Schweizerische Eidgenossenschaft
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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final report

Endogenous energy efficiency improvement

Source: Alberto Masnovo, iStock, 2017

Date: 28.09.2021

Location: Lausanne and Zurich

Subsidiser:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Section
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
École Polytechnique Fédérale de Lausanne (EPFL)
Route Cantonale, 1015 Lausanne
https://www.epfl.ch

Infras AG
INFRAS, Binzstrasse 23, 8045 Zurich
Phone +41 44 205 95 95
https://www.infras.ch

Authors:
Philippe Thalmann, EPFL, philippe.thalmann@epfl.ch
Quirin Oberpriller, Infras AG, quirin.oberpriller@infras.ch
Sergey Arzoyan EPFL, sergey.arzoyan@epfl.ch
Marc Vielle, EPFL, marc.vielle@epfl.ch
Rolf Iten, Infras AG, rolf.iten@infras.ch

SFOE project coordinators:
Anne-Kathrin Faust, anne-kathrin.faustl@bfe.admin.ch

SFOE contract number: SH/8100087-00-01-03

The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.

Zusammenfassung

Es ist uns gelungen, zwei neuartige und funktionale Methoden zu erstellen, welche die Entwicklung von Energieeffizienzverbesserungen (EEI) in zwei Schweizer Sektoren darstellen. Dadurch konnten wir eine bessere Darstellung der durch die Energie- und Klimapolitik ausgelösten EEI erreichen. Obwohl wir best-möglich verfügbare Daten verwenden, um die Modelle zu kalibrieren, lag der Fokus dieser Übung nicht darin, präzise quantitative Ergebnisse zu erhalten. Vielmehr wollten wir einen «proof of concept» geben. Durch die Simulation verschiedener Politikszenarien über den Zeitraum 2015-2050 haben wir gezeigt, dass es wichtig ist, die Reaktion auf verschiedene Politiken zu berücksichtigen. So ist es zum Beispiel wichtig, nicht nur monetäre Anreize (wie Subventionen oder Steuern) zu berücksichtigen, sondern auch "weichere" Massnahmen wie z.B. Informationskampagnen. Dies gilt insbesondere für den Gebäudesektor, da viele Eigentümer unter unvollständiger Information leiden. Folglich kann ein bestimmtes Ziel zu geringeren Kosten erreicht werden, wenn eine intelligente Mischung aus harten und weichen Massnahmen eingesetzt wird.

Im Einzelnen sind die Modelle und relevantesten Ergebnisse wie folgt:

Wohngebäudemodell

Das Modell unterteilt den Schweizer Wohngebäudebestand in verschiedene Energieeffizienzklassen. Um die Sanierungsentscheidung der Eigentümer zu simulieren, haben wir ein zweistufiges Modell entwickelt. Im ersten Schritt sind den Eigentümern die Kosten und der Nutzen der Sanierung zunächst nicht bekannt. Ein bestimmter Prozentsatz der Eigentümer wird jedes Jahr dazu veranlasst, ihr Gebäude zu auditieren und das Potenzial für Energieeinsparungen zu berechnen. Im zweiten Schritt entscheiden sich solche Eigentümer für eine Nachrüstung, je nach dem Ergebnis einer Kosten-Nutzen-Analyse.

Wir haben ein Referenzszenario und verschiedene Politikszenarien berechnet, die jeweils mehr Sanierung als das Referenzszenario anregen. Besonders erwähnenswert sind die folgenden Ergebnisse unseres Modells: Selbst eine starke Erhöhung der CO_2-Abgabe (bis zu 1000 CHF pro Tonne CO2 im Jahr 2050) führt nicht zu einer signifikanten Erhöhung der Sanierungsrate, da in unserem Modell-Setting die Durchführung von Energie-Audits (Schätzung des Energiesparpotenzials) auch bei einer solch hohen Abgabe das wesentliche Nadelöhr bleibt. Wenn der Anteil der Eigentümer, die ihr Gebäude auditieren, erhöht werden kann, steigert dies die Sanierungsrate in unserem Modell signifikant. Diese Ergebnisse hängen stark von der Wahl der Parameter unseres Modells ab. Vor allem für die Kalibrierung der Entscheidung zum Audit existieren jedoch kaum Daten. Wir haben das Modell so kalibriert, dass es die aktuelle Sanierungsrate repliziert. Die Ergebnisse zeigen, dass sich von Modellen abgeleitete Politikempfehlungen erheblich ändern, wenn verhaltensökonomische Hürden explizit berücksichtigt werden. So ändern sich beispielsweise Empfehlungen für weiche Politiken (z.B. Informationskampagnen) unter unvollständiger Information. Für präzisere Aussagen müsste unser Modell aber verfeinert und mit empirischen Verhaltensdaten zur Kalibrierung bereichert werden.

Schliesslich zeigen unsere Simulationen, dass eine tiefgreifende Dekarbonisierung nicht durch eine einzelne Lenkungsmassnahme erreicht werden kann, sondern nur durch eine Kombination mehrerer Massnahmen.

Kopplung von GEMINI-E3 mit dem Wohngebäudemodell

Da der Zweck dieses Projekts die Endogenisierung von Energieeffizienzverbesserungen in rechenbaren allgemeinen Gleichgewichtsmodellen (CGE) war, haben wir unser CGE-Modell namens GEMINI-E3 mit dem Wohngebäudemodell gekoppelt.

Ausgangspunkt ist die Standardversion des CGE-Modells GEMINI-E3, bei der der Wohnungssektor ein Sektor wie jeder andere ist, dessen Energieeffizienz sich über die Jahre exogen verbessert. Durch die Koppelung mit dem Wohngebäudemodell wird dieser Wohnungssektor durch einen

Datenaustausch mit diesem sektoralen Modell ersetzt. Was dies bewirkt testen wir zuerst anhand eines Szenarios, bei dem eine einheitliche CO_2-Lenkungsabgabe auf alle CO_2-Emissionen ausser jene der grossen Quellen, die dem Emissionshandelsystem (EHS) unterstellt sind, erhoben wird. Die Abgabe wird schrittweise erhöht und der Deckel im EHS gesenkt, so dass der Gesamt-CO2-Ausstoss sich bis 2050 auf eine Tonne pro Kopf verringert. Wir stellen fest, dass das gekoppelte Modell eine höhere CO_2-Abgabe benötigt, um das Ziel zu erreichen, als die Standardversion. Das kommt daher, dass die CO_2-Abgabe im Wohngebäudemodell relativ wenig Effizienzverbesserungen auslöst, wenn die Gebäudeeigentümer nicht gezielt dazu veranlasst werden, ihre Gebäude zu auditieren (siehe oben).

Um die Auswirkungen der zusätzlichen Funktionen der gekoppelten Version zu testen, haben wir im Wohngebäudemodell Subventionen und Informationskampagnen hinzugefügt. Dies sind Funktionen, die GEMINI-E3 allein nicht modellieren kann. Wie erwartet, stellen wir fest, dass die CO_2-Abgabe, die erforderlich ist, um das 1-Tonne-CO_2-Pro-Kopf-Ziel zu erreichen, wesentlich geringer ist als ohne diese zusätzlichen Anreize.

Modell der Zementindustrie

Wir modellieren Energieeffizienzverbesserungen für jedes der sechs Schweizer Zementwerke. Ausgehend von einer anfänglichen Zuteilung von bereits implementierten Effizienzmassnahmen, werden die Werke durch die Implementierung zusätzlicher Massnahmen und durch den Ersatz von bestehenden technischen Lösungen durch neuere energieeffizienter. Wir modellieren die Umsetzung dieser Massnahmen auf der Grundlage einer Kosten-Nutzen-Analyse in Kombination mit anderen Regeln, die sich auf den Ersatz ineffizienter Anlagen am Ende der Lebensdauer beziehen.

Zwischen 2015 und 2050 sinken der Brennstoff- und Stromverbrauch sowie die CO_2-Emissionen in den Szenarien ohne CO_2-Abscheidung und -Speicherung (CCS) um etwa 30 bis 37%. Die Entwicklung des Preises für CO_2-Emissionszertifikate macht in diesen Szenarien keinen grossen Unterschied. In den Szenarien mit CCS sinken die CO_2-Emissionen um 92%, während der Kraftstoff- und Stromverbrauch drastisch ansteigen. Dies zeigt die enorme Bedeutung der Verfügbarkeit dieser Technologie für die Zementindustrie und wie wichtig es ist, sie so schnell wie möglich zu implementieren. Sie könnte bereits 2030 eingeführt werden, wenn ein Mindestpreis von 133 CHF pro Tonne CO_2, die durch CCS vermieden wird, festgelegt würde.

Résumé

Nous avons réussi à créer deux méthodes fonctionnelles et nouvelles qui représentent l'évolution des améliorations de l'efficacité énergétique (EE) dans deux secteurs suisses. Cela nous a permis d'obtenir une meilleure représentation des gains d'EE initiés par les politiques énergétiques et climatiques. Bien que nous utilisions les meilleures données disponibles pour calibrer les modèles, l'objectif de cet exercice n'était pas d'obtenir des résultats quantitatifs précis. Nous voulions plutôt établir une "preuve de concept". En simulant différents scénarios politiques sur la période 2015-2050, nous avons montré qu'il est important de prendre en compte les réponses à ces politiques. Par exemple, il est important d'envisager non seulement des incitations monétaires (telles que des subventions ou des taxes), mais aussi des mesures "plus douces" comme des campagnes d'information. Cela est particulièrement vrai pour le secteur immobilier, car de nombreux propriétaires sont mal informés. Par conséquent, un objectif donné peut être atteint à moindre coût si un mélange intelligent de mesures dures et douces est utilisé.

Plus précisément, les modèles et les résultats les plus pertinents sont les suivants :

Modèle des bâtiments résidentiels

Le modèle divise le parc suisse de bâtiments à usage d'habitation en différentes classes d'efficacité énergétique. Afin de simuler la décision de rénovation énergétique des propriétaires, nous avons développé un modèle à deux étapes. Dans un premier temps, les propriétaires ne sont pas conscients des coûts et des avantages de la rénovation. Un certain pourcentage de propriétaires sont incités chaque année à faire auditer leur bâtiment et à calculer le potentiel d'économies d'énergie. Dans un deuxième temps, ces propriétaires décident de procéder à une rénovation, en fonction des résultats d'une analyse coûts-avantages.

Nous avons calculé un scénario de référence et différents scénarios de mesures, chacun d'entre eux encourageant davantage la rénovation que le scénario de référence. Les résultats suivants de notre modèle sont particulièrement remarquables : même une forte augmentation de la taxe sur le CO_2 (jusqu'à 1000 CHF par tonne de CO_2 en 2050) n'entraîne pas une augmentation significative du taux de rénovation, car dans notre modèle la mise en œuvre des audits énergétiques (estimations du potentiel d'économie) reste essentiellement le goulet d'étranglement, même avec une taxe très élevée. Il est nécessaire que la proportion de propriétaires qui font auditer leur bâtiment augmente pour accroître le taux de rénovation. Ces résultats dépendent du choix des paramètres de notre modèle et surtout de la calibration de la décision d'audit, pour laquelle il n'existe pratiquement aucune donnée. Nous avons calibré le modèle de telle sorte qu'il réplique le taux de rénovation actuel. Nos résultats montrent que les recommandations politiques dérivées des modèles peuvent changer de manière significative quand des barrières comportementales sont explicitement prises en compte. Ainsi, les recommandations pour des mesures de type information et persuasion changent en présence d'information incomplète des acteurs. Pour des déclarations plus fiables, notre modèle devrait être affiné et surtout enrichi de données comportementales empiriques.

Enfin, nos simulations montrent que la décarbonisation profonde ne peut être réalisée par une seule mesure incitative, mais seulement par une combinaison de mesures.

Couplage de GEMINI-E3 et du modèle des bâtiments résidentiels

Comme le but de ce projet était de rendre endogènes les améliorations de l'efficacité énergétique dans les modèles macroéconomiques d'équilibre général calculable (EGC), nous avons couplé notre modèle EGC appelé GEMINI-E3 avec le modèle des bâtiments.

Le point de départ est la version standard de GEMINI-E3, où le secteur résidentiel est un secteur comme un autre, dont l'efficacité énergétique s'améliore de manière exogène au fil des ans. En couplant ce modèle avec le modèle des bâtiment résidentiels, ce secteur résidentiel est remplacé par un échange de données avec le modèle sectoriel. Nous testons d'abord l'effet de ce couplage à l'aide d'un scénario dans lequel une taxe incitative uniforme est imposée sur toutes les émissions de CO_2 à l'exception de celles des grandes sources soumises au système d'échange de quotas d'émission (SEQE). La taxe est progressivement augmentée et le plafond du SEQE est abaissé de manière à ce que les émissions totales de CO_2 soient ramenées à une tonne par habitant d'ici 2050. Nous constatons que le modèle couplé nécessite une taxe CO_2 plus élevée pour atteindre la cible que la version standard. Cela s'explique par le fait que la taxe CO_2 déclenche relativement peu d'améliorations de l'efficacité dans le modèle des bâtiments résidentiels tant que les propriétaires de bâtiments ne sont spécifiquement incités à effectuer un audit de leurs bâtiments (voir ci-dessus).

Pour tester l'impact des caractéristiques supplémentaires de la version couplée, nous avons ajouté des subventions et des campagnes d'information dans le modèle des bâtiments résidentiels. Ce sont des caractéristiques que GEMINI-E3 ne peut pas modéliser à lui seul. Comme prévu, nous constatons que la taxe sur le CO_2 nécessaire pour atteindre l'objectif d'une tonne de CO_2 par habitant est bien inférieure au niveau requis en l'absence de ces incitations supplémentaires.

Modèle de l'industrie du ciment

Nous modélisons les améliorations de l'efficacité énergétique pour chacune des six cimenteries suisses. À partir d'une allocation initiale de mesures d'efficacité déjà mises en œuvre, les usines deviennent plus efficaces sur le plan énergétique en mettant en œuvre des mesures supplémentaires et en remplaçant les équipements existants par des versions devenues plus efficaces. Nous modélisons la mise en œuvre de ces mesures sur la base d'une analyse coûts-avantages en combinaison avec d'autres règles relatives au remplacement en fin de vie des installations inefficaces.

Entre 2015 et 2050, les consommations de combustibles et d'électricité et les émissions de CO_2 diminuent d'environ 30 à 37% dans les scénarios de référence sans possibilité de séquestrer le CO_2 (CCS). L'évolution du prix des certificats d'émissions de CO_2 ne fait pas une grande différence dans ces scénarios. Dans les scénarios avec CCS, les émissions de CO_2 diminuent de 92%, tandis que les consommations de combustibles et d'électricité augmentent de façon spectaculaire. Cela démontre l'énorme impact de la disponibilité de cette technologie pour l'industrie du ciment ainsi que l'importance de la mettre en œuvre le plus tôt possible. Elle pourrait être adoptée dès 2030 si un prix plancher de 133 CHF par tonne de CO_2 évitée grâce à la CCS était fixé.

Summary

We managed to construct two novel and functional methodologies to depict the evolution of energy efficiency improvements (EEI) in two Swiss sectors. This allowed us to obtain a better representation of EEI triggered by energy and climate policies. Although we use available data to calibrate the models, the focus of this exercise was not to obtain precise quantitative results, but rather to construct a proof of concept. Simulating different policy scenarios over 2015-2050, we showed that it is important to consider the responsiveness to various types of policies. It is, for example, important to not only consider monetary incentives (such as subsidies or taxes), but also “softer” measures such as information campaigns. This is especially true in the building sectors, as many owners suffer from incomplete information. Consequently, a given target can be achieved at lower cost when using a smart mix of hard and soft policies.

More specifically, the models and most relevant results are as follows:

Housing Stock Model

The model divides the Swiss stock of residential buildings into different energy efficiency classes. To simulate the retrofit decision of the owners, we developed a two steps model. In the first step, owners are initially unaware of the retrofit’s costs and benefits. A certain percentage of the owners are triggered each year to audit their building and calculate the potential for energy savings. In the second step, triggered owners decide on doing a retrofit, depending on the results of a cost-benefit analysis.

We run a reference and various policy scenarios, each inducing more retrofitting than the reference scenario. Especially noteworthy are the following results of our model. Even a steep increase of the CO_2 levy (up to 1000 CHF per ton CO_2 in 2050) does not significantly increase the retrofit rate, because in our model-setting there remains the bottleneck of conducting energy audits (estimation of the energy saving potential), even for such a high levy. If the proportion of owners who audit their building can be stepped up, this significantly increases the retrofit rate in our model. These results depend strongly on model parameters, yet especially for the calibration of the audit decision, hardly any data exist. We calibrated the model in such a way that it replicates the current retrofit rate. Our results show that policy recommendations derived from models change significantly when behavioural hurdles (here incomplete information) are explicitly considered. For example, recommendations regarding soft policies (e.g. information campaigns) change when the actors' incomplete information is considered. For more reliable statements, our model would need to be refined and enriched with observation-based calibration data.

Finally, our simulations show that decarbonization cannot be achieved by a single policy alone, but only by a combination of policies.

Coupling GEMINI-E3 with the Housing Stock Model

As the purpose of this project was to endogenize energy efficiency improvement in large computable general equilibrium (CGE) models, we coupled our CGE model called GEMINI-E3 with the Housing Stock Model.

The starting point is the standard version of the CGE model GEMINI-E3, where the residential sector is a sector like any other, whose energy efficiency improves exogenously over the years. By coupling it with the Housing Stock Model, this residential sector is replaced by a data exchange with this sectoral model. We first test what this does using a scenario in which a uniform CO_2 incentive levy is imposed on all CO_2 emissions, except those from large sources that are subject to the Emissions Trading Scheme (ETS). The levy is gradually increased and the cap in the ETS is lowered, so that total CO_2 emissions are reduced to one ton per capita by 2050. We find that the coupled model requires a higher levy to reach the target than the standard version. This is because the CO_2 levy triggers relatively little energy retrofitting in the Housing Stock Model when building owners are not specifically incentivised to audit their buildings (see above).

To test the impact of the additional features of the coupled version, we added subsidies and information campaigns in the Housing Stock Model – features GEMINI-E3 alone is not able to model. As expected, we find that the CO_2 levy required to reach the 1-ton CO_2 per capita target is substantially lower than in the absence of these additional incentives.

Cement Industry Model

We model energy efficiency improvements for each of the six Swiss cement plants. Starting from an initial allocation of already implemented efficiency measures, plants become more energy efficient by implementing additional measures and by replacing equipment by newer, more efficient versions. We model the implementation of these measures based on a costs-benefit analysis in combination with other rules related to the replacement of inefficient equipment at the end of the lifetime.

Between 2015 and 2050 fuel and electricity consumptions as well as CO_2 emissions drop by about 30 to 37% in baseline scenarios dans do not allow for CCS. The evolution of the ETS price does not make much of a difference. In the scenarios with CCS, CO_2 emissions decrease by 92%, while fuel and electricity consumption increase strongly. This shows the huge impact of the availability of this technology for the cement industry and the importance of implementing it as soon as possible. It could be adopted as early as 2030 if the federal government set a floor price of CHF 133 per tonne of CO_2 avoided through CCS.

Main findings

- We developed a Housing Stock model, which represents the energy retrofit behavior of housing owners in a tractable fashion as a two-step decision process – decision to audit and decision to retrofit – which allows for incorporating realistic barriers and for testing policies designed to overcome them.
- In the absence of soft policies designed to overcome barriers for energy efficiency improvement, even a high price signal yields little CO_2 reduction in buildings.
- For the industry sector, we developed a cement model which, in a plant-specific bottom-up approach, depicts the impact of measures on fuel and electricity consumption as well as CO_2 emissions. Technical progress stems from a mixture of measure-induced and autonomous progress.
- Between 2015 and 2050, technical progress leads to a reduction of fuel and electricity consumptions as well as CO_2 emissions in cement production of about 30 to 37% in scenarios without CCS. The impact of the CO_2 price is minor for energy efficiency measures.
- The implementation of CCS depends crucially on the ETS price. A price floor could induce early implementation. If the plant operators do not anticipate escalating ETS prices, CCS could come very late. Early implementation is highly desirable because it has the potential to lower CO_2 emissions by over 90%, at the cost, however, of strongly raising fuel and electricity consumption.

Contents

Abbreviations

BAT	Best available technology
BAU	Business as usual
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CHF	Swiss franc
CO_2	Carbon dioxide
EEI	Energy efficiency improvement
EP2050+	Energy Perspectives 2050+
EPB	ETS price baseline
ERA	Energy reference area
ETS	Emissions trading system
EUP	Essential unit processes
HSM	Building stock model
Mt	Megatons
NPV	Net present value
PEEM	Pure energy efficiency measure
SFOE	Swiss Federal Office of Energy
toe	Tons of oil equivalent

1 Introduction

1.1 Background information and current situation

The evolution of energy efficiency is of vital importance for the future energy consumption. Models used to simulate energy and climate policies generally allow for some energy efficiency improvement (EEI) in response to measures raising the relative price of energy, generally in the form of substitution of energy by other production factors, mainly capital. Most models, particularly the large computable general equilibrium (CGE) models but also most bottom-up models (e.g. Markal), assume a form of autonomous EEI, i.e. a reduction in every simulation period of the energy needed to produce the same output in the absence of any policies and without greater use of other factors of production (Azar et Dowlatabadi, 1999). Indeed, it is assumed that producers gradually replace their "machines" (including vehicles, buildings, etc.) by more energy efficient ones, as technical progress makes new machines more efficient than older ones for the same cost.

This reflects, of course, an observed trend. However, it means that this important component of EEI is not affected even by climate or energy policies designed to foster innovation and the development and adoption of more efficient production and consumption options (Shiell and Lyssenko, 2014). This is despite clear evidence that energy efficiency improvement is influenced by economic activity, relative price increases and is responsive to climate or energy policies. Therefore, it is likely that such models systematically underestimate the impact of policies. Incorporating a more realistic representation of EEI into model improves upon this problem.

We apply this concept for the residential buildings and the cement industry in Switzerland. These sectors are important contributors of Swiss energy consumption and CO_2 emissions and they harbour considerable reduction potentials. Households use 17.5% of total final energy consumption for room temperature (2018)[1] and account for 20.6% of CO_2 emissions (2018).[2] Streicher (2017) estimated that large-scale energy retrofit of the Swiss stock of residential buildings, using the best available technology, could result in energy savings of up 84% of its current energy consumption. The cement industry is one of the most energy and CO_2 intensive sectors in Switzerland. Its share in the total final energy use of the Swiss economy (industry + services) was 6% in 2019.[3] The NOGA sector 23, of which cement manufacturing is a large component, accounted for 10% of the Swiss economy's CO_2 emissions in 2018.[4]

1.2 Objectives and main ideas of the project

The fundamental purpose of this research was to introduce a new methodology in an existing computable general equilibrium model of the Swiss economy (GEMINI-E3, see e.g. Bernard and Vielle, 2008) aiming at a better representation of EEI triggered by energy and climate policies. The second target was to illustrate this by assessing the impacts of a set of realistic policies on the diffusion and adoption of technologies associated with energy consumption in Switzerland, and finally on energy use as well as structural changes. A prudent representation should as far as possible consider the effects of barriers such as incomplete information. This may significantly influence the rigorousness of a policy (e.g. the level of a tax) needed to achieve a given target. Thus, assessing the sensitivity of the results to these assumptions is another key contribution of our work.

To incorporate EEI as accurately as possible, we focused on a rather detailed description of two sectors as a proof of concept: the housing sector and the cement industry (as an exemplary industry). We quantified the impacts of policies using data wherever available and considered various barriers.

[1] SFOE, Analyse des Schweizerischen Energieverbrauchs 2000-2018 nach Verwendungszwecken, Oct. 2019, tables 7 and 18.
[2] FOEN, Greenhouse gas inventory, Evolution of Switzerland's greenhouse gas emissions since 1990, April 2020.
[3] SFOE, Energy consumption statistics in the industry and services sectors, Results 2019.
[4] FOS, Air emissions accounts of economy and households. STAT-TAB extraction on 19 Oct. 2020.

Although we use available data to calibrate the model, the focus of this exercise was not to obtain precise quantitative results, but rather to construct a proof-of-concept. The main contribution of this exercise is thus not to provide exact numbers but insights: our model is a coherent approach to scrutinize these aspects and make assumptions and approaches transparent.

We built models of the housing and the cement sectors that are detailed enough in describing the relevant actors (types of owners and buildings, individual cement plants) for allowing for a fine representation of energy efficiency measures and their determinants. Such models cannot easily be integrated into large macroeconomic simulation models. As a result, we had to resort to coupling the models. Thereby, the housing component of the macroeconomic model is replaced by the exchange of the corresponding price and quantity variables between the macroeconomic model and the separate housing model. We did not conduct the same exercise for the cement industry, because it is too small to be actually represented as a separate sector in GEMINI-E3. Before endogenizing energy efficiency improvements in industry, the method developed for the cement industry ought to be extended to all energy-intensive industries at least.

Note that we endogenized the adoption of new technologies in the economy, but we did not endogenize technological change itself (see Box 1).

Box 1: The idea behind endogenization of energy efficiency improvements

Every model contains endogenous variables, exogenous variables and parameters:

- The value of an **endogenous** variable is determined within the model. Typical endogenous variables in macroeconomic models are investment, production, employment, consumption, prices, wages, and interest rates.
- The value of an **exogenous** (also known as autonomous) variable value is determined outside of the model, i.e. the model takes its value as given. Typical exogenous variables in macroeconomic models are tax rates, government spending and population growth. They are usually determined by some political process. They can also be the result of some economic process, e.g. the price of crude oil on the world oil market, but because each model represents only a part of reality, the modelers decided to not explicitly model the determination of these variables. Instead, they assume a trajectory for these variables, usually based on scenarios or other authors' forecasts.
- **Parameters** are like exogenous variables in that their values are taken as given. They are distinct, however, in that they tend to represent things that are given by "nature" such as consumer preferences or technical production and substitution possibilities. Parameters are usually constant or they follow a very simple trend.

Roughly, a model consists of formulas that use parameters and exogenous variables as inputs to determine endogenous variables. Hence, endogenizing a variable means to transform it from a parameter or exogenous variable (with a predetermined trajectory) into a variable whose values through time are computed with the help of one or more formulas that use parameters, other exogenous variables or even other endogenous variable as determinants. Endogenization makes a model richer in its capacity to simulate how variables respond to changes in exogenous variables.

In this study we endogenize autonomous energy efficiency improvement, i.e. we show how a macroeconomic model can be refined by making the adoption and diffusion of technical progress responsive to economic variables such as prices and to policies. Specifically, we introduce a more sophisticated representation of the acceleration of EEI induced by energy and climate policy in GEMINI-E3. In the housing sector, GEMINI-E3 models EEI using a nest structure, where consumption of “shelter” is combined with the consumption of “energy” (see Figure 2). We replace this simple representation with a more realistic sub-model (the Housing Stock Model), which can be coupled with GEMINI-E3 or used as a stand-alone.

We do not endogenize technological change in the sense of introducing a model that explains the improvement of technology. Instead, endogenization of EEI refers to a more realistic model of how new technology is adopted within the economy.

2 Description of the methodology

In the following we describe the main features of the three modelling frameworks we developed within this project. More detail is provided in the attached working papers.

2.1 The Housing Stock Model

Based on the Cantonal Energy Certificate for Buildings, we divide the Swiss stock of residential buildings (single- and multi-family buildings) into seven energy classes, A to G, each representing a different range of the space heating demand (see Table 1). The Energy classes refer to useful energy, which is the amount of energy required to actually heat the building.[5]

Energy class	Space heating demand in kWh/m^2	Assumed mean space heating demand 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

Table 1: Thresholds of energy classes based on the Cantonal Energy Certificate of Buildings. Source: Own Table.

