit Matrix		sqm
Γ_{EC}^t	Proportion of owners conducting energy audit		%
$\Omega_{EC,EC'}^{H,t}$	Probability of doing retrofit		%

A.2 Cantonal energy classes for buildings

The Cantonal Energy Certificate for Buildings (CECB/GEAK) (see Table A.2) demonstrates the use of heating, domestic hot water, and other energy consumption-related uses of residential buildings that can be subjected to an energy audit. The CECB/GEAK certificate provides the possibility to compare different buildings and, if necessary, suggest particular energy-efficient optimisation measures.

The CECB certificates are used for buildings already built and in use. The calculation of the energy consumption of the building is based on the actual energy consumption for heating, the heated surface, hot water, and electrical technical equipment.

The CECB energy classes are ranked on a scale from A (best) to G (worst). Energy class A takes into account only the insulation performance of the building envelope, while energy class G takes into account the overall energy performance (considering the share of renewable energies and all the energy consumed). The energy class of the building provides information to future buyers, tenants, or occupants about the energy status of the building and, hence, the degree of energy consumption expected.

In numerous Swiss cantons, it is already obligatory to render a CECB/GEAK certificate of the property when making a real estate transaction, as well as in the case of installing a new heating system.

Table A.2: CECB Energy Classes

Energy Class	Efficiency of the building envelope	Overall energy efficiency	Average energy consumption in kWh/m^2 (own estimations)
A	Excellent thermal insulation with triple-glazed windows	State-of-the art technical installations in the building for the production of heat (heating and domestic hot water) and light; use of renewable energies	20
B	New building achieved a B rating, according to the legislation in force	Standard for new buildings and technical installations; use of renewable energies	30
C	Older properties where the building envelope has been completely retrofitted	Older properties that have been completely retrofitted (building envelope and technical installations), most often using renewable energies	50
D	A building that has been satisfactory and completely insulated retrospectively, but with some thermal bridges remaining	The building has been retrofitted to a large extent but presents some obvious shortcomings, or does not use renewable energies	70
E	A building with significantly improved thermal insulation, including the installation of new insulating glazing	A partially retrofitted building, with a new heat generator and possibly new appliances and lighting	90
F	A partially insulated building	A building partially retrofitted at best, with the replacement of some equipment or use of renewable energies	110
G	A non-retrofitted building with retrofitted insulation that is incomplete or defective at best, and having the extensive potential for retrofit	A non-retrofitted building with no use of, renewable energies and with extensive potential for retrofit	150

A.3 The distribution of buildings

The aim of this section is to catalogue the data collected from separate surveys, which helped us to achieve the ERA per construction periods and energy labels for building stock in different cities (see Figure 2.1). Data were provided to us by: Société Coopérative d'Habitation Lausanne (SCHL), Allgemeine Baugenossenschaft Zürich (ABZ), Estia and die Mobiliar. The amount of ERA corresponding to each construction period and survey is indicated in Table A.5.

In order to find the ERA of buildings in each energy label and their year of construction, we made tables with energy classes and their energy thresholds, as well as the year of constructions. Minimal and maximal energy thresholds are taken in kWh/m^2.

Since the data for Geneva is for the year 2019 and the data for Zürich and Lausanne is for the year 2020 we needed to take the same climate conditions for all 3 cities. We did climate corrections (with the help of Swiss Meteo data [126]) by multiplying each city's energy consumption by a total correction coefficient in order to establish a basis to the same reference year: 2019 (see Table A.3).

For SCHL (see Figure A.1) we took into account heating degree days and climate corrections (see the total correction in Table A.3). For ABZ (see Figure A.2), Geneva (see Figure A.3) and die Mobiliar's (see Figure A.4) dwellings, the heating degree days were already taken into account in the initial data provided.

