Evaluation of the effect of the CO_2 tax on reducing CO_2 emissions from residential building stock in Switzerland

Master's Thesis

Author: FANG Xiaolu (SCIPER: 308092)
Supervisor: Prof. Philippe Thalmann

Environmental Sciences and Engineering Section
Laboratory of Environmental and Urban Economics
École Polytechnique Fédérale de Lausanne

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Abstract

As the impacts of climate change intensify and concerns about it rise, it is increasingly urgent to reduce greenhouse gas (GHG) emissions. Many countries have set ambitious GHG emission reduction targets and are committed to developing their abatement strategies. In August 2019, Switzerland also set its goal of achieving zero GHG emissions by 2050. As the building sector accounts for a large share of both energy consumption and GHG emissions in Switzerland, improving its energy efficiency to reduce GHG emissions is crucial to achieving the targets set. The CO_2 tax is a key climate policy for the Swiss building sector. To assist policymakers in better developing emission reduction strategies and policies, it is necessary to evaluate the contribution of the CO_2 tax to CO_2 reduction in the Swiss building sector.

This thesis adopts a two-step decision building stock model to simulate three CO_2 tax increasing policy scenarios to investigate how CO_2 taxes need to be increased to achieve an 80% reduction in CO_2 emissions from the Swiss residential building sector in 2050 relative to 1990. This two-step decision building stock model projects the evolution of the building stock through building demolition, retrofitting and new construction, with three distinct advantages: it's dynamic modeling; it's endogenous modeling; it represents energy barriers.

The simulation results show that for CO_2 emissions from residential buildings to be reduced by 80% in 2050 compared to 1990, the following growth conditions must be met in three different CO_2 tax increase scenarios: 1. Keep Low - Rapidly Increase Policy scenario: 2019-2021: 96 CHF/tCO_2, 2022-2030: 120 CHF/tCO_2, 2031-2050: at least 95 CHF increase per year; 2. Gradually Increase Policy scenario: 2019: 96 CHF/tCO_2, 2020-2050: at least 48 CHF increase per year; 3. Rapidly Increase scenario - Keep High Policy: 2019: 96 CHF/tCO_2, 2020-2030: at least 101 CHF increase per year, 2031-2050: remain at the same level as in 2030. For all three of these different CO_2 tax increase scenarios, the tax rates reach extremely high in 2050, with the highest even increasing to 17 times the current rate.

The simulation results demonstrate that a CO_2 tax is an effective financial mitigation measure. Nevertheless, a CO_2 tax alone is not sufficient to achieve the emission reduction targets set by Switzerland, which must be used in conjunction with other financial instruments(e.g. subsidies), regulatory instruments(e.g. building certificate, higher regulations on building energy efficiency, setting standards for heating equipment and energy efficiency in new buildings) and informative instruments.

Key words: CO_2 tax; energy retrofit; climate policy; building stock models; energy efficiency

Contents

List of Figures

List of Tables

Acronym

GHG Greenhouse Gas

CCS Carbon Capture and Storage

NETs Negative Emission Technologies

CO_2 Carbon Dioxide

IEA International Energy Agency

FOEN Federal Office for the Environment

BSMs Building Stock Models

DID Difference-in-Difference

GIS Geographic Information System

NPV Net Present Value

NC New Construction

ERA Energy Reference Area

EC Energy Class

CP Construction Period

OT Owner Type

SHD Space Heating Demand

DR Demolition Rate

RM Retrofit Matrix

RG Retrofit Gain

PEC Energy Price

RC Retrofit Cost

SFOE Swiss Federal Office of Energy

SFH Single-family House

MFH Multi-family House

ERAD Desired Energy Reference Area

SNC Share of New Construction

PI Price of Retrofit

CC Construction Cost

RI Rental Income

MC Maintenance Cost

MP Market Price of Rental

ES Energy Saving

DEC Difference in Energy Classes

SA Building Surface Area

PVNI Present Value of Net Income

PR Profit

TEC Total Heating Energy Consumption

KL-RIP Keep Low - Rapidly Increase Policy

GIP Gradually Increasing Policy

RI-KHP Rapidly Increase - Keep High Policy

1 Introduction

1.1 Background

The issue of climate change has drawn ever-increasing attention. The Paris Agreement signed in 2015 set the goal of limiting the rise in global mean temperature to 2 °C relative to the pre-industrial era, the achievement of which relies on the reduction of greenhouse gas (GHG) emissions. Under the Paris Agreement, many countries have set their GHG reduction targets and are committed to developing corresponding long-term climate strategies.

In accordance with the Paris Agreement, Switzerland has set a target of reducing its GHG emissions by at least 50% by 2030 compared to 1990 levels. In August 2019, the Swiss government made its goal of net zero GHG emissions by 2050. To achieve the set mitigation targets, Switzerland has developed its Long-Term Climate Strategy to 2050, which was adopted on January 27, 2021. This Long-term Climate Strategy suggests that Switzerland can reduce its GHG emissions to about 90 percent of 1990 levels by 2050, and the remaining emissions must rely on carbon capture and storage (CCS) or negative emission technologies (NETs) to be balanced. NETs are technical or natural processes that remove carbon dioxide (CO_2) from the atmosphere and store it permanently.

The building sector contributes a significant share of energy use and GHG emissions, accounting for more than one-third of global final energy consumption and nearly 40% of total direct and indirect CO_2 emissions, and has been rising in recent years (IEA, 2020). Energy consumption in the building sector is mainly for space heating, cooling, ventilation, hot water, lighting and appliances. In Switzerland, about 80% of energy consumption in the building sector is used for space heating (Alberini et al., 2013). Analysis by the International Energy Agency (IEA) suggests that the building sector has significant untapped abatement potential owing to the facts of continued use of fossil fuels, lack of effective energy efficiency policies and underinvestment in sustainable buildings. The IEA estimates that energy-related CO_2 emissions from the buildings sector could be reduced by more than 30% by 2030 (IEA, 2020).

The Swiss building stock accounts for about 45% of the total end energy demand and one third

of CO_2 emissions in Switzerland[I]. The building sector bears a major responsibility in achieving Switzerland's ambitious carbon reduction targets. Figure 1.1 shows the carbon emissions by sector in Switzerland, and it is evident that Switzerland's previous emission reduction achievements are mainly attributed to the building sector. Improving energy efficiency to reduce carbon emissions from the buildings sector will continue to be a priority for Switzerland's subsequent carbon reduction efforts. Switzerland's Long-term Climate Strategy also indicates that to achieve net zero, the buildings sector must become almost or completely free of fossil emissions.

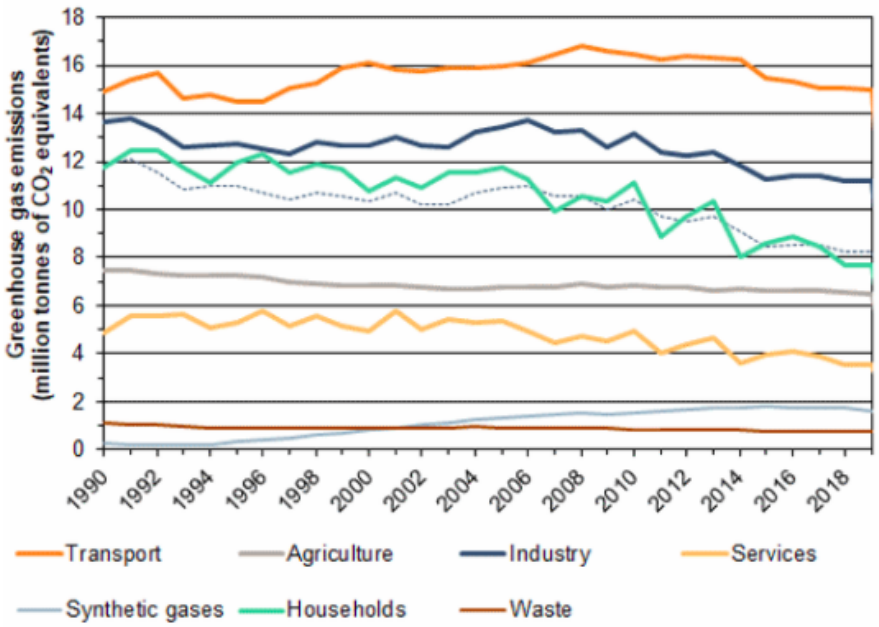

Figure 1.1: Evolution of CO_2 emissions by sector in Switzerland, source: Federal Office for the Environment (FOEN) https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data/greenhouse-gas-inventory.html

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1.2 Swiss climate policies

Policy instruments are effective tools to improve energy efficiency and reduce GHG emissions in the building sector, taking various forms such as regulatory (e.g. building codes, restrictions on the installation of heating systems in new buildings), financial (e.g. subsidies, CO_2 taxes, etc.) and informative (Giraudet et al., 2021). Switzerland has developed a policy framework of regulatory and financial measures at the national or regional level. CO_2 taxes, buildings programme and CO_2 provisions are the main instruments for reducing emissions in the building sector in Switzerland.

The CO_2 Act is the foundation of Swiss climate policy and has been in force since 2000. It

[I] https://www.bfe.admin.ch/bfe/en/home/efficiency/buildings.html

has been updated several times since 2000. It was revised in the fall of 2020, which provided more measures and regulations for emission reductions in the building sector, while it was not approved in the referendum in June 2021. So the version in force is the CO_2 Act of 2011. According to the CO_2 Act, the buildings programme will continue, which will subsidize energy-related renovations, support the transition to renewable energy, and support the development of building technologies and low-emission new buildings. The buildings programme is financed by one-third of the CO_2 tax revenue.

Table 1.1: Swiss CO_2 tax rate evolution

Year	2008	2009	2012	2014	2016	2018	2022
CO_2 tax (CHF/tCO_2)	12	24	36	60	84	96	120

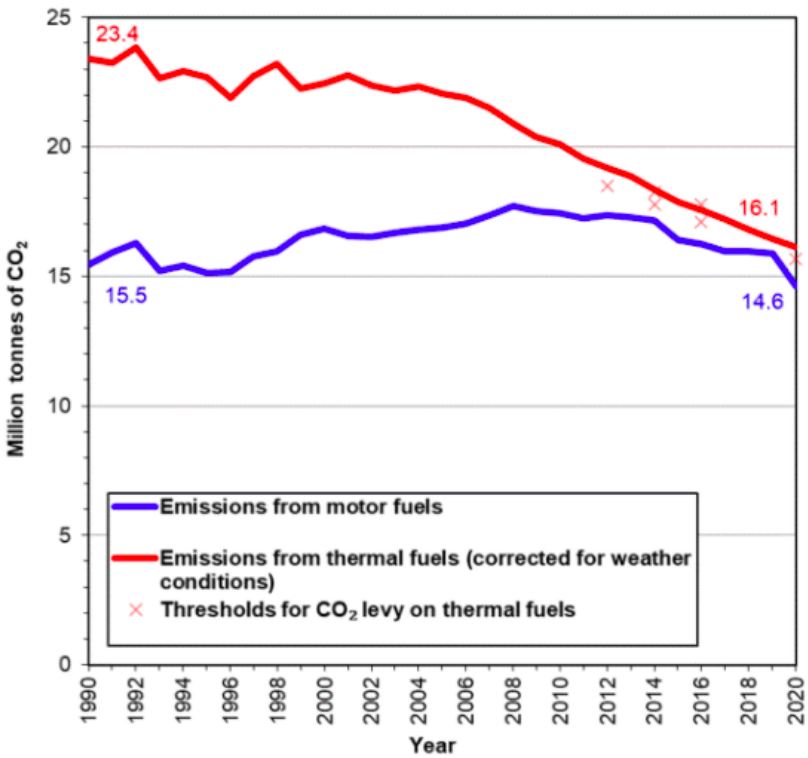

Figure 1.2: Evolution of CO_2 emissions from thermal fuels and the thresholds, source: FOEN https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data/co2-statistics.html

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Switzerland introduced a CO_2 tax of 12 CHF/tCO_2 on fossil thermal fuels (oil, gas, coal) since 2008, and the tax has been gradually increased to the current level of 120 CHF/tCO_2, the evolution of which is shown in Table 1.1. The red line and red cross in Figure 1.2 show the CO_2 emissions from thermal fuels and the thresholds, respectively. Under the Swiss CO_2 ordinance, an increase in the CO_2 tax will be triggered if the CO_2 emissions from thermal fuels exceed the thresholds set by law. The CO_2 emissions from fuel combustion in 2020 are 31% lower

than in 1990, falling short of the intended 33% and thus triggering an auto increase in the CO_2 tax. Since January 1, 2022, the Swiss CO_2 tax has been increased from 96 CHF/tCO_2 to 120 CHF/tCO_2. Switzerland has one of the highest carbon taxes in the world. Two-thirds of the revenue from the CO_2 tax is redistributed to the population and the companies, and one-third to the buildings programme.

There is no doubt that the CO_2 tax has played an important role in reducing emissions in the Swiss building sector, however, it is not easy to quantify its effect. Hintermann and Zarkovic stated that in Switzerland, the effect of CO_2 taxes on emission reductions increases with tax increases (Hintermann & Zarkovic, 2020). The CO_2 tax will remain a key part of Swiss climate policy after 2022, then how should the CO_2 tax be raised to move Switzerland towards a net-zero end point? From this, the research question of this thesis will be: *How must the existing CO_2 tax be increased to reduce CO_2 emissions from the Swiss residential building stock by at least 80% in 2050 relative to 1990?*

To answer the proposed research questions, estimates for the future development of energy demand and CO_2 emissions in the Swiss building stock are needed to simulate the effectiveness of CO_2 tax policies. Bottom-up building stock models (BSMs) can be used to assess the impact of various abatement measures on total energy demand, which are a powerful tool to quantify the effectiveness of climate policies. This thesis will apply a two-step decision model on energy retrofits in buildings to simulate several CO_2 tax policy scenarios and answer the research question. A detailed description of this two-step decision model is presented in a later chapter.

1.3 Swiss building sector

In 1990, there were 1.3 million residential buildings in Switzerland. By the end of 2020, this number has increased by roughly 38% to 1.8 million [II]. Since a large proportion of buildings were constructed in early years and many of them use fossil fuels for heating, they are not very energy efficient. Energy efficiency retrofits are thought to significantly reduce the energy consumption of buildings (Palmer et al., 2013). Swiss buildings have a very long lifetime, with about 61% of buildings built before 1980 and about 83% before 2001 [III]. Based on this fact, the reduction of CO_2 emissions in the Swiss building sector requires a strong emphasis on retrofitting existing buildings.

The majority of Swiss households choose to rent rather than own. By the end of 2019, about 60% of Swiss households live in rented dwellings [IV]. This characteristic makes the "split incentive" barrier non-negligible for energy efficiency improvements in Switzerland, which will be further discussed in subsequent sections.

[II] https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/buildings.html
[III] https://www.bfs.admin.ch/bfs/en/home/news/whats-new.assetdetail.17944121.html
[IV] https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/dwellings/rented-dwellings.html

2 Literature review

2.1 Carbon tax

2.1.1 Background of carbon tax

Among the various forms (regulatory, financial, informative) of abatement policy tools, financial instruments are considered to be the most effective (Giraudet et al., 2021). The carbon tax is one of the most promising examples of financial instruments. Carbon taxes were first introduced by Finland in 1990, and as of April 2021, 27 countries have implemented carbon taxes, as shown in Figure 2.1.

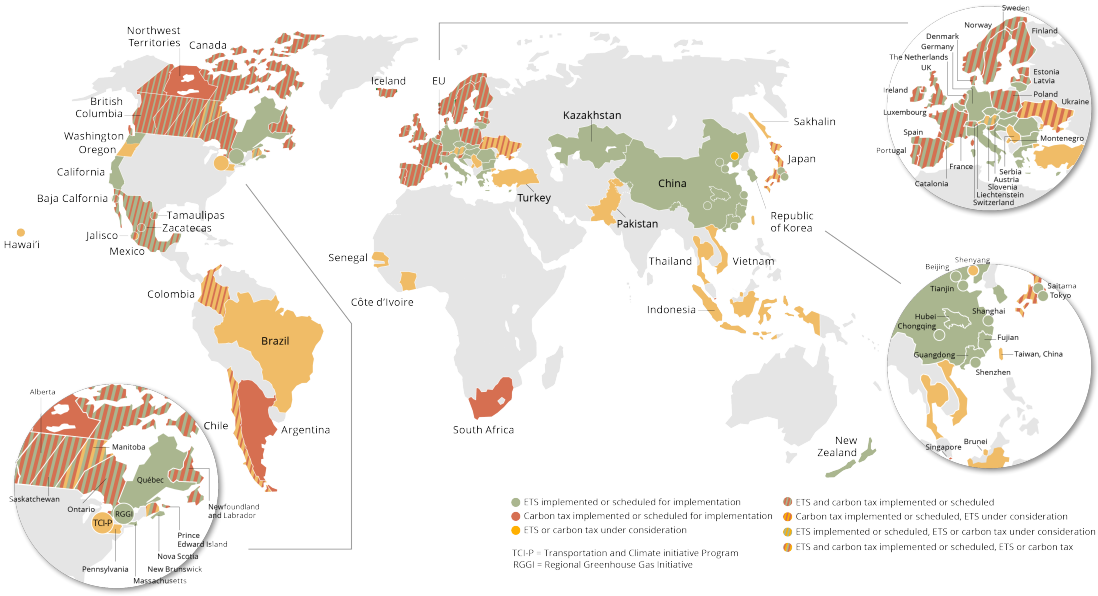

Figure 2.1: Map of carbon taxes and emissions trading systems worldwide (as of May 2021)), source: The World Bank https://openknowledge.worldbank.org/handle/10986/35620

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2.1.2 Effect of carbon tax

The effect of carbon taxes on energy efficiency has been extensively studied (Freyre et al., 2020; Giraudet et al., 2021; Hájek et al., 2019; Martin et al., 2014; McKibbin et al., 2018), and studies have shown that carbon taxes can improve energy efficiency and reduce fossil fuel consumption (Al-Abdullah, 1999). It is widely recognized that carbon taxes provide incentives for technological innovation (Zhang et al., 2016), which are one of the most efficient and cost-effective instruments to reducing GHG emissions (Hagmann et al., 2019; Zhang et al., 2016). In January 2019, more than 3,600 economists, including the former chairs of the Federal Reserve and 28 Nobel Laureate Economists signed a public statement that stated, *"A carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary"* (Akerlof et al., 2019). The statement also proposed that a carbon tax should be levied and should be gradually increased (Akerlof et al., 2019).

Jonsson et al. presented a review of Sweden's carbon tax, which has made a significant contribution to carbon reduction in Sweden (Jonsson et al., 2020). Since the implementation of the carbon tax in 1991, Sweden's carbon emissions have decreased by 27% between 1990-2018 (Jonsson et al., 2020). Another quasi-experimental study of the significant causal effect of carbon taxes on emissions in Sweden showed that the implementation of the carbon tax reduced CO_2 emissions from the transport sector by almost 11% (Andersson, 2019). A review of British Columbia's carbon tax experience by Murray and Rivers showed that the carbon tax has reduced the province's GHG emissions by 5-15% since its implementation (Murray & Rivers, 2015).

However, there are a few studies suggesting that carbon taxes do not always contribute to GHG emission reductions. Lin and Li assessed the abatement effect of carbon taxes in Denmark, Finland, Sweden, the Netherlands, and Norway using the difference-in-difference (DID) method (Lin & Li, 2011). The results showed that carbon taxes exhibited their abatement effects only in Finland. In Norway, the carbon tax did not show its impact on carbon emission reduction, while in Denmark, Sweden and the Netherlands, the impact was even negative, though not significant. Although different views exist, the prevailing view remains that a carbon tax is a powerful tool to reduce carbon emissions.