We estimate the initial allocation of the Swiss housing stock within these energy classes in terms of energy reference area (ERA). Our estimation is based on energy consumption data by construction period from several unpublished sources[6] coupled with FSO data on the construction periods of the Swiss housing stock.[7]

Starting from this initial distribution, the energy efficiency of the stock of residential buildings increases from 2015 to 2050 because (i) some buildings are retrofitted every year, (ii) more energy-efficient buildings are constructed and (iii) old inefficient buildings are demolished. We represent each of those contributions separately in the model. For (ii) and (iii), we draw on and extrapolate data for each energy class from FSO data. The choice of new buildings' energy class is an important source of energy efficiency improvement in our model. Yet, we do not model this choice explicitly, but assume that new buildings have a certain energy class mix that changes with time.[8]

[5] For reference, the CO_2 Act as adopted by Parliament in 2020 places a cap of 20 kg CO_2 per m^2 ERA as of 2023 (art. 10). Using an emission factor of natural gas of 0.203 kg/kWh and a heating system efficiency of 90%, this would allow for a space heating demand of appr. 90 kWh/m^2. The cap value of 20 kg CO_2 per m^2 ERA shall be reduced by 5 kg every five years.
[6] The data describe the housing stocks of Société Coopérative d'Habitation Lausanne in the Lausanne area, Allgemeine Baugenossenschaft Zürich in the Zurich area, and die Mobiliar in all of Switzerland. Furthermore, we use a rich dataset describing the rental housing stock in the canton of Geneva provided by Estia.
[7] See https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.4582090.html (retrieved 30.03.2021)
[8] For 2015, we assume new residential buildings belong to energy classes as follows: 20% A, 35% B and 45% C. The share of class C decreases by 2.5% per year and that of class A buildings increases correspondingly, so that no more building is realized in class C in 2033. From 2033 onwards, the share of new buildings in class B decreases by 2% per year.

Our main contribution is modelling energy efficiency improvement factor (i), the retrofitting of a share of buildings every year, i.e., their transfer to a better energy class. To this end, we created a two-step model that represents the building owners' retrofit decision.

- We assume that building owners are basically unaware of the retrofit costs and benefits for their buildings, until they conduct an energy audit. In the first step, a certain percentage of these owners are triggered each year to conduct such an audit. This trigger might be an information campaign or a significant increase in energy prices.
- In the second step, owners who had their building audited estimate the costs and benefits of a retrofit. If the latter exceed the former, they undertake the retrofit.

Step 1 allows considering the barrier of incomplete information. Even when retrofits would be profitable, they are not undertaken because owners do not even consider them. We assume that there is a certain baseline probability that an owner conducts such an audit. This probability increases with the information level or if energy prices increase suddenly or smoothly. For lack of available data, we made ad-hoc assumptions for calibrations. Step 1 results in a certain proportion of owners who conduct an energy audit and subsequently enter Step 2.

In Step 2, triggered owners conduct a cost-benefit analysis. Costs depend on the degree of retrofitting, so we define an investment cost matrix with respect to changes in energy classes. This matrix is calibrated to obtain realistic results compared to BFE (2016). We assume the matrix to be non-linear, so that the unit costs to reach higher energy classes increase successively. The benefits are the net present value of future energy cost savings, based on a future energy price scenario and assuming perfect foresight by property owners. A retrofit from one energy class to the next is conducted if it is profitable and if a retrofit to another class is not even more profitable. Possible subsidies enter the models at this step as they decrease the net investment costs.

To model additional barriers, we introduce several owner types in the second step, which has the following impacts on the benefit side. First, we distinguish between owner-occupied buildings and those let for rent by a landlord. This accounts for the well-known barrier that only parts of the energy saving can be financially recovered by the landlord through a rent increase. Specifically, we introduce a split incentive parameter, which lowers the benefits for a landlord by 50 percent. In addition, we implement different discount rates for different characteristics of the owners. In total, there are thus six owner types (see Table 2).[9]

Code	Owner type	Share of ERA by owner type	Owner characteristics	Share of ERA by characteristics within owner type	Discount rate
1	owner-occupier		young wealthy	20%	2%
2	owner-occupier	37%	other	60%	4%
3	owner-occupier		old /poor	20%	6%
4	landlord		non-profit	10%	2%
5	landlord	63%	profit-oriented	30%	4%
6	landlord		private person	60%	6%

Table 2: Owner types in the Housing Stock Model. Source: Own Table.

To calculate CO_2 emissions, we also model energy carriers (oil, natural gas, district heating, heat pumps, pure electricity heating and wood), which can change through two pathways:

- The energy carrier mix within each energy classes changes with time: We defined an initial mix of the energy carriers within each energy class based on energy consumption data and our expert

[9] Further barriers such as liquidity constraints or myopia with respect to energy cost savings are not implemented in this version of the model.

judgment (e.g. there are more heat pumps in efficient buildings). This mix changes with time in response to changes in relative prices of the energy carriers (this is modelled using GEMINI-E3's CES-function within each energy class).

- Retrofitting moves a building to a better energy class: The energy carrier changes in parallel with a retrofit of the building's hull, as the building takes over the average energy carrier mix of its new energy class at the time of the transition on the way to 2050.[10]

2.2 Coupling the Housing Stock Model with GEMINI-E3

The Housing Stock Model (HSM) and the GEMINI-E3 model are coupled using the framework described in Figure 1. GEMINI-E3 computes energy prices, including the CO_2 levy, and passes them to the HSM. The HSM uses these prices to compute the use of each energy carrier for residential heating from 2015 to 2050. This information is passed back to GEMINI-E3, which calculates resulting CO_2 emissions and adjusts the CO_2 levy as needed to meet the target. The new energy prices are returned to the HSM. This stops when the quantities of each energy carrier in each year converge, that is, they change little enough relative to the previous iteration.

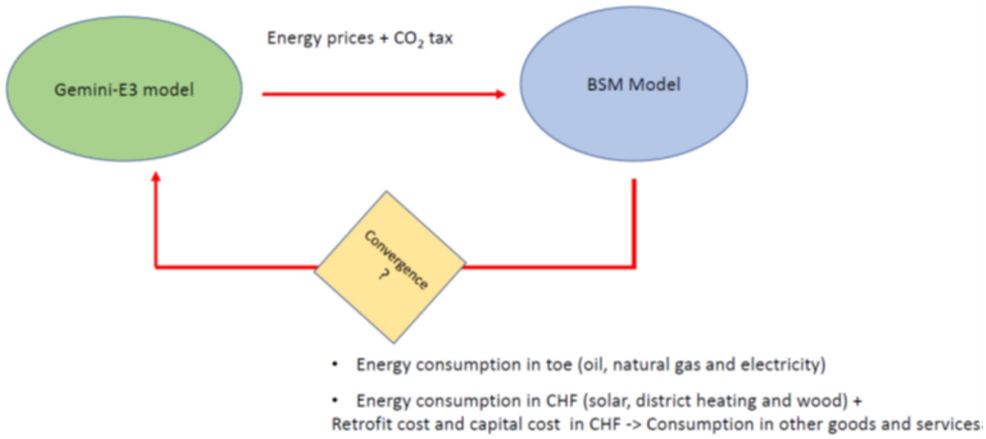

Figure 1: Coupling framework. Source: Own Figure.

The two models are harmonized first using the same assumptions for population, energy prices and existing CO_2 price (i.e., the current CO_2 levy). Next, we calibrate the GEMINI-E3 model with the aim to achieve the same energy mix and overall consumptions for residential heating in GEMINI-E3 alone as with the coupled models. This step is required to be able to later meaningfully compare results of the policy scenarios (otherwise there would be two different reference scenarios). This calibration is achieved by adjusting in GEMINI-E3 alone the autonomous technical progresses associated to the energy consumption.

Figure 2 shows the nested CES structure that is used in GEMINI-E3 to represent household consumption. The energy consumption linked to residential heating is represented in the nest titled "Housing". It assumes that consumers can improve related energy consumption substituting, to a certain degree, fossil energy use with an improvement of "Shelter". Fossil energy consumption includes oil and gas, but it is also important to notice that in GEMINI-E3, we do not consider energy carriers like wood and district heating. Therefore, we will concentrate our comparison on energy

[10] We do not consider the costs of a change in the energy carrier. That is, we do not consider the costs of a new heating system.

carriers that are considered by both models: natural gas, oil and electricity (the latter including both direct joule processes, gradually phased out, and heat pumps).

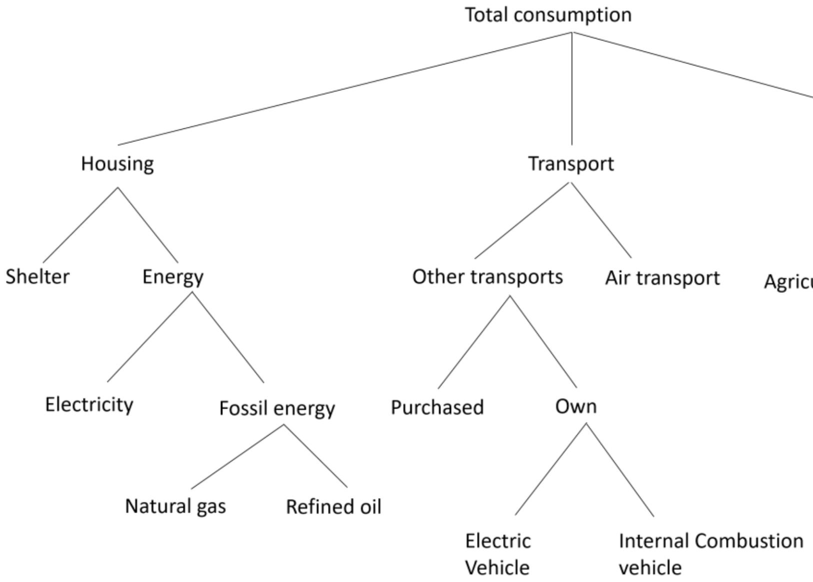

Figure 2: Nested CES structure of household consumption. Source: Own Figure.

One important difference between the HSM and the representation of housing in the CGE (Figure 2) is that an increase in the (relative) price of energy in the latter will automatically trigger a substitution with "Shelter", i.e. retrofitting, and thus energy savings, while this is mediated by energy audits in the HSM. Indeed, building owners in the HSM must first be induced to assess the energy saving potential of their building, partly through higher energy prices, before they actually compute the economic opportunity of retrofitting. As a consequence, their response to higher energy prices will, quite plausibly, be more subdued in the HSM, and thus in the coupled framework, than in the CGE alone.

Figure 3 shows the energy mix for the two reference scenarios (GEMINI-E3 alone and with the coupled models) after we performed this calibration. The reference scenarios are almost identical, with a difference in energy carrier consumptions of less than 5%.

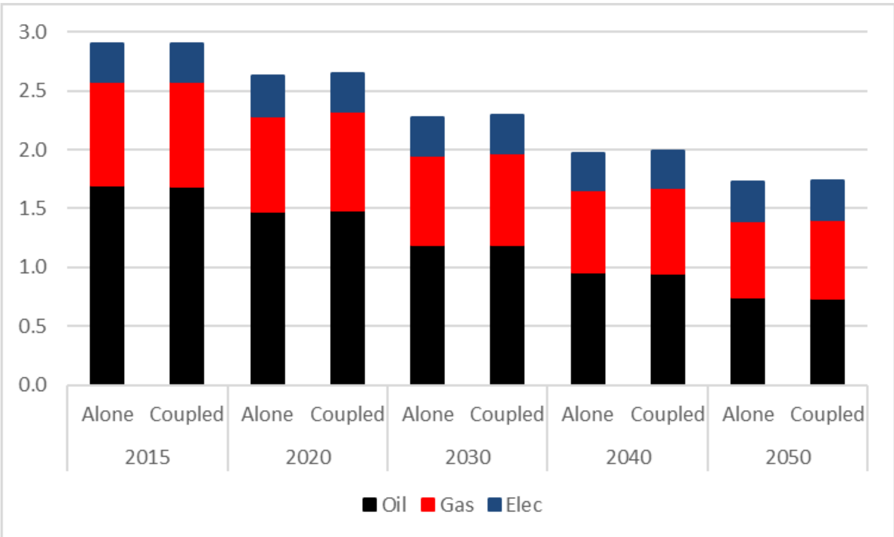

Figure 3: Residential energy consumption in Mtoe – Reference scenarios. Source: Own Figure.

2.3 The Cement Industry Model

We selected the cement industry as an example to model energy efficiency improvement in industry. The reasons for this choice are that its product is quite homogeneous; it has a high energy intensity; and data are available. We model energy efficiency improvements for each of the six Swiss cement plants. They become more energy efficient by implementing efficiency measures. Following Zuberi and Patel (2017), we distinguish between essential unit process (EUP) measures and pure energy efficiency measures (PEEM). An EUP is an essential part of the manufacturing process. Therefore, implementing such a measure means replacing an inefficient equipment by an efficient one, thereby directly making the process more efficient (e.g. replacing a mill by a more efficient one).[11] A PEEM, on the other hand, is not part of the manufacturing process, but only serves to improve the overall energy efficiency of the plant (e.g. waste heat recovery). Implementing a PEEM the first time means adding new equipment.

We model approximately 15 measures based on the thorough analysis of Zuberi and Patel (2017), who provide a list of energy efficiency and CO_2 mitigation measures that are applicable for Swiss cement plants (see Appendix 6.1). This list also includes investment costs, fuel savings, electricity savings, CO_2 abatement potentials, lifetimes as well as adoption rates. Examples of measures are mill or grinder replacement, changes in the kiln or replacing a pneumatic with a mechanical transport system.

Our model starts with an initial allocation of plant-specific measures. Zuberi and Patel (2017) do not indicate which plants adopted which measures, but only provide overall adoption rates. We assume that these adoption rates are weighted by the six plants' clinker production, so they indicate what share of total clinker production is affected by each measure. Using the data on the plants' clinker production, we are able to determine an initial allocation that replicates the mean adoption rates of Zuberi and Patel (2017) (see Table 3). As we did not verify whether our assumed initial allocation corresponds to reality, we simply labelled the plants A to F, so that no conclusions can be drawn as to a specific plant.

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

Other calibration data for the model are the current energy consumption and CO_2 emissions of the individual plants. From Zuberi and Patel's (2017) estimates, we infer that the current average energy consumption for the six plants is 3.5 GJ of fuel[12] per ton of clinker and 0.5 GJ of electricity. CO_2 emissions are 0.74 tons per ton of clinker. Using these averages and the saving potential of the measures implemented in the initial allocation allows us to calculate the current fuel and electricity consumption as well as CO_2 emissions for each plant.[13] Based on Zuberi and Patel (2017) and

[11] When a EUP measure is implemented, the operation of the plant has to be stopped. Therefore, one might take into account the lost profits during the construction time of the measure and that no energy is consumed during an interruption. However, according to a representative of the cement industry, many EUP measures can be implemented during the regular annual maintenance shutdown periods, which last 3-5 weeks. Other EUP measures and all PEEM can be implemented without stopping the cement production. For these reasons, we decided to not account for production losses in our model.

[12] In Switzerland cement plants use fossil fuels (mainly coal) as well as alternative fuels such as waste oil or tyres, which are partly organic (e.g. sewage sludge). We did not differentiate between these two sources of fossil fuels nor did we consider changes of the organic share as a measure.

[13] In more detail, we "backward engineered" the data, to determine that a hypothetical plant without any measures (using only old equipment) would have an energy consumption of 5.85 GJ fuel and 0.564 GJ electricity and CO_2 emissions of 1.11 tons per ton of clinker. From this starting point, we derived the plant-specific energy consumption and CO_2 emissions considering the initially implemented measures. The resulting sum over all plants matches Zuberi and Patel's (2017) estimates of overall current energy consumption and CO_2 emissions.

confirmed by a representative of the cement industry, the current best-available technology would need 3.0 GJ fuel and 0.4 GJ electricity per ton of clinker.

Plant	**A**	**B**	**C**	**D**	**E**	**F**	
Share of total clinker production (Mt/y)	16%	19%	20%	17%	6%	21%	
Technical measure							Rate of adoption
RM1	YES	YES	YES	YES		YES	94%
RM2	YES	YES		YES	YES	YES	80%
RM3	YES	YES			YES	YES	63%
RM4	YES						16%
CP1	YES	YES	YES	YES		YES	94%
CP2	YES	YES		YES	YES		58%
CP3			YES	YES			37%
CP5	YES	YES	YES	YES		YES	94%
CP6	YES			YES			33%
CG1			YES				20%
CG2			YES		YES		27%
CG3		YES		YES	YES		42%
CG4					YES	YES	28%
CG5a	YES	YES	YES	YES	YES	YES	100%
CG5b							0%
FR1	YES	YES	YES	YES			70%
FR2							0%
I1	YES	YES	YES	YES			72%
I2							0%
I3							0%

Table 3: Initial allocation of technical measures. The measures are described in the appendix. Source: Own table derived from Zuberi and Patel (2017).

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

1. Measure-induced technical progress (MI-TP): Inefficient EUP equipment is replaced by efficient equipment that fulfils the same function but is of another type (e.g., a ball mill is replaced by a vertical roller mill). Or a PEEM is newly introduced (e.g. waste heat recovery). We refer to this process as implementation of a measure. The magnitude of the MI-TP is measure specific.
2. Autonomous technical progress (A-TP): Efficient equipment that has been state-of-the-art at the time of its implementation will be obsolete at the end of its lifetime. This obsolete equipment is replaced by the same type – yet of an improved variant (e.g., a vertical roller mill version 1 is replaced by a vertical roller mill version 2; or waste heat recovery version 1 is replaced by waste heat recovery version 2). We refer to this process as reimplementation of the measure. We assume that A-TP yields an improvement of the saving potential of 1% per year. We assume that investment costs are not affected by technological progress. We do not further endogenize this part of the technological progress within our model.

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

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

1. *EUP-Implementation at the end of lifetime*: An inefficient EUP-equipment is replaced by an efficient EUP-equipment at the latest when the lifetime of the inefficient EUP-equipment is over.
2. *EUP-Implementation when beneficial*: An inefficient EUP-equipment may be replaced by an efficient EUP-equipment earlier, if and when the net present value (NPV) of this replacement becomes positive (see below).
3. *PEEM-Implementation when beneficial*: If a PEEM is not implemented in the initial allocation, it is implemented as soon as its NPV turns positive for a given year. A PEEM may, thus, never be implemented, if its NPV remains negative over the modelling period.
4. *Reimplementation of EUP and PEEM*: Once EUP measures or PEEM are in place, they always get reimplemented at the end of their lifetime using the state-of-the-art technology.[14] They never get reimplemented before the end of their lifetime.

The NPV is thus only relevant for the implementation of measures (definition see above), including the replacement of inefficient by efficient EUP-equipment. If a measure is already in place in the initial allocation, it is simply always reimplemented at the end of its lifetime. If relevant, we calculate the NPV yearly, comparing the investment costs of the measure (difference of investment costs of inefficient and efficient equipment) with the energy savings (including CO_2 price). The future energy savings are discounted as a rate of 11 percent (in line with Zuberi and Patel, 2017).

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

For a PEEM (rule 3 above), this aspect is not relevant. Costs are never depreciated, and benefits are counted over the lifetime of the PEEM.

Rule 1 follows from the logic of rule 2, as at the end of the lifetime the replacement costs of a measure are zero. It implies that inefficient EUP-equipment is never replaced by inefficient EUP-equipment.[15] And once an efficient EUP-equipment is in place, it is always replaced by efficient EUP-equipment.

[14] Our NPV calculations show that the data of Zuberi and Patel (2017) on investment costs and saving potential do not square with their stated adoption rate for several measures. The adoption rate of several measures is high despite their highly negative NPV. Therefore, we think that even if the NPV of some measures is negative at replacement, the fact that plants already implemented these measures in the past (based on the adoption rates of Zuberi and Patel, 2017) is a better guide for our model than the NPV calculations (based on the same source).

[15] This is also based on a discussion with a representative of the cement industry, stating that the industry strives to install best-available technology for regular replacements, as sustainability is an important topic in the industry and it is encouraged by existing policies such as the emission trading scheme or energy efficiency target agreements.

The NPV of measures changes with time due to

- technical progress: we assume that technical progress manifests itself through an improvement of the energy saving potential of 1% per year,
- changes in fossil fuel prices (including the CO_2 price), and
- linear depreciation of investment costs for EUP-measures only.

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

Concerning barriers, we considered that measures may be competing. That is, some measures cannot be implemented in parallel (e.g., there are several measures related to cement grinding). In addition, we allow carbon capture and storage in the policy scenarios only, not in the baselines. Its introduction could be delayed to 2040 by technical and legal barriers. It could be delayed even further if cement plant operators are myopic and do not anticipate the rising ETS price.

CCS is a particular measure with a very high CO_2 mitigation potential in cement production. As is has not been implemented yet, it is difficult to know how much it would cost. We rely on Zuberi and Patel's (2017) data for monoethanolamine scrubbing.[16] They assume that emissions are first reduced by all other measures and remaining emissions are subsequently reduced by 95% with CCS. This reduction requires, per ton of clinker produced, a capital investment of 8 CHF with a lifetime of 20 years and annual operating and maintenance costs of 40 CHF; it would increase the use of fuels by 3 GJ and the use of electricity by 0.34 GJ (all numbers rounded). With their energy prices, this implies a mitigation through CCS somewhat above 50 CHF per tonne CO_2 (Zuberi and Patel, 2017, Fig. 7). With higher energy prices, this cost could rise substantially (see below).[17]

Finally, we treated Zuberi and Patel's (2017) measure CG5 in a special way. This measure concerns blending of cement, which refers to mixing cement with additives other than clinker. This reduces the demand for clinker and, in consequence, energy consumption and CO_2 emissions.[18] Zuberi and Patel assume a fixed fraction of 35% additives by mass of cement for measure CG5, implicitly assuming that either there is blending in a plant at this scale or none at all. As in reality blending can occur on a continuous scale, we use a slightly more realistic assumption and split CG5 into two parts: CG5a is 2/3 of CG5 in terms of costs and savings and it is part of the initial allocation of each plant. This allows us to match Zuberi and Patel’s adoption rate of 33%. CG5b (which is 1/3 of CG5 in terms of costs and savings) is in no plant’s initial allocation and subsequently treated as a standard PEEM.

We envision implementing additional barriers in a next version of the model:

- the fact that, according to the representative of the cement industry, old equipment is often repaired rather than replaced and thus used much longer than its technological lifetime[19]
- non-financial constraints, such as the need of a building permit for implementing some measures
- a fixed cost of implementing a measure

[16] Due to the importance of this assumption for our results, we have undertaken a plausibility check and compared the fuel and electricity impact of CCS as given in Zuberi and Patel (2017) with Osk Gardarsdottir et al. (2019). This paper considers different CCS-technologies, which have different impacts. Focusing on the MEA-technology (which underlies Zuberi and Patel, 2017), our comparison shows that results of the two sources agree within a range of 15%. We thus consider Zuberi and Patel's (2017) data on CCS plausible.

[17] Prognos/TEP Energy/Infras/Ecoplan (2020) assume that the cost of CO_2 capture will lie slightly below 100 CHF/tCO_2 in 2050, to which 34 CHF tCO_2 must be added for transportation. Storage in Switzerland would cost about 30 CHF/tCO_2 (p. 32).

[18] It is not clear if a sufficient quantity of additives would be available in Switzerland. The NRP70 Energy project "Low-clinker cements" does not use the standard fly ash, which stems mainly from coal power plants, but rather locally available burnt oil shale and limestone. Therefore, we do not consider a constraint on the supply of additives in our model.

[19] Often, repair is considered environmentally beneficial. However, in the case of products that use a lot of energy during their utilization phase (e.g. refrigerators), replacement is often preferable to repair.

- the fact that the efficiency potential of a measure depends on how many measures are already implemented (some measures save a fraction of the total energy consumption and not an absolute value).

In addition, our approach is open to new technologies and measures helping to reduce the energy consumption or CO_2 emissions in cement making. They can be added to the model as soon as good estimates for their costs and effectiveness exist. This contributes to making technical progress endogenous.

3 Results and discussion

3.1 Housing Stock Model alone

The following briefly describes the most relevant results of the Housing Stock Model. More details can be found in the attached working paper.

3.1.1 Scenarios

We simulated one reference and six policy scenarios for illustrative purposes. In each case, the model runs from 2015 to 2050. The exogenous trajectories of energy reference area (ERA), population growth and energy prices are the same for all scenarios. The policy scenarios are as follows:

1. "Subsidy on retrofits": Increase of existing subsidy on retrofits by 1 percentage point every year.
2. "Moderate CO_2 levy": The existing CO_2 levy increases by 9 CHF every year up to appr. 400 CHF/ton CO_2 in 2050.
3. "High CO_2 levy": The existing CO_2 levy increases by 26 CHF every year up to appr. 1000 CHF/ton CO_2 in 2050.
4. "Information level": The information level related to Step 1 of the model (see section 2.1) starts at a value 1, the constant value in the reference scenario. In 2020, the government starts conducting more intense information and sensibilization campaigns promoting retrofits, so that the information level reaches the value 2, which means that the proportion of owners conducting an energy audit is doubled. The intensity of the campaigns increases thereafter every five years, so that by 2030 the information level reaches the value 4, i.e. four times as many audits as in the reference scenario, and remains at this value till 2050. We assume that the provision of information incurs at no cost.
5. "First combination": It combines a reduced "Subsidy on retrofits" (it increases by 0.5 percentage point per year only) with the "Moderate CO_2 levy" and "Information level".
6. "Second combination": It combines the full "Subsidy on retrofits" with the "High CO_2 levy" and "Information level".

Although these scenarios are partly inspired by currently discussed options, they do not represent any particular policy. That is, these scenarios are illustrative, and their main purpose is to demonstrate the functioning of the model. In the two combination scenarios, we calibrate the subsidy rate on retrofits in such a way that the revenues from the CO_2 levy are approximately sufficient to finance it.[20]

[20] In the current and revised CO_2 Act, only a third of the revenues of the CO_2 levy are used for retrofit subsidies, the rest being refunded to households and firms. We assume a more ambitious policy for the decarbonisation of the building stock, which uses 100% of the levy's revenues to subsidize retrofitting. There is not equality of revenues and subsidies every year but in sum over the full period up to 2050.

3.1.2 Main results

Figure 4 shows how the ERA and energy class mix change through time in the reference scenario. The ERA increases due mainly to population growth. This is an exogenous input to our model, such that in all seven scenarios the ERA increases exactly as in Figure 4. The energy class mix, however, differs. In the reference scenario, the energy class mix already improves so that the housing stock gets more energy efficient (see also Table 4). However, the reference scenario does not induce sufficient retrofits to reach ambitious climate targets, as even in 2050 there is still a considerable share of inefficient buildings. An important reason is that in the reference scenario the rate of retrofit gradually decreases (not shown), as the options for the most profitable retrofits out of the F and G classes dwindle and the owners most likely to retrofit their buildings have largely done so.