INFRAS provided the number of 29.8 kWh/m^2/a that shows how much hot water is used per square meter in each apartment (see Table A.4). In order to compare this number with our own data and eventually check if our calculations are right, we multiplied hot water in kWh/m^3 by litres of hot water in m^3 (using SCHL data). We divided the resulting factor by total ERA of all apartments in the building. The outcome is the amount of hot water used per meter square per apartment. The average number determined was: 31.8 kWh/m^2/a, which is close to the number provided by INFRAS: 29.8 kWh/m^2/a. Additionally, we wanted to determine the overall number of ERAs for three cities and Mobiliar dwellings together. For the results, see Figure A.5.

Table A.3: Heating Degree Days and Climate Corrections

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

Table A.4: Derivation of the Parameter: Standardised Energy Demand, Hot Water (source: INFRAS)

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

Table A.5: ERA in m^2 per Construction Period and Survey

	SCHL	ABZ	ESTIA	die Mobiliar
Before 1919	0	1,418	3,309,001	8,435
1919-1945	18,915	99,887	3,397,053	9,298
1946-1960	26,474	59,201	3,833,428	22,844
1961-1970	17,616	79,500	8,266,051	37,950
1971-1980	34,409	50,089	7,052,355	42,160
1981-1990	13,440	45,582	3,402,803	28,351
1991-2000	17,906	22,326	6,121,797	32,057
2001-2010	44,688	66,866	2,847,581	112,723
2011-2020	10,264	25,538	6,766,762	0

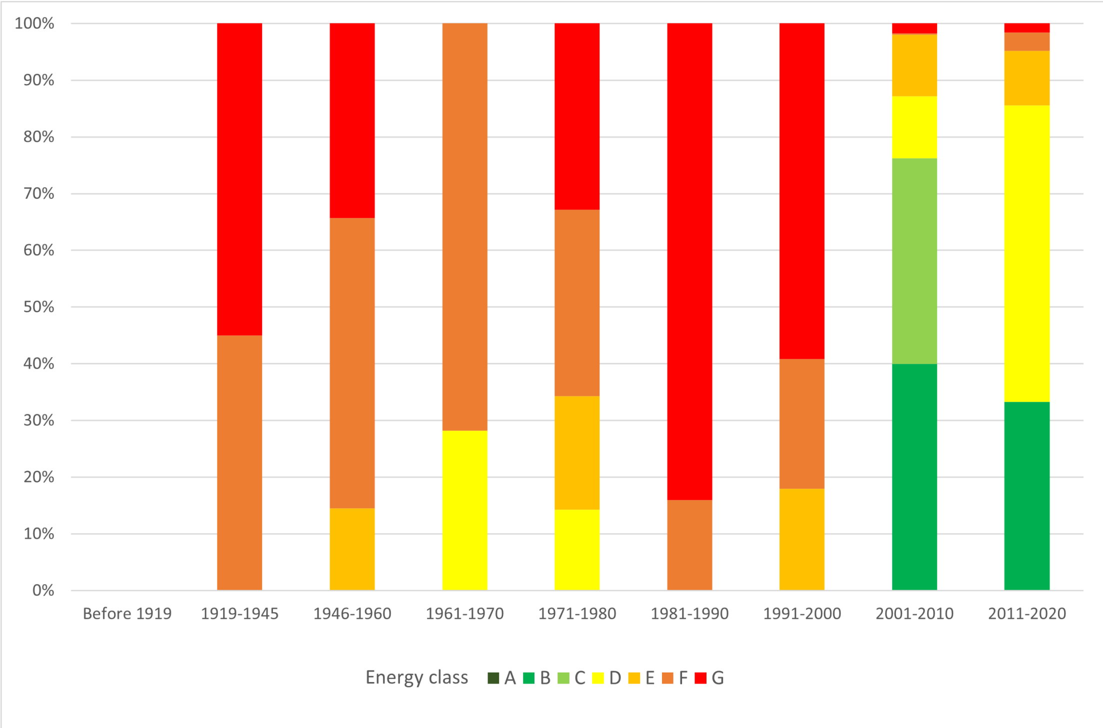

Figure A.1: Distribution of ERA (source: SCHL - Lausanne)