2.1.3 Design of carbon tax

While the effectiveness of carbon taxes in promoting GHG emissions reductions has been widely recognized, however, a well-designed carbon tax faces many challenges, whose effectiveness depends on how well policymakers address the following three issues: setting the tax rate, collecting the tax, and using the resulting revenue (Marron & Toder, 2014).

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 other 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 (Hájek et al., 2019; Hintermann & Zarkovic, 2020). Figure 2.2 shows the tax rates for countries currently implementing carbon taxes, with data updated to April 1, 2021. Note that the Swiss CO_2 tax in Figure 2.2 is 96 CHF/tCO_2 (US \$101.47/tCO_2) in 2021, which has been updated to 120 CHF/tCO_2 [I] since January 1, 2022.

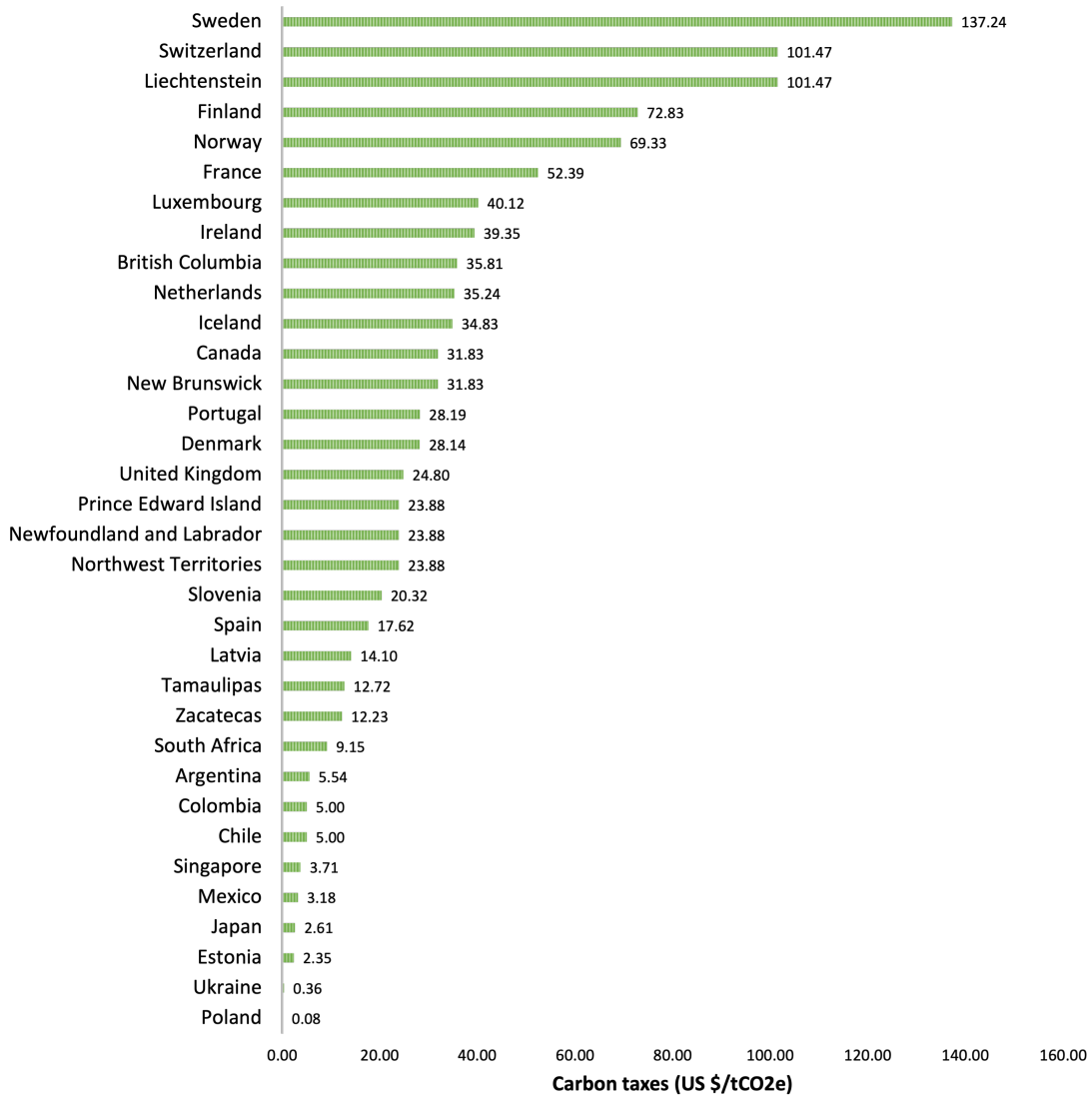

Figure 2.2: Tax rates for countries implementing carbon taxes, updated on April 1, 2021, source: The World Bank https://carbonpricingdashboard.worldbank.org/map_data

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The uses of carbon tax revenues are varied and may be used as subsidies for energy efficiency projects (Freyre et al., 2020), offsetting tax reductions, reducing future deficits, or providing transitional assistance to those particularly hard hit by the carbon tax (Marron & Toder,

[I] At the time of writing, 1 CHF is equivalent to 1.09 USD.

2014). Carbon taxes are often considered to be regressive and impose a greater burden on lower-income households than on higher-income households. This is because poorer households typically spend a higher proportion of their income on carbon-intensive goods and services (Marron & Toder, 2014). Making carbon taxes more progressive can often be achieved by reducing income taxes or redistributing revenues generated by carbon taxes to lower income groups. The Swiss CO_2 tax is revenue-neutral. Two-thirds of the revenue from the CO_2 tax is redistributed to the population and companies, and one-third is used for a buildings programme to promote building renovation, renewable energy use and advances in environmental technology. The IEA has stated that it is sound fiscal practice for Switzerland to recycle carbon tax revenues to citizens and enterprises (IEA, 2007). The destination of the revenue from the carbon tax will also affect the effect of this policy on energy savings and carbon emission reduction. A study of the use of carbon tax revenues in France revealed that recycling the revenue of the French carbon tax as an energy efficiency subsidy would achieve more energy savings compared to lump sum recycling (Bourgeois et al., 2021).

2.2 Building stock models

BSMs are a powerful tool for anticipating energy consumption in the building sector and assessing energy strategies, which can assist policymakers. These models have been applied for purposes such as policy effectiveness assessment by establishing functional relationships between input parameters and energy demand. In recent years, many BSMs have been developed, which may differ in various aspects such as the country or region of applicability, the scale (national or regional), and the requirements for input data. However, BSMs are widely considered to fall into two categories: top-down and bottom-up.

There have been several high-quality and comprehensive reviews on BSMs (Johari et al., 2020; Kavgic et al., 2010; Li et al., 2017; Lim & Zhai, 2017; Swan & Ugursal, 2009). A review of energy consumption modeling techniques for the residential sector by Swan and Ugursal provided a further breakdown of these modeling techniques based on the two broad categories of top-down and bottom-up, as shown in Figure 2.3. In addition to pure top-down and bottom-up models, there are also some models that combine the characteristics of both, referred to as "hybrid models".

Besides the classification shown in Figure 2.3, updated classifying methods that expand on it have also emerged in recent years, which aim to accommodate developments in energy modeling and to include new and hybrid techniques, such as the one developed by (Langevin et al., 2020). Langevin et al. developed a new multi-layer quadrant scheme for classifying BSMs, according to the models' design (top-down or bottom-up) and degree of transparency (block-box or white-box), as shown in Figure 2.4 (Langevin et al., 2020). The main changes compared to previous classification methods are that it is not hierarchically structured; it can incorporate hybrid models and new modeling techniques such as machine learning, agent-based models, etc.; and it takes into account some dimensions such as system boundaries,

spatio-temporal resolution, dynamics, and uncertainty.

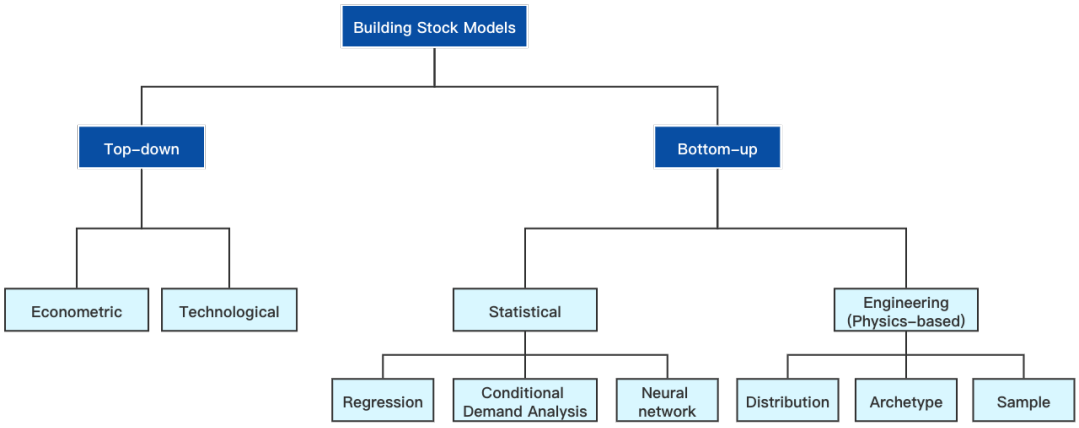

Figure 2.3: Hierarchical structure of the building stock modeling approaches (Kavgic et al., 2010; Swan & Ugursal, 2009)

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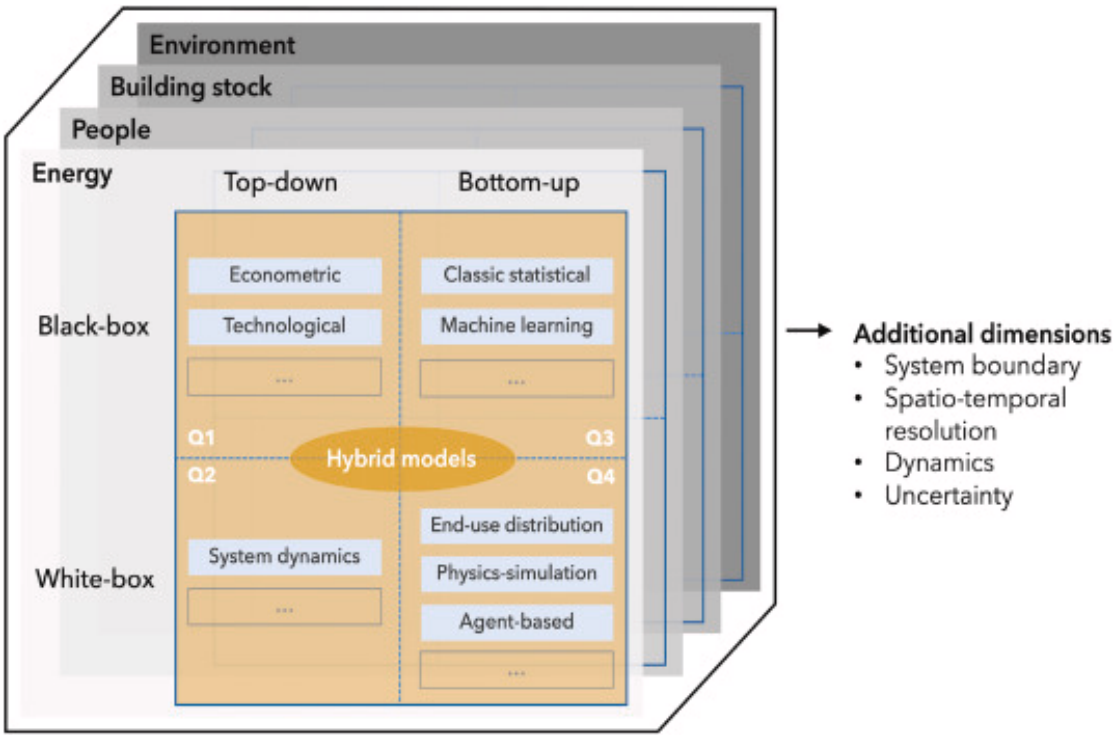

Figure 2.4: An updated classification approach for building stock models developed by Langevin et al. (Langevin et al., 2020)

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2.2.1 Top-down building stock models

Top-down models perform modeling at the aggregate level, as shown in Figure 2.3, which are further divided into econometric and technological top-down models in Kavgic et al.'s review (Kavgic et al., 2010). There are also studies that further divide top-down models into econometric, technological, physical and other (Li et al., 2017)). Econometric top-down models rely on historical data, and are typically developed with statistical relationships between historical aggregate energy consumption and driven economic parameters (e.g., gross domestic product, energy prices, etc.) as well as some other factors (e.g., climatic conditions). Technological top-down models usually involve some technological factors such as technological progress, structural changes, etc., but these factors are not described in detail in the models (Kavgic et al., 2010). Typically, since top-down models emphasize on the interaction between energy and economy, they do not require detailed data on things like energy consumption technologies (Lim & Zhai, 2017; Swan & Ugursal, 2009).

Top-down models rely on historical data and are therefore not so appropriate for forecasting energy consumption and assessing the impact of new technologies on energy efficiency. This also means that top-down models cannot quantify and elaborate on the effectiveness of specific policy measures. When working on the issue of climate change, top-down models may not be a good choice because environmental, social and economic conditions may differ significantly from "historical" ones. In addition, top-down models generally assume that markets are efficient and do not take into account energy gaps, which are out of touch with reality. There have been many studies pointing out the existence of energy efficiency gaps, which will be discussed in detail in the subsequent Section 2.2.3.

2.2.2 Bottom-up building stock models

Bottom-up models perform modeling at the disaggregate level. Bottom-up models calculate the energy consumption of individual buildings or groups of buildings and then aggregate them using different weighting methods to obtain the total (regional or national) energy consumption. As shown in Figure 2.3, bottom-up models are further divided into a statistical method and an engineering method (or physics based method).

Bottom-up statistical models are similar to top-down models in that both rely on historical data, but differ in that they rely on individual rather than aggregate level data. Bottom-up statistical models typically use energy billing data from energy suppliers or survey data containing occupant behavior and building characteristics to establish a functional relationship between energy consumption and various parameters that affect energy consumption (i.e., building characteristics or other parameters that can be physically meaningful or not) through various statistical techniques (regression, conditional demand analysis, neural network) (Lim & Zhai, 2017). Bottom-up statistical models are mostly based on regression techniques. Recently, some studies have emerged to combine geographic information system (GIS) techniques with bottom-up statistical models, which play a significant role in data acquisition and results

visualization (Mastrucci et al., 2014; Mattinen et al., 2014). Bottom-up statistical models are advantageous in that they are easy to establish when data are available, and they take into account demographic and occupant behavior characteristics, which have a significant impact on energy consumption. But accordingly, when the data are limited, the statistical bottom-up models will not be applied. Whereas the data is usually difficult to obtain, due to high cost, or privacy restrictions.

Bottom-up engineering models calculate the energy consumption of individual end-uses based on their ratings or building characteristics (e.g., envelope, equipment type, ventilation rate, occupancy, exterior temperature, etc.) and then aggregate them to obtain the total energy consumption. Bottom-up engineering models can model each individual building, which is called sample method, but this approach is often very time consuming. Therefore, a more commonly used approach is to use "archetypes". This approach starts by developing a limited number of archetypes for all buildings, with each archetype representing a class of buildings that have commonalities in construction period, building type, size, or other characteristics. Modeling the energy consumption of each archetype and multiplying it by the corresponding weight (e.g., the house heating area or the number of dwellings represented by each archetype) to obtain the total energy consumption. Compared to the sample technique, the simulation time of the archetype technique is greatly reduced. As with bottom-up statistical models, the technique of combining GIS with bottom-up engineering models has been developed in recent years. The advantage of bottom-up engineering models is their high flexibility and capability, which can be implemented without historical energy consumption data. The disadvantage, however, is that it requires many assumptions about the effects of occupant behavior characteristics on energy consumption (Kavgic et al., 2010; Lim & Zhai, 2017; Swan & Ugursal, 2009).

In conclusion, bottom-up models are considered to be a promising tool for assessing the effectiveness of energy or climate policies and strategies, and identifying technologies for energy efficiency improvements.

2.2.3 The bottom-up two-step decision model

In recent years, many bottom-up BSMs have been developed to assist policymakers in abatement policy assessments in the context of growing concerns about climate change. In this thesis, a bottom-up two-step decision model for the Swiss residential building stock is applied for CO_2 tax policy simulation with some distinct merits as follows:

- *It is dynamic modeling.*

  The modeling of building stock can be static or dynamic. Dynamic stock methods can show the evolution of the building stock over time and facilitate insight into the flows driving systems' activities, which are considered to be a more reliable method for modeling future scenarios and medium- to long-term projections (Kohler & Hassler,

2002; Mastrucci et al., 2017). This bottom-up two-step decision model is a dynamic model, which means that the temporal evolution of the building stock can be observed.

- *It is endogenous modeling.*

  Bottom-up BSMs model the evolution of building stock energy performance through demolition and renovation of existing buildings, construction of new buildings, energy switching, etc., and thus project the energy consumption and GHG emissions of the building stock (Nägeli et al., 2020). Many bottom-up BSMs project the evolution of the building stock by exogenously setting fixed demolition rates, new construction rates, building retrofit rates, etc. These rates are usually assumptions based on historical data or expert judgment (Mastrucci et al., 2017). In contrast to the methods that exogenously set these rates, the two-step decision model uses parameters such as energy prices, population growth, information campaign, etc. to endogenously generate retrofit decisions and new construction decisions. This allows the two-step decision model to account for the influence of economic, environmental, or policy factors on homeowners' decisions to renovate or construct new buildings, which would increase the reliability of the results (Nägeli et al., 2020).

- *It represents energy barriers.*

  The energy efficiency gap, or known as the energy paradox, has been widely discussed in many studies (Bradshaw et al., 2016; Jaffe & Stavins, 1994; Palmer et al., 2013; Sorrell, 2004). Building retrofits are often considered a potential investment opportunity because homeowners can save significant amounts of energy through building energy efficiency retrofits, and the value of these savings can exceed the upfront investment (Bradshaw et al., 2016; Palmer et al., 2013). However, for this profitable investment opportunity, homeowners often do not respond as enthusiastically as expected, and many energy efficiency improvements are often not implemented, referred to as the energy efficiency gap. The rate of building renovation in Switzerland is only about 1 percent (IEA, 2018). There are studies that attribute the energy efficiency gap to market failures, non-market failures and behavioral anomalies from an economic perspective (Gillingham et al., 2009).

  Information barriers are considered to be one of the causes for the energy efficiency gap. There are homeowners who are not aware of the energy efficiency performance of their buildings, and some who do not perform retrofits because they do not have the expertise in energy efficiency retrofits or have no concept of the return on the renovation investment (Palmer et al., 2013). Giraudet provided a review of information barriers in building energy efficiency improvement, classifying them into symmetric-information problems (non-market failures) and asymmetric-information problems (true market failures) (Giraudet, 2020). Symmetric information problems include incomplete information (e.g., incomplete disclosure of product attributes) and imperfect information (e.g., uncertainty in energy prices, weather conditions). Whereas asymmetric-information problems relate to adverse selection and principal-agent problems.

The landlord-tenant dilemma, also known as the "split incentive" problem, is another major barrier to retrofitting, i.e., another cause of the energy efficiency gap. The cost of retrofitting is paid by the landlords, while the benefits of retrofitting (lower energy costs) are enjoyed by the tenants, who are the ones paying the energy bills. This incentive mismatch that exists between landlords and tenants is known as the split incentive problem. While landlords can increase rents to recover the investment in energy efficiency improvements, this is often difficult to achieve because they are not able to increase rents as much as they want due to legal or market restrictions. Under such circumstances, landlords are seen as having motivation not to undertake energy efficiency retrofits. This is also corroborated by studies, which showed that retrofitting investment rates for rental housing are typically lower than for owner-occupied housing (Melvin, 2018; Trotta, 2018). A study by Giraudet et al. on French energy policies suggested that the rental housing problem must be better addressed in order to meet the energy saving targets set by the French government (Giraudet et al., 2021).