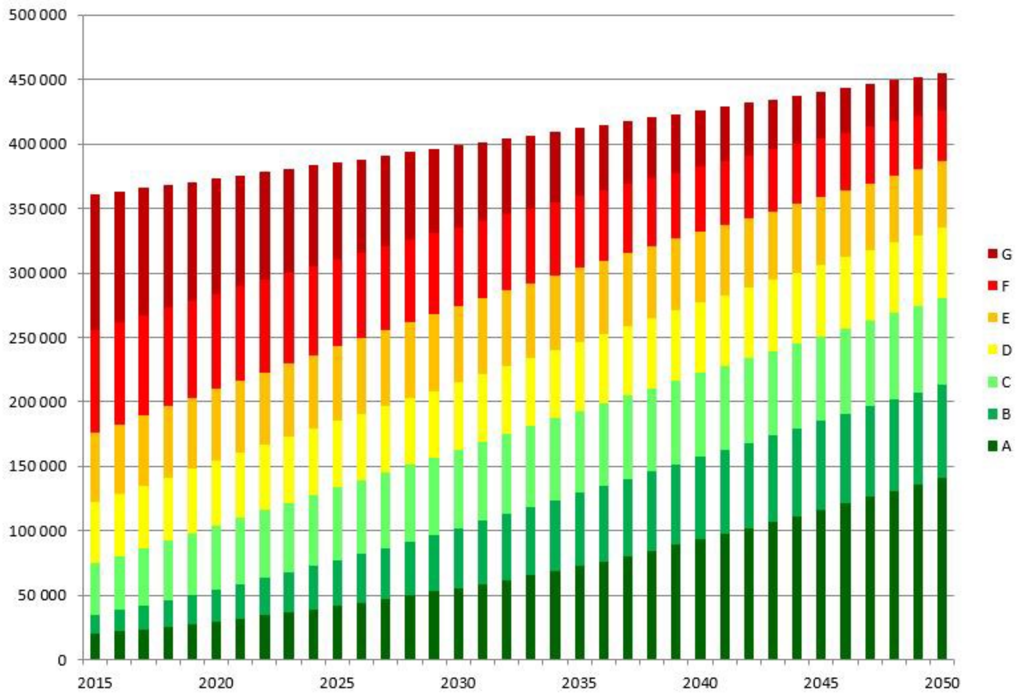

Figure 4: Total ERA per energy class in 1000 m^2 - reference scenario. Source: Own Figure.

Scenarios	Reference	Subsidy on retrofits	Moderate CO_2 levy	High CO_2 levy	Information level	First combination	Second combination
Average retrofit rate (average 2016-2050)	0.8%	1.01%	0.89%	1.05%	1.37%	1.86%	2.24%
Change in investment for retrofits (compared to reference scenario)	–	46%	15%	44%	55%	115%	201%
Useful energy demand total (2050 compared to 2015)	-28%	-34%	-31%	-35%	-40%	-49%	-60%
CO_2 emissions (2050 compared to 2015)	-58%	-64%	-64%	-71%	-69%	-80%	-90%

Table 4: Overview of results from the Housing Stock Model. Source: Own Table.

Table 4 shows that the various measures of the policy scenarios each induce more retrofits than in the reference scenario, and thus energy demand and CO_2 emissions decrease. Especially noteworthy are the following results of our model:

- Even a high increase of the CO_2 levy (up to 1000 CHF/ton CO_2 in 2050 for "High CO_2 levy") does not significantly increase the average retrofit rate. This is due to the stepwise increase of the levy. As long as it is relatively small, it has only a limited effect on step 1, where owners decide to energy audit their buildings. Note that this result depends crucially on the parameter we have chosen to model the impact of an energy price increase (including the CO_2 levy) on the probability of owners entering Step 2. As there is little data available for calibration, we basically made ad-hoc assumptions. For that reason, quantitative results particularly at this point have to be interpreted cautiously.
- An increase of the information level significantly increases the retrofit rate in our model, showing the importance of tackling this barrier. Again, this quantitative result has to be interpreted cautiously. It rests on the possibility to double, triple and even quadruple the proportion of owners who get their building audited.
- Decarbonization cannot be achieved by a single policy alone, but only by a combination.

Figure 5 shows the heating system mix for all scenarios. The mix remains roughly the same. That is, energy carriers change roughly in proportion with the total energy use. Oil use decreases more than proportionally in the decarbonization scenarios (first and second combination), while gas remains significant. The significance of wood and heat increases in all scenarios compared to the reference.

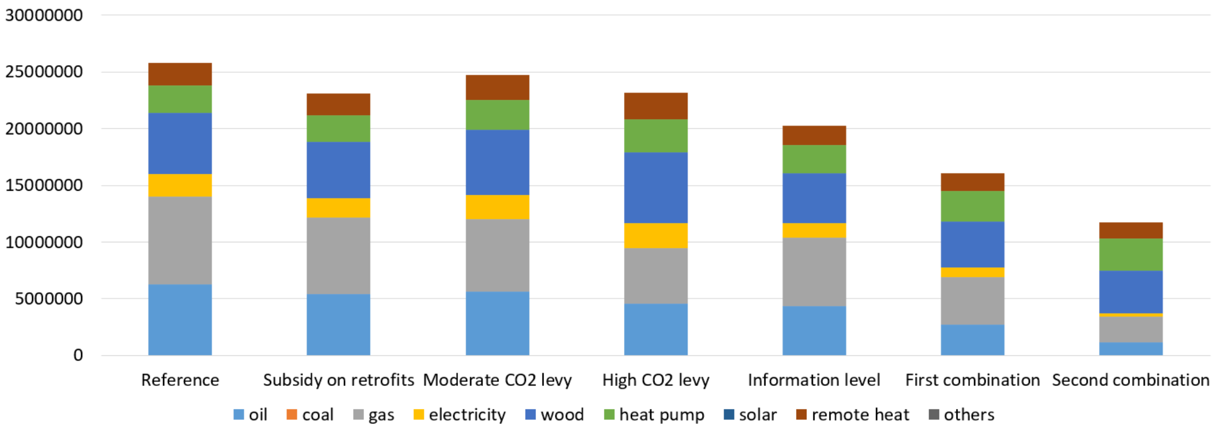

Figure 5: Quantities of the different energy carriers used for heating changes in the different scenarios in 2050 in TJ. Source: Own Figure.

3.2 Coupling of Housing Stock Model with GEMINI-E3

3.2.1 Policy scenario: ETS and CO_2 levy

We assume that Switzerland implements a decarbonization strategy aiming at reducing CO_2 emissions from energy combustion to 1 ton of CO_2 per capita in 2050, which amounts to a reduction of 72.7% relative to 2015.[21] Energy intensive industries such as refineries, cement or steel plants have to participate in the Swiss ETS linked with the EU ETS. We assume that the cap of the EU ETS is 43% lower in 2030 than in 2005, which corresponds to a reduction rate of 2.22% each year relative to the previous.[22] We extend this percentage reduction rate until 2050 and use this decreasing cap to simulate the resulting price for emission allowances on the EU (and Swiss) market within GEMINI-E3. All other sources of energy-related CO_2 emissions, including from transportation, are subject to a uniform CO_2 levy, which is endogenously determined in order to reach a target of 1 ton of CO_2 per capita in 2050.

We run this scenario with GEMINI-E3 alone and with GEMINI-E3 coupled with the Housing Stock Model, as described in section 2.2. Figure 6 shows the energy consumption in the two models. They give the same energy consumption level (of oil, natural gas and electricity) in 2050, but with different energy mixes. The transitions are also comparable, but with more abatement in the GEMINI-E3 alone in 2030 and 2040. The contribution of heating oil is similar between the two models. However, GEMINI-E3 alone shows a higher penetration of electricity associated with a lower share of natural gas. The limited penetration of natural gas in GEMINI-E3 alone arises from the assumptions of the energy prices in the reference scenario. Indeed, the assumptions based on the World Energy Outlook 2019 are that the price of crude oil is multiplied by 2 between 2018 and 2040, whereas the price of natural gas in Europe increases only by 30% over the same period. Therefore, the same CO_2 levy raises the consumer price of natural gas in much greater proportion than that of heating oil. This mechanism is less significant within the HSM, where the energy mix is rather driven by the distribution of energy classes.

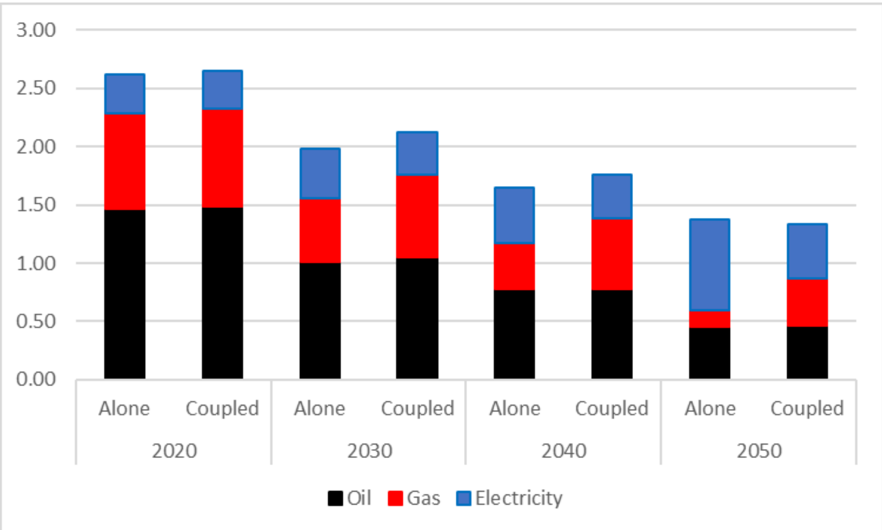

Figure 6: Residential energy consumption in Mt – CO_2 levy scenario. Source: own figure.

[21] Not within the scope of the model are e.g. non-CO_2 GHG or process-related emissions.

[22] With this constant rate of reduction, the cap is in 2050 down to 36% of its value in 2005. With a constant decrease by 2.22% of the level of 2005, the cap would be down to zero in 2050, which we do not consider as plausible and which would require much higher ETS prices.

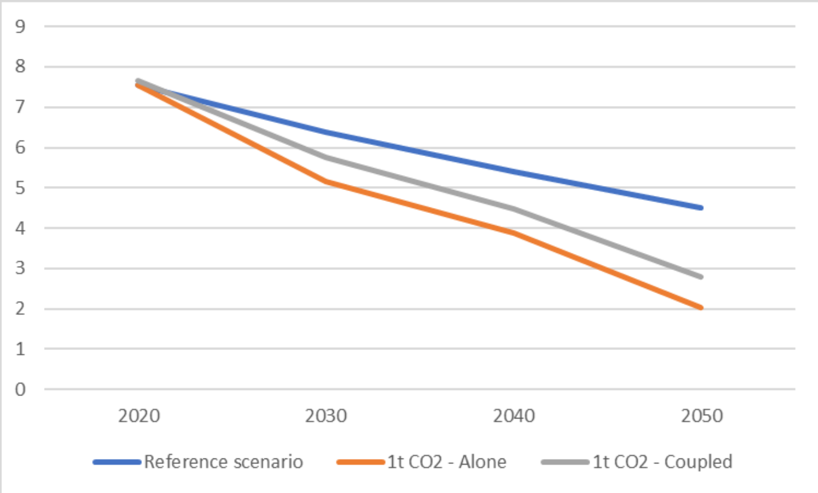

Figure 7: Residential CO_2 emissions from heating in Mt – CO_2 levy scenario. Source: own figure.

Figure 7 presents the resulting CO_2 emissions from residential heating. They decrease more in the policy scenarios than in the reference scenario with both models. However, GEMINI-E3 alone shows a reduction in emissions greater by approximately 0.8 Mt CO_2 in 2050 than the coupled model, because the latter has more natural gas in the remaining energy mix.

The CO_2 prices (ETS and CO_2 levy) are given in Table 5. Less abatement in the residential sector requires more abatement in other non-ETS sectors and therefore a steeper CO_2 levy increase. For that reason, GEMINI-E3 alone requires a lower CO_2 levy (1402 CHF in 2050) than the coupled version (1665 CHF). This is explained by the fact that the exogenous energy efficiency improvement in GEMINI-E3 is relatively high – 4% per year, which means that the energy demand for the same ERA decreases by 75% between 2015 and 2050. This is partly offset (by about a third) by a rebound effect, i.e. more ERA. The baseline EEI in the reference scenario of the Housing Stock Model is only 1.6%. The ETS prices are almost unchanged between the two models.

	GEMINI alone			Coupled		
	2030	2040	2050	2030	2040	2050
ETS price	153	184	272	153	183	271
CO_2 levy	351	498	1402	384	552	1665

Table 5: CO_2 prices in CHF – CO_2 levy scenario. Source: own table.

These carbon prices are very high and should not be seen as predictions. Recent improvements of our model lead to substantially lower values. The goal here is only to show how these prices are affected by a more realistic representation of the adoption of technical progress.

These high prices are only attained in the last decade, when CO_2 emissions are down to close to one ton per capita. Most firms would face this price as a marginal cost on emissions, but not actually pay it (exemption in exchange for a mitigation commitment). The ETS price is high because the model was calibrated on the year 2011, when renewables were still quite marginal in Europe, and it does not consider the rapid reduction in their costs. Nor do our simulations account for the possibility of carbon capture and storage (CCS).[23] As of today, CCS is only a realistic option for large point sources, which are included in the ETS. Therefore, it would give these sources an option to reduce their CO_2 emissions by the order of 90% at a cost possibly below CHF 100. This would cap the ETS price at about that level. Total emissions of the ETS sectors could be lowered faster by lowering the cap in

[23] As CCS has quite different cost implications in different sectors, we only model it in the Cement Industry Model (section 3.3).

response to the new mitigation potentials. In that case, the pressure to reduce their emissions would be lower on the non-ETS sectors, so that the CO_2 levy would not have to rise as much. Even in the absence of CCS, the difference between the ETS price and the CO_2 levy is hardly desirable nor sustainable. Firms would press to enter the ETS or to be allowed to use ETS certificates towards their own obligations. The ETS cap would be lowered to leave more of the emissions budget outside of the ETS.

The welfare cost is measured as an equivalent reduction of household consumption in the reference scenario. It reaches 1.24% in 2050 with GEMINI-E3 alone, while for the same abatement the welfare cost is equal to 1.39% with the coupled models, as they require higher CO_2 prices.[24]

3.2.2 Policy scenario: Combined instruments

One strength of the coupled framework is its capability to simulate non-price policies that can hardly be simulated with a standard computable general equilibrium model such as GEMINI-E3. We illustrate this point by comparing a 1 ton of CO_2 per capita in 2050 target within the coupled model using (i) the above described CO_2 levy policy and (ii) a policy mix that combines three instruments in the residential sector:

- a subsidy that increases by 1 percentage point per year until 2050,
- an information level increase, by 1 level every five years up to maximum information level 4, which means that the proportion of energy-audited buildings is multiplied by two, three and then four — relative to its level in the absence of this information campaign,
- and finally, a CO_2 levy applied on all economic sectors except the ETS sectors.

As can be seen in Figure 8, this policy mix yields more decarbonization in the residential heating sector: in 2050, CO_2 emissions are reduced by more than a factor 2 compared to the pure CO_2 levy scenario. Thus, other sectors (except the ETS sectors) must abate less CO_2 emissions to reach the target of 1 ton per capita. As Figure 9 shows, especially emissions from the road transport sector are higher in the combined model, as the abatement cost in this sector is higher than in other sectors. To reach the CO_2 target, the combined model thus reduces the welfare cost from 1.39% to 0.66% of household consumption in 2050. And finally, the maximum required CO_2 levy in 2050 decreases to 1200 CHF, compared to 1665 CHF when the CO_2 levy is used alone. There is no impact on the price of emission allowances (ETS price).[25]

[24] We calculate and express the welfare cost of policies as follows. Welfare in the reference and the policy scenarios is calculated using a standard utility function for the representative consumer, the arguments of which are his consumption of the different consumer goods. The result depends on the units used for the utility function, which are arbitrary. Total consumption is not a good measure either, as is depends on the prices of the different goods. Therefore, we calculate for each year a uniform change in the consumption basket of the reference scenario for that year that would yield the consumer the same utility as the basket calculated in the policy scenario. We can thus measure the welfare impact of a policy as an equivalent proportional change in the quantities consumed by the representative consumer in the reference scenario.

[25] The reason is that this price is determined exogenously by the model for the EU market. In any case, the Swiss market is too small to significantly influence EU prices.

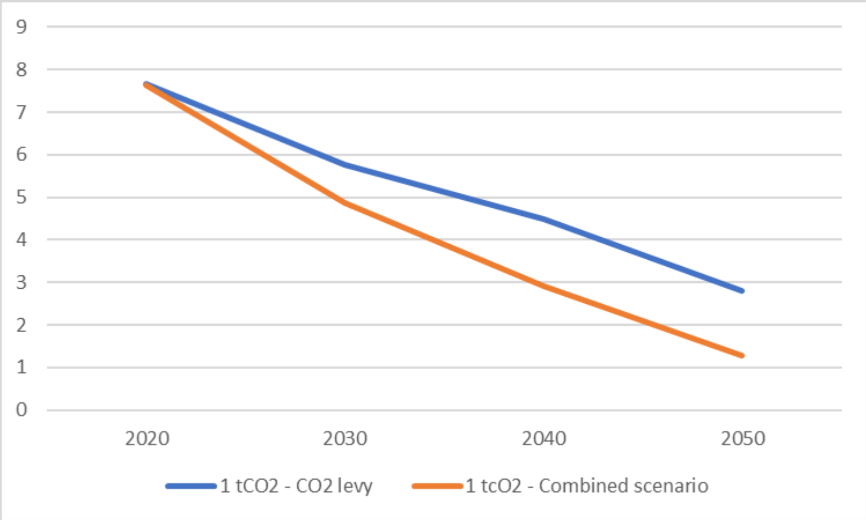

Figure 8: CO_2 emissions in Mt – CO_2 levy scenario versus policy mix scenario. Source: own figure.

Figure 9: CO_2 emissions per sector in Mt – CO_2 levy scenario versus policy mix scenario. Source: own figure.

3.3 Cement Industry Model

The following briefly describes the most relevant results of the cement industry model. More details can be found in the attached working paper.

3.3.1 Two baselines

The main climate policy applying to the cement industry is its required participation in the Swiss emission trading system (ETS). The Swiss ETS is linked with the EU ETS since 2020. Swiss cement plants receive an allocation of emission allowances under the Swiss cap, but they may sell them or buy more on the EU ETS market. The price of emission allowances (the "ETS price") is determined at the European level and, presumably, little affected by the activities of Swiss participants. Therefore, this price is not a parameter for Swiss climate policy. The ETS price is highly uncertain, as it will depend on the future emission caps decided by the European Union, the development of the European economy and how the participants to the ETS respond to the price signal. To account for this uncertainty, we shall work with two baselines, i.e. reference scenarios without policy changes:

- A low ETS price baseline ("Low EPB"), corresponding to BAU of the Energy Perspectives 2050+ (Prognos/TEP Energy/Infras/Ecoplan, 2020): the ETS price rises from 7 USD_{2017}/tCO_2 in 2015 to 54 USD_{2017}/tCO_2 in 2050. We extend the linear trend assumed from 2031 on (about +1 USD_{2017}/year) to 2090, as needed for the NPV calculations (Figure 10).
- A high ETS price baseline ("High EPB"), corresponding to ZERO Basis of the EP2050+: the ETS price rises from 7 USD_{2017}/tCO_2 in 2015 to 397 USD_{2017}/tCO_2 in 2050. We extend the linear trend assumed from 2041 on (about +25.66 USD_{2017}/year) to 2090 (Figure 10).

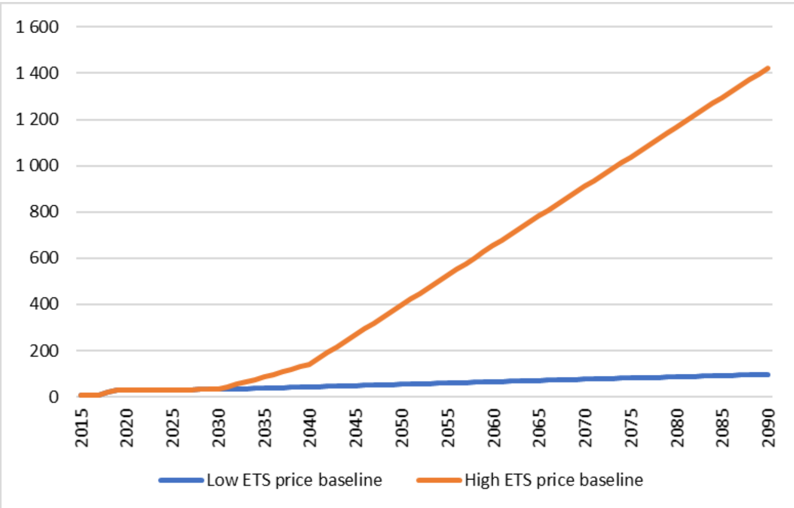

Figure 10: ETS price assumptions in the two baselines ($USD2017/tCO_2$). Source: own figure.

The two EP2050+ baselines differ not only in the assumptions about the ETS price but also on the evolution of energy prices. Indeed, the ETS prices reflect different climate and energy policies in the EU, which also have an impact on energy prices. Furthermore, the ETS price has an impact on the demand for coal for electricity generation and on the price of electricity. The corresponding price assumptions are represented in Figure 11 for coal and Figure 12 for electricity, two of the three energy vectors most relevant for cement production. Again, we extrapolate the price trends of the EP2050+ beyond 2050. For the third important energy vector, alternative fuels, we assume a constant price of 3 CHF/GJ.

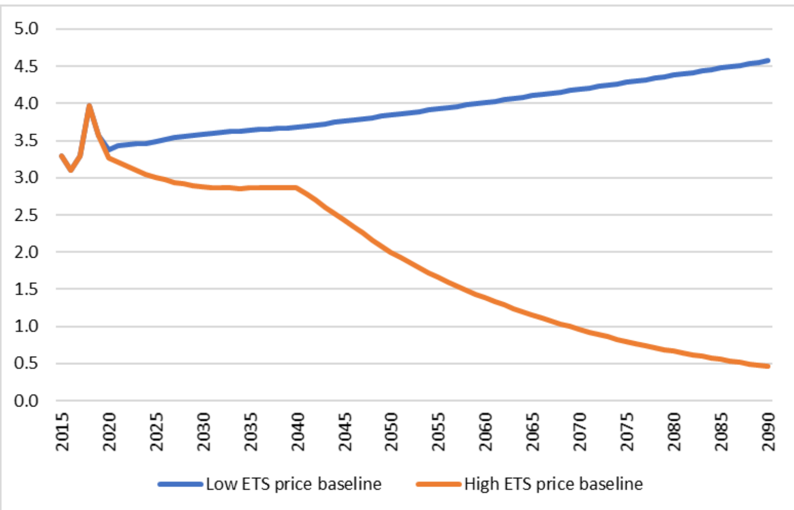

Figure 11: Coal price assumptions in the two baselines (CHF/GJ). Source: own figure.

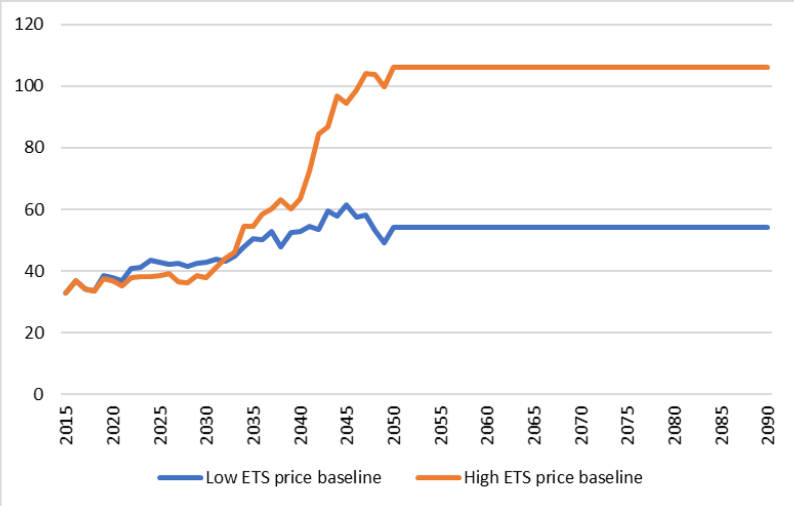

Figure 12: Electricity price assumptions in the two baselines (CHF/GJ). Source: own figure.

There is not difference in cement production in the two baselines. Indeed, it is a fundamental assumption of the Energy Perspectives that the energy transition can take place without altering economic activity. We shall discuss, however, a reduction in cement production as one option to reduce the sector's CO_2 emissions.

3.3.2 Results of the low ETS price baseline

In this section, we first show the results of the Low EPB in some detail, in order to illustrate the functioning of the model.

The following figures show that energy consumption as well as CO_2 emissions decrease continuously for all plants. There is heterogeneity among the plants, which comes from the different initial allocation of measures and the fact that certain measures are competing, so that not all plants implement the same set of measures. In the first approximately ten modelling years, measure-induced technical progress dominates, that is measures get implemented according to the NPV calculations. Afterwards, most measures (all EUP and most PEEM) are already implemented, so that further improvements occur at reimplementation. In the latter case, autonomous technical progress dominates.

For example, Figure 13 shows that fuel consumption drops at the plants in C and F around 2019. This is connected to the implementation of the PEEM CP2,[26] which has a significant impact on fuel consumption and is already in the initial allocation of all other plants. Around 2033 and 2044, there are drops in fuel consumption in all plants, when the blending measures CG5a and CG5b are reimplemented with higher efficiency (meaning that due to autonomous technical progress there is an abrupt increase in the use of additives[27]).

For electricity consumption, the improvements are smoother, as it is affected by more and smaller measures (Figure 14). The pattern of CO_2 emissions basically follows the fuel consumption pattern. However, for plants E and F emissions are consistently higher until 2044, because these two plants implement several measures, particularly I4, much later than the other four (see Table 3).

In the other following simulations, the mechanism is essentially the same. The six plants evolve similarly, albeit with some small differences in level and timing. Therefore, we shall not show plant-specific results any more.

[26] Upgrading preheater kiln to a preheater/ precalciner kiln.
[27] In reality, the amount of blending could change continuously (see the discussion on this topic in section 2.3).

Please note that the plant-specific results are purely model-theoretic and not meant to be a representation nor a prediction of the energy consumption or CO_2 emission of a real plant. In particular, we did not verify that our assumed initial allocation of measures corresponds to reality.

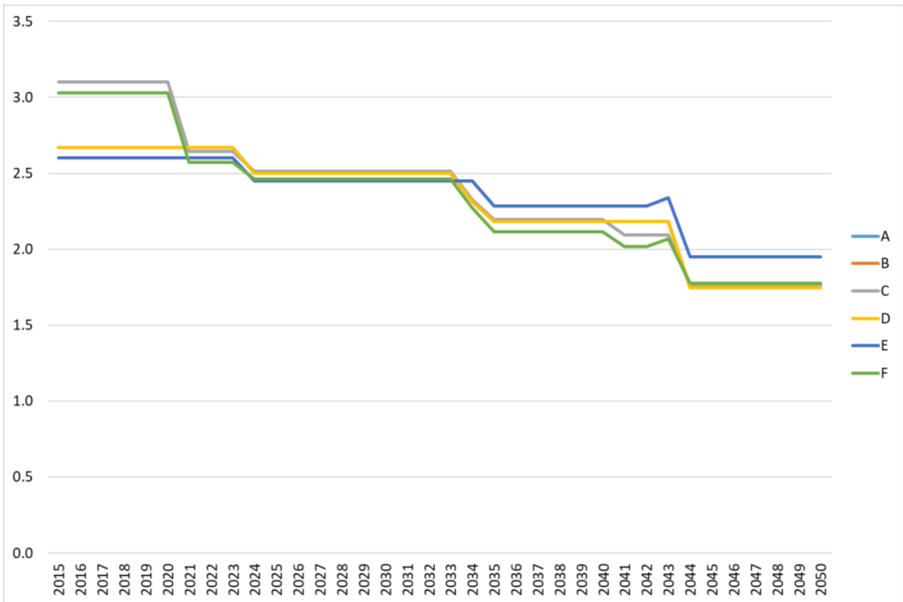

Figure 13: Plant specific fossil fuel consumption in GJ per ton clinker – Low EPB. Source: Own Figure.