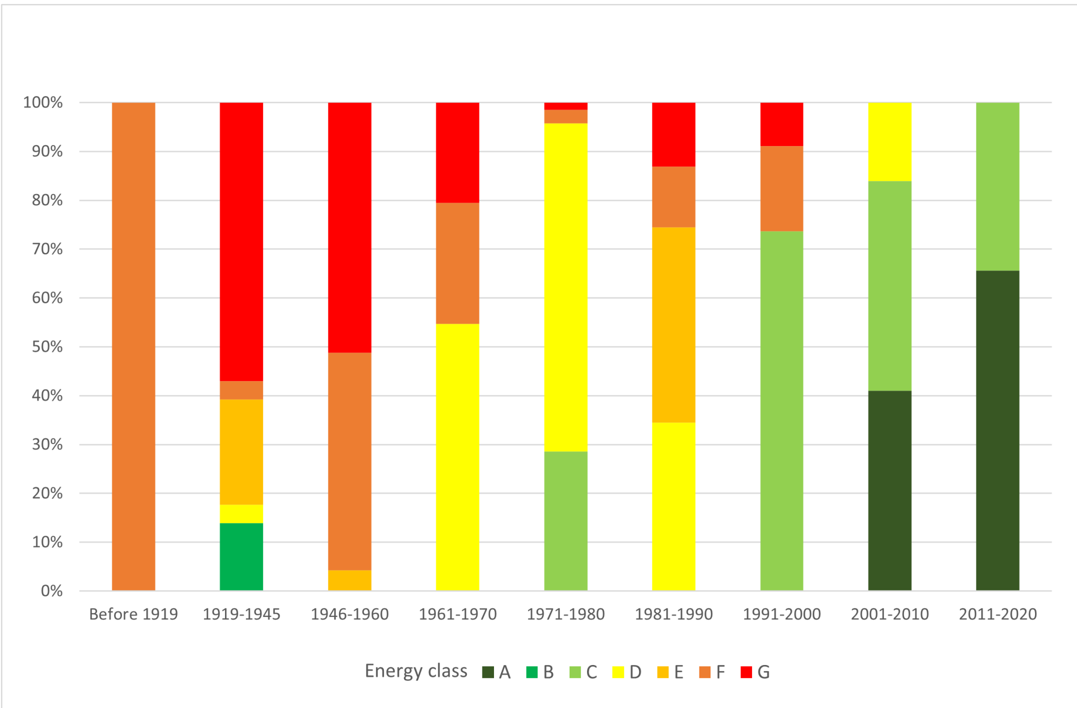

Figure A.2: Distribution of ERA (source: ABZ - Zürich)