The energy efficiency gap is usually not considered in top-down models, while it is usually overestimated in bottom-up models (Giraudet et al., 2012). Most bottom-up BSMs ambiguously use an abnormally high discount rate to represent all energy efficiency barriers without reasonable explanations. In this bottom-up two-step decision model, the split-incentive problem is captured in two ways: 1) homeowners are classified based on characteristics such as ownership (owner-occupied or rented), age (young or old), and income (poor or wealthy), and different discount rates (r) are assigned to different owner types; 2) a split incentive parameter (χ) is introduced, which will only apply to the landlords. This is particularly valuable for the Swiss building stock analysis, since Switzerland is characterized by a majority of rental housing, as discussed in Section 1.3.

3 Methdology

In this thesis, a two-step decision building stock model is used to perform CO_2 tax policy simulations. Through this two-step decision model, dynamic changes in the building stock due to demolition, renovation, new construction, etc. are captured, thereby enabling changes in energy demand and carbon emissions to be captured. The specific process of the model is described in this chapter, and the values of the specific variables and parameters are presented in Chapter 4.

3.1 Characterization of building stock evolution

In Switzerland, the building stock is characterized using the Energy Reference Area (ERA), which is a measure of the effective heating area, in square meters (m^2). In this model, ERA is allocated based on three dimensions: energy class (EC), construction period (CP) and owner type (OT).

The evolution of the building stock is represented by the year-to-year change of the ERA, which is calculated based on the yearly demolition, retrofitting (transfer between energy classes), and new construction of buildings, as shown in Equation 3.1.

$$\begin{aligned} ERA_{t+1,OT,EC} = & \Big((1-DR_t)\cdot ERA_{t,OT,EC}\Big) + \Big(NC_{t,OT,EC}\Big) \\ & + \Big(\sum_{EC'<EC}^{G} RM_{t,OT,EC,EC'} - \sum_{A}^{EC'>EC} RM_{t,OT,EC,EC'}\Big) \end{aligned} \tag{3.1}$$

3.1.1 Demolition

The demolition of buildings is calculated through the demolition rate (DR).

3.1.2 Retrofitting

The retrofitting of buildings is modeled as a transition from the initial energy class to any higher final class. The decision maker for energy retrofitting is the property owner, whose decision is determined by the following two-step decision model:

- Step 1: energy audit

  Calculate the proportion of buildings that perform energy audits (Γ) in a given year, which may be triggered by energy price increases or information campaigns. Assume that owners do not know the costs and benefits of retrofitting until an energy audit is performed on the building. The calculation of Γ is shown in Equation 3.2, where:

$$\Gamma_{t,EC} = \left(1 + \Theta \cdot \left(\frac{(PEC_{t,EC} \cdot SHD_{t,EC}) - (PEC_{t-1,EC} \cdot SHD_{t-1,EC})}{PEC_{2019,EC} \cdot SHD_{2019,EC}}\right) + \theta \cdot \frac{PEC_{t,EC} \cdot SHD_{t,EC}}{PEC_{2019,A} \cdot SHD_{2019,A}}\right) \cdot \Pi_{EC} \cdot Inf_t \tag{3.2}$$

  - Θ is the elasticity;
  - PEC is the energy price in CHF/kWh;
  - SHD is the space heating demand per m^2, in kWh/m^2;
  - θ is the impact price level;
  - Π is the baseline probability that buildings would perform an energy audit;
  - Inf is the information level.

- Step 2: retrofitting decision

  Conduct a cost-benefit analysis of the buildings that are triggered to perform an energy audit. The owners decide whether to retrofit based on the results of the cost-benefit analysis.

  The retrofit gain (RG), in CHF/m^2, is the difference between the net present value of all future energy savings due to the retrofit (from initial EC to any higher EC') and the cost of the retrofit, which is calculated in Equation 3.3, where:

$$RG_{t,OT,EC,EC'} = \chi_{OT} \sum_{t'=t}^{t+T} \frac{SHD_{t,EC} \cdot PEC_{t',EC} - SHD_{t,EC'} \cdot PEC_{t',EC'}}{(1 + r_{OT})^{t'-t}} - RC_{t,EC,EC'} \cdot (1 - \tau_{t,EC,EC'}) \tag{3.3}$$

  - χ is a split incentive parameter;

- T is the investment horizon, in years;
- SHD is the space heating demand per m^2, in kWh/m^2;
- PEC is the energy price, in CHF/kWh;
- r is the discount rate;
- RC is the retrofit cost in CHF/m^2;
- τ is a subsidy on retrofitting.

After the cost-benefit analysis, the homeowner will retrofit from the initial EC to the final EC' if both of the following two rules are satisfied:

1. The retrofit gain (RG) from EC to EC' is positive.
2. The retrofit gain (RG) from EC to EC' is higher than any other retrofit options (i.e., the options of which final class to retrofit to).

The two rules above are represented by Equation 3.4, where Ω is the probability of performing the retrofit.

$$\Omega_{t,OT,EC,EC'} = 1 \text{ if} \begin{cases} RG_{t,OT,EC,EC'} > 0 \quad and \\ RG_{t,OT,EC,EC'} > RG_{t,OT,EC,EC^*} \quad \forall\, EC^* \neq EC' \end{cases} ; 0 \text{ otherwise} \tag{3.4}$$

The transition between energy classes is represented by the retrofit matrix (RM), which is equal to the multiplication of the following three variables: the probability of performing an audit (Γ), the probability of performing a retrofit (Ω), and the energy reference area (ERA), as shown in the Equation 3.5.

$$RM_{t,OT,EC,EC'} = \Gamma_{t,EC} \cdot \Omega_{t,OT,EC,EC'} \cdot ERA_{t,OT,EC} \tag{3.5}$$

3.1.3 New construction submodel

Similar to retrofits, new construction (NC) can be determined by a two-step submodel:

- Step 1, the total desired energy reference area ($ERAD$ in m^2) of the new construction is determined, which is linked to the population growth. The population growth is based on national projections provided by the Swiss Federal Statistical Office[I].

[I] https://www.bfs.admin.ch/bfs/en/home/statistics/population/population-projections/national-projections.html

- Step 2, the share of new construction (SNC) in each EC is determined. Due to increasingly demanding building regulation, it is assumed that new construction can only be A, B, or C energy classes. The choice of which EC will be determined through a cost-benefit analysis.

Then the new construction (NC) is the multiplication of the desired reference area ($ERAD$) and the EC share (SNC), see Equation 3.6.

$$NC_{t,OT,EC} = ERAD_t \cdot SNC_{t,OT,EC} \tag{3.6}$$

The share of new construction (SNC) in each EC is determined by the profit (PR) of NC, which is the difference between the present value of the net income ($PVNI$, in CHF/m^2) and the construction cost (CC, in CHF/m^2), as given in Equation 3.7. The most profitable energy class will be chosen by the homeowners for their new construction.

$$PR_{t,OT,EC} = PVNI_{t,OT,EC} - CC_{EC} \tag{3.7}$$

$$PVNI_{t,OT,EC} = \frac{MP_{t,OT,EC} - MC_{EC}}{r_{OT}} \cdot (1 - \frac{1}{1 + r_{OT}})^T \tag{3.8}$$

$$MP_{t,OT,EC} = RI_{OT,C} + ES_{t,C,EC} = \left(\frac{CC_C \cdot r_{OT}}{(1 - \frac{1}{1+r_{OT}})^T} + MC_C \right) + \left(\frac{DEC_{C,EC} \cdot SA \cdot PEC_{t,EC}}{12} \right) \tag{3.9}$$

The new construction will choose among energy classes A, B and C. We take energy class C as the reference class, i.e. the profit of C is assumed to be zero ($PVNI_{t,OT,C} = CC_C$). The present value of the net income ($PVNI$) is calculated by Equation 3.8, where MC is the maintenance cost, in CHF/m^2; r is the discount rate; T is the lifetime years; MP is the market price of rental, in CHF/m^2. The calculation of MP is given in Equation 3.9, where $RI_{OT,C}$ (in CHF/m^2) is the rental income of energy class C; ES (in CHF/m^2) is the energy saving compared to energy class

C; DEC (in kWh/m^2) is the difference in energy consumption between energy classes. SA (in m^2) is the building surface. PEC (in CHF/kWh) is the energy price.

3.2 Total energy consumption and CO_2 emissions

3.2.1 Total energy consumption

The total heating energy consumption (TEC), in kWh, is the sum of the energy consumption for all energy classes and all owner types, as shown in Equation 3.10.

$$TEC_t = \sum_{OT=1}^{6} \sum_{EC=G}^{A} ERA_{t,OT,EC} \cdot SHD_{t,EC} \tag{3.10}$$

3.2.2 CO_2 emissions

The CO_2 emissions are related to the composition of the energy classes. In this model, each energy class has a specific mix of energy carriers (oil, natural gas, district heating, heat pump, direct electricity and wood). A building retrofit from an initial energy class to a higher energy class will switch to the mix of energy carriers for its final energy class.

4 Model variables and parameters

4.1 Energy class (EC)

The EC is classified into seven classes, corresponding to the class A (highest) to G (lowest) of a Swiss classification (see Appendix A for a detailed description). The unit space heating demand (SHD), or average energy consumption, in kilowatt hours per square meter (kWh/m^2), increases progressively from class A to class G, as shown in Table 4.1. These average energy consumption values are derived from the own estimates.

Table 4.1: Ranges and averages of space heating demand per energy class

Energy class	Averages in kWh/m^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

4.2 Construction period (CP)

The allocation of construction periods in each energy class is derived from the own calculations, which are detailed in Appendix B. Figure 4.1 shows the ERA allocation by EC and CP for year 2015.

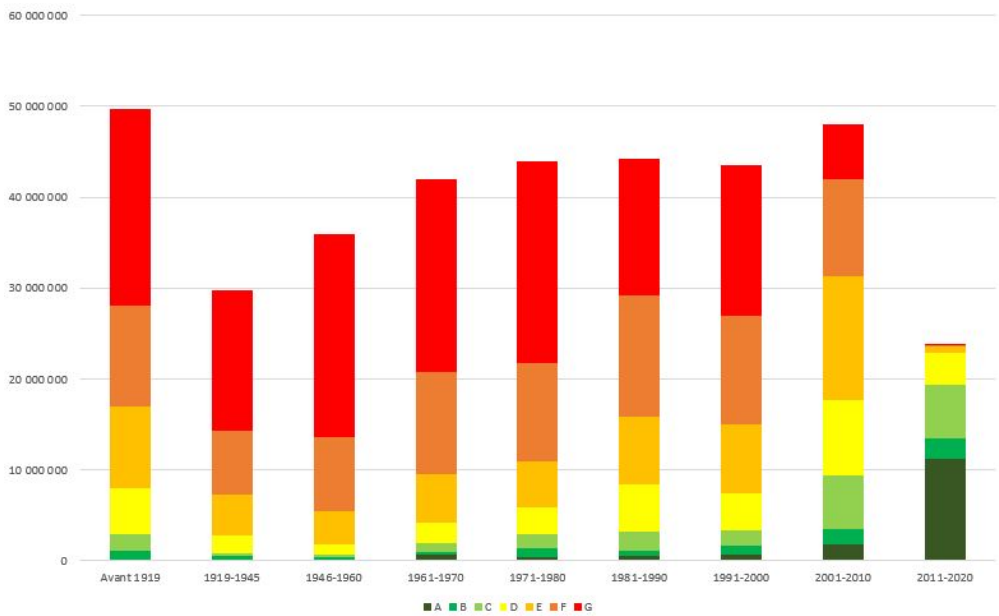


Figure 4.1: Energy reference area in m^2 per construction period and energy class in 2015 (source: (Arzoyan, 2019))

4.3 Owner type (OT)

Different owner types are applied to existing buildings and new constructions.

4.3.1 Owner types for existing dwellings

In the building retrofitting dynamics, the owner types are classified into 6 categories based on the characteristics listed in Table 4.2. The "Owner-occupied" means that the occupant of the housing is simultaneously the homeowner, with a 37% share; the "rental" means that the occupant is not the homeowner, with a 63% share [I]. For "owner-occupied", it is further classified into 3 categories based on age and income (Young wealthy, Other, Old/poor); for "rental", the rental property may be profit-based (e.g., investment companies, pension funds), non-profit-based (e.g., cooperatives, municipalities), or private, so it is further classified into 3 categories (Non-profit-based, Profit-based, Private).

The above 6 owner types are assigned different discount rates (r) based on the following principles:

- *Old owner-occupiers have a higher discount rate than young owner-occupiers.*

  This is because old owner-occupiers are perceived to have a limited time to recover their investment costs and turn a profit. This is consistent with previous studies revealing

[I] Federal Statistical Office https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/dwellings/housing-conditions/tenants-owners.html

Table 4.2: Owner types, shares and their discount rates for retrofitting

Share of total ERA that is owner-occupied/rental	Type	Owner type	Characteristics	Share of ERA	Discount rate (r)
37%	1	Owner-occupier	Young wealthy	20%	2%
	2	Owner-occupier	Other	60%	4%
	3	Owner-occupier	Old/poor	20%	6%
63%	4	Landlord	Non-Profit-based	10%	2%
	5	Landlord	Profit-based	30%	4%
	6	Landlord	Private	60%	6%

that the discount rate increases with the age of the homeowner (Hausman, 1979).

- *Poor owner-occupiers have a higher discount rate than wealthy owner-occupiers.*

  This is because poor owner-occupiers are perceived to have less access to funds. This is also consistent with previous studies revealing that the discount rate decreases with increasing income (Hausman, 1979).

- *Non-profit-based landlords have a lower discount rate than profit-based landlords.*

  This is because the goal of non-profit-based landlords is to satisfy the needs of their tenants rather than high returns.

There have been many studies on the discount rate for energy efficiency investments. It has been suggested that discount rates of 4-6% and 10-12% for private investors are probably justified for developed and developing countries, respectively (Braungardt et al., 2014). Steinbach and Staniaszek (Steinbach & Staniaszek, 2015) summarized the different levels of discount rates adopted in the recent energy scenarios for Germany and their justifications, which ranged from 4% to 9.5%. Anna Alberini et al. (Alberini et al., 2013) surveyed 473 Swiss homeowners on their preferences for energy efficiency retrofits and inferred an implied discount rate range of 1.5%-3%.

Taking into account the above studies, in our energy retrofit model for Switzerland, we assign different discount rates to owners with different characteristics (see Table 4.2), which vary in the range of 2% to 6%.

As discussed in Section 2.2.3, the "split incentive" problem is a salient barrier to energy efficiency retrofits. In this model, this barrier is captured by assigning different discount rates to different owner types.

4.3.2 Owner types for new constructions

New construction (NC) is calculated based on the homeowner's investment decision (i.e. the decision as to which energy class the new construction will be), which is based on cost-benefit analysis.

In the cost-benefit analysis, the "cost" refers to the construction cost (CC, CHF/m^2), which varies among different energy classes. Obviously, the higher the energy class, the more expensive the construction cost. However, there are still homeowners who choose to invest in buildings with a high energy class, as the income also varies among different energy classes. In the cost-benefit analysis, the "benefit" refers to the return to homeowners, which has a different meaning for rental and owner-occupied housing. For the owner of the rental property, the return obviously refers to the rental income. Whereas for owner-occupiers, the return is more of an implicit income, which represents housing expenses that they do not need to pay, as they would have to rent someone else's house and pay the corresponding rent if they did not live in their own house. The amount of the implicit income is thus equal to the rental income if the owner rents out their new building. As such, when calculating the benefit, we can consistently regard the return as "rental income" for both owner-occupied and rental housing, which is different from the retrofit model. Naturally, the higher the energy class of the building, the higher the rental income will be, as the occupants will have lower energy costs, resulting in them having to pay higher rents to compensate for these costs borne by the owner.

As with energy retrofits, investment decisions for new construction are very dependent on the characteristics of the homeowner, which is captured in our NC model through the discount rate (r). We distinguish five owner types, whose characteristics and shares are shown in Table 4.3. The owner types differ from that in the energy retrofit model in two ways: firstly, based on the discussion of "rental income" above, we do not take into account the owner-occupied/rental characteristic in the NC model; and secondly, we merge the share of "Old/poor" type with the "Young/wealthy" type in the retrofit model to form the new "Young/wealthy" type. Different owner types are assigned different discount rates, whose values are shown in Table 4.3.

Table 4.3: Owner types, shares and their discount rates for NC submodel

Type	Share of ERA	Owner type	Discount rate (r)
1	16%	Young wealthy	1.0%
2	24%	Other	2.0%
3	6%	Non-Profit-based	3.0%
4	18%	Profit-based	4.0%
5	36%	Private	5.0%

4.4 Retrofit cost

RC is the retrofit cost in CHF/m^2, as shown in Table 4.4, which is an estimate based on a study of The Swiss Federal Office of Energy (SFOE) and is a weighted average of the retrofit costs for the single-family house (SFH) and the multi-family house (MFH). Table 4.4 gives the RC from any initial EC to a higher EC', which is based on the assumption that the higher the initial EC, the higher the RC for retrofitting to a final EC'.

Table 4.4: Matrix for weighted average (SFH and MFH) 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	

4.5 Construction cost of new construction

The construction costs in Switzerland are among the highest in the world. According to information from the *Statista*[II], construction costs in Zurich range from 2,030 to 3,075 CHF/m^2 in 2018, depending on the type of the dwelling. An Office Cost Model developed by CEEC[III] shows that the construction cost in Switzerland in 2020 is €2,113.00/m^2.

This information on construction costs does not refer to the energy performance of the houses. It is generally assumed that the higher the energy efficiency of a building, the higher the construction costs will be. A review by Dwaikat and Ali (Dwaikat & Ali, 2016) summarized empirical studies that had compared the costs of green buildings with similar non-green buildings. The results showed that most of the empirical studies confirmed that green buildings cost more than non-green buildings, but there were a very few studies that contradicted this conclusion. The results showed that 92% of the studies (12 out of 13) had a green cost premium of -0.4% to 21%; 62% of the studies (8 out of 13) had a green cost premium of 5% to 21%. The study by Manganelli et al. (Manganelli et al., 2019) compared the construction costs of buildings with different energy performance in Italy and showed that the better the energy performance, the higher the construction costs. The variation of construction costs between energy class C and A was 38.0%.

Taking into account the above studies/data, in our *NC* model, we set different construction costs for energy classes A, B and C. The values and variations of the neighbouring classes are shown in Table 4.5.

Table 4.5: Construction costs (*CC*) for different energy classes

Energy classes	*CC* in CHF/m^2	Additional cost in CHF/m^2	% variation
C	4,500		
B	5,250	7,50	16.7%
A	6,000	7,50	12.5%

[II] https://www.statista.com/statistics/892504/building-costs-per-square-meter-by-residential-building-type-switzerland/

[III] CEEC: The Council of European Construction Economists https://www.ceecorg.eu/?avada_portfolio=office-cost-model

4.6 Summary of all indices, variables and parameters

Table 4.6 summarizes all the indices, variables, and parameters involved in the model.