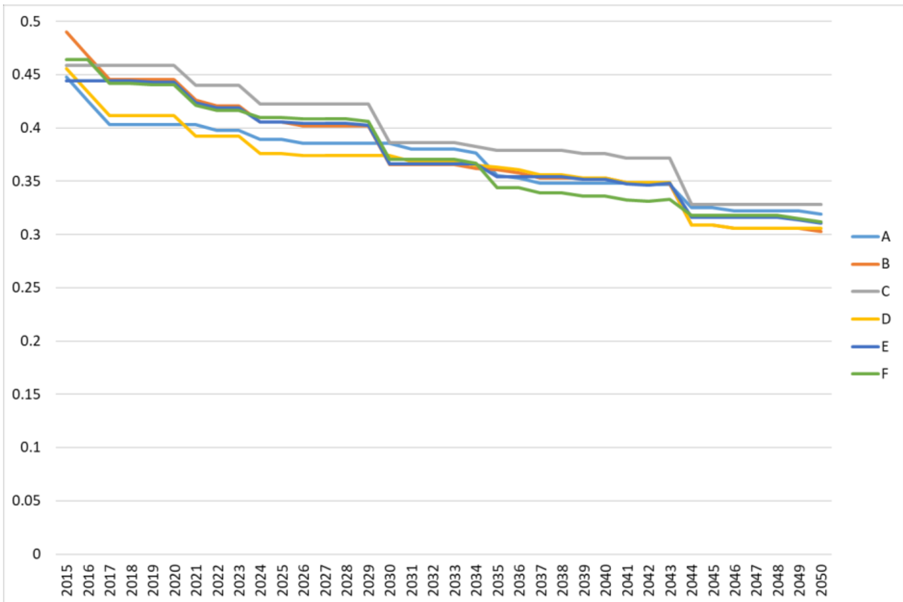

Figure 14: Plant specific electricity consumption in GJ per ton clinker – Low EPB. Source: Own Figure.

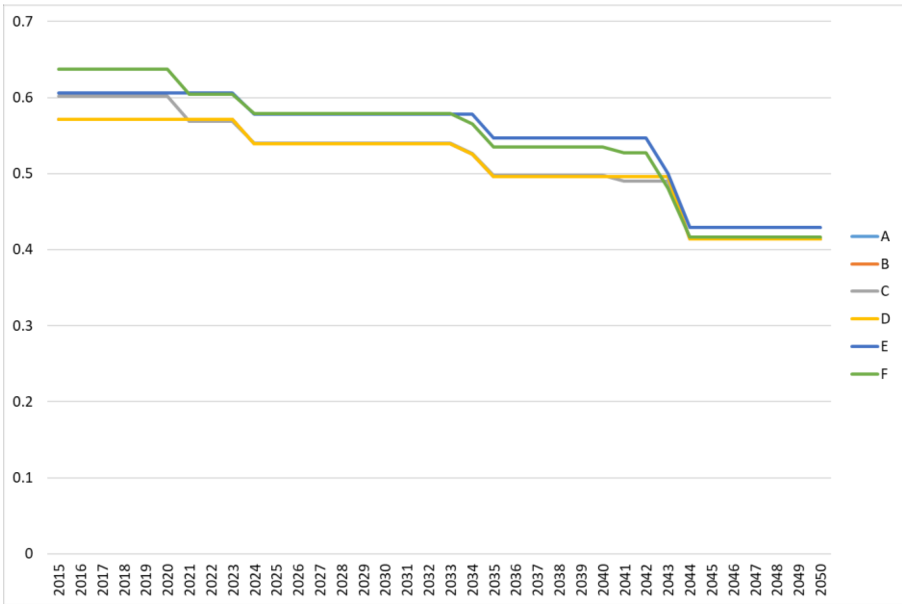

Figure 15: Plant specific CO_2 emissions in t CO_2 per ton clinker – Low EPB. Source: Own Figure.

3.3.3 Results of the high ETS price baseline

Even though the ETS price rises much higher in the High EPB than in the Low EPB, this does not lead to more CO_2 mitigation in the cement industry in the absence of a CCS option (Figure 16). Indeed, few of the energy efficiency improvement measures are sensitive to the price of CO_2 emissions. They are reimplemented when they reach the end of their lifetime, possibly a few years earlier if the NPV calculation justifies it, considering that early replacement has an opportunity cost (cf. section 2.3). The energy efficiency improvement when an equipment is replaced by a newer version is independent of energy and CO_2 prices. Thus, even though Figure 16 shows that emission reductions occur a few years earlier in the High EPB scenario than in the Low EPB scenario, that has only a limited effect on total emissions. A high ETS price only triggers strong mitigation if it induces emitters to adopt emission reduction technologies that they would not adopt in the absence of this nudge, such as CCS. Such technologies do not exist in this scenario.

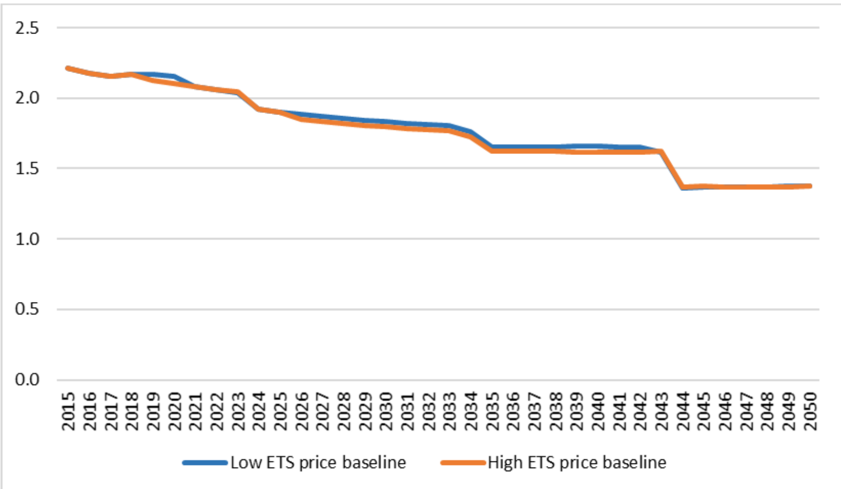

Figure 16: Total CO_2 emissions in tCO_2 of cement industry in the two baselines. Source: Own Figure.

3.3.4 Policy scenarios

In the following, we describe the choice of the policy scenario considered in the cement industry model. Note that — contrary to the building stock model — we do not consider a scenario with a predefined reduction target, but the policy scenario is related to specific measures. Many options can be considered to reduce the CO_2 emissions of the cement industry (cf. Favier et al., 2018; Obrist et al, 2021). The comparison of the two baselines above shows that many measures would have only marginal effects. This is the case of subsidies to accelerate the implementation or replacement of some energy conservation measures. Even closing down the ‘worst’ plant would not improve the CO_2 footprint of cement production significantly, as the plants are not that different (cf. Figure 15). Four measures could: (1) reduced production of cement, (2) increased mixing-in of other materials when making cement with the clinker, (3) increased use of fuels whose emissions do not count as additional CO_2 emissions (alternative fuels), and (4) carbon capture and storage (CCS). Option (1) implies macroeconomic changes in construction or increased imports, neither of which is the outcome likely of a plausible policy. Furthermore, no simulations are needed to estimate its effect on CO_2 emissions: they would decline in proportion to domestic cement production. Option (2) depends on the availability of additives, which is quite uncertain. Option (3) is already used to the maximum by the cement plants in competition with waste incineration plants. There remains option (4).

Indeed, one potentially large lever to reduce the CO_2 emissions of Swiss cement plants with constant production is carbon capture and storage (CCS). Today, technical, economic and legal barriers hinder the implementation of CCS. We shall assume that the technical and legal barriers are lifted in 2040 for cement plants, following Prognos/TEP Energy/Infras/Ecoplan (2020, Tab. 15).

CCS available from 2040 on

Implementing CCS is a choice of each cement plant, comparing in NPV the costs of CCS described in section 2.3, including the costs of the additional fuel and electricity use, with the price of the emission certificates that the plants could sell or would not need to buy after implementing CCS. In the Low EPB, CCS never becomes profitable in our 2015-2050 horizon. In the High EPB, it is profitable in 2040, so it gets implemented when technically and legally possible. It would actually be profitable much earlier, in 2032. This shows the importance of these barriers.

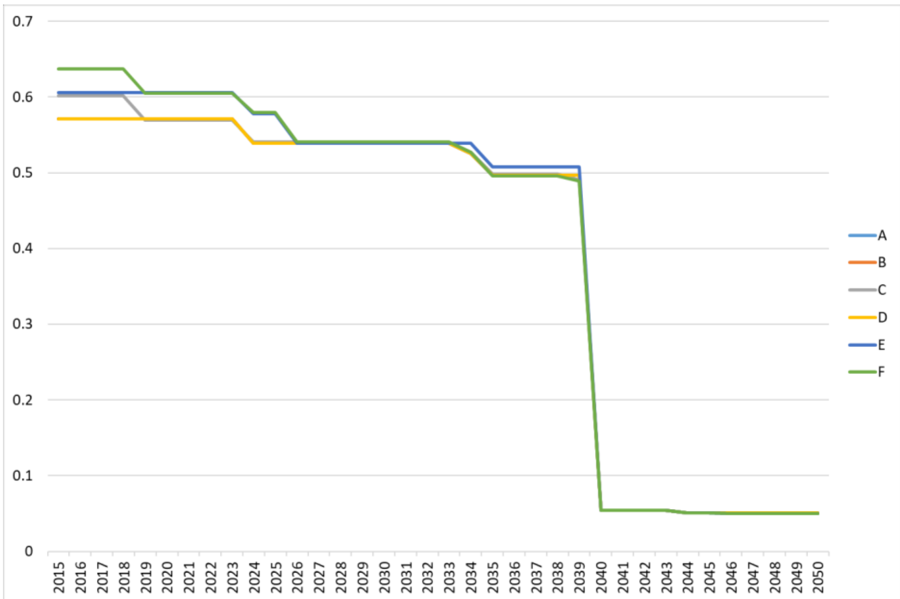

Figure 17: Plant specific CO_2 emissions in t CO_2 per ton clinker – High EPB with CCS in 2040. Source: Own Figure.

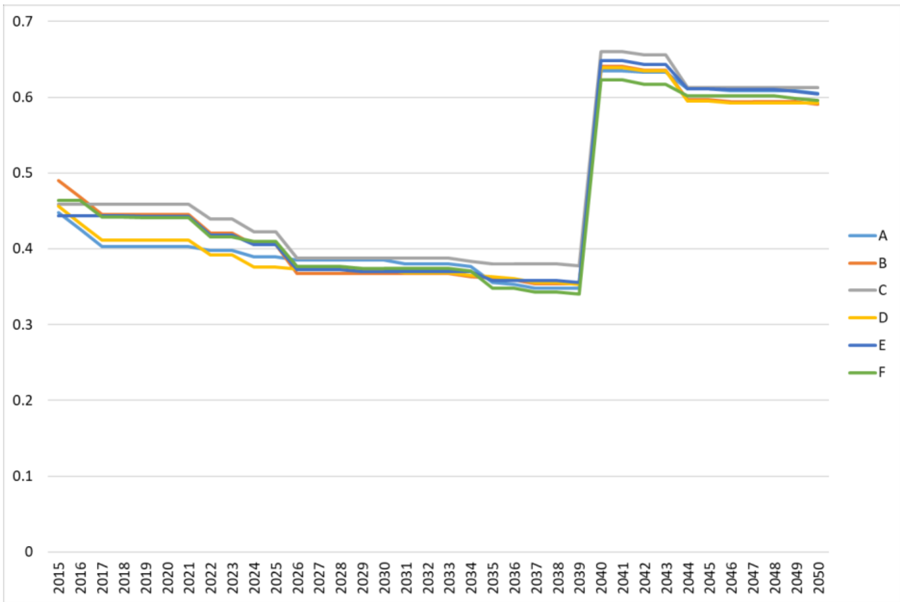

Figure 18: Plant specific electricity consumption in GJ per ton clinker – High EPB with CCS in 2040. Source: Own Figure.

Figure 17 shows the stark impact of CCS on CO_2. It leads to a synchronised drop of emissions by 95% in 2040.[28] This comes at the cost of sharply increased energy consumption, by a factor of about 2, as shown in Figure 18 for electricity.

Promoting CCS with a CO_2 price floor

As indicated earlier, CCS never pays for the cement plants in the low ETS price baseline. Switzerland could, of course, count on rising ETS prices to induce decarbonisation of cement production, as in the high ETS price baseline. It would be safer to announce a price floor for CO_2 emissions.[29] This could take the form of the Confederation committing to buy back the emission certificates that cement plants no longer need thanks to CCS at a guaranteed price. If the ETS market price is higher, this price floor is ineffective. If it is lower, the Confederation would pay the difference between the price floor and the market price. Such a mechanism would take away a substantial part of the economic risk of implementing CCS for the cement plants.

The higher the price floor, the earlier CCS is implemented. We chose to look for a constant price floor sufficient to trigger the implementation of CCS in 2030 already. Our simulations show that a price floor of 133 CHF/tCO_2 achieves this goal in the Low EPB. In this baseline, the price floor implies that the ETS price evolves as in Figure 10 up to 2029, when it reaches 31 CHF, and then it jumps to 133 CHF in 2030 and stays at that level. The consequences for the CO_2 emissions of the six plants are shown in Figure 19. After the drop in 2030, there is a further slight reduction in 2050, when the CCS installation is replaced by a new one, which has become more fuel efficient in the meantime.

[28] The six plants are operated independently of each other and installation of CCS does not require shutting down a plant, so nothing speaks against all plants installing CCS simultaneously, as soon as it becomes possible.
[29] One could also imagine a subsidy on installing the CCS equipment, but the capital cost is very small relative to variable costs (cf. section 2.3), so this lever would be quite weak.

Figure 19: Plant specific CO_2 emissions in t CO_2 per ton clinker – Low EPB with CCS and ETS price floor in 2030. Source: Own Figure.

When setting the price floor, the administration cannot be sure that the ETS price would not rise anyway to levels high enough to encourage the implementation of CCS. Therefore, we simulate the effects of the same price floor of 133 CHF/tCO_2 in the high ETS price baseline. It turns out that this does not make a significant difference, CCS still gets implemented in 2030 and not earlier, even though the ETS price exceeds the price floor from 2040 on (Figure 10).

Myopic expectations

If the administration cannot be sure of the path of future ETS prices, nor can the cement plant operators. Until now, we assumed that they knew whether they were in the Low or High EPB and how the ETS price evolves un to 2090 in each baseline. In order to test the implication of this assumption, let us assume the complete opposite, i.e. perfect myopia. Under perfect myopia, the operators assume every year that the ETS price will remain at the level of that year ever after, even though their anticipations are proven wrong every year.

The consequence of myopia is that CCS is implemented in 2044 in the High EPB (Figure 20) (never in the Low EPB). In 2044, the ETS price reaches 238 CHF, a price high enough, when it remains constant, to offset the high electricity prices of the High EPB (cf. Figure 12). This shows that if cement plant operators do not anticipate the relatively steep increase in the CO_2 prices of the high ETS price baseline, they will delay implementing CCS even beyond the 2040 earliest year we had assumed for technical and legal reasons.

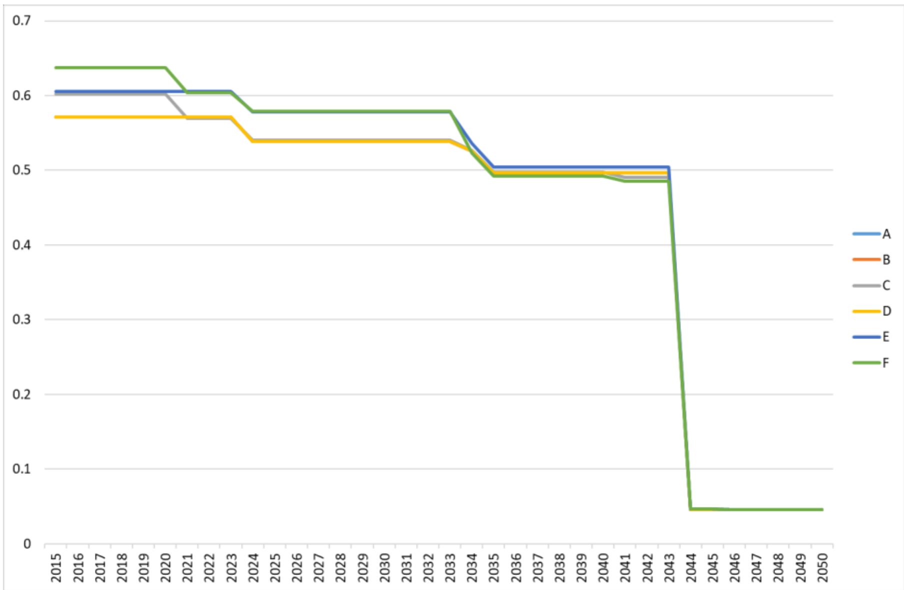

Figure 20: Plant specific CO_2 emissions in t CO_2 per ton clinker – High EPB with CCS and myopic expectations. Source: Own Figure.

Overview

Measured per ton of clinker produced, fuel and electricity consumptions as well as CO_2 emissions decline by about 30 to 37% between 2015 and 2050 in the baselines without CCS (Table 6). There is no significant difference between the low and high ETS price baselines. The reason is that in each case the later phase is dominated by autonomous technical progress, which makes up for the somewhat slower measure-induced technical progress in earlier phases of the Low EPB. Cumulated over 2015 to 2050, total CO_2 emissions are only 1.1% lower in the High EPB than in the Low EPB.

In the scenarios with CCS, CO_2 emissions in 2050 are only 8% or 9% of the 2015 level, which reflects the assumption that CCS reduces emissions by 95%, but also the increased fuel consumption induced by CCS. Indeed, the implementation of CCS leads to a strong increase of fuel and electricity consumptions, while they decrease in the baseline thanks to the various energy efficiency measures. This increase is higher the earlier CCS is implemented, because earlier means that the technology is less advanced, i.e. more energy intensive. The scenario with the ETS price floor from 2030 is a little particular in that respect, because the CCS system is renewed at the end of its lifetime of 20 years, i.e. precisely in 2050. As a result, the energy consumption is higher in 2049 than in the other CCS scenarios, but the energy consumption in 2050 is lower.

CCS implementation in 2030 saves 46% of the cumulative CO_2 emissions over 2015-2050 of the baseline. Implementation in 2040 saves 22% and in 2044 only 13%. This shows the huge importance of the early availability of this technology for the cement industry, even if it means more energy consumption.

The first four rows in Table 6 do not exactly correspond to the change in energy consumption and CO_2 emissions in the cement industry in the different scenarios, because they are calculated per ton clinker produced. Changes in clinker production could offset or reinforce these changes. An assumption compatible with the Energy Perspectives 2050+ is that total clinker production in Switzerland will be 3.4% larger in 2050 than in 2015.[30] Taking this small increase into account, the energy savings and CO_2 reductions in the cement industry would be somewhat smaller. Note the last row of Table 6 is based on total CO_2 emissions, not per ton clinker.

[30] Cement production will grow somewhat more, but clinker is expected to be partly replaced by other additives in cement making.

	Baselines	High EPB with CCS from 2040	ETS price floor from 2030	High EPB with myopia
Fossil fuels consumption	–37%	+53%	+61% / +39%	+39%
Electricity consumption	–32%	+30%	+36% / +20%	+20%
CO_2 emissions before sequestration	–30%	+71%	+80% / +55%	+55%
CO_2 emissions after sequestration	–	–91%	–91% / –92%	–92%
Cumulative CO_2 emissions 2015-2050 relative to baseline	–	–22%	–46%	–13%

Table 6: Variation between 2015 and 2050 of energy consumption and CO_2 emissions per ton clinker produced, except last row. When two values are given, they correspond to 2049 and 2050. Source: own table.

4 Conclusions and outlook

We managed to construct two functional and novel methodologies to depict the evolution of energy efficiency improvements in two sectors that are important users of energy and sources of CO_2 emissions. This allowed us to obtain a better representation of EEI triggered by energy and climate policies. Although we use available data to calibrate the models, the focus of this exercise was not to obtain precise quantitative results, but rather to construct a proof of concept. Simulating different policy scenarios, we showed that it is important to consider the responsiveness to various types of policies. It is, for example, important to not only consider monetary incentives (such as subsidies or taxes), but also “softer” measures such as information campaigns. This is especially true for building owners, as many suffer from incomplete information and may not even assess the potential savings from energy refurbishment. Consequently, a given target can be achieved at lower cost when using a smart mix of hard and soft policies.

With our two sectoral models, the Housing Stock Model and the Cement Industry Model, we showed that it is possible to find a middle way between a very detailed representation of a sector, which can hardly be combined with a macro-economic model, and the standard one-fits-all representation common in macroeconomc models. Our models were specifically designed for their capacity to make energy efficiency improvements responsive to policies. The actors in these models explicitly decide to adopt EEI measures, depending on their information level and incentives. Therefore, these models allow for a more accurate prediction or evaluation of the impact of energy-related policies on energy use and CO_2 emissions. They should not be used for predicting the general evolution of the housing sector or cement industry or for simulating policies unrelated to energy use.

We consider several possible extensions:

- To obtain more data for better calibration of the models, e.g. (i) realistic measures to increase the share of energy-audited buildings; (ii) the investment cost function in the Housing Stock Model; (iii) not yet considered efficiency and abatement measures in the Cement Industry Model; or (iv) a better representation of costs and benefits in this model, e.g. including fixed costs.
- To represent particularly the implementation of CCS at cement plants more carefully, considering more barriers than just cost and a general authorization.
- To endogenize the choice of energy class for new construction in the Housing Stock Model and to allow for a gradual evolution of energy carriers per energy class.
- To extend the models to account for additional barriers/features such as (i) myopia or uncertainty with respect to cost savings from an energy carrier switch; (ii) financing constraints; or (iii) the uncertainty surrounding authorizations for retrofit.
- To update the exogenous inputs (e.g. energy prices or energy consumption) with the newest energy perspectives.

- To simulate more policy scenarios.
- To improve the calibration of the models (e.g. on the audit probability based on data). In case no data is available in the literature, a Delphi method could be applied to obtain parameters from experts.
- To experiment with alternative representations of energy vector choice, not only based on a constant elasticity of substitution between vectors but considering that substitution becomes more likely at much higher prices.

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6 Appendix

6.1 Technical measures used in the cement model

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

Table 7: List of technology measures for cement plants. Source: Zuberi and Patel (2017).

6.2 National and international cooperation

We presented preliminary results at:

10th SAEE (Swiss Association for Energy Economics) Student Chapter Workshop 2018, ETH Zurich, (23 Nov, 2018), Oral presentation.

3rd AIEE (Italian Association for Energy Economics) Energy Symposium on Energy Security, Bocconi University, Milan, (10-12 Dec, 2018), Oral presentation.

18th SSES (Swiss Society of Economics and Statistics) Annual Congress, Geneva, (13-14 June, 2019), Oral presentation.

16th IAEE (International Association for Energy Economics) European Conference, Energy Challenges for the Next Decade, University of Ljubljana, (25-28 August, 2019), Oral presentation.

CISBAT 2019 – Climate Resilient Cities - Energy Efficiency & Renewables in the Digital Era, International Scientific Conference, EPFL Lausanne, (4-6 September, 2019), Oral presentation.

Swiss-US Energy Innovation Days 2019, Austin and San Antonio, Texas, USA, (6-9 Oct, 2019), Oral presentation. Accepted with a full travel grant.

Swiss-US Energy Innovation Days 2020, Bern, Switzerland (4th July, 2020). Deep Decarbonization in the Swiss Building Sector. Oral presentation.

Brenet 21st Status-Seminar, Aarau, Switzerland, (3-4 September, 2020). Oral presentation.

6.3 Working paper 1: A two-step decision model on energy retrofitting buildings

6.4 Working paper 2: Modelling endogenous energy efficiency improvement: Swiss cement production

A two-step decision model on energy retrofitting buildings

Sergey Arzoyan[a,*], Quirin Oberpriller[b], Philippe Thalmann[a], Marc Vielle[a]

[a]*Laboratoire LEURE, École polytechnique fédérale de Lausanne (EPFL), Station 16, CH-1015 Lausanne, Switzerland.*
[b]*INFRAS, Zurich, Switzerland.*

Abstract

In standard analyses of Swiss energy and climate policies, the speed and extent of energy efficiency improvements (EEIs) are usually assumed to be unaffected, even by policies designed to foster innovation. This project introduces endogenous EEIs and barriers to retrofitting in the housing sector. To achieve decarbonisation, we explain how Swiss building stock has evolved and how retrofitting decisions and heating system improvements may reduce energy consumption. We use a two-step model to illustrate how homeowners make decisions about retrofitting, then we consider several scenarios. Our results showed that, to achieve deep decarbonisation in the building sector, a number of different economic instruments need to be used simultaneously.

Keywords: Switzerland, endogenous, residential, modelling, energy, retrofitting, efficiency, housing

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Highlights

- We build a tractable building stock model that details the years of construc-

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

tion, energy classes and owner types

- Retrofitting is triggered by a two-step decision model that considers energy auditing and classic economic retrofit gain
- Decarbonising Switzerland's residential sector will require the use of several economic instruments that combine price incentives and information campaigns

1. Introduction

1.1. Swiss context

Switzerland initiated its climate policy in 1990, in extremely close combination with an energy policy that aimed to reduce the country's dependence on imported energy (no fossil fuels are extracted in Switzerland). The first goal to stabilise CO_2 emissions by 2000 at the 1990 level, which was achieved. The next goals were to reduce CO2 emissions by 10% and by 20% by 2010 and 2020 respectively. The first of these two goals was only achieved when foreign offsets were taken into account and the second will likely be missed, mostly due to a lack of reductions in the transport sector. The buildings sector is on track, with CO_2 emissions from fossil energy carrier in 2018 28% less relative to 1990 (Federal Office for the Environment, 2020). The main instruments for encouraging emission reductions in the building sector are: (1) energy efficiency requirements that the cantons apply when delivering a building permit for a new construction or substantial retrofit, (2) a CO_2 tax on heating fuels introduced in 2008 at the rate of 12 CHF/tCO_2 and gradually raised to 96 CHF/tCO_2 in 2018 – 2020 and (3) an energy retrofit subsidy programme funded through the CO_2 tax.

In August 2019, the Swiss government announced its intention to reduce greenhouse gas emissions to net zero by 2050. The building sector is expected to be among the first to stop emitting any CO_2. It is the sector that has contributed most, since 1990, to the reduction in greenhouse gas emissions (Federal Office for the Environment, 2020). Most new buildings are constructed without fossil-based heat generation; heat pumps are the favourite choice for single-family dwellings. Deep decarbonisation simulations have shown that it is economically feasible, but needs high carbon prices. The magnitude of carbon pricing is, however, markedly reduced when exogenous energy efficiency improvement is permitted (Babonneau et al., 2016). This is assuming that a fixed rate of energy efficiency improvement is numerically convenient, but it does not allow for the influence that price changes can have on the rate of innovation and adoption of new technologies. Large integrated assessment models need to be enriched with a theoretically sound yet numerically tractable representation of endogenous energy efficiency improvement for these models to better allow simulation of energy and climate policies. This paper proposes such a representation for the buildings sector, which accounts for one-third of all CO_2 emissions in Switzerland.

When considering energy efficiency improvement and fossil energy replacement in the buildings sector, it is important to keep some characteristics of this sector in mind. One is, naturally, the fact that buildings have a very long lifecycle. Between 2010 and 2017, years when there was relatively strong construction, about 1.2% of new dwellings were added to the housing stock every year. Over the same period, 0.07% of dwellings were demolished on average. This illustrates housing stock's very high inertia. One half of the existing housing stock was built before the first oil price shock. The second characteristic of Swiss housing is the high proportion of rental housing at about 60% - the highest share among all comparable countries. It implies that housing construction and retrofitting is very much the responsibility of landlords. This also applies to office and commercial buildings, which mostly belong to investors rather than to their users.