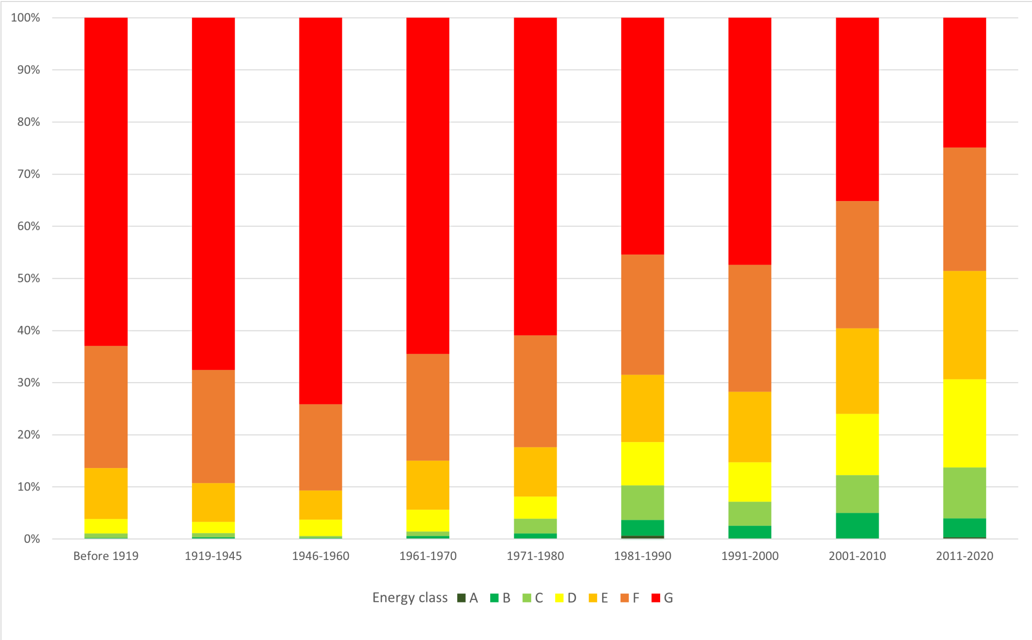

Figure A.3: Distribution of ERA (source: ESTIA - Geneva)

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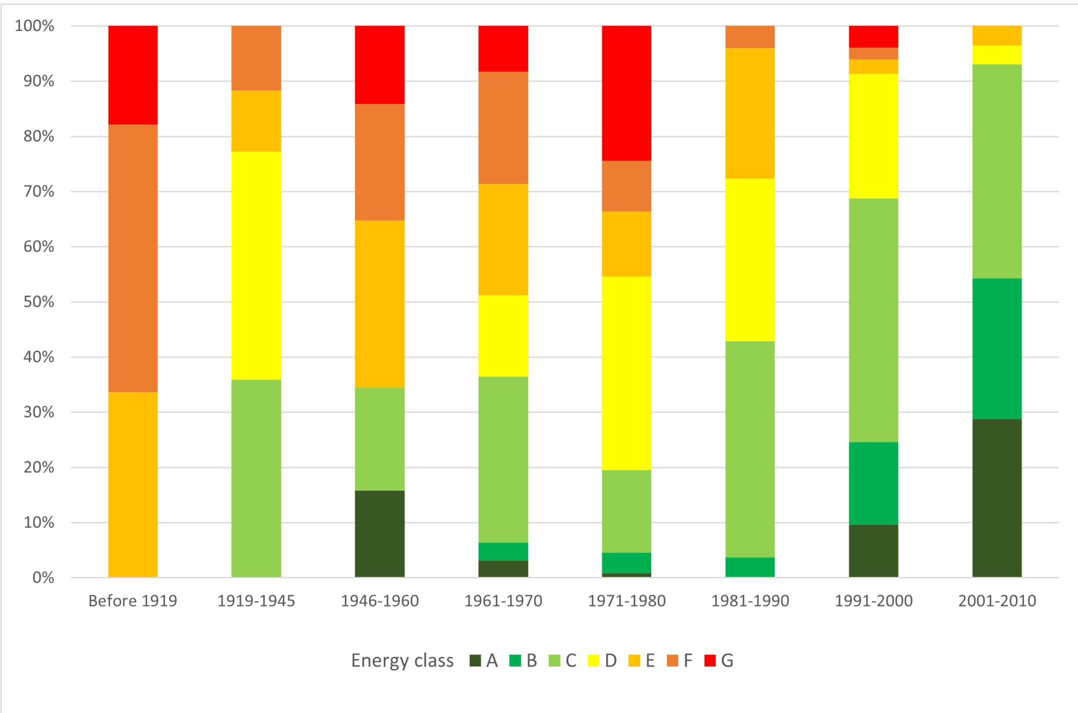

Figure A.4: Distribution of ERA (source: die Mobiliar - different cities)