Table 4.6: Summary of all indices, variables and parameters

	Meaning	Unit	Values	Sources/Description
Indices				
t, t'	Time period			
OT	Owner type		For retrofitting: see Table 4.2; For new construction: see Table 4.3	See Section 4.3
EC, EC'	Energy class		{A; B; C; D; E; E; G}	Energy classes according to CECB, see Appendix A
Variables				
$ERA_{t,OT,EC}$	Energy reference area	m^2		
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		
$RM_{t,OT,EC,EC'}$	Retrofit matrix	m^2		
Γ	Proportion of building performing energy audit	%		
$RG_{t,OT,EC,EC'}$	Retrofit gain	CHF/m^2		
Ω	Probability of performing the retrofit	%		
$ERAD_t$	Desired energy reference area	m^2		

Continuation of Table 4.6

	Meaning	Unit	Values	Sources/Description
$SNC_{t,OT,EC}$	Share of new construction in each EC	%		
$PR_{t,OT,EC}$	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	
TEC_t	Total heating energy consumption	kWh		
Parameters				
$SHD_{t,EC}$	Space heating demand	kWh/m^2	See Table 4.1	Increase progressively from energy class A to G
$RC_{t,EC,EC'}$	Retrofit cost	CHF/m^2	see Table 4.4	RC is an estimate based on a study of SFOE and is a weighted average of the retrofit costs for the SFH and the MFH
CC_{EC}	Construction cost	CHF/m^2	See Table 4.5	See Section 4.5
$DEC_{C,EC}$	Difference in energy consumption between energy classes	kWh/m^2	For energy class B and C: 20; For energy class A and C: 30	

Continuation of Table 4.6

	Meaning	Unit	Values	Sources/Description
$PEC_{t,EC}$	Energy price	CHF/kWh		Derived from the World Energy Outlook 2021 (the *Stated Policies* will be used); (International Energy Agency, 2021)
r	Discount rate		For existing dwellings: {2%; 4%; 6%; 2%; 4%; 6%}; For new construction: {1%; 2%; 3%; 4%; 5%}	See Section 4.3
DR_t	Demolition rate		0.32%	DR is an exogenous value in this model. The DR represents an average value, calculated from the evolution of the ERA in Switzerland from 2010 to 2016
Θ	Elasticity		1	
θ	Impact price level		0.2	
Π	Baseline probability that buildings would perform an energy audit		{0; 0.5%; 1%; 1.5%; 2%; 2.5%; 3%}	Inversely proportional to the energy class, i.e., it decreases as the energy class increases (G→A)
Inf	Information level		{1; 2; 3; 4}	
χ	Split incentive parameter		{1%; 1%; 1%; 0.5%; 0.5%; 0.5%}	Landlords who rent out their buildings are assumed to receive only 50% benefits of the energy savings due to retrofitting. This parameter is meant to represent the split incentive barrier
T	Investment horizon	Year	For existing dwellings: 40; For new construction: 60	

Continuation of Table 4.6

	Meaning	Unit	Values	Sources/Description
τ	Subsidy rate on retrofitting		30%	Equal to the current values in Switzerland

5 Simulations

The purpose of this thesis is to explore how the CO_2 tax must rise to achieve an 80% reduction in CO_2 emissions in 2050 relative to 1990. However, since the base year is 2019, it is not possible to directly obtain the emission reductions in 2050 relative to 1990 through the model. This is solved by a simple conversion. The CO_2 emissions from residential buildings in 1990 and 2019 are 11.61 Mt and 7.62 Mt, respectively, so an 80% reduction in 2050 relative to 1990 is equivalent to a 70% reduction relative to 2019, as shown in Table 5.1. In the subsequent sections, all reduction percentages are relative to the base year 2019 if not specifically stated.

Table 5.1: CO_2 emissions (targets) from residential building sector in 1990 & 2019 (2050)

Year	CO_2 (in million tonnes)	Reduction compared to 1990	Reduction compared to 2019
1990	11.61	0%	
2019	7.62	34%	0%
2050	2.32	80%	70%

The design of a CO_2 tax involves the setting of a starting tax rate and its change over time. In this thesis, a baseline scenario and three different CO_2 tax increase scenarios are simulated:

1. **Keep Low - Rapidly Increase Policy (KL-RIP)**: a policy of keeping the CO_2 tax low at the beginning and then rapidly increasing.
2. **Gradually Increase Policy (GIP)**: a policy of gradually increasing the CO_2 tax.
3. **Rapidly Increase - Keep High Policy (RI-KHP)**: a policy of rapidly increasing the CO_2 tax at the beginning and then keeping it at a high level.

Since the CO_2 ACT is continuously updated, the current CO_2 tax (120 CHF/tCO_2) might be extended. Year 2030 has been chosen as the intermediate time point among the 3 different policy scenarios. The increase of the CO_2 tax over time for the three policy scenarios is shown in Table 5.2.

As presented in the previous methodology sections, in this model, besides the CO_2 tax, two other policies are considered, namely subsidies and information campaign. Since the aim

Table 5.2: The growth of CO_2 tax over time for three policy scenarios (in CHF/tCO_2)

Year	Baseline	KL-RIP	GIP	RI-KHP
2019	96	96	96	96
2020-2021	96	96	Whatever constant increment is needed to reach 2.32 Mt in 2050	Whatever constant increment is needed to reach 2.32 Mt in 2050
2022-2030	120	120	Keep the same constant increment as in 2020-2021	Keep the same constant increment as in 2020-2021
2031-2050	120	Whatever constant increment is needed to reach 2.32 Mt in 2050	Keep the same constant increment as in 2020-2021	Keep level reached in 2030

of this thesis is to explore the reduction effect of the CO_2 tax, these two policies will remain unchanged in all scenarios. The subsidy is the same as the current level in Switzerland - 30% subsidy ($\tau_{t,EC,EC'}$) for retrofitting investments. The information level (Inf) is equal to 1 for all scenarios. Furthermore, for all scenarios, the energy reference area (ERA), the population growth and the energy price (PEC) are kept unchanged.

In order to find the minimum yearly CO_2 tax increment (Tax_YI, in CHF/year) that enables 70% reduction (compared to 2019) in each scenario, different Tax_YI need to be input exogenously and continuously adjusted (raising or lowering) based on the results. In this thesis, 12, 7, and 12 simulations were conducted for the KL-RIP, GIP, and RI-KHP scenarios, respectively, and the Tax_YI and the CO_2 tax changes over time for all simulations are shown in Appendix C. The numerical results for all 31 simulations are shown in Table D.1 in Appendix D. The Table 5.3 compares the simulation results for the year 2019, baseline and the 3 scenarios where 70% reduction is achieved (with minimum Tax_YI).

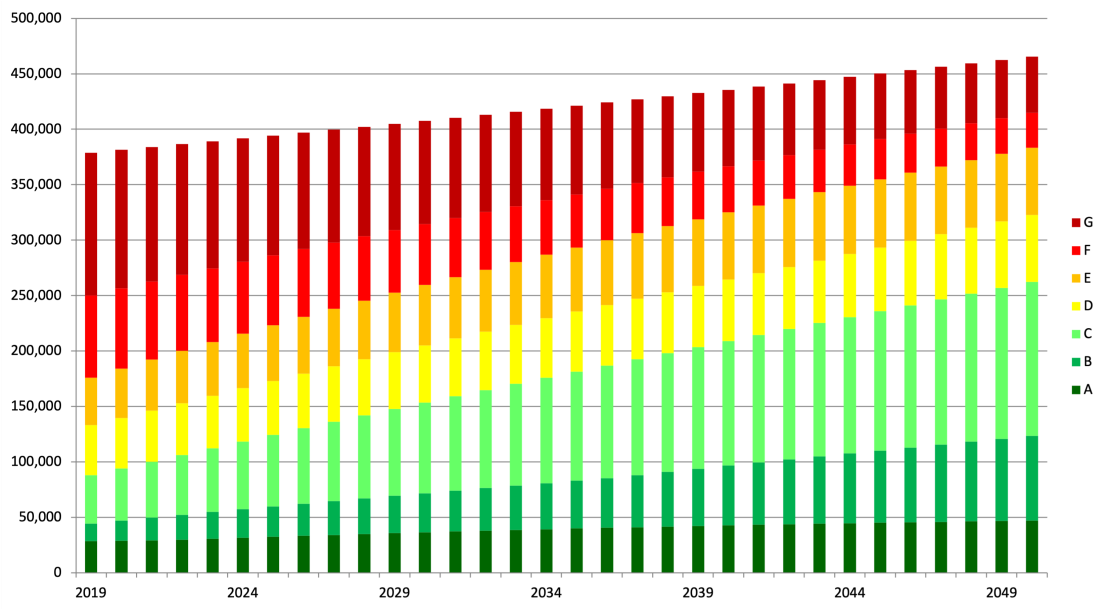
5.1 Baseline scenario

In the baseline scenario, the CO_2 tax is based on the realistic Swiss tax rate, which will remain unchanged after 2022 until 2050. The evolution of the CO_2 tax over time is shown in Table C.1.

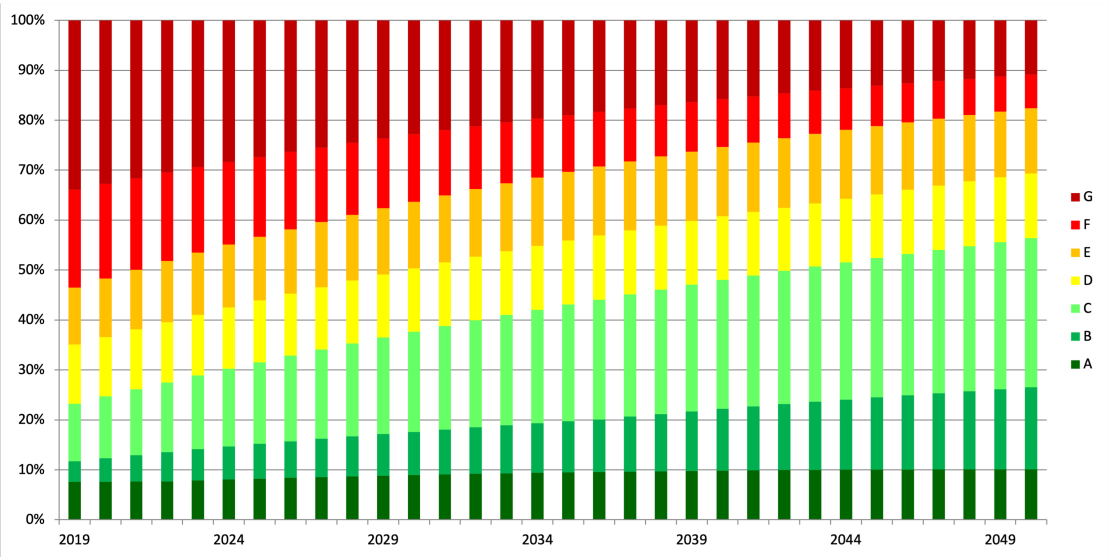
Figure 5.1a and Figure 5.1b show the evolution of the ERA in absolute value and share for each energy class in the baseline scenario from 2019 to 2050, respectively. It can be seen that the total ERA shows an increasing trend, with energy classes A, B, C, D and E experiencing an increase in ERA of 64%, 387%, 218%, 34% and 41%, respectively. The ERA of energy classes F and G decreases in 2050 compared to 2019, by 58% and 61%, respectively. The share of each energy class also changes, with the combined share of energy classes A, B, C increasing to 56% from 23%, while the share of energy classes F and G declines to 18% from 54%.

This result is consistent with the retrofit dynamics shown in Figure 5.2, where it can be seen that the ERA increases for energy classes A, B, C, D and E is from the retrofit of F and G, and mostly from G. From 2019 to 2042, buildings are mostly retrofitted to energy class E, while from 2043 to 2050 they are mostly retrofitted to energy class D. The growth in ERA for energy classes B and C is also partially attributable to the construction of new buildings, most of which are energy class C, as shown in Figure 5.3. The share of energy class B in new constructions has increased since 2036, probably due to the increase in energy prices. Energy class A can be seen to be absent from new constructions, perhaps because the CO_2 tax does not increase in the baseline scenario, and therefore the energy price increase is not large enough to motivate homeowners to choose the most energy efficient (energy class A) new constructions.

Table 5.3 shows the average retrofit rate from 2020 to 2050 in the baseline scenario with a value of 0.8%, which is lower than the retrofit rate of 1.2% in 2019 and the average Swiss retrofit rate of 1% from the IEA (IEA, 2018). This is due to the gradual reduction of the retrofit rate from 2020. The average energy demand in 2050 is 66.4 kWh/m^2, which is 34.4% lower than in 2019, implying an energy efficiency improvement in the building envelope. The total CO_2 emissions in 2050 are reduced by 44.8% compared to 2019, which is still far from the target of 70% reduction. This suggests that current abatement policies are not sufficient to reduce Switzerland's CO_2 emissions by 80% in 2050 compared to 1990, and that an increase in the CO_2 tax is essential.

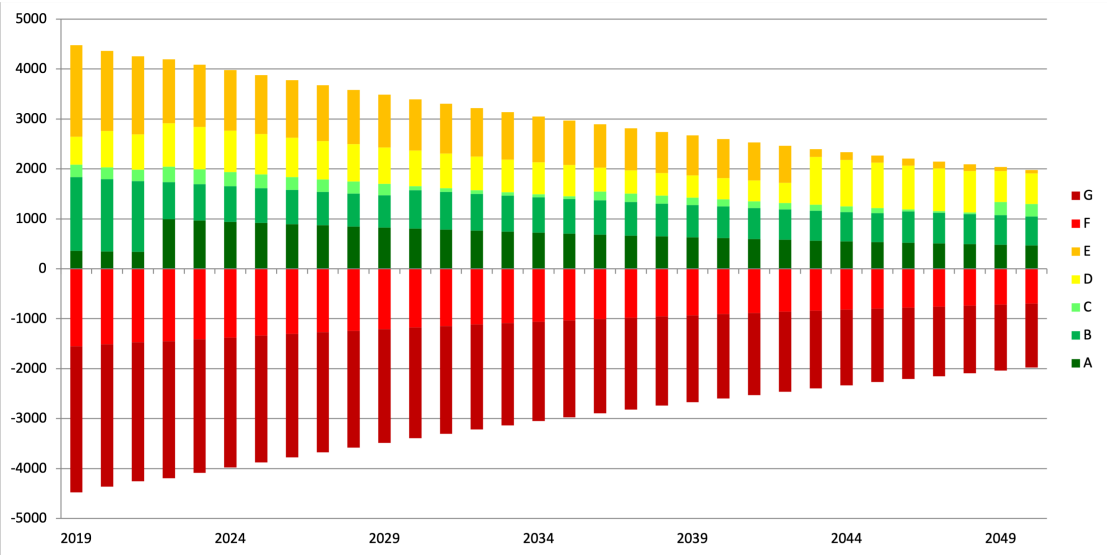


(a) Energy reference area per energy class, in 1000 m^2

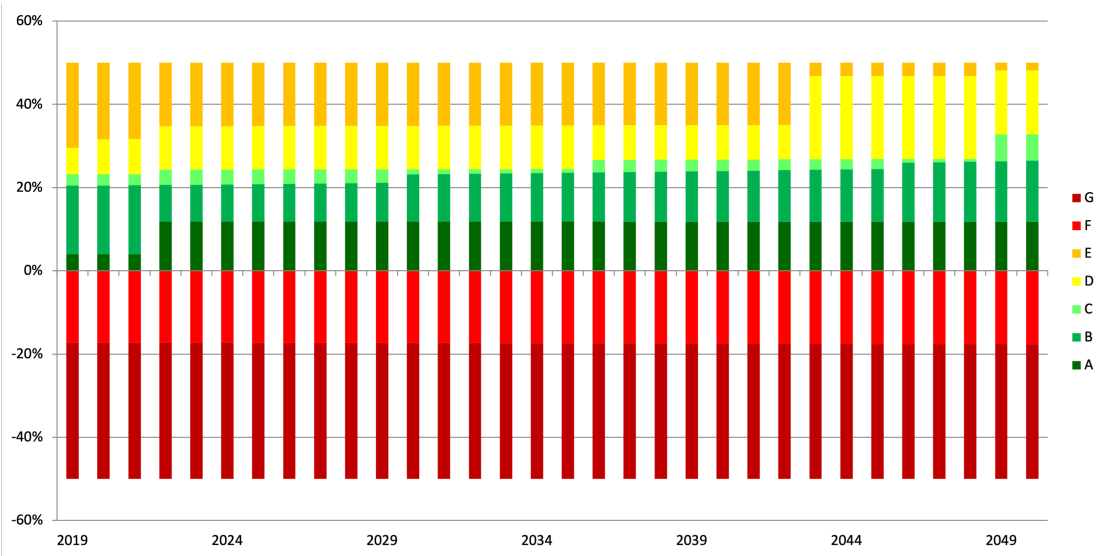


(b) Energy reference area share per energy class

Figure 5.1: Evolution of the energy reference area per energy class - baseline scenario

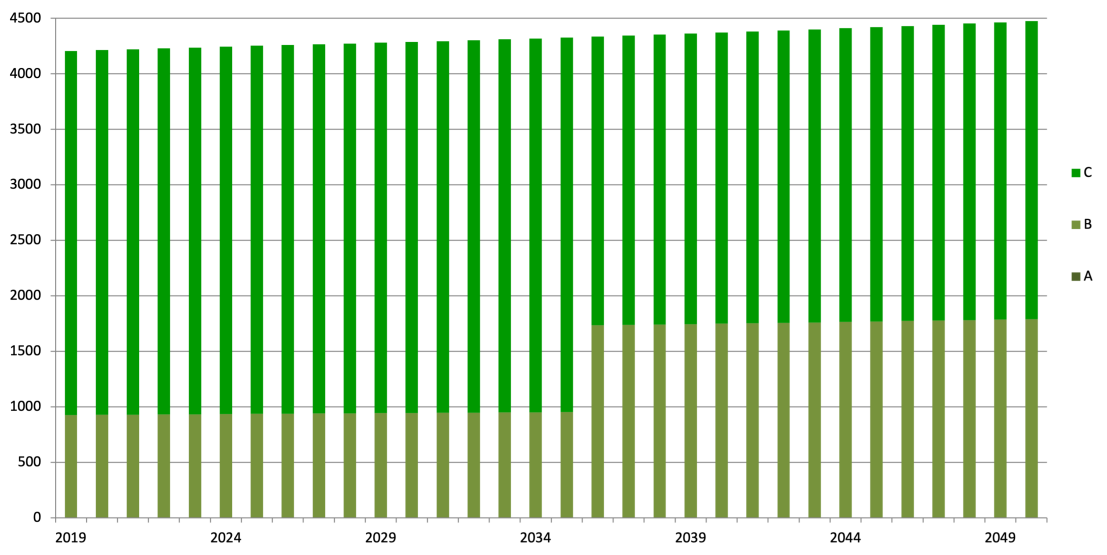


(a) Energy reference area for retrofitting per energy class, in 1000 m^2

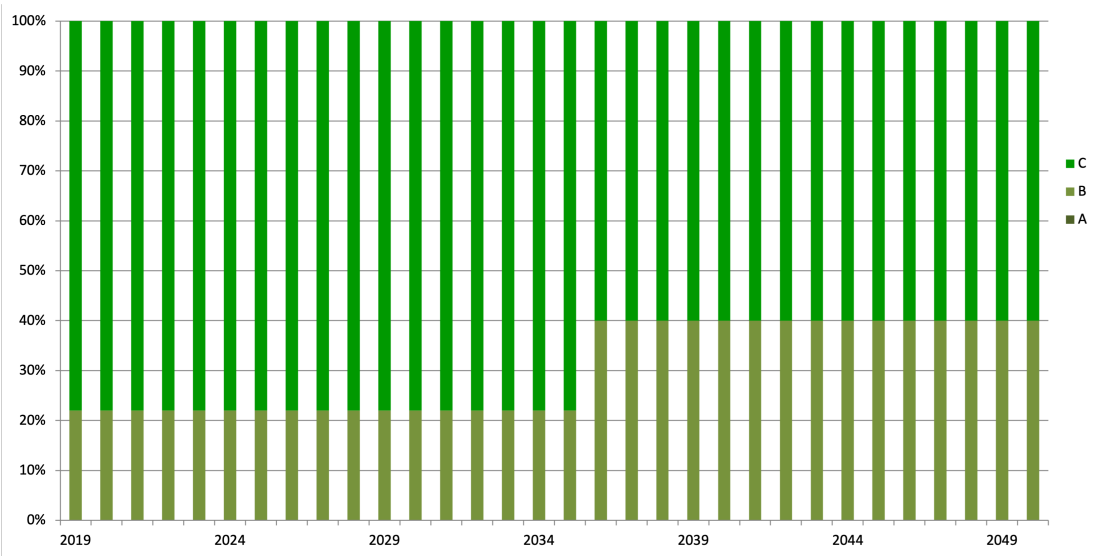


(b) Energy reference area share for retrofitting per energy class

Figure 5.2: Evolution of the energy reference area for retrofitting per energy class - baseline scenario



(a) Energy reference area for new construction per energy class, in 1000 m^2



(b) Energy reference area for new construction share per energy class

Figure 5.3: Evolution of the energy reference area for new construction per energy class - baseline scenario

5.2 KL-RIP scenario

In the KL-RIP scenario, the CO_2 tax is kept at a low level at first and then rapidly increases. Specifically, the CO_2 tax is an actually implemented CO_2 tax of 96 CHF/tCO_2 from 2019 to 2021; constant at 120 CHF/tCO_2 from 2022 to 2030; and increases at a constant yearly increment of Tax_YI from 2030 to 2050.