1.2. Analysis of Swiss building stock

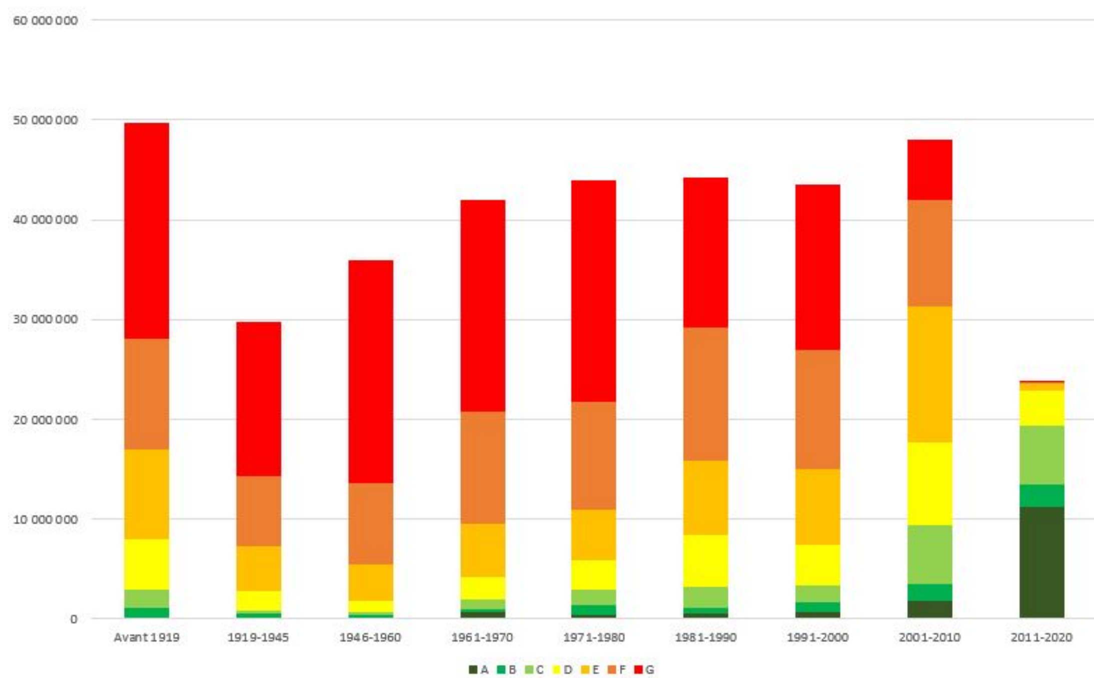

Figure 1: Energy reference area in m^2 per construction period and energy class (for energy thresholds, see Table 1); the year 2015 (source: our estimations, using data from the SFOE. See Appendix C)

The quantity of housing in Switzerland is measured by the total energy reference area (ERA) in square metres, i.e. the total heated surface. The overall energy reference area is allocated by construction period (CP) and energy class

Table 1: Thresholds of energy classes

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

(EC). Energy classes rank from A (best) to G (worst), following a Swiss classification described in Appendix 7. The thresholds of energy classes are given in Table 1, where thresholds are presented as useful energy, which is the final amount of energy available to the customer after final conversion for their use.

The allocation of ERA by CP and EC for the year 2015 in Switzerland is represented in Figure 1. According to the Swiss Federal Statistical Office [1], there were a total of 4.5 million dwellings in Switzerland in 2017, 1.7 million of which were single-family dwellings. In the construction period before 1919, there were many inefficient buildings (see Figure 1), whereas the buildings built from 1961 to 2000 have relatively the same efficiency. As can be seen from Figure 1, there was a considerable decrease in building construction in the period between 1919 and 1945, when the buildings rated as energy class G are still prevalent. The most efficient buildings are those built since 2001. As seen in Figure 1, the number of buildings with A and B energy ratings substantially increased.

[1] `https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/dwellings.html`

2. Literature review

Nowadays, there are many models and tools to evaluate energy consumption in building stock. Kavgic et al. (2010) and Swan and Ugursal (2009) provide highly valued reviews of existing building stock models and also represent the difference between the top-down and bottom-up approach in building stock level energy consumption modeling. Both reviews discuss the disadvantages of each type. In the case of restricted data accessibility, pure top-down models are a suitable way of describing building stock. Nonetheless, since top-down models cannot explicitly take into account the system's components, they are in reality incapable of exploring the effect of particular technologies or measures (Kavgic et al., 2010) (Swan and Ugursal, 2009).

2.1. Bottom-up models

Numerous bottom-up models used to conduct energy and carbon analyses on building stock (Mata et al., 2013; Wiedenhofer et al., 2015; Nemry et al., 2010; Meijer et al., 2009; Hrabovszky-Horváth et al., 2013). Many authors including Charlier and Risch (2012) and Uihlein and Eder (2010) applied bottom-up models to European countries.

The whole building stock or an individual dwelling is taken into consideration in bottom-up models. A distinction was made between bottom-up models by Swan and Ugursal (2009). They set the models apart by using them in engineering (EM) and statistical models (SM). EM is based on equipment use, heat transfer, and thermodynamics relationships, as well as power ratings. SM is based on types of regression analysis and on historical information. The regression analysis usually attributes a particular dwelling's energy consumption to particular end uses.

The advantage of bottom-up models compared to top-down ones is their ability to model in detail the energy demand of end users and technologies. The fact that bottom-up models lack the consideration of occupier behaviour is a significant disadvantage of this approach. Swan and Ugursal (2009) mentioned that, today, statistical bottom-up models try to conduct regression analyses from the data available (e.g. energy bills) with the purpose of decreasing the number of restrictions. Additionally, Swan and Ugursal (2009) categorised bottom-up models into “distribution”, “archetype” and “sample” types. In the “archetype” category, reference buildings are grouped along with characteristics that identify the building stock. This approach is most appropriate when solely aggregate data is available.

The future energy consumption’s decrease perspective has long been recognised as a problem that deserves serious attention. To solve this issue, it is important that we understand the building stock’s long-term dynamics. This will help us to get a more profound understanding of the flow that drives the system’s activities and ought to be a stipulation of a more reliable way to address advancements of building stock’s current and future energy demands (Kohler and Hassler, 2002). A model of UK housing stock for energy use and CO_2 emissions was developed by Johnston (2003). He analysed several scenarios where the decrease in CO_2 emissions is achieved by 2050. Based on the Building Research Establishment Domestic Energy Model (BREHOMES), he developed a model that includes a two-step approach: data model as well as CO_2 emissions and an energy model. It was concluded that, by requiring enthusiastic demand-side activities,the UK housing sector can conceivably be decarbonised by 60%. The author relied only on four dwelling types that can be distinguished by size and construction period.

The call to action was heeded by researchers, who began to study the existing gaps in the residential stock's monitoring. For example, Meijer et al. (2009) mentioned the existence of serious gaps in the monitoring of residential stock and also pointed out that none of the countries observed the impact of retrofitting on housing. Additionally, it was pointed out that there is a lack of big data in models' inputs and outputs for building stock's energy and carbon analyses (Kavgic et al., 2010),(Meijer et al., 2009).

Furthermore, scientists recognised just how important it was to collect building stock data during building stock modelling and when assessing its potential for energy consumption improvement in the future. For instance, Kavgic et al. (2010) underlined that, in building physics-based bottom-up models, the limitations of quantification and transparency of inherent uncertainties are significant. Additionally, they concluded that the lack of data that can be easily acquired is a major issue. They mentioned that building stock's energy consumption data will enable determination of the tendency of technological and social aspects. Moreover, a study from 2010 by Michelsen and Muller-Michelsen (2010) analysed 150 multi-family dwellings and obtained the data from consumption-based energy performance certificates. They differentiated between size, year, energy consumption and retrofit measures, ulimately reaching to the conclusion that the pre-modern building stock performs better than recommended engineering-based assessments.

These findings and techniques were further developed and revised in numerous scientific papers. Two of these studies are worth mentioning here: works by Charlier and Risch (2012) and McKenna et al. (2013).

The study by Charlier and Risch (2012) assessed the effect of environmental public policy measures in France in a simulation model where housing stock energy consumption and the housing categories' GHG emissions until 2050 were modelled. Ultimately, it was shown that, with the existing policy measures, the 2050 target for GHG emissions and primary energy consumption will not be achieved. The paper did not focus on elaborated categorisation for residential stock (age or size); rather, it centres on connecting the results with policy incentives in the 2050 horizon.

McKenna et al. (2013) depicted a residential block classification method that can be reached by 2050 to determine Germany's energy-saving goals. They differentiated between building types, taking into account age, size and location, as well as computed energy demand. The paper concluded by modelling retrofits and demolition rates to meet building stock's future energy demands. The results acquired are extrapolated far in the future and have not been confirmed: the use of the computed energy consumption in buildings was insufficient for making a retrofit decision.

To conclude, it is worth mentioning that the future development of scenarios for building stock's energy demand can face numerous divergences and variances, in addition to requiring vigorous data collection and further improvements (Harvey et al., 2014).

2.2. Top-down models

Typically, top-down models aim to fit historical time series of both CO_2 emissions and national energy consumption. This kind of models acts as an aggregated level and is usually used to explore the energy sector and the economy at large. The top-down approach can be categorised as an econometric and technological model.

Econometric models are based on energy use depending on variables such as fuel price, income and gross domestic product (they might also incorporate climatic conditions, etc.). Nevertheless, top-down models might not include the data on present and future technological options, because they would focus on the past macroeconomic trends and relationships, rather than the building's physical factors, which can affect the energy demand.

Scientists responded to this call to action and started to construct top-down models. For example, Tornberg and Thuvander (2004) developed an energy model where they used energy data that was measured at metering stations and was dispensed between buildings. The distribution was made based on the building's age and use. As a result, the model demonstrated the energy use inside building stock, which could also show the high consumption areas. Nevertheless, they could not succeed in making a point-blank connection between energy consumption and individual buildings. The findings of Tornberg and Thuvander (2004) were used to build the retrofit model created by Balarasa et al. (2007), who studied how to apply energy conservation measures to dwellings lacking retrofitting and who built a retrofit model of the housing sector in Greece. They used current energy consumption and an assessment of the housing stock figures to estimate the effect of 14 energy conservation measures. These energy conservation measures were applied to dwellings requiring a retrofit. The result shows that housing stock greatly lacks insulation. They predicted that adding insulation would cut demand for space heating by up to 49%.

In addition, numerous regressions models that use the average heating season temperature and energy price (regulated according to inflation) were developed. As far back as in 2010, Summerfield (Summerfield et al., 2010) built and described a simple top-down model: the annual delivered energy price and temperature (ADEPT) for the annual energy condition of building stock in the UK since 1970. The ADEPT model permits comparison of the yearly consumption data with what would be anticipated following authorisation of temperature and price settings. The model cannot quantify the role of the other factors and how efficient policy measures are.

2.3. Swiss analyses

Some of the studies also analysed Swiss building stock. A variety of specific techniques were suggested to address the issue of building stock division and retrofit in Switzerland. For example, Ott et al. (2005) surveyed 600 building owners/agencies to determine the envelope condition, past retrofit measures and difficulties that did not allow for better retrofitting. The conclusion showed that the retrofit rate, as well as improved energy efficiency, is not enough for policy targets to be reached. Additionally, the authors of Siller et al. (2007) evaluated Swiss building stock in 2007 with respect to heating systems and the building envelope. They based their model on three building types and by seven construction periods to create a total of 21 archetypes. Moreover, Heeren et al. (2009) compared different scenarios in a Swiss building stock model and their potential to achieve the 2050 energy savings goal. The building stock was presented in five construction periods and two building types and the study was focused on the long-term advancement of building stock. These findings and techniques were used in Aksoezen's recent study (Aksoezen et al., 2015) where the authors used four building types and four different construction periods in 19 districts/counties in the canton of Basel.

These valuable findings were used by Heeren et al. (2013), who developed a methodology of a cycle-based building stock model that proposes a new assessment methodology. The stock was divided by buildings cohorts of comparable equipment and construction characteristics. The characteristics are: type, construction period and systems of building technologies. Moreover, the model encompasses a relationship with energy efficiency measures and the substitution of fossil energy-based heating systems, and advances the inclusion of material flow (including environmental impacts and cost). The results demonstrated that the city of Zurich can decrease building sector-related GHG emissions by up to 85% by 2050. It is worth mentioning that M. Jakob (2014), using a new assessment methodology by Heeren et al. (2013), claimed that if separate building elements are retrofitted, this will not necessarily result in improved energy efficiency. In the paper, it was remarked that existing retrofit measures for energy efficiency improvements make up a small part of the total quantity of retrofit measures. This shows that Swiss building stock still has high potential with respect to retrofitting and energy efficiency improvements.

The outcome of an important study that showed that GHG emissions and energy demand can vary a great deal across building stock in Switzerland was the results of a new method developed by Nägeli et al. (2018) for building stock modelling and GHG emissions accounting. The method is based on generating of synthetic building stocks. Disaggregating synthetic building stock permits detailed description of different building stock. Additionally, the study illustrated the separation of the building stock as regards GHG emissions among newly retrofitted buildings that use renewable energy as a source of heating and old buildings heated using fossil fuels.

However, it is clear that further research is needed to deal with exciting difficulties and issues linked to residential stock modelling as well as to develop effective models to address these challenges for the world of tomorrow.

3. Methodology

3.1. Housing owners

Our model's main variable is the energy reference area (ERA), which, in combination with the structure's energy class (EC) and climate, gives the heating needs for the Swiss residential sector. As shown in Figure 1, a house/flat is characterised by its year of construction (called CP, i.e. construction period) and its energy class (EC). We add another dimension that represents the property owner type (OT) of the house/flat. Indeed, energy retrofitting decision very much depends on the characteristics of the owners represented in our model through different discount rates (r) and split incentive parameters (χ), which demonstrates the fact that the landlord of a rented house cannot reap all the benefits of a retrofit.

We do not model individual housing. Instead, we assume that all properties' owners within an energy class conduct an identical cost-benefit analysis regarding retrofitting decisions. This would lead to unrealistic results, as all owners within an energy class would retrofit at the same time, leading to a spike on the retrofit rate at certain time periods. To smooth retrofit rates, we have to introduce further heterogeneity into the model (apart from the six energy classes). Therefore, we include the following two features. Firstly, we apply a two-step model, where in the first step only a certain proportion of owners is triggered to conduct the cost-benefit analysis (see Chapter 3.3.1). The remaining owners do not consider retrofits, even if they were profitable. This reflects the barrier that owners have incomplete information. Secondly, we introduce owner types, which differ with respect to the discount rate and whether they inhabit the dwelling themselves or

Table 2: Owner types, shares and their discount rates

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

rent it (see Table 2). This reflects such barriers as that owners to some extent lacking foresight and the landlord-tenant dilemma.

We distinguish between six owner types whose characteristics are shown in Table 2: there are owner-occupied and rental properties (37% and 63% of dwellings respectively, based on the data from the Swiss Federal Statistical Office). In the case of owner-occupied properties, the owner of the property is simultaneously the occupier. In the case of rental property, the owner/landlord is not the occupier of the property.

Owner-occupiers of properties can be set apart by the following characteristics: young, old, poor or wealthy. Depending on these characteristics, the discount rates change, because for some owner-occupiers retrofitting is less profitable in the long-term, they have less access to funding and a limited time horizon (elderly owner-occupants). For example, for the old/poor owner, who has a high discount rate because of a short horizon and less access to funding, it is improbable that retrofitting will be profitable. In contrast the young and wealthy owner, who has a low discount rate and easier access to funding, is more likely to find a retrofit profitable (see Table 2).

The owners of a rental property are cooperatives (non profit-based), municipalities (non profit-based), investment corporations (profit-based), pension funds (profit-based)and individuals (people). Here, the discount rate changes too, depending on the owner's characteristics. For example, non-profit owners typically expect a small or no return on their investment because their goal is to satisfy the needs of their tenants (hence a low discount rate of 2%). Private individual owners of rental housing generally seek a return on their investment, often for retirement purposes, so we assume that they calculate with a discount rate of 6%. Moreover, profit-based institutional landlords (group 5) hold diversified portfolios, while individual landlords (group 6) often own a single building. Hence, the former are content with a lower expected return from a particular building (see Table 2).

Split incentives are one of the most salient barriers to energy efficiency retrofits in buildings. This barrier arises only for rental dwellings. In this situation, the landlord is responsible for investing capital into retrofits, whereas the tenant benefits as their energy bill is reduced. The costs and the benefits of retrofits thus do not directly accrue to the same actor - the incentives are split. The landlord has option of raising the rent to recover their investment. Yet there are rather strict rules on this option in Switzerland (and elsewhere, such that the corresponding payoff time for the landlord is usually very high. As a result of the split incentive barrier, the retrofit rate for rental dwellings is lower than for owner-occupied dwellings. In our model, we introduced a parameter (χ), which applies only to landlords.

3.2. Evolution of the housing stock

The law of motion of the energy reference area is given in Eq.(1) (for the list of all the variables and parameters, see Table 6). The energy reference area changes from one period to the next because of a proportion that is demolished (DR), through new construction (NC) and by transfers between classes due to a retrofit matrix (RM) (see Eq. 4).

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

New constructions (NC) are computed from the desired reference area that is linked to population growth. We assume that new constructions are only built in energy classes A, B and C, the proportion of which change over time as the contributions of the most efficient energy classes increase

The share of construction in 2015 in energy classes A, B and C was 20%, 35%, and 45% respectively. We assume that new buildings' shares in energy classes A and B will increase. The share of buildings in energy class C will presumably decrease by 2.5% per year and consequently disappear in 2033. Over that period, it will be replaced by buildings in energy class B. After 2033, we assume that the share of B will also decrease by 2% per year and all new constructions will be built in energy class A.

The aggregate demolition rate (DR) used in our model is based on the calculation of the evolution of the energy reference area (ERA) from 2010 to 2016 in Switzerland (see Appendix C). According to our calculations, the average demolition rate of buildings in Switzerland is extremely low and equal to 0.32%. Residential buildings are almost never demolished to rebuild them in a more energy-efficient manner. Rather, demolition and reconstruction are mainly triggered by the possibility of building more square metres (Rey, 2015).

3.3. *The retrofitting decision*

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

- First step: energy audit.

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

- Second step: retrofitting decision.

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

3.3.1. *First step: energy audit*

The percentage of owners who conduct an audit (Γ) is represented by Eq.2, where SHD is the representative heating demand per m^2 for each EC and PEC is the energy price. Based on the dwelling's current energy class, there is a certain baseline probability (Π) that the owner will conduct the audit. The baseline probability increases in a straight line with energy classes up until energy class G, where it is 3$\%$. The actual probability deviates from the baseline probability when higher energy prices (PEC) raise awareness. The probability also increases with the owner's information level (Inf: $\{1; 2; 3; 4\}$). For example, a standard information campaign would raise the owner's information level from 1 to 2; a targeted personalised message to an owner would raise it to 3, and direct contact by an energy specialist, possibly with the offer to pay all or part of the energy audit costs, would raise their information level to 4.

$$\Gamma_{t,EC} = \left(1 + \Theta \cdot \left(\frac{(PEC_{t,EC} \cdot SHD_{t,EC}) - (PEC_{t-1,EC} \cdot SHD_{t-1,EC})}{PEC_{2014,EC} \cdot SHD_{2014,EC}}\right) + \theta \cdot \frac{PEC_{t,EC} \cdot SHD_{t,EC}}{PEC_{2014,A} \cdot SHD_{2014,A}}\right) \cdot \Pi_{EC} \cdot Inf_t \quad (2)$$

3.3.2. Second step: retrofitting decision

In the second step, those owners who commissioned an energy audit calculate the highest economic balance of retrofitting their building, i.e. the retrofit gain (RG). The retrofit gain is the net present value of the retrofit measure from energy class EC to EC', i.e. discounting all future energy-saving gains over the investment horizon (T). This retrofit gain is given in Eq.(3), where RC is the retrofit cost, τ is a subsidy on retrofit and PI is the price of the retrofit. In the case of the landlord (owner types 4 to 6), we fix the split incentive parameter (χ) to 0.5 (instead of 1 for the other owner types). Thereby, we assume that the landlord can only recover 50% of the monetary energy saving through increasing the rent.

$$RG_{t,OT,EC,EC'} = \chi_{OT} \sum_{t'=t}^{t+T^R} \frac{SHD_{t,EC} \cdot PEC_{t',EC} - SHD_{t,EC'} \cdot PEC_{t',EC'}}{(1 + r_{OT})^{t'-t}} - RC_{t,EC,EC'} \cdot (1 - \tau_{t,EC,EC'}) \cdot PI_t \quad (3)$$

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

1. The economic gain from EC to EC' is positive.
2. The retrofit gain is higher than any other retrofit, that can be done from EC.

3.3.3. Retrofit matrix

Transitions between energy classes are represented by a retrofit matrix (RM) (see Eq. 4). The retrofit matrix (RM) is calculated by multiplying the probability of conducting the audit (Γ) by the probability of performing the retrofit (Ω) (see Eq. 5) and by the energy reference area (ERA).

$$RM_{t,OT,EC,EC'} = \Gamma_{t,EC} \cdot \Omega_{t,OT,EC,EC'} \cdot ERA_{t,OT,EC} \tag{4}$$

$$\Omega_{t,OT,EC,EC'} = 1 \text{ if} \begin{cases} RG_{t,OT,EC,EC'} > 0 \quad and \\ RG_{t,OT,EC,EC'} > RG_{t,OT,EC,EC^*} \;\; \forall \; EC^* \neq EC' \end{cases} ;0 \text{ otherwise} \tag{5}$$

3.3.4. Retrofit costs

We base the retrofit costs on estimates from a study by the SFOE (BFE, 2015), where Table 25 provides an estimate of costs for a comprehensive retrofit. To obtain realistic retrofit rates, we increase these estimates by roughly a factor of 1.5. We assume a non-linear cost function, to account for the fact that retrofits from one energy class to the next are increasingly more costly (see Table 3). Additionally, we assume that the required investment is more than proportional to the number of EC of improvement, and that improving by one EC from a better energy class is more costly than from a worse one (see Table 3).

3.4. Energy consumption and CO_2 emissions

To compute total heating energy demand, we add up the demands of the seven ECs. In each EC, it is computed by multiplying the SHD of that class by the corresponding ERA. The mix of energy carriers (oil, natural gas, district heating,

Table 3: 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	

heat pump, direct electricity and wood) is specific to each EC. The substitution possibilities are represented by a CES function of the total energy demand in each EC. This implies that buildings retrofitted from one EC to another adopt the mix of energy carriers of their new class. It also implies that the mix of energy carriers, and hence the CO_2 intensity of heat production, can change within each EC in response to changing relative prices of energy carriers. This does not require any specific investment, nor does it count as retrofitting. Only the transfer of buildings from one EC to a better one does. We assume that, in the base year (i.e. 2015), the energy mix is the same for all construction periods and owner types within a specific energy class. The price of each energy carrier includes the fuel price and the cost of the heating equipment (boiler, heat pump, etc.).

3.5. Calibration of the model

Swiss official statistics provide the surface of occupied dwellings per construction period in square metres. Unfortunately, they do not provide any information about the average energy consumption or the allocation of dwellings per energy class for the different construction periods.

With the help of four different surveys (see Appendix C), the distribution of dwellings by energy carriers for each energy class was computed. The overall energy consumption by all construction periods is allocated by energy carriers and energy classes. Since 95.6% of the energy reference area in all surveys is represented only by the Geneva survey, we used the weighted average method and calculated adjustment factors to account properly for all four surveys. Thus, after performing the calculations, we obtain more representative results for all four surveys. Additionally, to calculate CO_2 emissions, we examine the energy mix and we sum up the emissions factor for every energy carrier from 2015 to 2050.

4. Numerical implementation: deep decarbonisation of the Swiss residential sector

In this section, we wil simulate several scenarios with our building stock model. The purpose of these simulations is twofold. Firstly, we want to demonstrate our model's capabilities in analyzing a range of scenarios. Secondly, we aim to study how Switzerland can achieve deep decarbonisation of its residential sector. We will first run a baseline scenario from 2015 to 2050 that is described in the next sub-section. Then, we will simulate six policy scenarios, as follows:

1. *A subsidy increase scenario*: the government increases the existing subsidy on retrofit investment by 1 percentage point every year.
2. *A moderate CO_2 tax increase scenario*: the government increase the existing CO_2 tax each year by CHF 9.

3. *A high CO_2 tax increase scenario*: the annual CO_2 tax increase is equal to CHF 26 in this scenario.
4. *An information level increase scenario*: we assume the government campaigns for retrofit investment, which we capture through an increase in the information level.
5. *A first combination scenario*: this scenario combines scenarios 1, 2 and 4.
6. *A second combination scenario*: this scenario combines scenarios 1, 3 and 4.

The following parameters will remain unchanged throughout all the above-mentioned scenarios: energy reference area (ERA), population growth and energy prices. The ERA is presented in Chapter 1.2. The population growth is based on national projections provided by the Swiss Federal Statistical Office [2]. Energy prices are derived from the World Energy Outlook 2018; we will use the current *policies scenario* (International Energy Agency, 2018).

4.1. Baseline scenario

In the baseline scenario, the retrofit subsidy and CO_2 tax are equal to the current values in Switzerland. The subsidy on retrofit ($\tau^{t}_{EC,EC'}$) is defined at cantonal level. On average, it pays 30% of the energy retrofit investment. The CO_2 tax on heating fuel equals CHF 60 in 2015, and from 2016 to 2017 it equals CHF 84. From the year 2018, it is constant and equals CHF 96. The information level (Inf) is equal to 1.