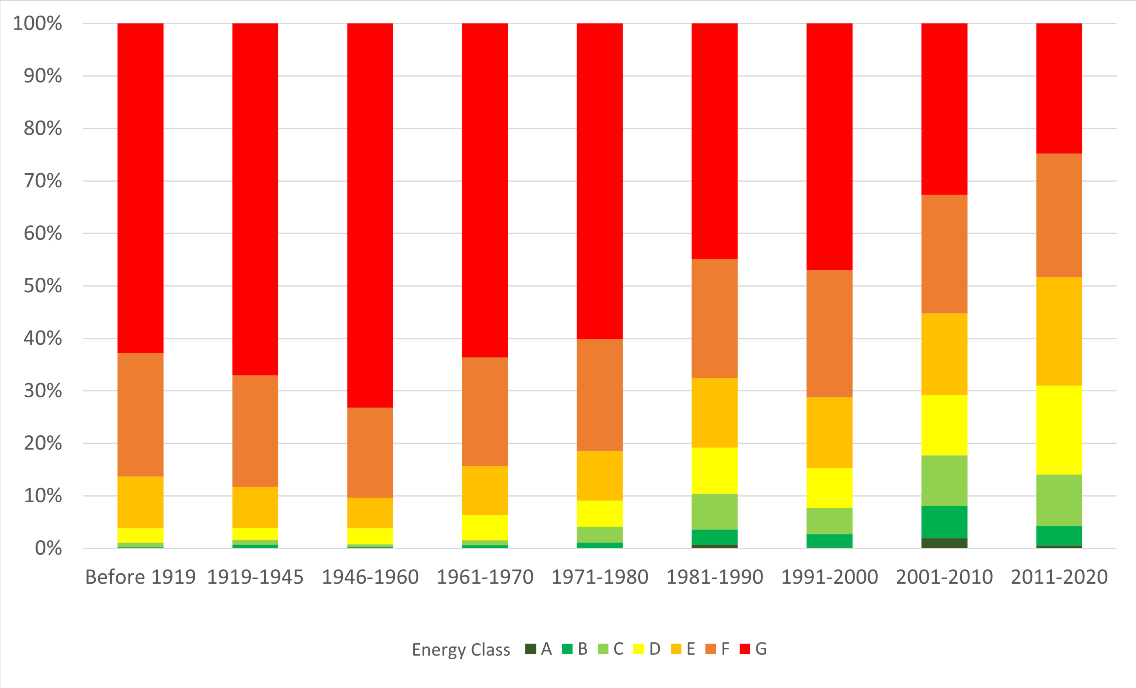

Figure A.5: Distribution of ERA: three cities and die Mobiliar

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

kWh/m^2(ERA)		20 A	30 B	50 C	70 D	90 E	110 F	150 G
10	A		91	172	245	308	363	408
30	B			82	154	218	272	317
50	C				73	136	190	236
70	D					63	118	163
90	E						54	100
110	F							45
170	G							

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

kWh/m^2(ERA)		20 A	30 B	50 C	70 D	90 E	110 F	150 G
10	A		55	104	148	186	219	246
30	B			49	93	131	164	191
50	C				44	82	115	142
70	D					38	71	98
90	E						33	60
110	F							27
170	G							

A.4 Retrofit cost calculation

We use a study by SFOE [127], which estimates retrofits from energy class G to energy class A for:

1. A single-family house (SFH) costs 410 CHF/m^2 and
2. A multi-family house (MFH) costs 250 CHF/m^2.

With a 30/70 split (SFH/MFH), this results in an average of 298 CHF/m^2. Using an average value of 30 kWh/m^2 for energy class A and 150 for energy class G, this corresponds to an improvement of 120 kWh/m^2. The result is a calibration point at (295 CHF/m^2; 120 kWh/m^2). To set up a function that implements this calibration in the model, we use the non-linear cost matrices for single-family houses (SFH) (see Table A.6) and multi-family houses (see Table A.7). We use a non-linear curve and cannot use the linear function, because, for example, basement ceiling insulation is highly economical, but entails low investments. Based on our calculation and after a consultation with field experts from INFRAS, it was decided to use slightly higher retrofit cost values. The retrofit costs for Swiss building stock (without differentiating between single and multi-family houses) are represented in Table A.8. Additionally, we assume that the required investment is more costly, the greater the improvement in energy class, i.e. a greater investment is required moving from energy class F to A, than C to A.

Table A.8: Matrix for Weighted Average Investment Cost (in CHF/m^2)

kWh/m^2	20	30	50	70	90	110	150
	A	B	C	D	E	F	G
A							
B	200						
C	350	150					
D	490	290	140				
E	590	390	240	100			
F	650	450	300	160	60		
G	690	490	340	200	100	40	

B Appendix

B.1 Data and calibration of the model

Table 5 from Zuberi et al. [14] demonstrates the final energy savings, costs, and estimated diffusion data for energy efficiency measures applicable to the Swiss cement industry in 2016.