In order to find the minimum Tax_YI that achieves a 70% reduction, a total of 12 simulations were performed, whose Tax_YI and CO_2 tax changes over time are shown in Table C.2. It's finally determined that in the KI-RIP scenario, to achieve a 70% reduction in emissions, the CO_2 tax would need to increase by at least 95 CHF per year from 2030, as shown in Figure 5.4. Figure 5.4 also shows that the higher the annual increment of the CO_2 tax, the greater the emission reduction.

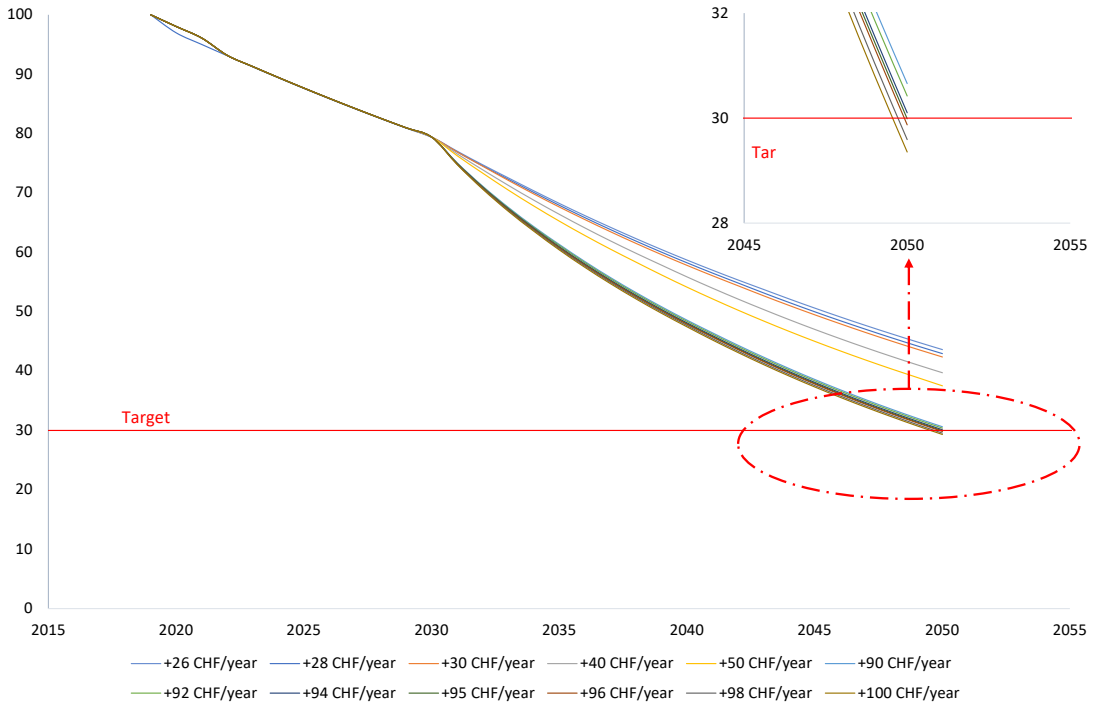


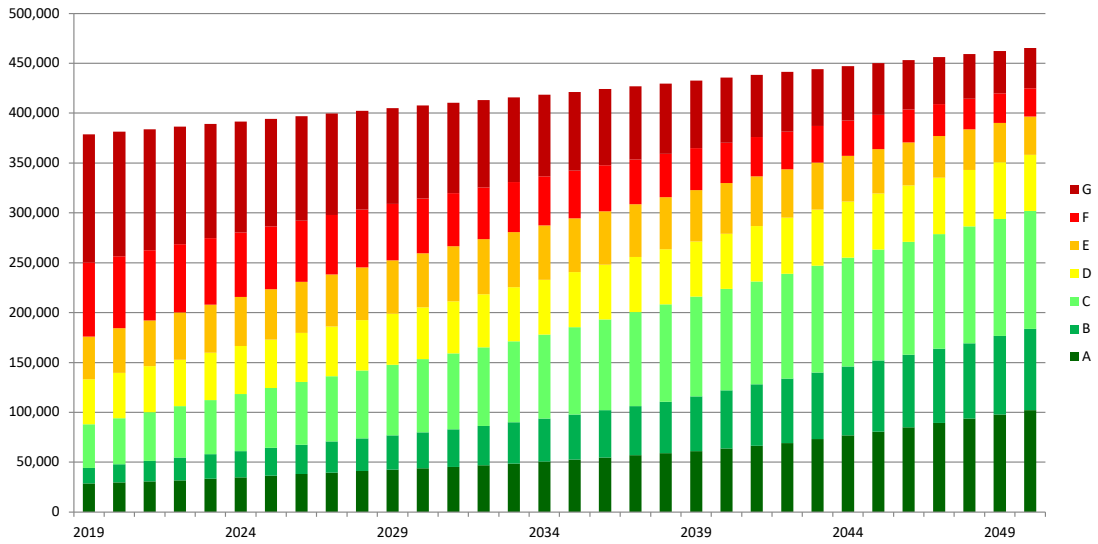
Figure 5.4: CO_2 emissions for all simulations in KL-RIP scenario from 2019 to 2050

Figure 5.5a and Figure 5.5b show the evolution of the absolute value and share of ERA for each energy class in the *KL-RIP (+95 CHF/year)* scenario from 2019 to 2050, respectively. The total ERA increases by about 23%, with increases in ERA for energy classes A, B, C and D, and decreases in E, F and G. The share of ERA for each energy class changes accordingly. The combined share of energy classes A, B and C increases substantially from 23% to 65%, and the share of D doesn't change, while the combined shares of E, F and G decrease from 65% to 23%.

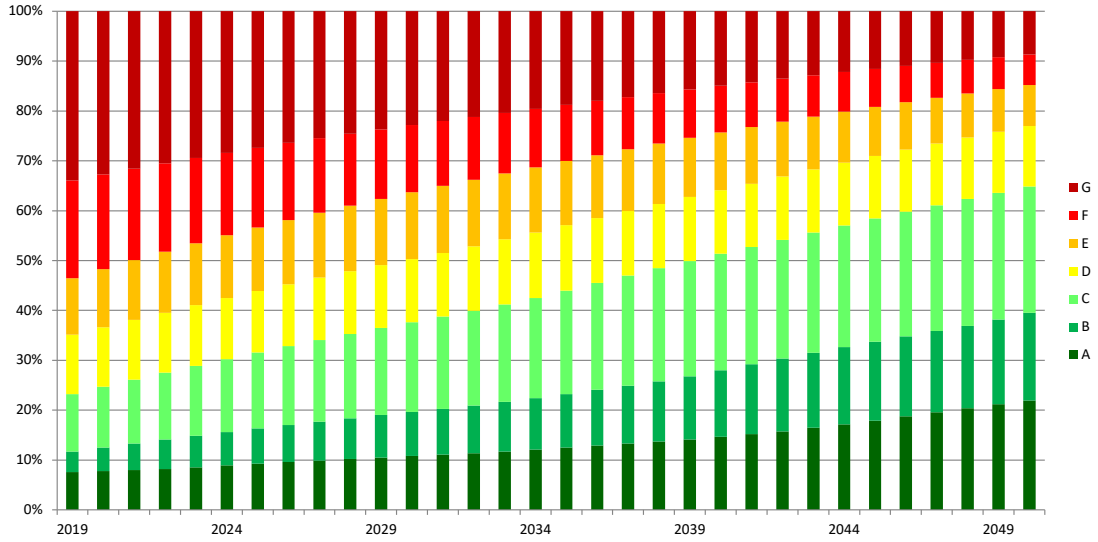
Figure 5.6 shows the retrofit dynamics of the *KL-RIP (+95 CHF/year)* scenario, where it can be seen that the growth of energy class A, B, C and D is due to the retrofit of E, F and G. In 2049

and 2050, a small amount of energy class D is also retrofitted to a more energy efficient energy class. The share of buildings retrofitted to energy class A increases gradually. New construction also leads to an increase in energy classes A, B and C. A larger share of new construction is initially in class C, and later more in classes A and B. This is due to the significant increase in CO_2 taxes leading to a more cost effective option to invest in new buildings with higher energy efficiency.

The *KL-RIP (+95 CHF/year)* scenario has an average retrofit rate of 1.03% from 2020 to 2050, slightly higher than the 0.81% of the baseline scenario (see Table 5.3). The retrofit investment increases by 67.9% compared to the baseline scenario, while the total CO_2 emission reduction increases to 70.0% from 44.8%. The average energy demand in 2050 is 58.0 kWh/m^2, which is 13% lower than the baseline scenario, indicating that the energy efficiency of the building envelope is higher than the baseline scenario.

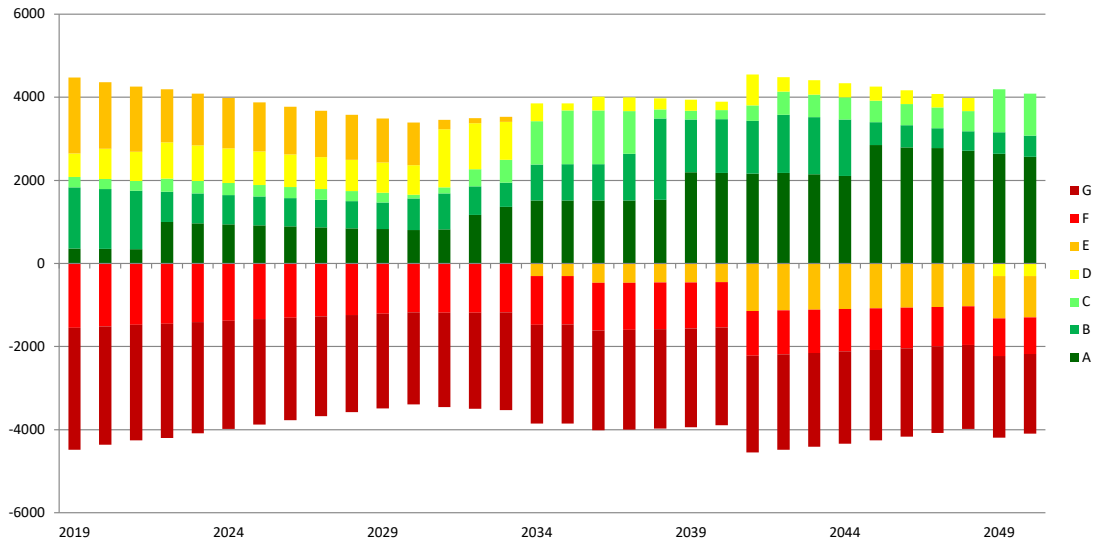


(a) Energy reference area per energy class, in 1000 m^2

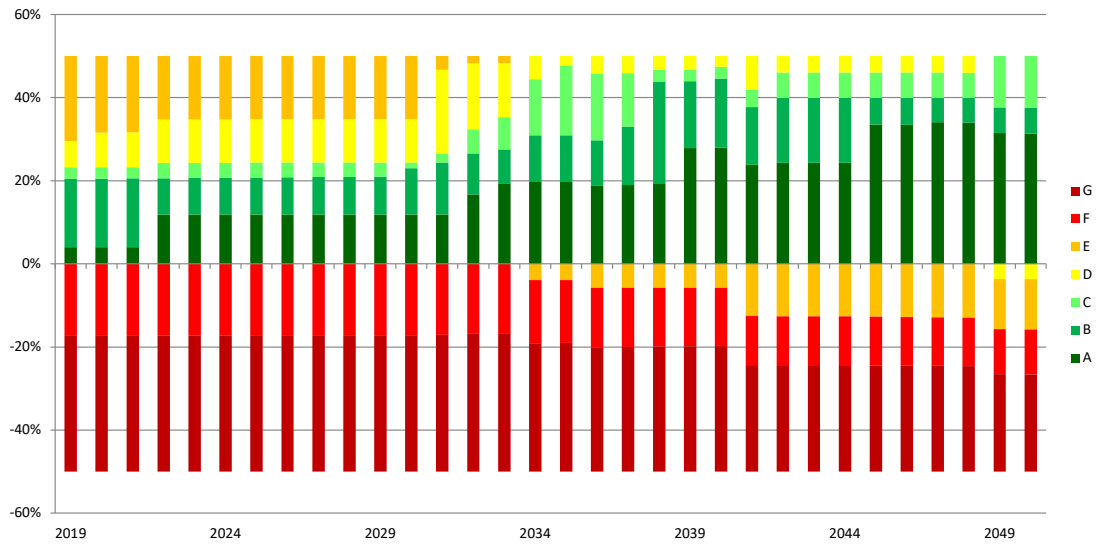


(b) Energy reference area share per energy class

Figure 5.5: Evolution of the energy reference area per energy class - KL-RIP scenario (+95 CHF/year)

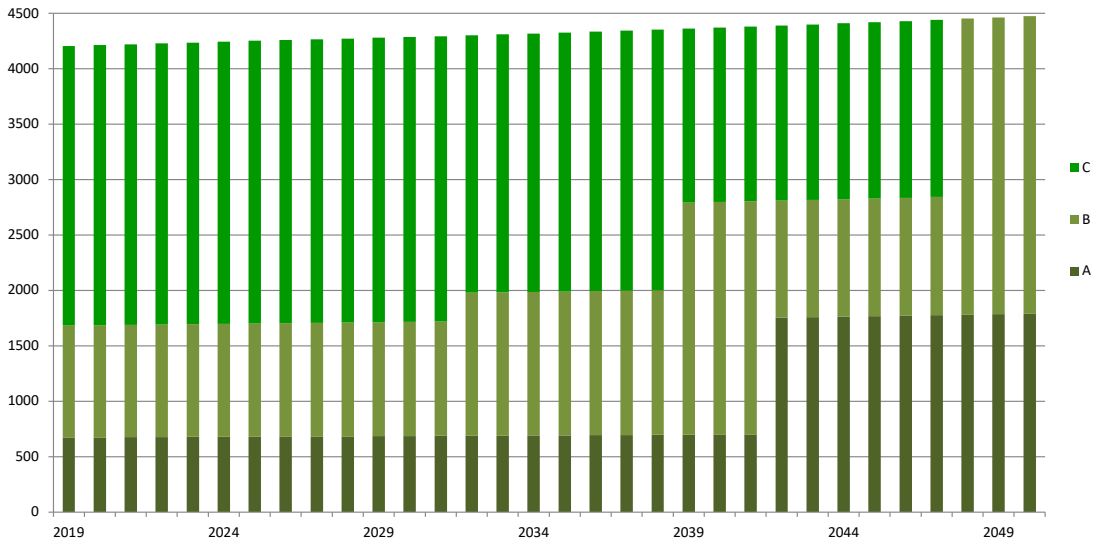


(a) Energy reference area for retrofitting per energy class, in 1000 m^2

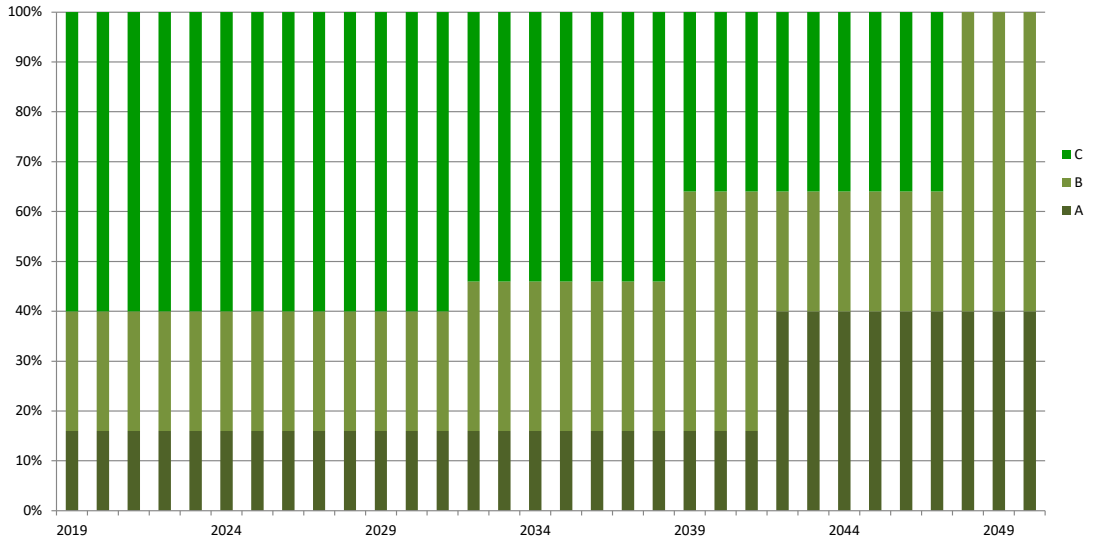


(b) Energy reference area share for retrofitting per energy class

Figure 5.6: Evolution of the energy reference area for retrofitting per energy class - KL-RIP scenario (+95 CHF/year)



(a) Energy reference area for new construction per energy class, in 1000 m^2



(b) Energy reference area for new construction share per energy class

Figure 5.7: Evolution of the energy reference area for new construction per energy class - KL-RIP scenario (+95 CHF/year)

5.3 GIP scenario

In the GIP scenario, the CO_2 tax in 2019 is an actual tax rate of 96 CHF/tCO_2, which grows at a constant yearly increment of Tax_YI from 2019 to 2050.

To find the minimum Tax_YI, a total of seven simulations were performed, whose Tax_YI and CO_2 tax evolution are shown in Table C.3. Figure 5.8 shows the CO_2 emissions from 2019 to 2050 for all simulations in the GIP scenario, which demonstrates that to reach a 70% reduction, the CO_2 tax would need to increase by at least 48 CHF per year.