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

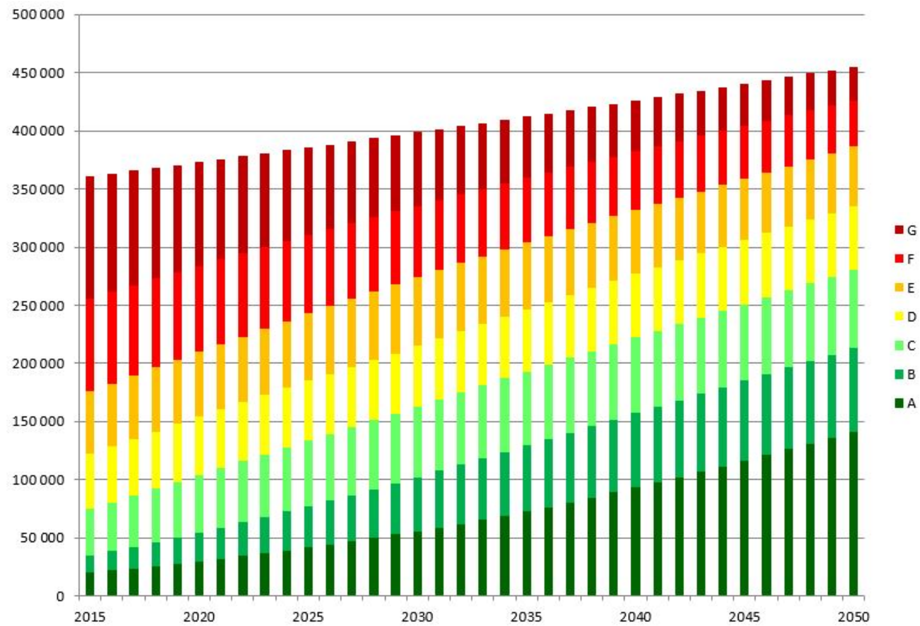

Figure 2: Total energy reference area per energy class in 1000 m^2 - baseline scenario

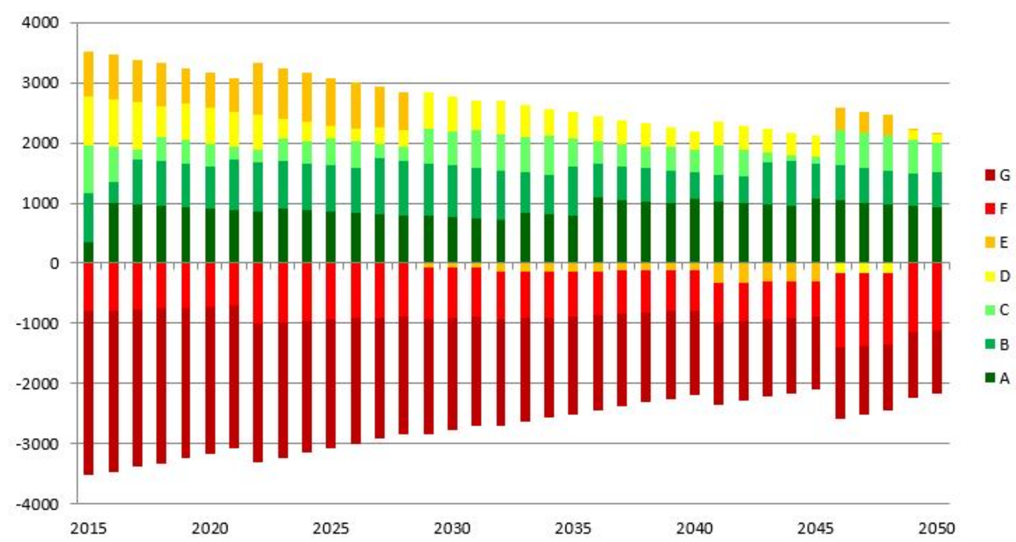

Figure 3: Retrofitting the total housing stock per energy class in 1000 m^2 - baseline scenario (negative numbers are buildings that are subtracted; positive numbers are buildings that are added to an energy class)

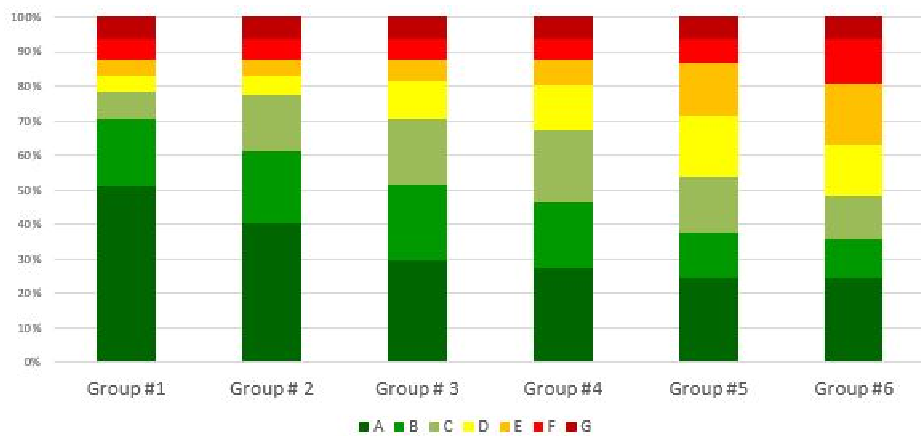

Figure 4: Energy reference area in % per energy classes by owner groups (2050) - baseline scenario

Figure 2 shows the evolution of the energy reference area from 2015 to 2050. The proportion of buildings in energy class A increases from 6% to 31%, whereas the share of buildings in classes E, F and G combined decrease from 66% to 26%. This result is driven by retrofitting (from G, F, E and D to B and A; see Figure 3) and new constructions that are supposed to be built in classes A, B and C. From 2015 to 2050, the average retrofit rate is equal to 0.81%, which is slightly below the current retrofit rate of about 1% (IEA, 2018). Additionally, from Table 5 it can be noted that the average retrofit rate for 2016 - 2050 in the baseline scenario is lower than in the year 2015; this is mainly due to the fact that the retrofit rate decreases gradually from the 2015 value to much less in 2050. In 2050, the average energy consumption is 56 kWh/m^2 and total CO_2 emissions decrease by 58% relative to 2015 (see Table 5). The total CO_2 emissions provide information about the envelopes' energy efficiency and the energy mix, and plus total ERA.

4.2. Subsidy increase scenario

We assume that the government will increase the current subsidy by 1 percentage point per year until 2050. The subsidy rate will reach 65% in 2050 since the initial subsidy is 30% in 2015. The government will pay subsidies from the general budget. More retrofit investments become profitable (see Figure 5) and the average retrofit rate will rise to 1.02%. The proportion of buildings in energy class A increases to 36%, while the share of buildings in classes E, F and G combined decrease to 21%. The average energy consumption in 2050 will decrease to 51 kWh/m^2 and the total CO_2 emissions will decrease by 64% relative to 2015 (see Table 5).

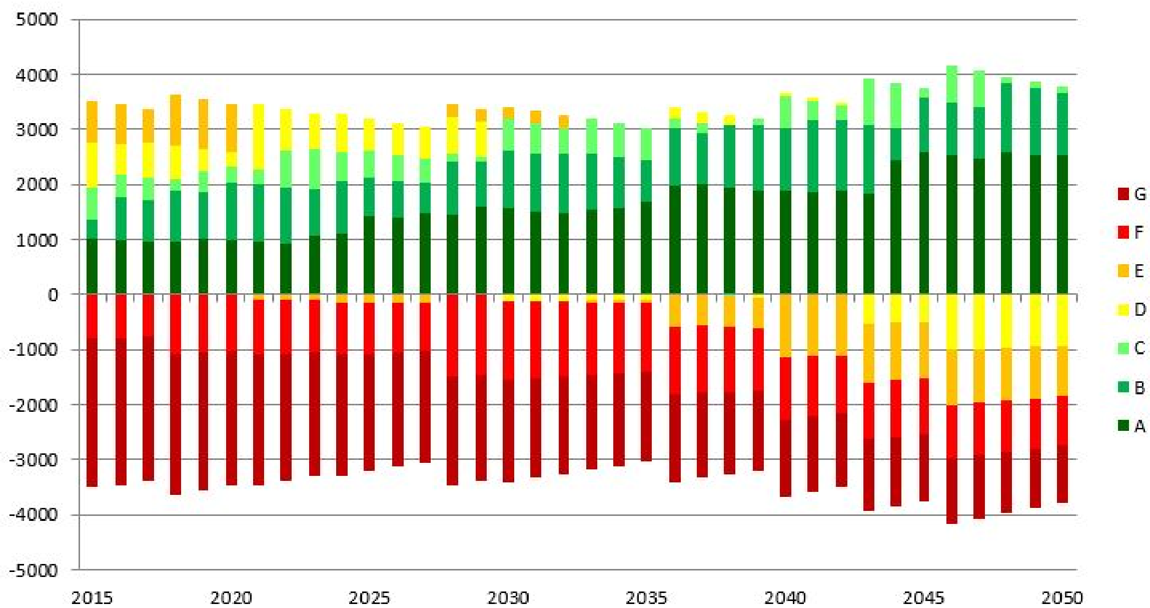

Figure 5: Retrofitting in 1000 m^2 – subsidy scenario

Table 4: CO_2 tax on emissions (CHF/tonne)

Year	Baseline	Moderate tax increase	High tax increase
2015	60	60	60
2016	84	93	110
2017	84	102	136
2018 to 2049	96	+9/year	+26/year
2050	96	411	1006

4.3. CO_2 tax increase scenarios

In the tax increase scenarios, we assume that the government will raise the level of CO_2 tax from 2016 above its level in the baseline scenario, as shown in Table 4.

Neither of the tax scenarios act as relatively strong incentives to carry out retrofitting. The average proportion of buildings in energy class A rises to 32% and 35%, while the share of buildings in classes E, F and G combined decrease to 24% and 20% respectively. The average retrofit rate increases slightly to 0.89% and 1.05%. The average energy consumption per square metre decreases moderately to 54 kWh/m^2 and 51 kWh/m^2 in 2050. Nonetheless, the total CO_2 emissions decrease by 64% and 71% relative to 2015. Indeed, if the retrofit decision and the average energy consumption are almost unchanged, the CO_2 tax significantly impacts the fuel that is used to heat the housing: less oil and natural gas are consumed and more heat pumps and wood are used. The results are compared in Table 5.

The comparison of the baseline and moderate CO_2 tax increase scenarios demonstrates the slight increase in average retrofit rates: 0.80% and 0.89%, which is also the case for the total useful energy demand (28% and 31% decrease relative to 2015, as well as for total CO_2 emissions (58% and 64% decrease relative to 2015) (see Table 5). The total useful energy demand is indicative of the envelopes' energy efficiency and the total ERA. Consequently, it can be concluded that a moderate tax increase scenario does not show considerably better results than in the baseline scenario, even though the increase in retrofitting investment is only 15% relative to the baseline scenario, which is relatively cheap compared to implementing other, more expensive scenarios. The overall retrofitting investments are calculated by summing up retrofitting investments from 2016 to 2050. As a result, in Table 5 we show how much investment costs increase in the following scenarios relative to the baseline scenario.

4.4. Information level increase scenario

In the information level increase scenario, we ran the model with an increase in the information level every five years up to information level 4. This means that from 2030 to 2050, the information level is constant. This scenario demonstrated that the average share of buildings in energy class A rises to 33%, while the proportion of buildings in classes E, F and G combined decreases to 17%. The average retrofit rate rises up to 1.37%, while total CO_2 emissions decline by 69% relative to 2015. This shows that solely increasing the information level cannot help with achieving a deep decarbonisation pathway. Retrofitting in square metres is given in Figure 6. The figure shows that, as the information level increases, the retrofit growth spikes. Nevertheless, after the last increase in the information level, retrofitting gradually decreases. The result comparisons for all the scenarios are displayed in Table 5.

The upshot of comparing the baseline scenario with the information level scenario is a strong rise in retrofit rate, from 0.80% to 1.37%. The reason for this is that more owners are going through step 1 (energy audit). This rings true not only for one specific type of owner, but rather for all types of owner. As a result, the total useful energy demand decreases to 40% compared to 28% in the baseline scenario (see Table 5). This is mainly due to the fact that all the buildings become more energy-efficient and the total CO_2 emissions decrease even further relative to the baseline scenario (69% drop compared to 58% in the baseline scenario), because there is also a little more substitution (away from fossil energy) in the context to retrofitting.

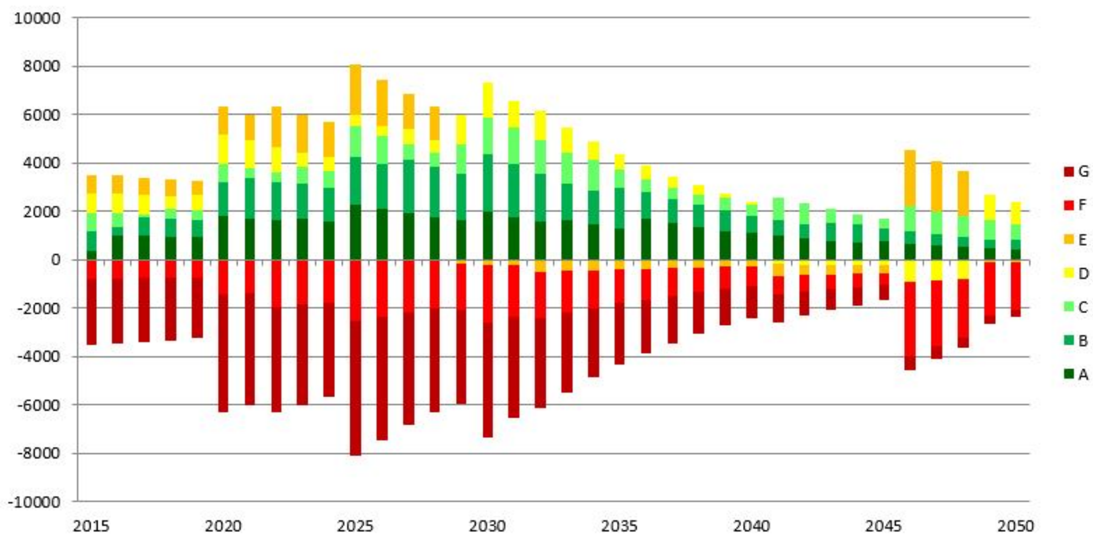

Figure 6: Retrofitting in 1000 m^2 - information level scenario

4.5. Combination scenarios

In the first combination scenario, we introduced the moderate CO_2 increase scenario (see Table 4) with a 0.5 percentage point of subsidy increase per year, as well as with an information level increase (as in the information level scenario). In this scenario, the subsidy reaches 49.5% in 2050. By increasing the subsidy we wanted to achieve equality between the cumulated cost of the subsidy and the cumulated revenues of the CO_2 tax between 2015 and 2050. The results of this scenario demonstrate that we accomplished this. The sum of the cost of the subsidy over 35 years is close to the sum of revenues of the CO_2 tax. In Figure 7 is demonstrated the evolution of costs of the subsidy and the revenues of CO_2 tax between 2015 and 2050 for the 1st combination scenario.

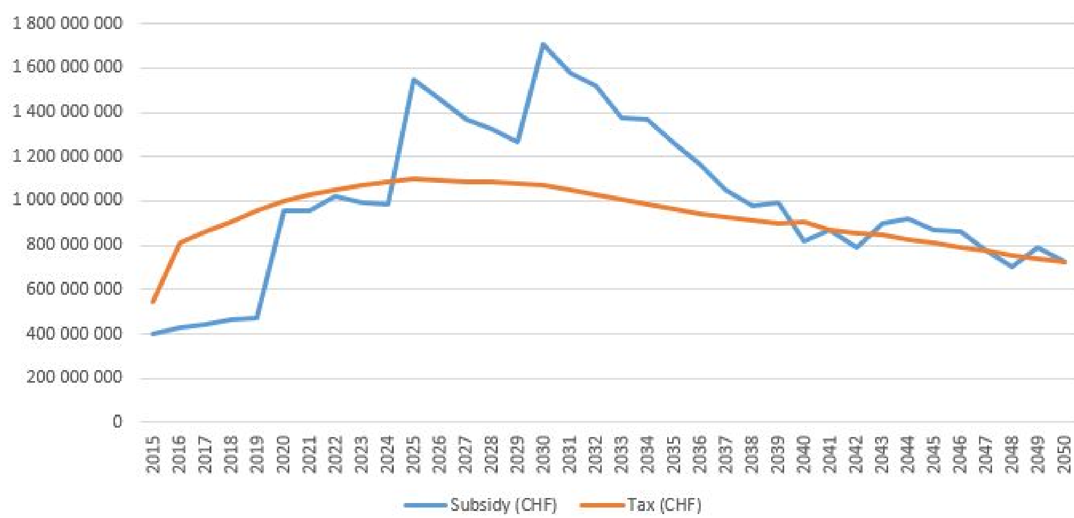

Figure 7: The cost of the subsidy and the revenues of CO_2 tax (in CHF) between 2015 and 2050 for the 1st combination scenario

In the second combination scenario, we used a 1 percentage point of subsidy increase per year and the high CO_2 increase scenario instead of the moderate

CO_2 increase scenario (see Table 4). In this scenario, the subsidy reaches 67% in 2050. Here, we also obtain that the sum of the cost of the subsidy and the sum of revenues of the CO_2 tax between 2015 and 2050 are nearly equal.

In Figure 8 the evolution of the costs of the subsidy and the revenues of CO_2 tax between 2015 and 2050 for the 2nd combination scenario is showed.

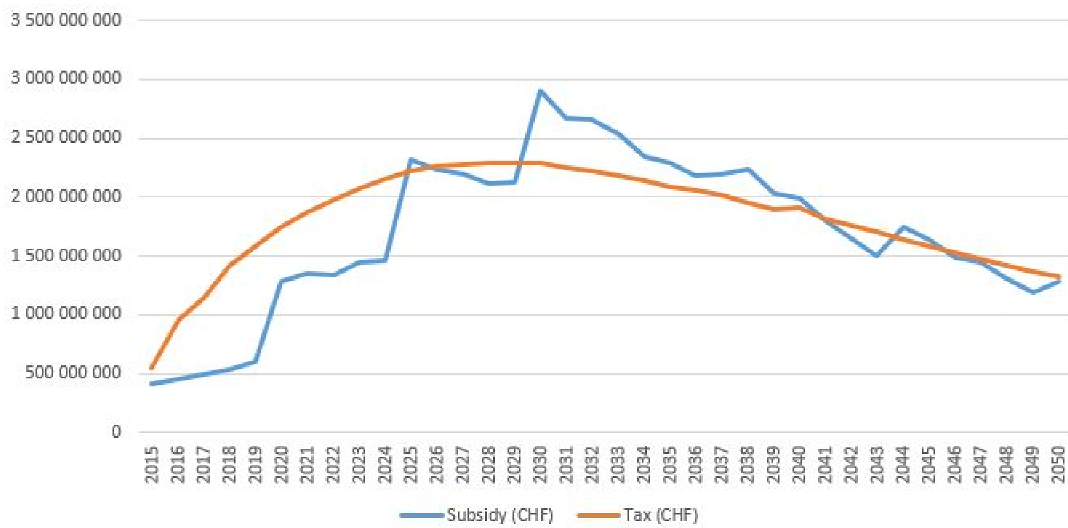

Figure 8: The cost of the subsidy and the revenues of CO_2 tax (in CHF) between 2015 and 2050 for the 2nd combination scenario

In both scenarios, we managed to achieve a deep decarbonisation pathway with total CO_2 emissions contracting by 80% and 90% relative to 2015. Here, there is a visible significant increase in the average percentage of buildings within the highest energy class A with 39% in the first scenario and 49.5% in the second scenario. Additionally, buildings in classes E, F and G together combined reach 6% and 1.9% respectively. Table 5 shows that the average retrofit rate climbed to 1.86% and 2.24%.

4.6. Comparison of all scenarios

All of the scenarios are compared in Table 5. Comparing the two CO_2 tax increase scenarios shows that the higher tax level strongly raises the retrofit rate, particularly for owners in the sixth category (from 0.59% to 0.81%). Nevertheless, total useful energy demand does not decrease by much less in the low-tax scenario: down by 31% relative to 2015, compared to 35% in the high-tax scenario. The same is true for total CO_2 emissions: down by 64% and 71% respectively. A striking difference between these two scenarios concerns retrofit investment costs: they increase by 44% relative to the baseline in the high-tax scenario, compared to only 15% in the low-tax scenario. This, as we saw, for not much additional benefits. This illustrates the rapidly rising marginal costs.

When we compare the moderate CO_2 tax increase scenario with the subsidy increase scenario, we can notice the identical total CO_2 emissions decrease by 64% relative to 2015, very similar drop in total useful energy demand of 31% and 34% relative to 2015 and the slight variance between retrofit rates. As a result, we can conclude that, when the outcome of both scenarios is almost identical, it would be coherent to implement the scenario with lower investment costs. Thus, it is worth implementing the moderate tax increase scenario, relative to the baseline scenario, the investment costs only increase by 15% in the moderate tax increase scenario, whereas in the subsidy increase scenario the investment costs climb to 46%. This is due to the fact that the higher CO_2 tax also encourages investors to replace fossil fuels as the source of energy while the subsidy only encourages energy saving.

Comparing the information level increase scenario with the high CO_2 tax increase scenario exhibits almost equal total CO_2 emissions: they are down by 69%

and 71% relative to 2015. Besides, even though we have a big difference in retrofit rates (1.05% and 1.37%), the outcome indicates a slight transformation in the useful energy demand drop: by 49% and 53% relative to 2015. This can be explained by the fact that the CO_2 tax does not trigger many more stage 1 energy audits. It is interesting to note that, with high CO_2 tax, we can achieve almost identical results with the information level scenario in terms of a reduction in CO_2 emissions and, additionally, very similar total useful energy demand. Obviously, when the results are almost identical, it makes sense to choose the one with lower investment costs. Therefore, when comparing these two scenarios, we can see that it would be cheaper to implement the high CO_2 tax increase scenario, because it cuts CO_2 emissions with less investment: 44% (high CO_2 tax scenario) compared to 55% (information level scenario) investment cost increase relative to the baseline scenario.

Moreover, it is not surprising that the best possible cases are the two combination scenarios. It is important to note that, even though the main difference between these two cases is the increase in CO_2 tax, we do not see a substantial change when comparing the resulting retrofit rate, total useful energy demand and total drop in CO_2 emissions. Subsequently, when observing the investment costs of both scenarios, we can conclude that it would be rational to implement the scenarios with lower investment costs with the goal of achieving a deep decarbonisation pathway, as opposed to investing considerably more and achieving similar results. Thus, the comparison of two combination scenarios shows that the second scenario has a 86% increase in investment on retrofit relative to the first combination scenario. This demonstrates again that it is very costly to eliminate the last CO_2 emissions from buildings. Consequently, the first combination scenario would be worth implementing to achieve similar results as in the more expensive second combination scenario.

4.7. Concluding remarks

Our simulations show that the economic instruments are much more effective when combined with measures to raise owners' awareness of energy retrofitting, because the economic instruments influence owners only after they opted to energy audit their building. Hence, it is worth repeatedly providing comprehensive information about these price signals to obtain more CO_2 abatement.

To do this, we simulated two scenarios involving a combination of different economic instruments. In both cases, we successfully achieved a deep decarbonisation pathway.

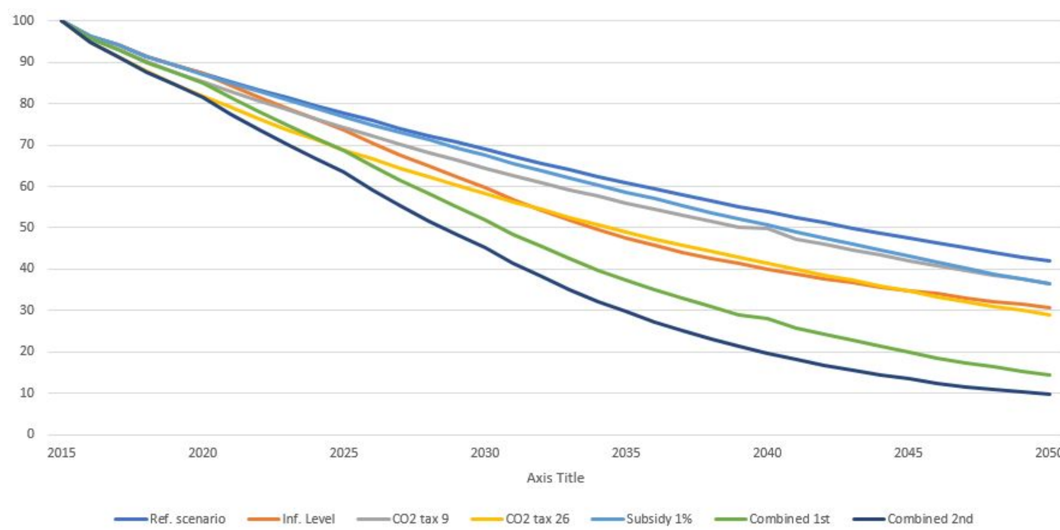

Figure 9: CO_2 emissions for all scenarios from 2015 to 2050 (year 2015=100)

Table 5: Comparison of scenarios

Scenarios	year 2015	Baseline	Subsidy increase	Moderate CO2 tax increase	High CO2 tax increase	Inf. level icrease	Combination 1st	Combination 2nd
Average value for 2016-2050 (except column '2015')								
Retrofit rate, average	1.08%	0.80%	1.01%	0.89%	1.05%	1.37%	1.86%	2.24%
Retrofit rate, type 1 ('best')	1.75%	1.22%	1.25%	1.27%	1.34%	2.08%	2.12%	2.33%
Retrofit rate, type 6 ('worst')	0.75%	0.50%	0.81%	0.59%	0.81%	0.86%	1.53%	2.17%
Sum 2016-2050 compared to baseline scenario								
Retrofit investment			46%	15%	44%	55%	115%	201%
2050 compared to 2015 (except column '2015')								
Useful energy demand per m2 (kWh)		-43%	-48%	-45%	-49%	-53%	-60%	-68%
Useful energy demand total (MWh)		-28%	-34%	-31%	-35%	-40%	-49%	-60%
CO2 emissions per m2 (kg)		-67%	-71%	-71%	-77%	-76%	-84%	-92%
CO2 emissions total (mton)		-58%	-64%	-64%	-71%	-69%	-80%	-90%

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Acknowledgements

We would like to pay special regards to Anne-Kathrin Faust and Roger Ramer. It is wholeheartedly appreciated that your great impact on the project and your advice proved monumental towards the success of this project. Moreover, we would to greatly thank the Swiss Federal Office of Energy for funding this project and without whom this work would not be possible to conduct.

Appendix A Indices, variables and coefficients

Table 6: Names of indices, variables and coefficients

Indices		Values	Units	Sources
$EC, EC', \overline{EC}$		Energy class according		
		to CECB $\in$ {A,B,C,D,E,F,G} see Table 7		
i	Energy carrier	{oil,coal,gas,electricity,wood,heat pump,solar,remote heat,others}		
t, t'	Time period			
CP	Construction Period	{before 1919; 1919-1945;		
		1946-1960; 1961-1970; 1971-1980; 1981-1990;		
		1991-2000; 2001-2010; 2011-2020; }		
OT	Owner types	{owner-occupant, landlord}		
$Parameter$				
Θ	Elasticity	1		
r^{OT}	Discount rate	{2;4;6;2;4;6}	%	
DR^t	Demolition rate	{1;0.9;0.72;0.5;	%	
		0.39;0.32;0.16;		
		0.1;0.05;0;0;0;0}		
$\overline{PEC_{EC}}$	Price of energy per energy class, base year		CHF	
θ	Impact price level	0.2		
T	Investment horizon in years	40	years	
$SHD^{t'}_{EC}$	Representative heating demand per m^2 for each EC	{150;110;	kWh/m^2	
		90;70;50;		
		30;20}		
$\tau^t_{EC,EC'}$	Subsidy rate on retrofit (baseline case)	30	%	
$\tau_{RC,t}$	Technical progress on retrofit	0	%	
$RC^t_{EC,EC'}$	Energy retrofit cost		CHF	
NC^{Ht}_{CEC}	New construction		number	
Inf	Information level {1; 2; 3; 4}		number	
$\Pi_{t,EC}$	Baseline probability that owner conducts an audit	{0;0.5;1;1.5;2;2.5;3}	%	
χ	Split incentive	{1;1.1;0.5;0.5;0.5;0.5}		
$Variables$				
$ERA^{OT,t}_{EC}$	Energy reference area		m^2	
CO_2	CO_2 emissions		per tonne	
$RG^{OT,t}_{EC,EC'}$	Energy retrofit gain		CHF	
PI_t	Price of investment in retrofit per kWh		CHF	
PEC^t_{EC}	Energy price per kWh		CHF	
$RM^{OT,t}_{EC,EC'}$	Retrofit Matrix		sqm	
Γ^t_{EC}	Proportion of owners conducting energy audit		%	
$\Omega^{H,t}_{EC,EC'}$	Probability of doing retrofit		%	

Appendix B Cantonal Energy Classes for Buildings

Table 7: 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

Appendix C Energy Reference Area

The data on occupied houses per construction periods were collected from the Swiss Federal Office of Energy (SFOE) [3]. Additionally, we used the data on the average surface of houses acquired from SFOE [4]. From this data, we could calculate the energy reference area in square meters per construction period for the year 2015 in Switzerland. The results can be seen in Figure 1.