Figure 1 from by Zuberi et al. [14] demonstrates the final energy demand by energy carriers, cement production and CO_2 emissions in the Swiss cement industry from 2002 to 2014.

We take the Energy consumption of 11 PJ/yr as a baseline. After the implementation of the measures, a comparison of the resulting energy consumption and a baseline energy consumption will be made.

We should describe the inefficient (worst/hypothetical) cement plant that does not have any energy-efficient measures implemented. The future worst (illustrative) plant will have today's best plant's specific final energy use of 3.38 GJ/t-cl. The worst illustrative plant does not have any energy-efficient measures. According to the study done by Zuberi et al. [14], the current average plant's final energy use in Switzerland today is 3.5 GJ/t-cl for fuel energy and 0.5 GJ/t-cl for electricity. The best cement plant could possibly achieve a final energy use figure of 3.0 GJ/t-cl for fuel energy and 0.4 GJ/t-cl for electricity in future.

Additionally, Zuberi et al. [14] observe that:

- The current average fuel consumption by the Swiss cement industry is 3.5 GJ/t clinker (and 0.5 GJ/t clinker for electricity).
- The lowest possible fuel consumption with currently the best available technology is 3.0 GJ/t-cl (and 0.4 GJ/t clinker for electricity).

Our simulations will show how fuel consumption is reduced after the incorporation of new measures, including those that become profitable earlier due to the policy measures.

B.2 Parameter values

Table B.9: Parameter Values

	GJ/t-cl	GJ/t-cl	x-axis for CO_2 (tCO_2/t-cl)	CHF/t-cl	CHF/t-cl	Years	(CHF) t-cl	(CHF/GJ)
Measures	(ElS) Electricity savings	(FlS) Fuel savings potential	(CA) (data) CO_2 abatement potential of each measure	(I) Initial investment (capital expenditure)	(O&M) Operation and maintenace cost	(L) Measure life-time	(B) Annual benefits of the measure	(ES) Annual final energy savings of the measure
RM1	0.04	0.00	0.00	29.42	0.00	20.00	1.74	44.19
RM2	0.01	0.00	0.00	16.83	0.00	20.00	0.48	143.96
RM3	0.01	0.00	0.00	5.91	0.00	25.00	0.43	22.00
RM4	0.02	0.00	0.00	10.78	0.00	20.00	0.78	27.03
CP1	0.02	0.90	0.06	167.35	0.00	40.00	4.46	14.98
CP2	0.00	0.43	0.03	32.33	-0.25	20.00	1.76	4.25
CP3	0.01	0.00	0.00	7.25	0.00	20.00	0.22	133.91
CP5	0.00	0.03	0.00	1.48	0.00	20.00	0.12	1.72
CP6	0.03	0.00	0.00	19.69	0.00	35.00	1.35	23.55
CG1	0.09	0.00	0.00	29.71	0.00	20.00	4.04	-8.06
CG2	0.22	0.00	0.00	9.70	0.00	20.00	9.55	-42.64
CG3	0.09	0.00	0.00	24.24	0.00	20.00	3.82	-13.58
CG4	0.02	0.00	0.00	4.67	0.00	10.00	0.95	-12.13
CG5	-0.03	1.77	0.40	1.27	-0.18	20.00	9.10	-5.82
FR1	0.00	-0.07	0.04	9.84	1.11	20.00	0.02	-33.44
FR2	0.00	0.00	0.06	0.00	28.31	20.00	0.62	0.00
I1	0.01	0.12	0.01	3.15	0.00	20.00	0.83	-4.12
I2	0.00	1.21	0.09	400.65	0.00	30.00	4.95	33.55
I3	-0.03	0.30	0.02	93.64	1.26	30.00	-0.17	46.10
I4	-0.34	-3.05	0.59	8.04	40.20	20.00	-18.34	-7.79