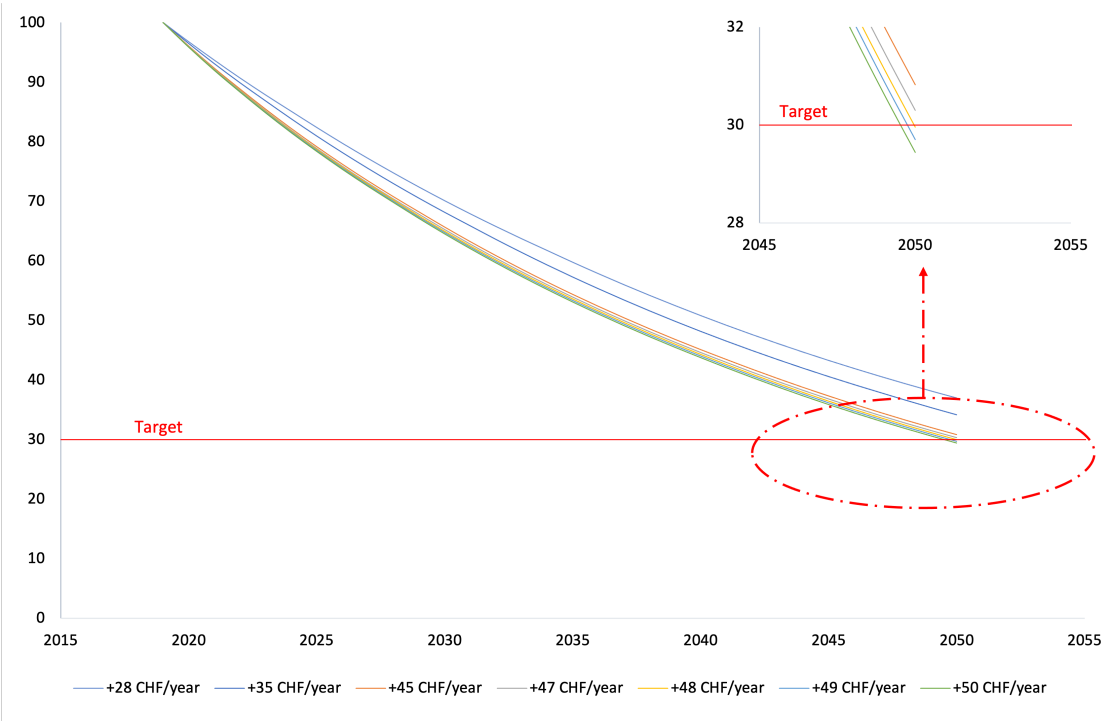
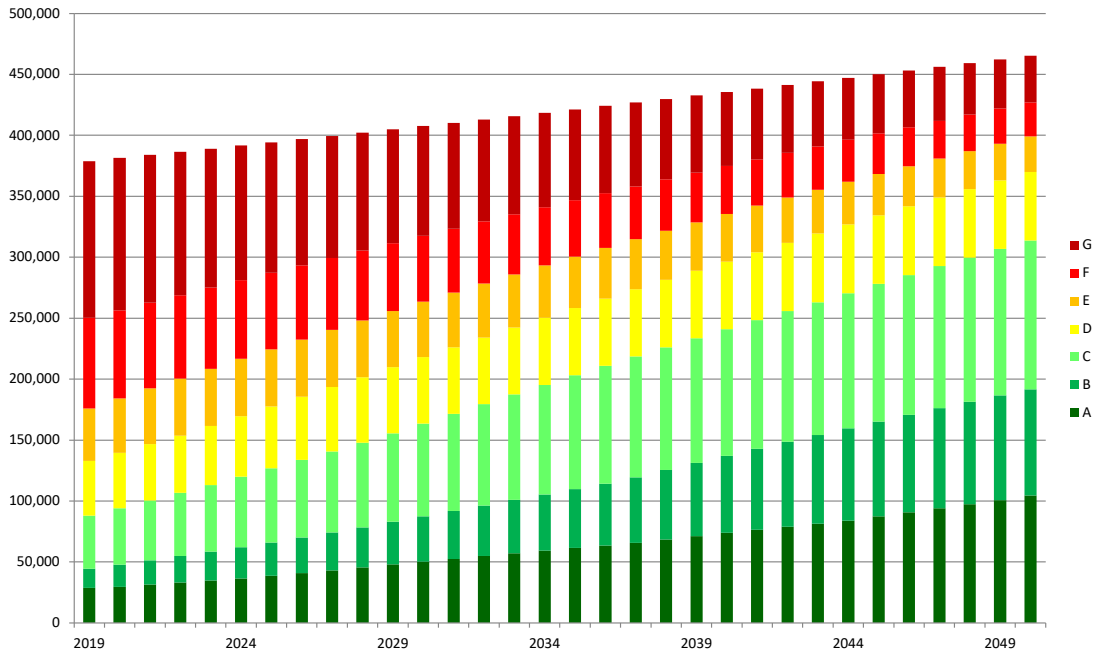


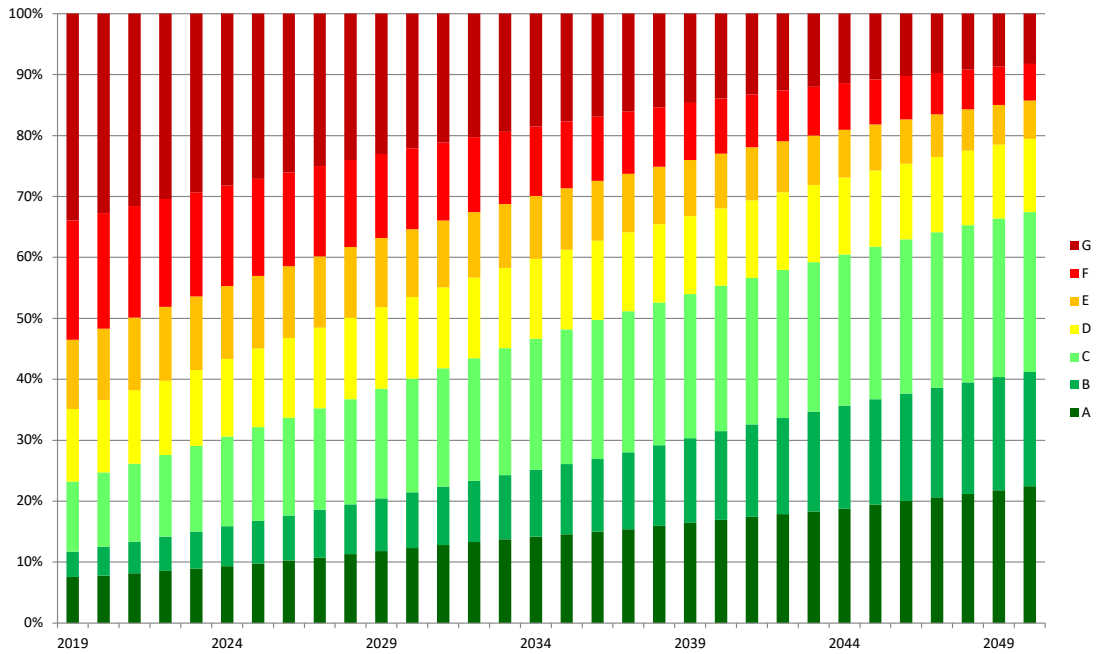
Figure 5.8: CO_2 emissions for all simulations in GIP scenario from 2019 to 2050

The growth in total ERA is the same for all scenarios, with an increase of 23%. In the *GIP (+48 CHF/year)* scenario, buildings with energy classes A, B, C and D increases, while buildings with energy classes E, F and G decreases, as shown in Figure 5.9. The combined share of energy classes A, B, and C increases from 23% to 67%, while the combined share of E, F, and G decreases from 65% to 21%. The *GIP (+48 CHF/year)* scenario has a higher average retrofit rate of 1.06% compared to the baseline and *KL-RIP (+95 CHF/year)* scenarios (see Table 5.3), implying that more energy inefficient buildings are being retrofitted, as shown in Figure 5.10. At the beginning, buildings of energy classes F and G are retrofitted, and from 2028 onwards more and more buildings of energy class E are retrofitted. The retrofitted buildings are mainly of energy classes D and E at the beginning, and later the vast majority are of energy classes A, B and C. Similar to the *KL-RIP (+95 CHF/year)* scenario, the share of new buildings with energy classes A and B grows gradually over time, as shown in Figure 5.11.

Compared to the baseline scenario, the *GIP (+48 CHF/year)* scenario has an 85.2% increase in retrofit investment, and the total CO_2 reduction rises from 44.8% to 70.0%. The average energy demand in 2050 is 56.3 kWh/m^2, which is close to the *KL-RIP (+95 CHF/year)* and lower than the 66.4 kWh/m^2 of the baseline scenario.

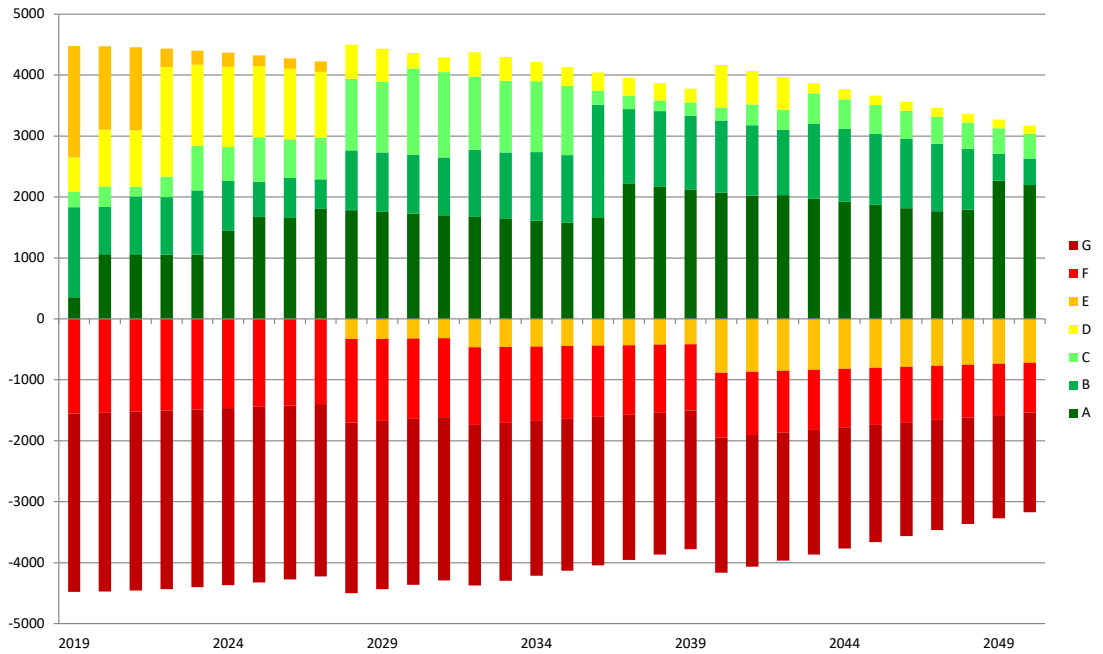


(a) Energy reference area per energy class, in 1000 m^2

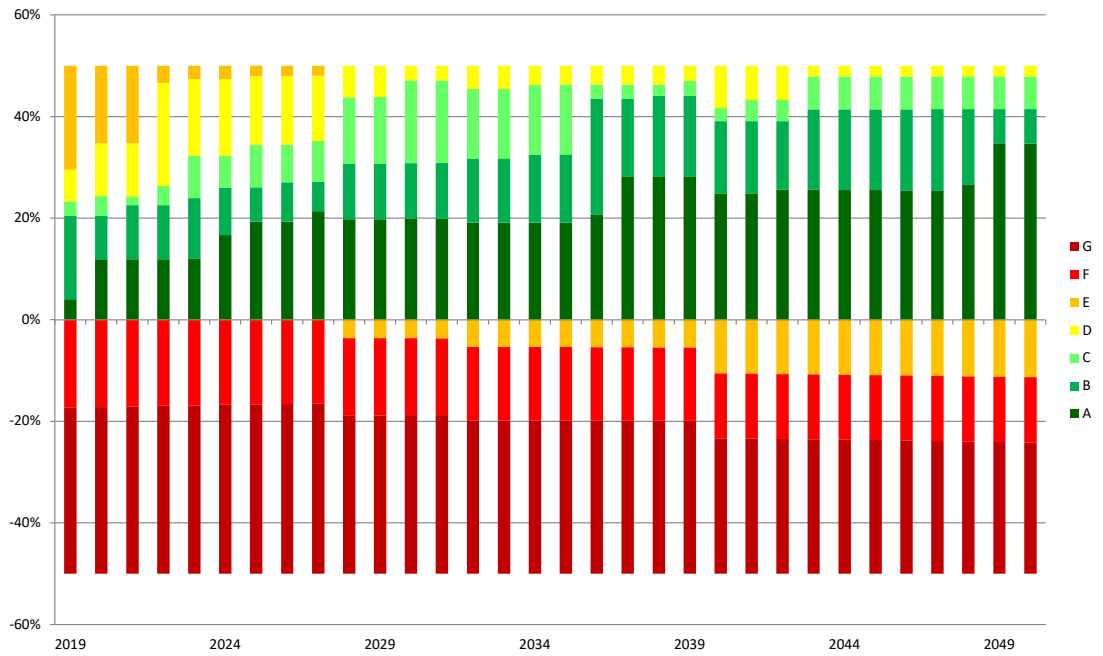


(b) Energy reference area share per energy class

Figure 5.9: Evolution of the energy reference area per energy class - GIP scenario (+48 CHF/year)

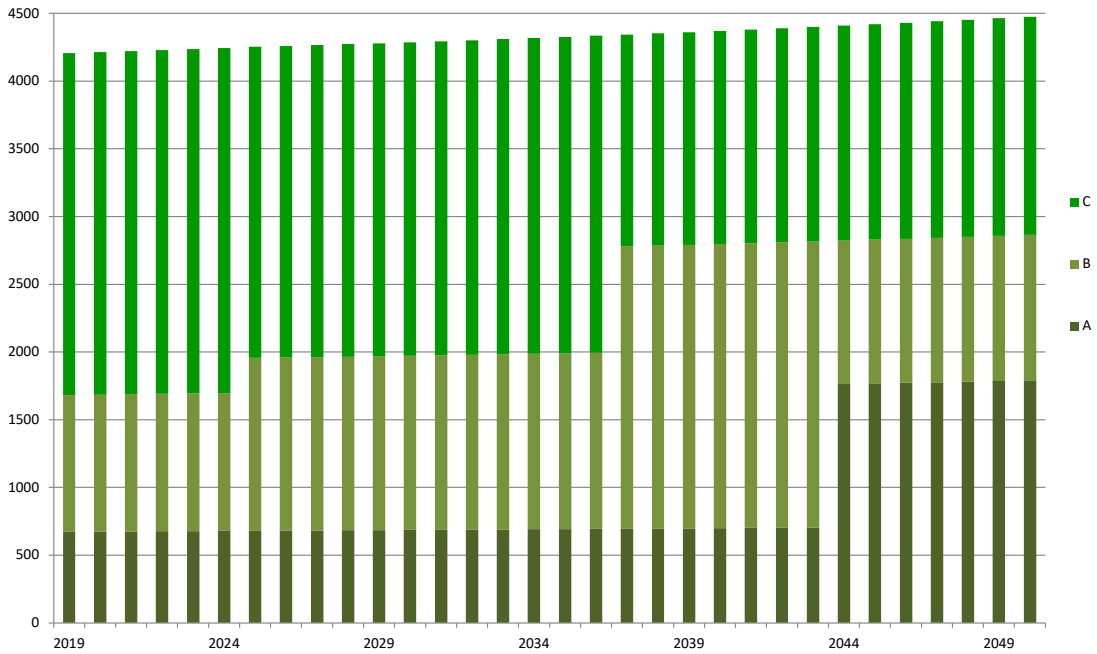


(a) Energy reference area for retrofitting per energy class, in 1000 m^2

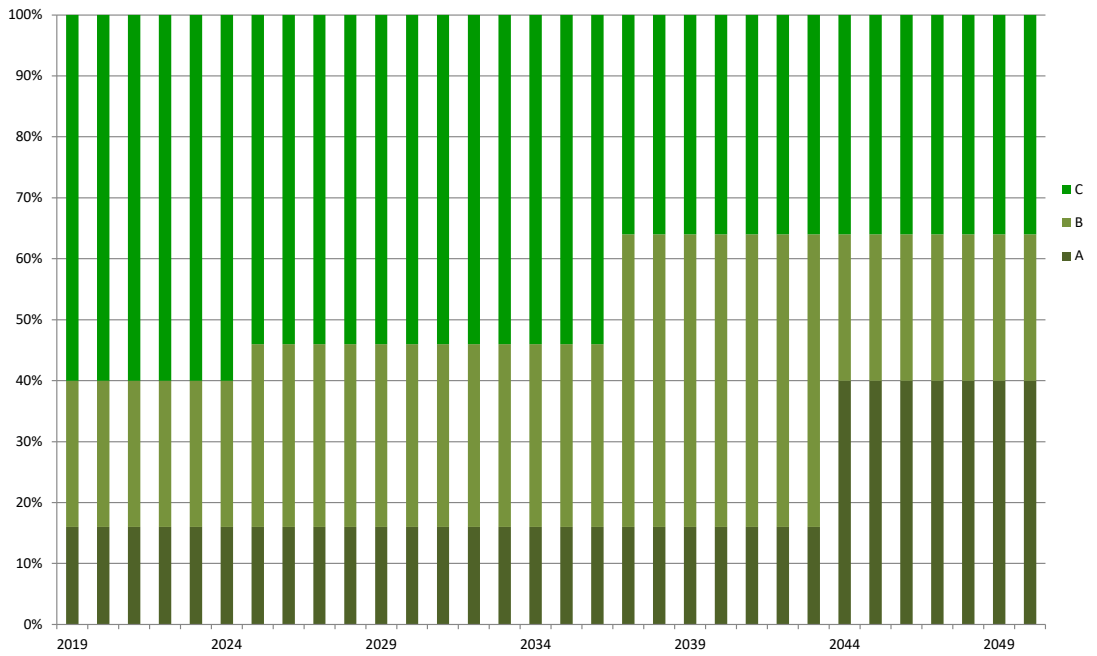


(b) Energy reference area share for retrofitting per energy class

Figure 5.10: Evolution of the energy reference area for retrofitting per energy class - GIP scenario (+48 CHF/year)



(a) Energy reference area for new construction per energy class, in 1000 m^2



(b) Energy reference area for new construction share per energy class

Figure 5.11: Evolution of the energy reference area for new construction per energy class - GIP scenario (+48 CHF/year)

5.4 RI-KHP scenario

In the RI-KHP scenario, the CO_2 tax rapidly increases at first and then keeps constant at a high level. Specifically, the CO_2 tax is the actually implemented tax rate of 96 CHF/tCO_2 in 2019; increases at a constant yearly increment of Tax_YI from 2019 to 2030; and keeps the tax rate of 2030 constant from 2030 to 2050.

Twelve simulations were performed in the RI-KHP scenario, whose Tax_YI and CO_2 tax evolution are shown in Table C.4. As shown in Figure 5.12, to reach a 70% emission reduction in the RI-KHP scenario, the CO_2 tax requires an increase of at least 101 CHF per year between 2020 and 2030.