C.0.1 Allocation of construction periods per energy classes

Cities' data description and sources. In order to allocate the construction periods per energy classes, firstly we needed to collect the data from separate surveys. The surveys helped us to get the energy reference area per construction periods and energy classes for building stock in different cities. The data were provided by Société Coopérative d'Habitation Lausanne (SCHL), Allgemeine Baugenossenschaft Zürich (ABZ), Estia and die Mobiliar. The details of data provided are shown in Table 8.

[3]https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.4582090.html

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

Table 8: Data collected

City	Source	Number of dwellings	Year taken	Energy
Lausanne	SCHL	2 011(app.)	2016/2017	Heating
Zürich	ABZ	4 540 (app.)	2016/2017	Heating + Hot water
Geneva	ESTIA	17 983 (app. + buildings)	2015	Heating + Hot water
Different cities	Mobiliar	236 (buildings)	2015	Heating

Table 9: Derivation of the parameter: Standardized energy demand hot water. INFRAS

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

Since the initial data for some of the surveys were provided including the energy for heating water, we needed to find a way to subtract this energy from our data. With this purpose, we used the data acquired from INFRAS, that shows how much energy for hot water is used per square meter in each apartment (see Table 9) .

Since initially for Zürich and Geneva the data on heating and hot water is incorporated, we subtracted the energy used for hot water. For Lausanne and die Mobiliar surveys this was not necessary.

The distribution of buildings. Moreover, we calculated the distribution of energy reference area of buildings for all four surveys in each energy class and in each construction period.

For SCHL (see Figure 10) we took into account heating degree days and climate corrections (see the total correction in Table 10). For ABZ (see Figure 11), Geneva (see Figure 12) and die Mobiliar's (see Figure 13) dwellings the heating degree days were already taken into account in the initial data provided.

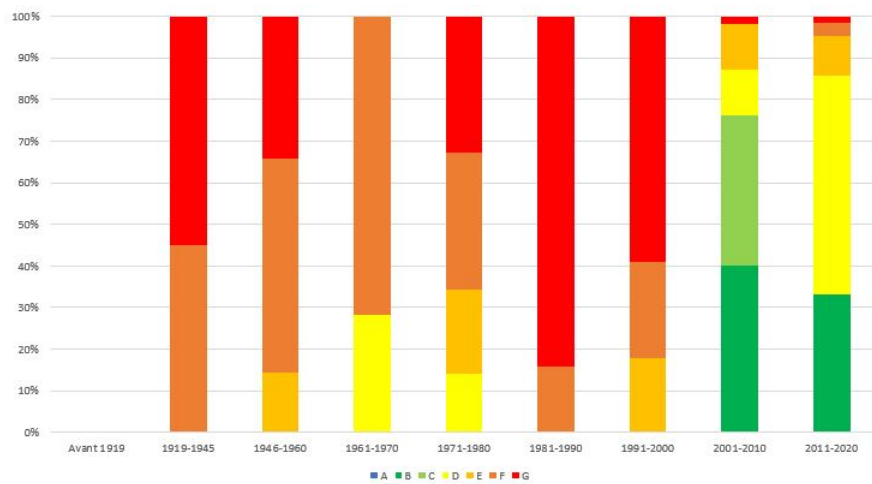

Figure 10: Distribution of ERA (source: SCHL - Lausanne)

The energy consumption data of the different surveys we used are not for the same years nor the same cities, which implies different weather conditions. We normalized these data using the corresponding numbers of heating-degree days as reported by MeteoSwiss (see Table 10).

Additionally, the overall energy reference area for three cities and die Mobiliar dwellings is shown in Figure 14.

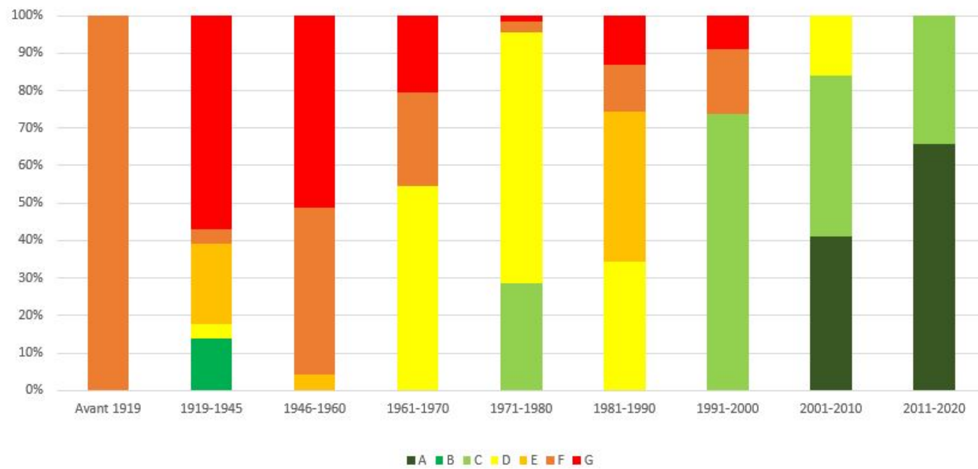

Figure 11: Distribution of ERA (source: ABZ - Zürich)

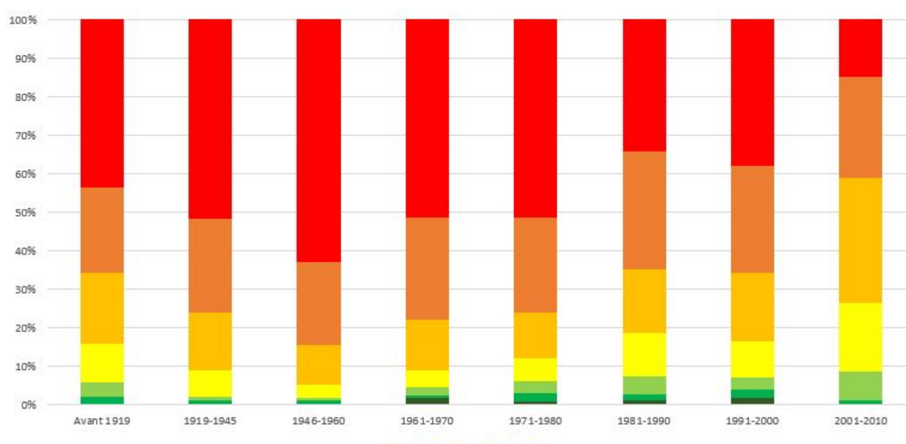

Figure 12: Distribution of ERA (source: ESTIA - Geneva)

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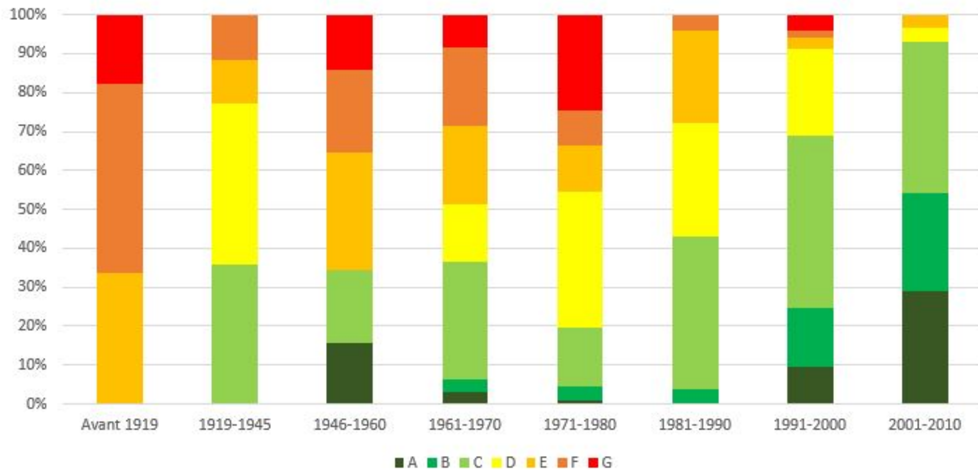

Figure 13: Distribution of ERA (source: die Mobiliar - different cities)

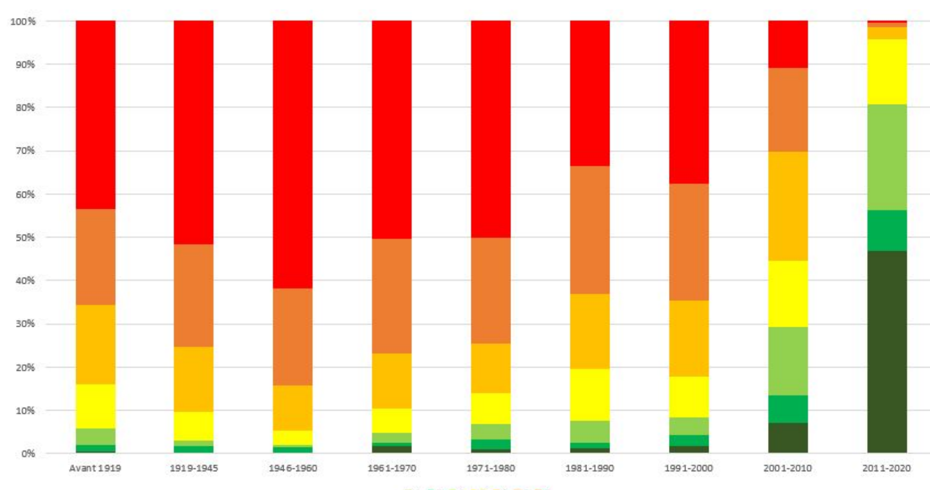

Figure 14: Distribution of ERA: three cities and die Mobiliar

Table 10: Heating degree days and climate corrections

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

Modelling endogenous energy efficiency improvement: Swiss cement production

Draft version V5.1
The research has been carried out with the support of the Swiss Federal Office of Energy (SFOE).
The authors bear sole responsibility for the conclusions and findings.
P r e l i m i n a r y

Sergey Arzoyan[a,*], Quirin Oberpriller[b], Philippe Thalmann[a], Marc Vielle[a]

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

Abstract

Currently, in Switzerland exist six cement plants that produce approximately 94% of the clinker in rotary dry kilns and the rest in semi-dry kilns. Throughout the year Switzerland produces about 5 million tonnes of cement in total. Thus, we model energy efficiency improvements for each of the six Swiss cement plants. Starting from an initial allocation of already implemented efficiency measures, plants become more energy efficient by implementing additional measures and by replacing equipment by newer, more efficient versions. The model implements these measures based on a costs-benefit analysis in combination with other rules related to the replacement of inefficient equipment at the end of the lifetime. We developed a cement model which, in a plant-specific bottom-up approach, de-

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

picts the impact of measures on fuel and electricity consumption as well as CO_2 emissions. Technical progress stems from a mixture of measure-induced and autonomous progress. Between 2015 and 2050, technical progress leads to a reduction of fuel and electricity consumptions as well as CO_2 emissions in cement production of about 30 to 37% in scenarios without CCS. The impact of the CO_2 price is minor for energy efficiency measures. In the scenarios with CCS, CO_2 emissions decrease by 92%, while fuel and electricity consumption increase drastically. CCS decreases the cumulative CO_2 emissions over the calculation period 2015-2050 by 2.2%. This shows the huge impact of the availability of this technology for the cement industry and the importance of implementing it as soon as possible. It could be adopted as early as 2030 if the federal government set a floor price of CHF 133 per tonne of CO_2 avoided through CCS.
Keywords: Cement, Industry, Switzerland, Hybrid modeling, Top-down models, Bottom-up models, Energy efficiency, Emission reduction

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Highlights

- We model energy efficiency improvements for six Swiss cement plants.
- The energy efficiency of the plants improves along two pathways: Measure-induced technical progress (MI-TP) and Autonomous technical progress (A-TP)
- We model approximately 15 measures which represent energy efficiency and CO_2 mitigation measures that are applicable for Swiss cement plants
- Each plant has in place a specific mix of inefficient EUP-equipment, efficient EUP-equipment, and PEEM.

- We calculate the NPV yearly, comparing the investment costs of the measure with the energy savings.

1. Introduction

1.1. World context

The main cause of the increase in global temperature (global warming) is the accumulation of greenhouse gases (GHGs), which threatens the life on earth (Realff et al., 2005) The level of GHGs in the atmosphere considerably increase since the industrial revolution. The reason for this was the industrial expansion and fossil fuel combustion. The level of GHG is projected to rise in the future. The carbon dioxide (CO_2) concentrations in the atmosphere have increased from 280 to 410 ppmV (Buis, 2019) comparing to the year 1750. This trend is awaited to continue in coming decades. The trend will result in a temperature increase of 5.8 degree centuries in this century. When comparing various GHGs, CO_2 is the gas with the gas the harshest consequences, which is being considered as the cause of the global warming-phenomenon (Mahmoud et al., 2009; Dias and Arroja, 2012). Hence, numerous of studies that are conducted on global warming related issues and which are working towards decreasing global mean temperature are mainly centering on mitigating CO_2 emissions that are caused by different emitting sources.

Undoubtedly the industry and its related sectors are the main sources of CO_2 emissions. According to (IEA statistics, 2019) four main industries (power plants, iron and steel production, cement manufacturing and (petro-)chemicals are accountable for approx. 40% of global CO_2 emissions. Additionally, the top 10 industrial counties are responsible for 70 % of global CO_2 emissions in 2018. In

2017, approx. 22 Gton CO_2 was emitted by the industry sector (IEA statistics, 2019).

The major part of CO_2 emissions in the industrial sector is explained by the intensity it combusts fossil fuels. Moreover, production processes such as iron, steel and cement production chemically produce CO_2 as a waste gas (Draft Inventory US, 2020).

Generally, the cement industry is not considered as an industry with high complexity. The main reason for this is the fact that the most cement produced is therefore consumed in the construction sector, the trade of cement is generally limited in the country of production and the process of cement manufacturing is common to all existing cement plants. The production of cement is an energy-intensive process that includes considerable thermal energy in order to decarbonise the primary raw material (limestone) into clinker, which is the principal component of cement (Kermeli et al., 2019). Since the cement industry has a high level of process emissions, this industry is the third top CO_2 emitter industry globally, responsible for 5% of global CO_2 emissions. (Draft Inventory US, 2020).

Nowadays, cement is considered a key construction material that is used in the construction of buildings and different infrastructures. Indeed, currently, the cement industry is facing numerous issues globally. In the cement production the energy accounts nearly for 30-40% of production costs. The main challenges for this industry are the conservation of energy and material resources as well as the goal of reducing CO_2 emissions caused by cement production and distribution processes. Undoubtedly, despite recent years' success in using alternative fuels the potential of increasing alternatives fuels' consumption stays very high (Chatziaras et al., 2014).

Numerous studies have been conducted to reduce CO_2 emissions related to the cement production process, because of its big impact on global CO_2 emissions. Nevertheless, the majority of these studies have never been adopted and implemented, because of numerous barriers.

1.2. Swiss context

On the global scene, Switzerland represents only 0.1% of cement production. To compare China represents about 60% of global cement production which is the largest cement producer in the world, India: 7%, the USA is responsible for 2 % of global cement production, while Russia is accountable for 1.6 % (IEA, 2018). Mainly due to the fact the cement industry has a comparatively small size and high competition, the data related to CO_2 emissions and energy usage is not widely accessible. It might be highly complicated to acquire related specific information regarding Switzerland's cement plants. Indeed, because of the lack of data, it might be complicated to evaluate the potential of energy efficiency improvement and to understand what are the hurdles to limit the implementation of the best technologies in cement production. Thus, it is indispensable to be able to face the challenges and to find energy efficiency indicators that will help to design effective policies in the Swiss context.

2. Literature review

One of the main sources used in our research was the study conducted by Zuberi and Patel (2017). This study adopted the bottom-up analysis to investigate energy efficiency improvement of technologies and carbon dioxide emission reduction potentials in the Swiss cement industry by means of energy efficiency cost curves. Additionally, a number of energy efficiency measures with high payback periods (4–8 years) have been observed. In this study, researchers used economic data for analyzing the cost-effectiveness of the implemented measures. Moreover, the study also focused on techno-economic barriers that limit the implementation of the best practices in Swiss cement plants. The outcome of this research displayed the EE gap in the cement sector. These results can be further used as a ground to formulate more effective policies to be implemented in the cement sector.

The study by Zuberi and Patel (2017) do not indicate which Swiss plants adopted which energy efficient measures, but only provide overall adoption rates. In our paper we assume that these adoption rates are weighted by the six plants' clinker production. Thus, they show the affected share of total clinker production by each measure.

Additionally, in our paper we "backward engineered" the data given in Zuberi and Patel (2017), to determine a hypothetical plant without any measures (using only old equipment). From this starting point, we derived the plant-specific energy consumption and CO_2 emissions considering the initially implemented measures. The resulting sum over all plants matched Zuberi and Patel (2017) estimates of overall current energy consumption and CO_2 emissions.

Furthermore, in our study, the NPV calculations show that the data of Zuberi and Patel (2017) on investment costs and saving potential do not square with their stated adoption rate for several measures. The adoption rate of several measures is high despite their highly negative NPV. Therefore, we assume that even if the NPV of some measures is negative at replacement, the fact that plants already implemented these measures in the past (based on the adoption rates of Zuberi and Patel (2017)) is a better guide for our model than the NPV calculations (based on the same source).

What is more, numerous studies have conducted research on the topic of the energy efficiency of cement-making and energy efficiency measures (EEMs) for the cement industry (Saygin (2010)). They collected information on cement production and energy from various studies and statistics. Saygin (2010) used benchmarking to be able to compare the individual performance of plants with the most energy efficient cement plant. The results showed the value of benchmarking as a basis for potential improvement estimating. Additionally, it demonstrated information on the energy use of the global cement industry. Energy benchmarking supplies with highly valuable information about energy efficiency potentials of cement industries.

Further, many studies looked at the potentials of how to reduce emissions and energy use in cement plants in the U.S. (Worrell et al., 2000) and in Europe (Moya et al., 2011). For example, the paper by Worrell et al. (2000) studies the energy intensity and energy use trends of the US cement industry (from 1970 to 1999). Consequently, they calculated and demonstrated the baseline energy consumption by cement process in the US in 1999. This study determines EEMs and computes investment costs, energy savings, operations and maintenance costs for each of the energy efficiency measures. In addition, another paper studied the energy saving potential for 16 plants in China. The data on plants was collected and was further used to benchmark the energy efficiency of individual plants Chinese and international best practices (Hasanbeigi et al., 2010). They used the Benchmarking and Energy Saving Tool for Cement (BEST-Cement). As result, 32 energy efficiency measures that can be potentially suitable for Chinese 16 cement plants were established. To add, the potential for energy efficiency was evaluated for the year 2008.

Likewise, in his study V. Hoenig (2009) showed that if there will be a use of alternative fuels and a decrease of the clinker-to-cement ratio, it could play a significant role in the cement industry which will affect the future consumption of energy and CO_2 emissions. This role can be larger if it is compared to the improvement analyzed in the study done by Moya et al. (2011). The improvement is expelled of the study done by Moya et al. (2011) mainly due to the reason that their advancement will depend on non-technological components. The components that will influence their development are: social acceptance and acceptance of the market, properties of the cement, cost of clinker substitutes, expenses of available alternative fuels, legislation on waste collection, proposed utilization of the new types of cement, standards, accessibility to raw materials (V. Hoenig (2009)). To add, the study by Moya et al. (2011) demonstrates that the analyses of the cost-effectiveness of potential improvements cannot be taken into account as the main barrier to close "the energy efficiency gap". There are other innovative technologies that the cement industry is not following, namely: Waste Heat Recovery and Carbon dioxide Capture and Storage. In this study, the authors show how close these technologies are being beneficial and cost-effective for this industry. The authors concluded by asking a question: how the "energy efficiency gap" can be closed by using potential technologies, if the cement industry is not willing to follow all potential future technology developments in a cost-effective way?

Similarly, possible energy-efficient improvements waiting to be captured were shown in an exhaustive review of European cement facilities (J.A. Moya (2010)). These improvements were shown to be independent of evaluation on capital investment decision-making which was used to examine the viability of retrofitting.

In this study, only the improvement margins in the operating costs (acquired through technological improvements) were covered (E. Worrell (2003)). Additionally, in this case, the possible related productivity improvements were not taken into account (Liu (2006)). The result showed that the financial tools used by companies have a secondary role when there is a process of investment making decisions. Conversely, these tools are rather used as communications tools that give weight to the strategic nature of the investment (Cooremans (2009)). Also, Cooremans (2009) showed in his paper that financial tools can be in some cases compulsory, although not as an adequate condition in the process of decision-making.

The investigation was done by Koroneos C (2005) where the study was conducted on recycled waste heating sources. These sources can potentially be used to minimize the energy costs by applying the exergy analysis. In addition, the authors of Wang J (2009) conducted their research on exergy analyses and parametric optimisations for power plants in the cement industry. The outcome exhibited the exergy losses in condenser, turbine and heat recovery steam generator. These exergy losses were considerably large. Thus, by reducing these exergy losses of it will be possible to significantly ameliorate the co-generation system's performance.

2.1. Supply curves

The development of the conservation supply curve started to evolve at the beginning 1980s in order to evaluate cost-effective energy efficiency measures (EEMs) A. Meier (1982). CSC is able to identify the potential of energy savings as well as to rank different EEMs against each other. CSC was used in many industries such as ammonia, cement, iron and steel industries. Additionally, with the help of CSC it is also possible to calculate the cost of conserving specific energy fuel (steam (S. Sathitbun-anan, 2015) or electricity (A. Hasanbeigi, 2010)). To add, T. Fleiter (2012) used CSC to evaluate CO_2 abatement.

Furthermore, Energy Conservation Supply Curves (ECSCs) have been used in several studies on energy efficiency in several energy-related industrial sectors. In the study by L. Kong (2017) the authors designed ECSCs for fuel and electricity for the pulp and paper industry in China. The result of this study demonstrated cost-effective conservation potentials of 27% potential for fuels and 4% for electricity. Cost-effective measures related to wastefully recovery in the iron and steel sector in China were studied by Q. Zhang (2017).

Additionally, for the Chinese ammonia industry D. Ma (2015) created electricity and fuel conservation curves. They demonstrate that it is possible to achieve a 14% reduction in electricity and fuel consumption when using a 30% discount rate, while T. Xu (2012) found out that with the help of conservation supply curves and with cost-effective efficiency potentials it is possible to achieve a 25% reduction in final energy consumption for the pulp and paper industry in the US. Similarly, the study conducted by S. Sathitbun-anan (2015) determined 17 steam conservation measures. S. Sathitbun-anan (2015) based his study on five leading Thai sugar mills. The study succeeded to develop steam conservation curves for 9 sugar mills in Thailand, while A. McKane (2011) conducted their research on four countries in Europe and in Brazil on the cost-effectiveness of electricity efficient potentials of industrial motor systems for these countries.

Indeed, CSCs are able to identify cost-effective EEMs in different industries. Nevertheless, there still exists a need to defeat barriers to the impugnation of energy efficiency measures. In his study, Sorrell S (2000) gave an explanation of barriers and in 2013, E. Cagno (2013) introduces further developments. This was studied by A. Trianni (2012) for the non-energy intensive manufacturing SMEs (medium-sized enterprises) as well as for the foundry industry by P. Rohdin (2007). Additionally, T. Fleiter (2011) conducted a study on barriers to energy efficiency bottom-up energy-demand models, while G. Tesema (2015) in their study for the cement industry calculated CSCs, where they highlighted the high importance of overcoming barriers in order to be able to apply EEMs.

G. Tesema (2015) used in their study data for eight operational plants and twelve plants under construction in Ethiopia in order to develop fuel and electricity curves for the cement industry. In the same way, A. Hasanbeigi (2013) developed fuel and electricity CSSs for the cement industry in China (2010-2030) and assessed the potential of adopting 23 energy efficiency technologies, while A. Hasanbeigi (2011) and A. Hasanbeigi (2010) estimated 47 energy efficiency measures and their cost-effectiveness in the cement industry in Thailand.

Furthermore, J. Sathaye (2010) worked on the curves for the cement industry in the United States in 2004. Also, in the study conducted by T. Xu (2013) on the US cement sector in 2010, it was demonstrated that it is possible to achieve cost-effective savings of 25%.

2.2. Models

Models that focus on the cement industry include cement production models that center on the production of dry kilns for clinker and on roller (or balls) mills for grinding. To add, some of these models take into account different types of cement: fly ash, Portland cement, blast furnace slug (Z. Wen, 2015). In all cement industry model, different types of cement as well as different production technologies are in competition with each other for production costs based on market share. Another important point to mention is that recycling is not taken into account for cement, mainly due to the reason that the demolition waste is used as gravel for infrastructures and roads. The amount of models that include retrofit measures for improvement of energy efficiency is scarce (Corsten, 2009).

A limited amount of large-scale models consider material efficiency improvements through material substitution or product life extension (J.M. Allwood, 2010). The same situation is for the models that take into account the option of reducing losses in production processes (R.L. Milford, 2011). Nevertheless, the number of studies on clinker substituting alternative materials in the cement industry has increased (S. Anand, 2006; Z. Wen, 2015). Also, the amount of models that focus on fundamental alternative strategies for the improvement of material efficiency or structural changes of end-use materials is small. To conclude, only a few models account for the potentials of carbon capture and storage (CCS) technology (Moya et al., 2011; Y. Wang, 2014).

Few models have modules with bottom-up details that focus on the cement industry. The globally integrated asset model (IMAGE) has a specific integrated module targeted to the cement industry. The model analyses future projections on GHG emissions (B.J. Van Ruijven, 2016). This model takes into account global and regional cement and clinker production and demand. Additionally, it also considers the trade of technologies, materials energy use, GHG emissions and stock turnover. Another such example is POLES, this model has the ability to project CO_2 emissions and energy use. To add, this model also takes into account retrofitting, technologies and stock turnover (Kermeli et al., 2019).

2.3. Bottom-up models

Bottom-up methods use the logic of bottom-up analysis in order to quantify all the influencing factors which will lead to the dispersion of measurement results and build models for mathematical synthesis. Numerous bottom-up studies assessed energy-saving potentials based on using the best available technology (BAT) or best practice technology (BPT) techniques. Thus, previously energy-saving potential was assessed under the idea that BAT and BPT were applied to the industrial process itself. This way of approach was used in a variety of industries in order to simulate energy efficiency improvement potentials (J.H. Xu, 2012, 2014). Nevertheless, the studies that use BAT approach did not take into account the effect of technology diffusion on energy-saving potential. Thus, they did not take into account the development over time and were not able to give a conclusion on the timescale required in order to unfold the potential.

Additionally, some bottom-up models have considered the technology diffusion influence (T. Fleiter, 2012; N. Karali, 2014; C. Li, 2014; Z. Wen, 2015; J.H. Xu, 2016). The main advantage of these models is the clearness of the technology' development. This gives a possibility to project a clear and realistic development path. It is worth mentioning that in this kind of model it is important that prior to modeling some essential parameters should be exogenously forecasted, which are usually acquired from different statistical methods. Nonetheless, these statistical models might lack fidelity, mainly due to the reason that they are based on historical data are unable to catch specific factors or changes of a dynamic environment.

Concluding, it can be seen that numerous models described above offer a bottom-up approach with detailed technology representation. Simultaneously, global models are more top-down oriented and generic. Moreover, the trade and embedding of the cement sectors in the global energy system are included in global and top-down models. The regional models generally do not take into account trade. These models generally only integrate industry and energy at the regional level. Furthermore, the literature does not yet include an equivalent to the model presented here. Thus, more research is needed to deal with remaining issues connected to cement related modelling as well as to develop effective models to address these challenges for the world of tomorrow.