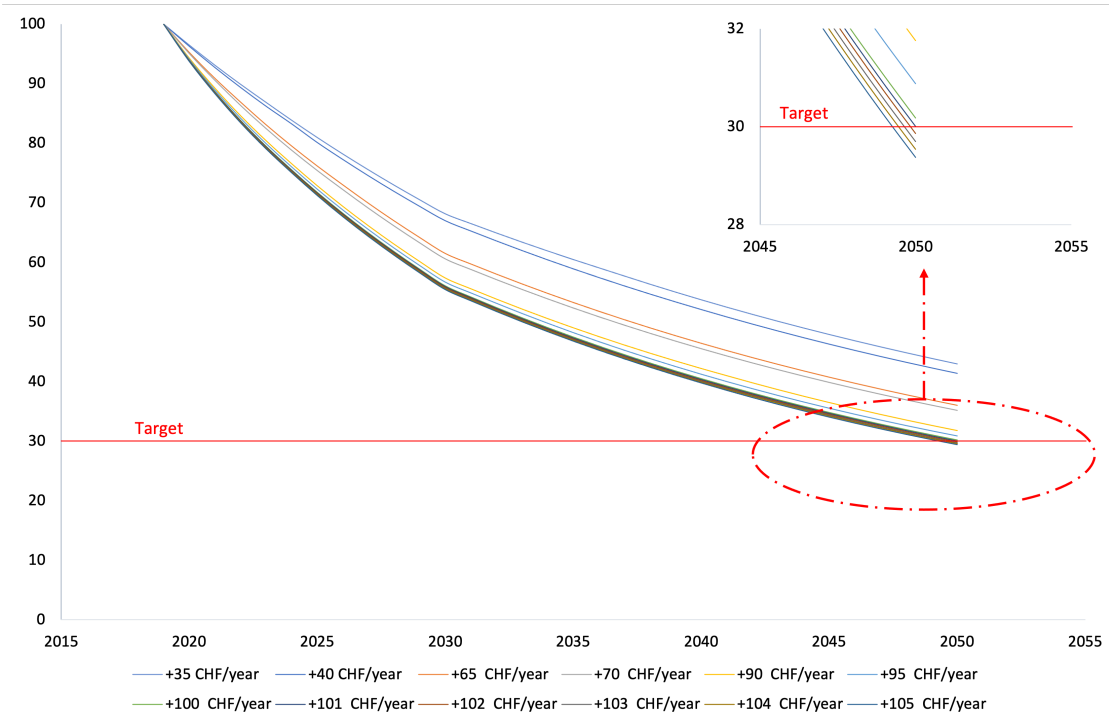
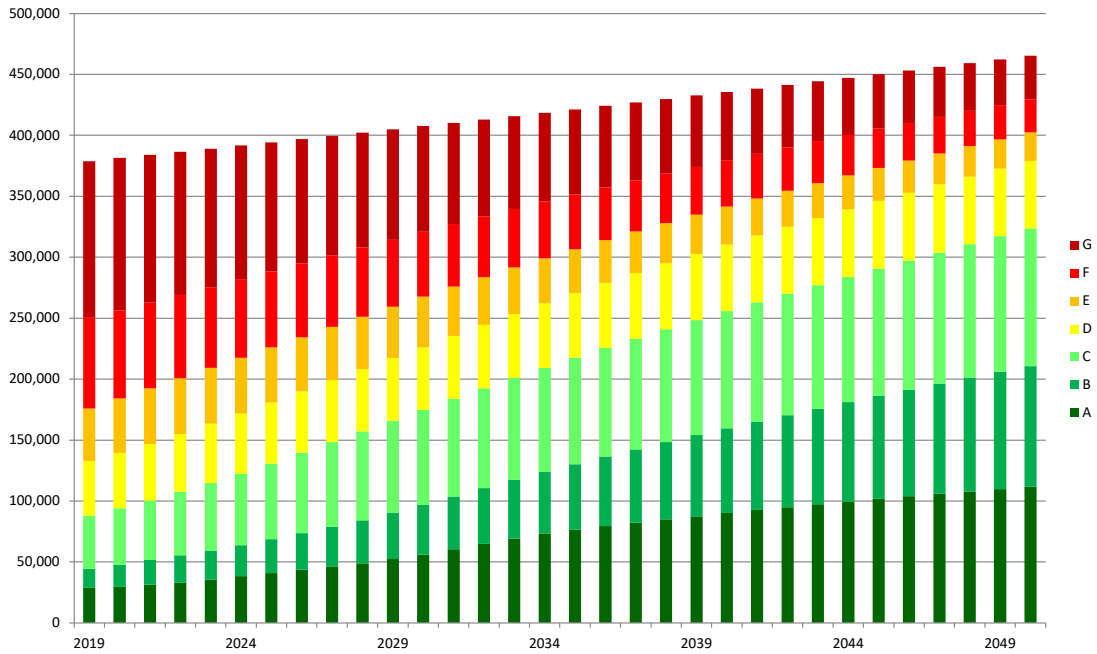


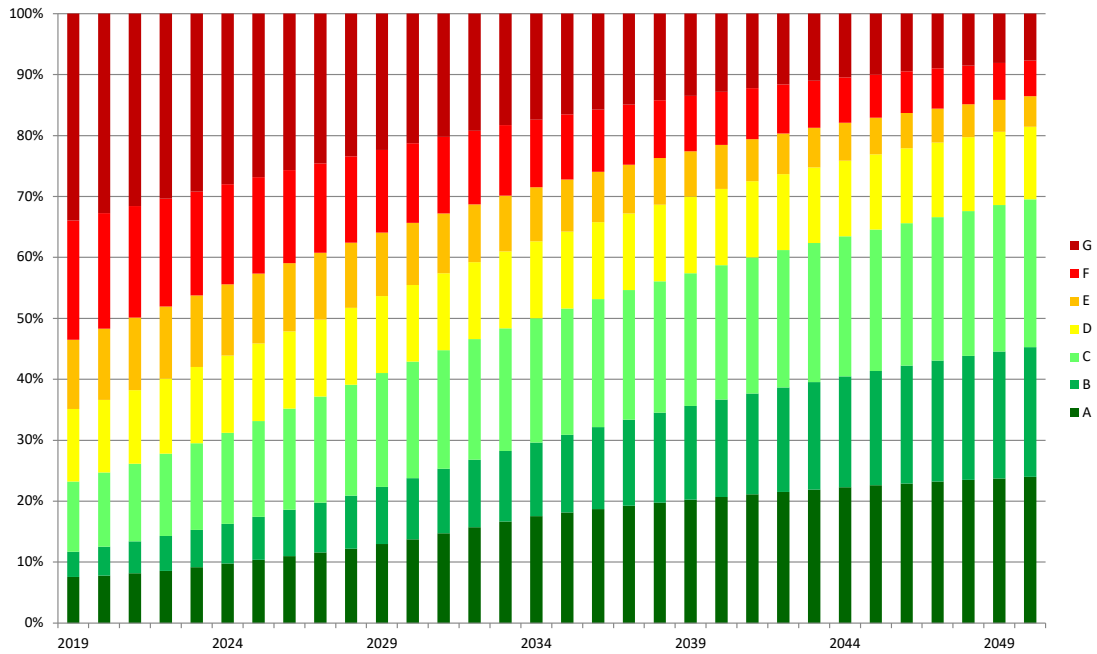
Figure 5.12: CO_2 emissions for all simulations in RI-KHP scenario from 2019 to 2050

In the *RI-KHP (+101 CHF/year)* scenario, the share of buildings in energy classes A, B and C increases from 23% to 70%, while the share of buildings in energy classes E, F and G decreases from 65% to 19%, as shown in Figure 5.13. The average retrofit rate increases to 1.13%, while the retrofit investment rises by 106.9% compared to the baseline scenario (see Table 5.3). The retrofit dynamics are similar to the GIP (+48 CHF/year) scenario, with the majority of retrofitted buildings initially in the energy classes D and E and later in the energy classes A, B and C. As for new constructions, there is a trend towards an increasing share of A and B in new buildings.

In the *RI-KHP (+101 CHF/year)* scenario, the average energy demand in 2050 is 54.1 kWh/m^2, which is 18% lower than the baseline scenario.

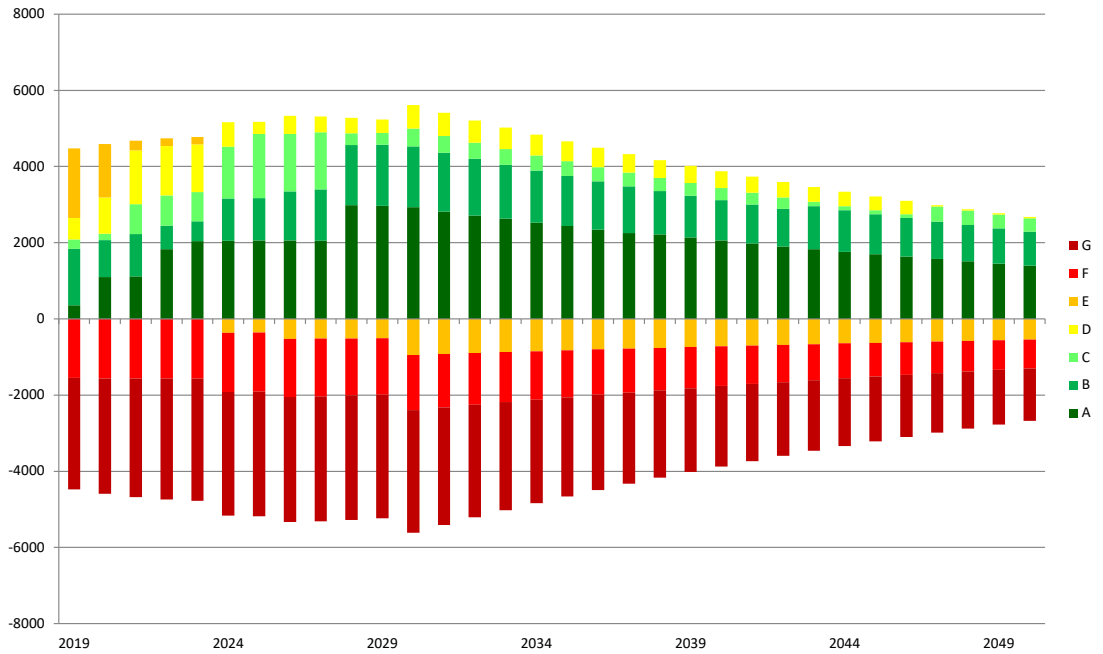


(a) Energy reference area per energy class, in 1000 m^2

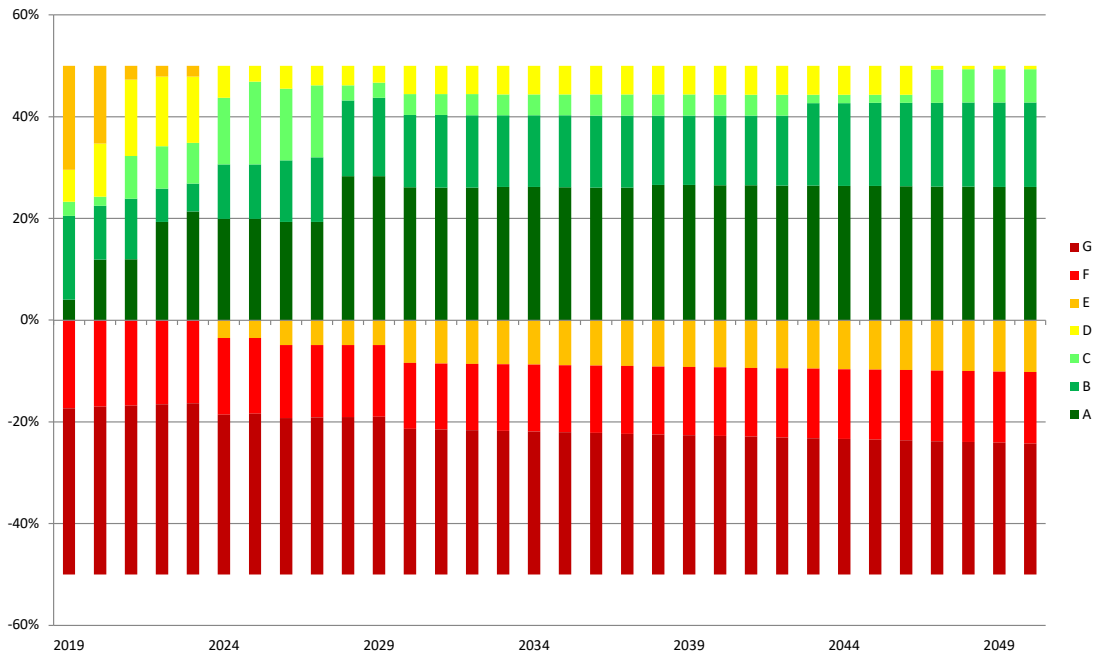


(b) Energy reference area share per energy class

Figure 5.13: Evolution of the energy reference area per energy class - RI-KHP scenario (+101 CHF/year)

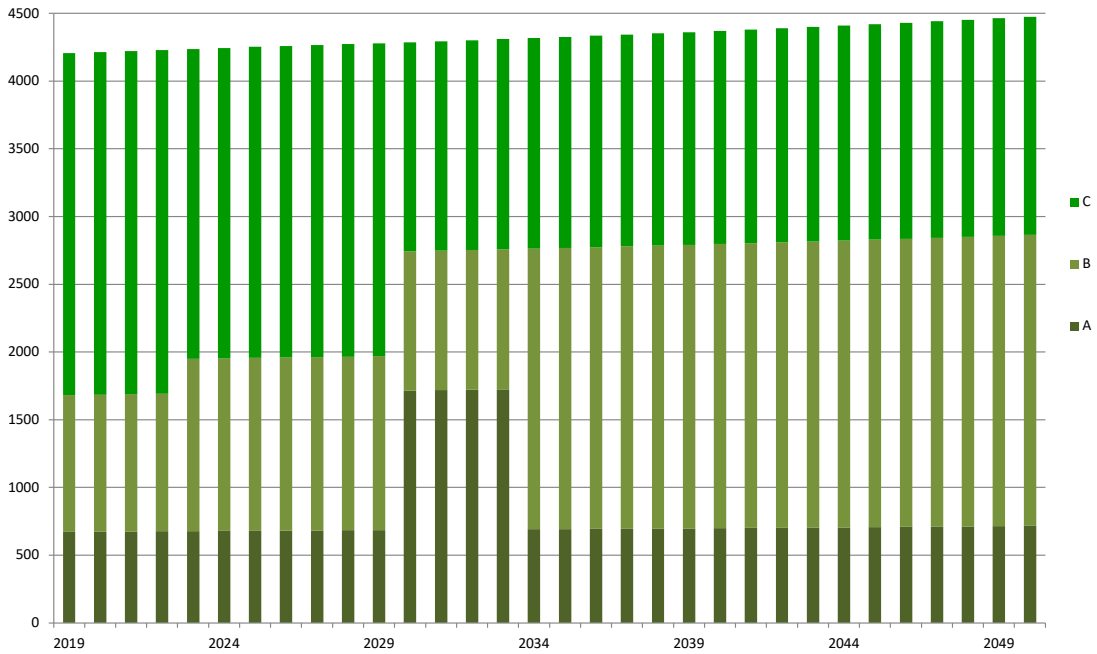


(a) Energy reference area for retrofitting per energy class, in 1000 m^2

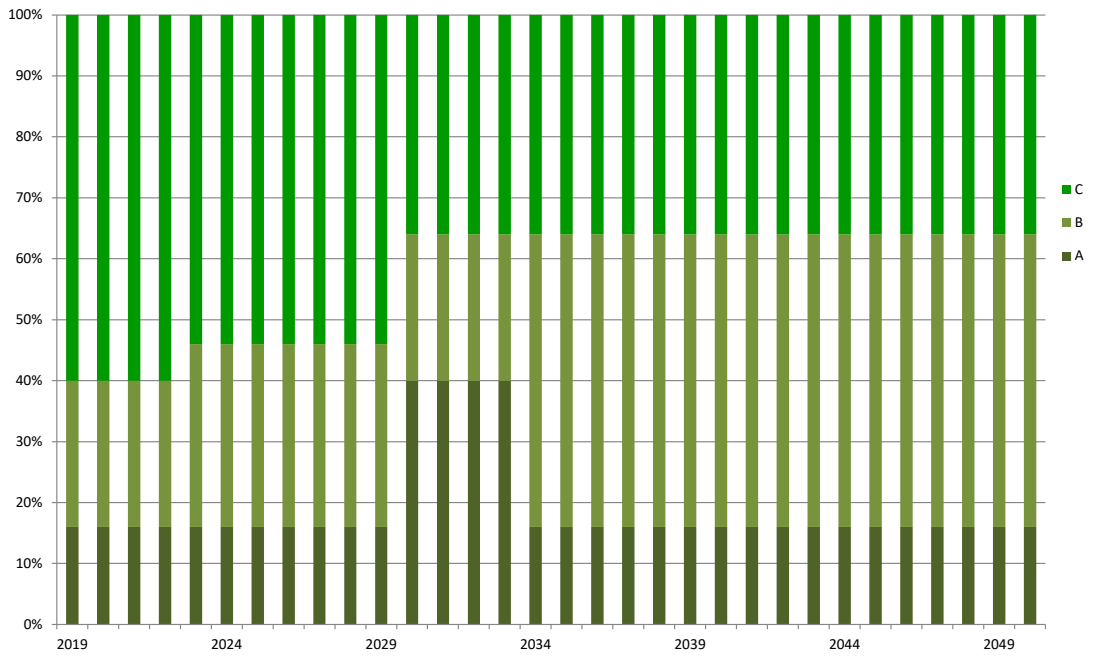


(b) Energy reference area share for retrofitting per energy class

Figure 5.14: Evolution of the energy reference area for retrofitting per energy class - RI-KHP scenario (+101 CHF/year)



(a) Energy reference area for new construction per energy class, in 1000 m^2



(b) Energy reference area for new construction share per energy class

Figure 5.15: Evolution of the energy reference area for new construction per energy class - RI-KHP scenario (+101 CHF/year)

5.5 Comparison of all scenarios

Table 5.3 compares the baseline scenario and the three CO_2 tax growth scenarios that achieve a 70% reduction with minimum Tax_YI. Figure 5.16 shows the total CO_2 emissions and CO_2 growth paths for all these four scenarios.

Table 5.3: Comparison of all simulations

Scenarios	**Year 2019**	**Baseline**	**KL-RIP**	**GIP**	**RI-KHP**
Minimum Tax_YI to meet 70% reduction (CHF/year)			+95	+48	+101
2050 CO_2 tax value (CHF/ton CO_2)	96	120	2020	1584	1207
Average value for 2020-2050					
Retrofit rate, average	1.23%	0.81%	1.03%	1.06%	1.13%
Retrofit rate, type 1 ('best')	1.74%	1.23%	1.35%	1.38%	1.41%
Retrofit rate, type 6 ('worst')	1.18%	0.74%	0.97%	0.96%	1.05%
Sum 2020-2050 compared to baseline					
Retrofit investment		0.0%	67.9%	85.2%	106.9%
2050 compared to 2019					
Useful energy demand per m^2 (kWh)		-34.4%	-41.8%	-43.4%	-45.6%
Useful energy demand total (MWh)		-17.3%	-26.5%	-28.6%	-31.4%
CO_2 emissions per m^2 (kg)		-56.3%	-76.2%	-76.3%	-76.2%
CO_2 emissions total (mton)		-44.8%	-70.0%	-70.0%	-70.0%

The *RI-KHP (+101 CHF/year)* scenario has the highest average retrofit rate (1.13%), followed by *GIP (+48 CHF/year)*, and finally *KL-RIP (+95 CHF/year)*, with little difference among them. However, compared to the baseline scenario, all these three scenarios have a significant increase in the average retrofit rate, with the *RI-KHP (+101 CHF/year)* scenario increasing by 39%. In addition, the CO_2 tax increase has a particularly significant effect on the retrofit rate increase for owner type 6, which increases by 42% (from 0.74% to 1.05%) in the *RI-KHP (+101 CHF/year)* scenario, whereas the increase for owner type 1 is only 15% (from 1.23% to 1.41%).

For both the average unit energy demand (in kWh/m^2) and total energy demand (in MWh), the *RI-KHP (+101 CHF/year)* scenario shows the greatest decrease compared to 2019, although the difference remains very small in the three CO_2 tax growth scenarios. The decrease in total energy demand (in MWh) is always lower than the decrease in average unit energy demand (in kWh/m^2) is due to the growth in total ERA.

All three CO_2 tax growth scenarios achieve a 70% reduction in total CO_2 emissions compared to 2019 (equivalent to an 80% reduction compared to 1990), which is higher than the 44.8% reduction in the baseline scenario. However, this also results in a significant increase in retrofit

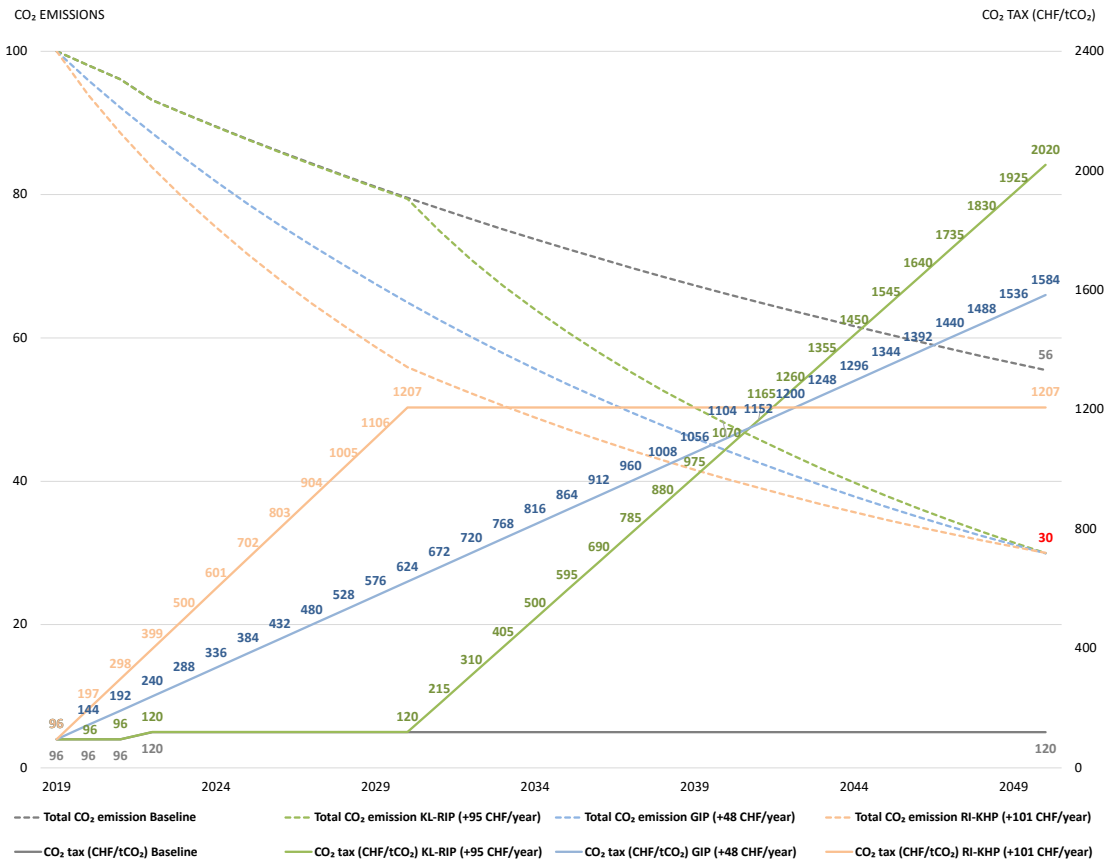


Figure 5.16: CO_2 tax and total CO_2 emissions for all simulations from 2019 to 2050

investment, with the *KL-RIP (+95 CHF/year)*, *GIP (+48 CHF/year)*, and *RI-KHP (+101 CHF/year)* scenarios increasing by 67.9%, 85.2%, and 106.9%, respectively, compared to the baseline scenario.

It is difficult to judge which CO_2 tax increase scenario is the best option, because the political resistance, public acceptance, etc. will be influential factors in the implementation of CO_2 tax policies. If we just consider the numerical results in Table 5.3, the *KL-RIP (+95 CHF/year)* scenario seems to be the best choice, as it has a significantly lower retrofit investment with other indicators (retrofit rate, energy efficiency, emission reductions) being approximately the same. However, when looking at the CO_2 tax increase, the *KL-RIP (+95 CHF/year)* scenario has the highest tax rate among all scenarios in 2050, reaching 2020 CHF/tCO_2, which is about 17 times the current rate (120 CHF/tCO_2). This is a very dramatic value. Certainly, not only the *KL-RIP (+95 CHF/year)* scenario, but also the *GIP (+48 CHF/year)* and *RI-KHP (+101 CHF/year)* scenarios reach extremely high CO_2 taxes by 2050, which are 1584 CHF/tCO_2 and 1207 CHF/tCO_2, respectively. When considering the acceptability, a gradual increasing CO_2 tax policy might have a higher public acceptance than a sudden rapid growth in CO_2 tax after a few years.

In any case, however, the tax rates in all three CO_2 tax increase scenarios seem to be impractical. These CO_2 taxes high enough to hit the target would have a huge impact on the economy. Switzerland already has one of the highest CO_2 taxes in the world today, as shown in Figure 2.2. There are significant differences in carbon tax rates across countries, and these differences would also act as resistance to increasing the carbon tax. Political resistance, public acceptance, and concerns about reduced international competitiveness will all deter an increase in carbon taxes.

Overall, while it is theoretically possible to achieve an 80% reduction in emissions by 2050 compared to 1990 through an increase in the CO_2 tax, it is unlikely to be implemented in practice. A carbon tax is an effective tool for reducing emissions, but it must be used in conjunction with other measures.

6 Conclusion and policy implications

In this thesis, a two-step decision building stock model is applied to simulate the abatement effect of CO_2 taxes on residential buildings in Switzerland. Three different CO_2 tax increase scenarios were considered and the simulations showed that to reduce CO_2 emissions from residential buildings in Switzerland by 80% in 2050 compared to 1990, the following increasing conditions would need to be met, respectively.

1. **KL-RIP**: 2019-2021: 96 CHF/tCO_2; 2022-2030: 120 CHF/tCO_2; 2031-2050: +95 CHF/year.
2. **GIP**: 2019: 96 CHF/tCO_2; 2020-2050: +48 CHF/year.
3. **RI-KHP**: 2019: 96 CHF/tCO_2; 2020-2030: +101 CHF/year; 2031-2050: remain at the same level as in 2030.

Compared to the baseline scenario of 44.8% reduction (relative to 2019), it is evident that all three carbon tax increase scenarios promote CO_2 reductions (70% reduction relative to 2019). However, the conditions for their achievement are very demanding, as all three scenarios require very high CO_2 tax increases. In 2050, the *KL-RIP (+95 CHF/year)*, *GIP (+48 CHF/year)*, and *RI-KHP (+101 CHF/year)* scenarios all reach very high CO_2 tax rates of 2020 CHF/tCO_2, 1584 CHF/tCO_2, and 1207 CHF/tCO_2, respectively. These exorbitantly high tax rates are very impractical.

Moreover, the effect of increasing the CO_2 tax on abatement declines as the tax rate increases. The implication of this statement is that suppose a CO_2 tax increase from 100 CHF/tCO_2 to 200 CHF/tCO_2 (doubling) reduces CO_2 emissions by 10%, while from 100 CHF/tCO_2 to 300 CHF/tCO_2 (tripling) the reduction is likely not to reach 20%, which is also reflected in Figure 5.4, 5.8 and 5.12. This may be due to the relatively low elasticity of energy. Even with continued increases in CO_2 taxes, the absence of alternatives prevents people from shifting to a further low carbon path.

In conclusion, it is true that a CO_2 tax is a powerful instrument for abatement, which could promote innovation in energy-efficient technologies and prompt consumers to choose cleaner,

renewable energy sources. Nevertheless, it would be irrational to pin all hopes of reducing CO_2 emissions on a CO_2 tax. As it is clear that a CO_2 tax alone will be impractical to achieve the set reduction targets, it must be combined with other financial instruments (e.g., increase retrofit subsidies), regulatory instruments (e.g., building certificate, higher regulations on building energy efficiency, setting standards for heating equipment and energy efficiency in new buildings), and informative instruments.

A Cantonal Energy Classes for Buildings

Switzerland introduced the Cantonal Energy Certificate for Building (CECB/GEAK) in 2009, which was created by the Conference of Cantonal Energy Directors (EnDK) [I].

The CECB certificate applies to buildings that have been constructed and are in use, which provides information on the energy efficiency of the building envelope and the amount of energy consumed by the building in the standard way (heating, domestic hot water, and electrical technical equipment). The CECB certificate is an effective evaluation and advisory tool for building renovation projects and is applicable nationwide.

The CECB represents the efficiency of the building envelope and the end energy use through an energy label ranging from A (very energy efficient) to G (not very energy efficient) (see Table A.1).

[I] https://www.cecb.ch/

Table A.1: CECB energy classes

Energy Class	Efficiency of the building envelope	Overall energy efficiency	Average energy consumption in 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

B Energy Reference Area

The energy reference area (ERA) distributed in each construction period and energy class was obtained by a calculation based on data from SFOE and four different surveys.

Firstly, the ERA for each construction period was calculated based on the data of the amount of houses in each construction period and the average area of houses in Switzerland, which was obtained from SFOE.

Secondly, the energy class allocation of the ERA for each construction period was further calculated from the building energy use data from four different surveys, which were provided by Société Coopérative d'Habitation Lausanne (SCHL), Allgemeine Baugenossenschaft Zürich (ABZ), Estia and die Mobiliar.

C The CO_2 tax over time (2019-2050) for all scenarios

C.1 Baseline scenario

Table C.1: The CO_2 tax over time (2019-2050) for baseline scenario

Year	**CO_2 tax (CHF/year)**
2019	96
2020	96
2021	96
2022-2050	120

C.2 KL-RIP scenario

Table C.2: The CO_2 tax over time (2019-2050) for KL-RIP scenario

	Yearly CO_2 tax increment (CHF/year)											
Year	+26	+28	+30	+40	+50	+90	+92	+94	**+95**	+96	+98	+100
2019	96	96	96	96	96	96	96	96	**96**	96	96	96
2020	96	96	96	96	96	96	96	96	**96**	96	96	96
2021	96	96	96	96	96	96	96	96	**96**	96	96	96
2022	120	120	120	120	120	120	120	120	**120**	120	120	120
2023	120	120	120	120	120	120	120	120	**120**	120	120	120
2024	120	120	120	120	120	120	120	120	**120**	120	120	120
2025	120	120	120	120	120	120	120	120	**120**	120	120	120
2026	120	120	120	120	120	120	120	120	**120**	120	120	120
2027	120	120	120	120	120	120	120	120	**120**	120	120	120
2028	120	120	120	120	120	120	120	120	**120**	120	120	120
2029	120	120	120	120	120	120	120	120	**120**	120	120	120
2030	120	120	120	120	120	120	120	120	**120**	120	120	120
2031	146	148	150	160	170	210	212	214	**215**	216	218	220
2032	172	176	180	200	220	300	304	308	**310**	312	316	320
2033	198	204	210	240	270	390	396	402	**405**	408	414	420
2034	224	232	240	280	320	480	488	496	**500**	504	512	520
2035	250	260	270	320	370	570	580	590	**595**	600	610	620
2036	276	288	300	360	420	660	672	684	**690**	696	708	720
2037	302	316	330	400	470	750	764	778	**785**	792	806	820
2038	328	344	360	440	520	840	856	872	**880**	888	904	920
2039	354	372	390	480	570	930	948	966	**975**	984	1002	1020
2040	380	400	420	520	620	1020	1040	1060	**1070**	1080	1100	1120
2041	406	428	450	560	670	1110	1132	1154	**1165**	1176	1198	1220
2042	432	456	480	600	720	1200	1224	1248	**1260**	1272	1296	1320
2043	458	484	510	640	770	1290	1316	1342	**1355**	1368	1394	1420
2044	484	512	540	680	820	1380	1408	1436	**1450**	1464	1492	1520
2045	510	540	570	720	870	1470	1500	1530	**1545**	1560	1590	1620
2046	536	568	600	760	920	1560	1592	1624	**1640**	1656	1688	1720
2047	562	596	630	800	970	1650	1684	1718	**1735**	1752	1786	1820
2048	588	624	660	840	1020	1740	1776	1812	**1830**	1848	1884	1920
2049	614	652	690	880	1070	1830	1868	1906	**1925**	1944	1982	2020
2050	640	680	720	920	1120	1920	1960	2000	**2020**	2040	2080	2120

C.3 GIP scenario

Table C.3: The CO_2 tax over time (2019-2050) for GIP scenario

	Yearly CO_2 tax increment (CHF/year)						
Year	+28	+35	+45	+47	**+48**	+49	+50
2019	96	96	96	96	**96**	96	96
2020	124	131	141	143	**144**	145	146
2021	152	166	186	190	**192**	194	196
2022	180	201	231	237	**240**	243	246
2023	208	236	276	284	**288**	292	296
2024	236	271	321	331	**336**	341	346
2025	264	306	366	378	**384**	390	396
2026	292	341	411	425	**432**	439	446
2027	320	376	456	472	**480**	488	496
2028	348	411	501	519	**528**	537	546
2029	376	446	546	566	**576**	586	596
2030	404	481	591	613	**624**	635	646
2031	432	516	636	660	**672**	684	696
2032	460	551	681	707	**720**	733	746
2033	488	586	726	754	**768**	782	796
2034	516	621	771	801	**816**	831	846
2035	544	656	816	848	**864**	880	896
2036	572	691	861	895	**912**	929	946
2037	600	726	906	942	**960**	978	996
2038	628	761	951	989	**1008**	1027	1046
2039	656	796	996	1036	**1056**	1076	1096
2040	684	831	1041	1083	**1104**	1125	1146
2041	712	866	1086	1130	**1152**	1174	1196
2042	740	901	1131	1177	**1200**	1223	1246
2043	768	936	1176	1224	**1248**	1272	1296
2044	796	971	1221	1271	**1296**	1321	1346
2045	824	1006	1266	1318	**1344**	1370	1396
2046	852	1041	1311	1365	**1392**	1419	1446
2047	880	1076	1356	1412	**1440**	1468	1496
2048	908	1111	1401	1459	**1488**	1517	1546
2049	936	1146	1446	1506	**1536**	1566	1596
2050	964	1181	1491	1553	**1584**	1615	1646

C.4 RI-KHP scenario

Table C.4: The CO_2 tax over time (2019-2050) for RI-KHP scenario

	Yearly CO_2 tax increment (CHF/year)											
Year	+35	+40	+65	+70	+90	+95	+100	**+101**	+102	+103	+104	+105
2019	96	96	96	96	96	96	96	**96**	96	96	96	96
2020	131	136	161	166	186	191	196	**197**	198	199	200	201
2021	166	176	226	236	276	286	296	**298**	300	302	304	306
2022	201	216	291	306	366	381	396	**399**	402	405	408	411
2023	236	256	356	376	456	476	496	**500**	504	508	512	516
2024	271	296	421	446	546	571	596	**601**	606	611	616	621
2025	306	336	486	516	636	666	696	**702**	708	714	720	726
2026	341	376	551	586	726	761	796	**803**	810	817	824	831
2027	376	416	616	656	816	856	896	**904**	912	920	928	936
2028	411	456	681	726	906	951	996	**1005**	1014	1023	1032	1041
2029	446	496	746	796	996	1046	1096	**1106**	1116	1126	1136	1146
2030	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2031	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2032	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2033	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2034	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2035	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2036	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2037	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2038	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2039	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2040	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2041	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2042	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2043	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2044	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2045	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2046	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2047	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2048	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2049	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251
2050	481	536	811	866	1086	1141	1196	**1207**	1218	1229	1240	1251

D Numerical results of simulations

Table D.1: The numerical results of all simulations

Scenarios		2050 CO_2 tax value (CHF/tCO_2)	Average value for 2020-2050			Sum 2020-2050 compared to baseline scenario	2050 compared to 2019			
			Retrofit rate, average	Retrofit rate, type 1 ('best')	Retrofit rate, type 6 ('worst')	Retrofit investment	Useful energy demand per m^2 (kWh)	Useful energy demand total (MWh)	CO_2 emissions per m^2 (kg)	CO_2 emissions total (mton)
Year 2019		96	1.23%	1.74%	1.18%					
Baseline		120	0.81%	1.23%	0.74%		-34.4%	-17.3%	-56.3%	-44.8%
KL-RIP	+26 CHF/year	640	0.87%	1.27%	0.77%	22.0%	-36.8%	-20.2%	-65.4%	-56.4%
	+28 CHF/year	680	0.88%	1.27%	0.77%	24.3%	-36.9%	-20.5%	-65.9%	-57.0%
	+30 CHF/year	720	0.88%	1.28%	0.77%	24.7%	-37.1%	-20.6%	-66.4%	-57.6%
	+40 CHF/year	920	0.90%	1.29%	0.78%	32.0%	-37.9%	-21.6%	-68.5%	-60.3%
	+50 CHF/year	1120	0.93%	1.30%	0.82%	39.1%	-38.5%	-22.5%	-70.3%	-62.5%
	+90 CHF/year	1920	1.02%	1.35%	0.97%	64.7%	-41.3%	-26.0%	-75.7%	-69.3%
	+92 CHF/year	1960	1.03%	1.35%	0.97%	65.4%	-41.5%	-26.2%	-75.9%	-69.6%
	+94 CHF/year	2000	1.03%	1.35%	0.97%	66.6%	-41.6%	-26.3%	-76.0%	-69.8%
	+95 CHF/year	**2020**	**1.03%**	**1.35%**	**0.97%**	**67.9%**	**-41.8%**	**-26.5%**	**-76.2%**	**-70.0%**
	+96 CHF/year	2040	1.03%	1.36%	0.97%	68.4%	-41.8%	-26.6%	-76.3%	-70.1%
	+98 CHF/year	2080	1.04%	1.36%	0.99%	69.5%	-41.9%	-26.8%	-76.5%	-70.4%
	+100 CHF/year	2120	1.04%	1.36%	0.99%	70.5%	-42.1%	-27.0%	-76.7%	-70.6%
GIP	+28 CHF/year	964	0.95%	1.33%	0.82%	52.5%	-39.9%	-24.2%	-70.7%	-63.0%
	+35 CHF/year	1181	0.99%	1.35%	0.87%	65.1%	-41.3%	-25.9%	-72.9%	-65.8%
	+45 CHF/year	1491	1.05%	1.38%	0.95%	80.8%	-42.9%	-28.0%	-75.6%	-69.2%
	+47 CHF/year	1553	1.05%	1.38%	0.95%	83.6%	-43.2%	-28.4%	-76.0%	-69.7%
	+48 CHF/year	**1584**	**1.06%**	**1.38%**	**0.96%**	**85.2%**	**-43.4%**	**-28.6%**	**-76.3%**	**-70.0%**
	+49 CHF/year	1615	1.06%	1.39%	0.96%	86.7%	-43.6%	-28.8%	-76.5%	-70.3%
	+50 CHF/year	1646	1.06%	1.39%	0.97%	88.2%	-43.7%	-29.0%	-76.7%	-70.6%
RI-KHP	+35 CHF/year	481	0.92%	1.30%	0.80%	43.5%	-38.8%	-22.8%	-66.0%	-57.1%
	+40 CHF/year	536	0.93%	1.31%	0.81%	50.0%	-39.5%	-23.7%	-67.2%	-58.7%
	+65 CHF/year	811	1.00%	1.36%	0.85%	69.2%	-41.8%	-26.6%	-71.4%	-64.0%
	+70 CHF/year	866	1.01%	1.37%	0.86%	75.6%	-42.5%	-27.4%	-72.1%	-64.9%
	+90 CHF/year	1086	1.08%	1.39%	0.96%	98.3%	-44.6%	-30.1%	-74.8%	-68.2%
	+95 CHF/year	1141	1.11%	1.40%	1.02%	102.2%	-45.1%	-30.7%	-75.5%	-69.1%
	+100 CHF/year	1196	1.12%	1.41%	1.05%	106.1%	-45.4%	-31.2%	-76.1%	-69.8%
	+101 CHF/year	**1207**	**1.13%**	**1.41%**	**1.05%**	**106.9%**	**-45.6%**	**-31.4%**	**-76.2%**	**-70.0%**
	+102 CHF/year	1218	1.13%	1.41%	1.05%	107.6%	-45.7%	-31.5%	-76.3%	-70.1%
	+103 CHF/year	1229	1.13%	1.42%	1.05%	109.0%	-45.9%	-31.7%	-76.5%	-70.3%
	+104 CHF/year	1240	1.13%	1.42%	1.05%	110.2%	-46.1%	-32.0%	-76.6%	-70.5%
	+105 CHF/year	1251	1.13%	1.42%	1.05%	111.2%	-46.2%	-32.2%	-76.7%	-70.6%

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