This study is unique in several ways. (1) It is focused on Swiss cement industry. The model replicates the investment decision of plant owners, introduces the energy efficiency improvement and describe the production processes of cement plants in Switzerland. (2) This model distinguishes between essential unit process (EUP) measures and pure energy efficiency measures (PEEM). Additionally, it takes into account competing measures (see Table 7). (3) The model functions with approximately 15 measures based on a list of energy efficiency and CO2 mitigation measures that are applicable for Swiss cement plants. (4) Three different policy scenarios for 2050 CO_2 emissions, fuel and electricity consumption are investigated, by combining fossil fuel prices, discount rate and availability of CCS measures in the future to evaluate the effects of such policies on the promotion of energy-saving technologies.

3. Methodology

3.1. Swiss context

Currently, in Switzerland exist six cement plants that produce approximately 94% of the clinker in rotary dry kilns and the rest in semi-dry kilns. Throughout the year Switzerland produces about 5 million tonnes of cement in total. According to (Cemsuisse, 2020) the specific energy use for Switzerland in 2019 is 3.54 GJ/t-c. It is below the maximum BAT value (4 GJ/t-cl) but approx. 7% above the minimum BAT value (3.3 GJ/t-cl). This demonstrates that Switzerland still has an energy efficiency potential to acquire. The development of final energy demand by energy carriers used for the production of cement in Switzerland from 2014 to 2019 is shown in Figure 1.

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

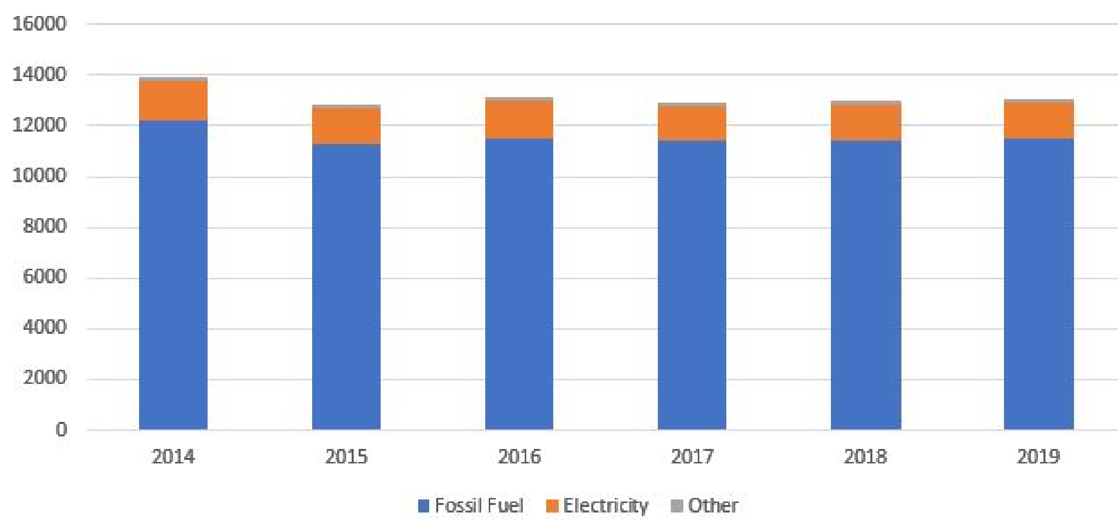

Figure 1: Final energy consumption by energy carriers (PJ) in the Swiss cement industry from 2014 to 2019 (source: Cemsuisse (2020))

Following Zuberi and Patel (2017), we distinguish between essential unit process (EUP) measures and pure energy efficiency measures (PEEM). A EUP is an essential part of the manufacturing process. Therefore, implementing such a measure means replacing inefficient equipment with an efficient one, thereby directly making the process more efficient (e.g. replacing a mill with a more efficient one). A PPEM, on the other hand, is not part of the manufacturing process, but only serves to improve the overall energy efficiency of the plant (e.g. waste heat recovery). Implementing a PPEM means adding a piece of equipment.

We model approximately 15 measures based on the thorough analysis of Zuberi and Patel (2017), who provide a list of energy efficiency and CO2 mitigation measures that are applicable for Swiss cement plants. This list also includes investment costs, fuel savings, electricity savings, CO_2 abatement potential, lifetimes as well as adoption rates. Examples of measures are mill or grinder replacement, changes in the kiln or replacing a pneumatic with a mechanical transport system. The abbreviation and the list of technology measures are given in Table 1.

3.2. The description of the model

The first step is to build a model for all six existing Swiss cement plants, replicate the investment decision of plant owners, model the efficiency improvement and describe the production processes of these plants, in particular which energy efficiency measures they already implemented. Starting from an initial allocation of already implemented efficiency measures, plants become more energy efficient by implementing additional measures. We model the implementation of these measures based on a costs-benefit analysis in combination with other rules related to the replacement of inefficient equipment at the end of the lifetime.

Table 1: Technology measures (source: Zuberi and Patel (2017))

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

The energy efficiency improvements for each of the six Swiss cement plants are modeled. Plants get more energy efficient by implementing efficiency measures. The model starts with an initial allocation of plant-specific measures. Zuberi and Patel (2017) do not indicate which plants adopted which measures, only adoption rates. The shares of total clinker production are given in Table 2. We assume that these adoption rates are weighted by the six plants' clinker production, so they indicate what share of total clinker production is affected by each measure. Using the data on the plants' clinker production, we are able to determine an initial allocation that replicates Zuberi and Patel (2017)'s adoption rate (see Table 3).

Table 2: Share of total Clinker Production (source: Zuberi and Patel (2017))

Plants	Share of total Clinker Production (Mt/y)
Untervaz	16%
Eclépens	19%
Siggenthal	20%
Wildegg	17%
Cornaux	6%
Reuchenette	21%

Table 3: Initial allocation of measures and calculation of rate of adoption in 2015 (based on adoption rate of Zuberi and Patel (2017))

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

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

Additionally, the gain of currently installed measures is determined with the help of the data on the initial allocation of measures (given in Table 6 in Zuberi and Patel (2017)) and Energy savings by each measure. Moreover, the initial allocation of measures (see Table 3) (YES = implemented) is calculated taking into account the remaining diffusion rates taken from Table 2 of Zuberi and Patel (2017).

The rate of adoption shows what percentage of cement plants have already implemented particular measures. The rate of adoption is calculated to reckon with the allocation of measures and the shares of total clinker production (Zuberi and Patel, 2017).

Furthermore, Zuberi and Patel (2017) estimate that the current average energy consumption for the six plants per ton of produced clinker is 3.5 GJ per ton of clinker (fuel) (see Table 4) and 0.5 GJ/t-cl (electricity) (see Table 5), respectively. Using these averages and the saving potential of the measures implemented in the initial allocation allows us to calculate the current fuel and electricity consumption for each plant with measures currently installed (see Table 4 and Table 5). Based on Zuberi and Patel (2017) and confirmed by a representative of the cement industry, the current best-available technology would need 3.0 GJ/t-cl (fuel energy) and (0.4 GJ/t-cl for electricity).

Table 4: Fuel Consumption w/o measures (GJ/t-cl)

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

Table 5: Electricity Consumption w/o measures (GJ/t-cl)

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

3.3. *Energy efficiency improvement*

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

- Measure-induced technical progress (MI-TP): Inefficient equipment is replaced by efficient equipment that fulfills the same function but is of another type (e.g., a ball mill is replaced by a vertical roller mill). Or a PEEM is introduced (e.g. waste heat recovery). We refer to this process as implementation of a measure. The magnitude of the MI-TP is measure specific

- Autonomous technical progress (A-TP): Efficient equipment that has been state-of-the-art at the time of its implementation but will be somewhat outdated at the end of its lifetime. This outdated equipment is replaced by the same type – yet of an improved variant (e.g., a vertical roller mill version 1 is replaced by a vertical roller mill version 2; or waste heat recovery version 1 is replaced by waste heat recovery version 2). We refer to this process as a reimplementation of the measure. We assume that A-TP yields an improvement of the saving potential of X% per year as well as a decrease in investment costs of Y% per year.

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

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

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

The values for parameters from the paper of Zuberi and Patel (2017) are given in Table 6:

The NPV is thus only relevant for the implementation of measures (definition see above), including the replacement of inefficient by efficient EUP-equipment, except if the measure is already in place (in which case it is simply always reimplemented at the end of its lifetime). If relevant, we calculate the NPV yearly, based on the investment costs of the measure (difference of investment costs of inefficient and efficient equipment) as compared to the energy savings (including CO_2 price). The future energy savings are discounted at a rate of 11 percent.

Regarding point 2, inefficient EUP-equipment can be replaced before the end of its lifetime if the NPV justifies this, i.e. if the anticipation of replacement by an efficient EUP-equipment is compensated by the energy savings obtained in comparison with the replaced equipment over the latter's remaining lifetime. Anticipating the replacement of equipment is assumed to imply a cost equal to

Table 6: Parameter values

Parameters		Values
r	Average discount rate	11%
P_e	Price of electricity	trajectory of prices (CHF/GJ)
P_f	Price of fuel	trajectory of prices (CHF/GJ)
P_{CO_2}	price of CO_2 emitted	trajectory of prices (CHF/GJ)
EF	Emission factor of coal	93.15 tCO2/GJ
L_y	Measure lifetime	depends on the technology
EIS_y	Electricity savings	depends on the technology
FIS_y	Fuel savings potential	depends on the technology
CA_y	Abatement potential for each measure, CO2 savings	depends on the technology
I_y	Initial investment	its value is zero for all years
		the base year of the implementation
$C_{spec,y}$	Specific cost	
ANF	Annuity factor	
NPV_y	Net present value	
CF_t	Cash flow	
PR_y	Clinker or cement production to which measure is applicable	t-cl/yr or t-cem/yr
$O\&M$	Operation and maintenance cost	CHF
B_y	Annual benefits of the measure	CHF
ES_y	Annual final energy savings potential of each technical measure potential of each technical measure	CHF

a fraction of the replacement measure, this fraction is equal to the fraction of the lifetime of the existing equipment wasted through anticipated replacement. Consider for instance an EUP-equipment with a lifetime of 20 years. Replacing it after 15 years, i.e. 5 years before its end of life, costs 5/20 of the replacement measure's cost and is justified if the present value of the energy savings that this replacement makes possible over the 5 years remaining exceed, in their discounted sum, this early replacement cost. Investment costs are thus linearly depreciated (e.g. if the age of the inefficient equipment is three-quarter of its lifetime, NPV-relevant investment cost is cut by three-quarter). At the same time, benefits are considered for the rest of the inefficient equipment's lifetime as well.

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

The NPV of measures changes with time due to

- technical progress: we assume that technical progress manifests itself through an improvement of the energy-saving potential of 2% per year,
- changes in fossil fuel prices (including the CO2 price), and
- linear depreciation of investment costs for EUP-measures only.

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

3.4. Barriers of the model

Concerning barriers, we took into account competing measures (see Table 7). That is, some measures cannot be implemented simultaneously (e.g., there are several measures related to cement grinding). In addition, we allow carbon capture and storage in special scenarios only: one scenario where CCS can be implemented as soon as it is profitable ("High ETS price with CCS") and one scenario there CCS is only available from 2040 on due to technical and legal barriers ("High ETS price with CCS 2040").

Table 7: Competing measures (=measures are in competition) (source: own Table based on Zuberi and Patel (2017))

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

Regarding the impact on fuel and electricity consumption of CCS, we use Zuberi and Patel (2017)'s data and assume that CCS acts "end-of-pipe". That is, emissions are first reduced by all other measures and remaining emissions are subsequently reduced by 95% with CCS. We assume that this percentage is not affected by technological progress.

Other barriers one may implement in the next version of the model are

- According to the representative of the cement industry, old equipment is often repaired rather than replaced and thus used much longer than its technological lifetime (often, the repair is considered environmentally beneficial, but in case of products that use a lot of energy during the consumption phase (e.g. refrigerator), replacement is often better the repair.)

- Include non-financial constraints (building permits)
- Fixed cost of implementing the measure
- The efficiency potential depends on how many measures are already implemented (some measures save a fraction of the total energy consumption and not an absolute value)

4. Numerical implementation: deep decarbonization of the Swiss cement sector

In this section, we simulate several scenarios with our cement model. The target of these simulations is twofold. First, we want to demonstrate the capabilities of our model in analyzing a various range of scenarios. Second, we aim to study how Switzerland can achieve deep decarbonization of its cement sector. The main climate policy applying to the cement industry is its required participation in the Swiss emission trading system (ETS). The Swiss ETS is linked with the EU ETS since 2020. Swiss cement plants thus receive an allocation of emission allowances under the Swiss cap, but they may trade allowances on the EU ETS market. The price of emission allowances (the ”ETS price”) is determined at the European level and presumably little affected by the activities of Swiss participants. Therefore, this price is not a parameter for Swiss climate policy. The ETS price is highly uncertain, as it will depend on the future emission caps decided by the European Union, the development of the European economy and how the participants to the

ETS respond to the price signal. To account for this uncertainty, we shall simulate a scenario where the ETS price remains relatively low and another scenario where it rises strongly. We use the scenarios which are derived from the Current Energy Policy Scenario and Zero Basis Scenario respectively of the Energy perspectives 2050+ (see Table 8).

One relevant lever for Swiss climate policy concerns carbon capture and storage (CCS). Today, technical, economic and legal barriers hinder cement plants from implementing CCS. We shall assume that the technical and legal barriers are lifted in 2040 for cement plants, following Kirchner et al. (2020).

Based on these considerations, we simulate four scenarios. In each case, the model runs from 2015 to 2050.

1. *Baseline scenario*: low CO_2 (ETS) price
2. *High tax scenario*: high CO_2 (ETS) price
3. *High tax with CCS constrained 2040*: high CO_2 (ETS) price + CCS measure available in 2040
4. *High tax with CCS unconstrained*: high CO_2 (ETS) price + CCS measure available as soon as it becomes profitable

4.1. Baseline scenario

We assume that in the Baseline scenario the technical improvement = 1%. Technological improvement means that fuel and electricity savings improve, but not the investment costs. Additionally, the Discount rate = 11%, the CO_2 price is derived from the Current Energy Policy Scenario of the Energy perspectives 2050+ (see Table 8). The CO_2 price from 2050 to 2080 is assumed to be constant.

In Figure 2 and in Figure 4 we can see a drop of fossil fuel consumption and CO2 emissions in 2035 and 2044 at the time the cement blending measure

Table 8: Energy prices

	Current Energy Policy			Zero Basis		
	Coal	Electricity	CO2	Coal	Electricity	CO2
2015	3.29	33	7	3.29	32.97	7
2016	3.10	37	7	3.10	36.80	7
2017	3.29	34	7	3.29	34.11	7
2018	3.97	33	18	3.97	33.41	18
2019	3.56	39	28	3.56	37.57	28
2020	3.38	38	28	3.27	36.95	28
2021	3.43	37	29	3.21	35.34	29
2022	3.44	41	29	3.15	37.83	29
2023	3.45	41	30	3.10	38.28	30
2024	3.46	44	30	3.05	38.04	30
2025	3.48	43	31	3.00	38.67	31
2026	3.51	42	31	2.97	39.09	31
2027	3.54	43	31	2.94	36.58	31
2028	3.56	42	32	2.92	36.28	32
2029	3.57	43	32	2.89	38.47	32
2030	3.59	43	33	2.88	37.88	33
2031	3.60	44	34	2.86	41.20	43
2032	3.61	43	35	2.86	44.26	54
2033	3.62	45	36	2.86	46.20	65
2034	3.63	48	37	2.86	54.49	76
2035	3.64	50	38	2.86	54.46	86
2036	3.65	50	39	2.86	58.49	97
2037	3.66	53	40	2.86	60.18	108
2038	3.66	48	41	2.87	63.24	119
2039	3.67	52	42	2.87	60.25	129
2040	3.68	53	43	2.87	63.39	140
2041	3.70	55	45	2.78	72.61	166
2042	3.71	54	46	2.70	84.54	191
2043	3.73	59	47	2.61	86.85	217
2044	3.74	58	48	2.52	96.82	243
2045	3.76	62	49	2.43	94.51	268
2046	3.78	58	50	2.34	98.84	294
2047	3.79	58	51	2.26	103.97	320
2048	3.81	53	52	2.17	103.88	345
2049	3.83	49	53	2.08	99.67	371
2050	3.84	54	54	1.99	106.11	397

(CG5), which has a big impact on CO_2 and fuel savings is replaced (due to the technical progress it is more efficient than in 2015). Additionally, in the case of the implementation of the CG5 measure, the electricity consumption increases only slightly. This is the reason we cannot see a significant decrease in electricity consumption in Figure 3. It is worth mentioning that in the initial allocation the measure CG5a is already in place for all the plants, which has a lifetime of 20 years.

Finally, we treated Zuberi and Patel (2017)'s measure CG5 in a special way. This measure concerns blending of cement, which refers to mixing cement with additives other than clinker. This reduces the demand for clinker and in consequence energy consumption and CO_2 emissions. Zuberi and Patel (2017) assume a fixed fraction of 35% additives by mass of cement for measure CG5, implicitly assuming that either there is blending in a plant at this scale or none at all. As in reality blending can occur on a continuous scale, we use a slightly more realistic assumption and split CG5 into two parts: CG5a is 2/3 of CG5 in terms of costs and savings and it is part of the initial allocation of each plant. This allows us to match Zuberi and Patel (2017)'s adoption rate of 33%. CG5b (which is 1/3 of CG5 in terms of costs and savings) is in no plant's initial allocation and subsequently treated as a standard PEEM.

4.2. High tax scenario

We assume that in the High tax scenario we have the same installation as in the Baseline scenario. The one difference is the change of the low CO_2 price to the high CO_2 price, as well as the setting of the constant price from 2050 to 2080.

In Figure 7 we can notice that the drop in 2024 is much smaller than in 2044, the reason for this is the technical progress. Thus, each year the measure increases

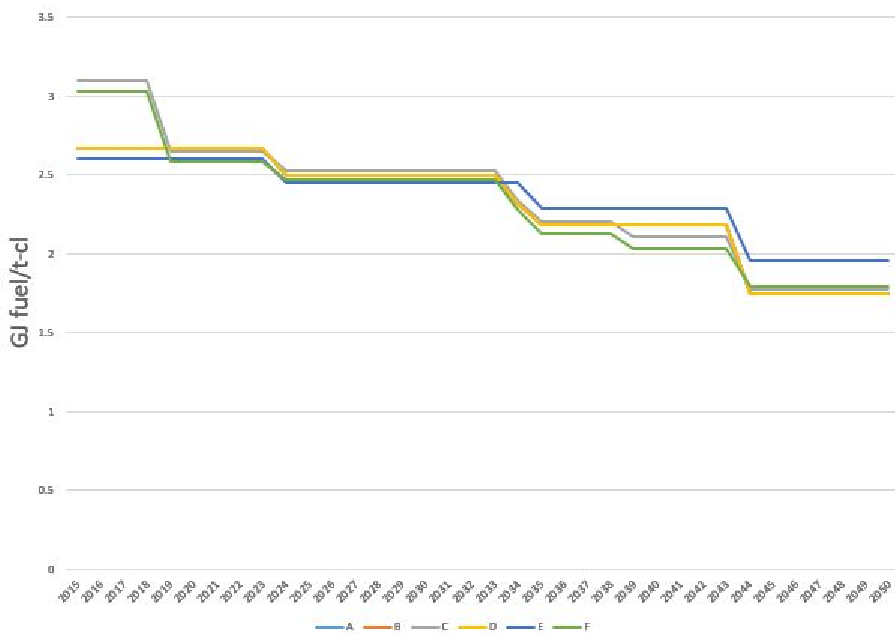

Figure 2: Fossil fuel consumption. Baseline scenario

the efficiency by 1%.

In this scenario, slow implementation of measures comes about, while close to the year 2050 the automatic replacement of measures is taking place. This occurs at the end of the lifetime of the measures (independent of the CO_2 price)(see Figure 7). Moreover, the drop in the year 2044 for CO_2 emissions takes place, as many of the measures are getting replaced at the end of their lifetime. This is because we have the first round of measure replacements in 2024 and then the second round in 2044 (we consider that the measures are already 10 years old in 2015).

The only impact of the CO_2 price is to bring some plants to replace earlier the measures. On one hand, we assume the NPV calculation, where the ETS price plays a role and then we have an automatic replacement at the end of the lifetime

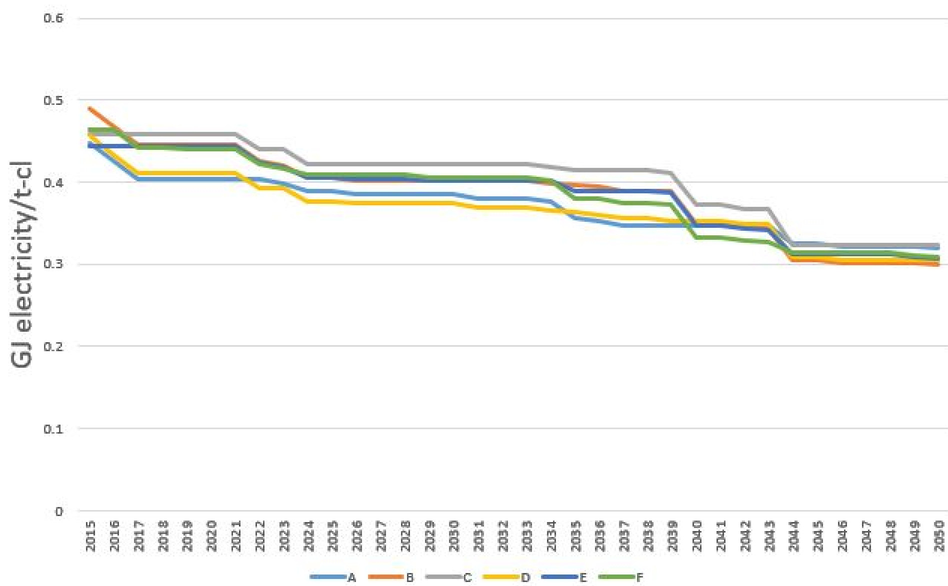

Figure 3: Electricity consumption. Baseline scenario

where CO_2 price does not play a role. We can see two drops taking place in 2044 for fuel and electricity consumption (see Figures 5 and 6). If we compare the Baseline scenario with the High tax scenario we notice that the impact of the CO_2 price on fuel and electricity consumption is low.

4.3. High tax with CCS constrained 2040

In this scenario, the CCS measure is allowed to be implemented in the year 2040. Here we use the high CO_2 price, as well as we set the constant price from 2050 to 2080. The rest of the parameters is the same as in the Baseline scenario.

In Figure 10 we can see that as soon as the CCS measure is introduced in 2040 we have a big drop in CO_2 emissions after sequestration. This is because the measure CCS is a CO_2 capture measure that provides significant CO_2 abatements. At the same time we can see in Figure 8 and Figure 9 that the fuel and

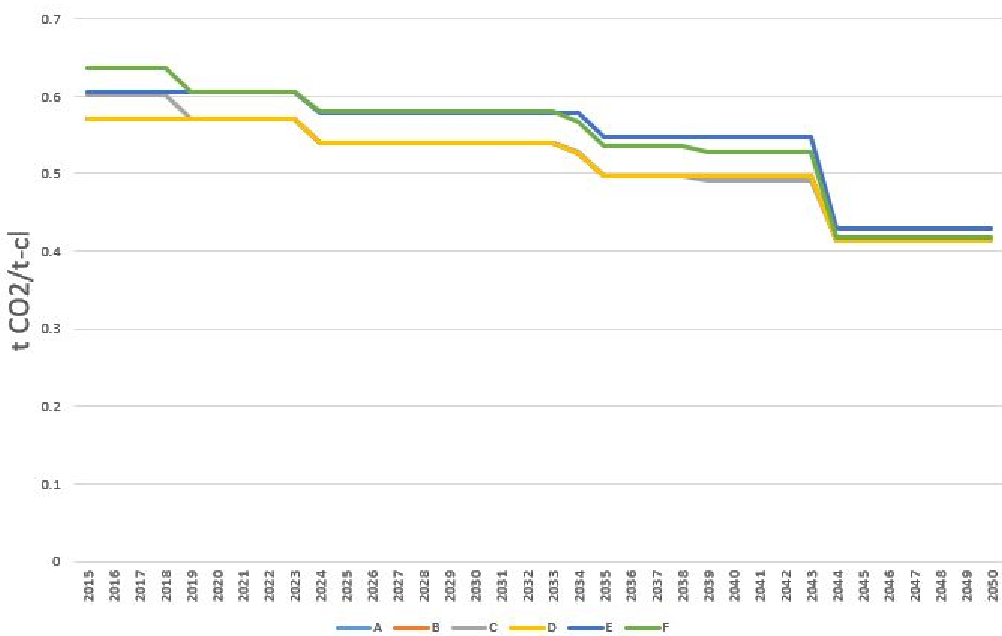

Figure 4: CO_2 emissions. Baseline scenario

electricity consumption spike in 2040 as soon as the CCS measure is becoming available. This is explained by the fact that the measure CCS requires additional energy.Thus, as soon as CCS measure becomes available in 2040 the fuel and electricity consumption increases.

We have undertaken the plausibility check and compared the numbers given in the Zuberi and Patel (2017) paper for fuel and electricity consumption for the CCS measure (e.g I4) with numbers given in Stefania Osk Gardarsdottir and Cinti (2019). We can conclude that Zuberi's assumption is plausible for both electricity and fuel.

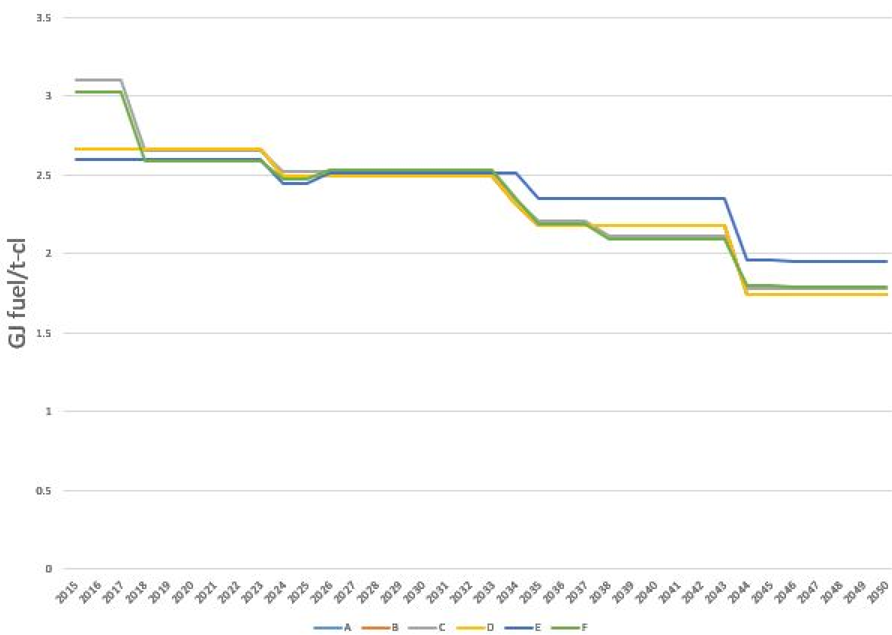

Figure 5: Fossil Fuel consumption. High CO_2 tax scenario

4.4. High tax with CCS unconstrained

In this scenario the CCS measure is implemented as soon as it becomes profitable. Here we also use the high CO_2 price, and similarly we set the constant price from 2050 to 2080. The rest of the parameters stays the same as in the Baseline scenario, in which the measure CCS never gets implemented.

According to the specification of this scenario we let the CCS measure to get implemented as soon as it becomes profitable. In Figure 13 we can see that the CCS measure gets profitable and thus gets implemented in 2033. This is also the reason why we have a big drop in CO_2 emissions after sequestration in 2033. The reason is similar to the scenario where the CCS measure is allowed to be implemented in 2040. Since the CCS measure is a CO_2 capture measure that provides a significant CO_2 abatement we can see a big drop in 2033. The same

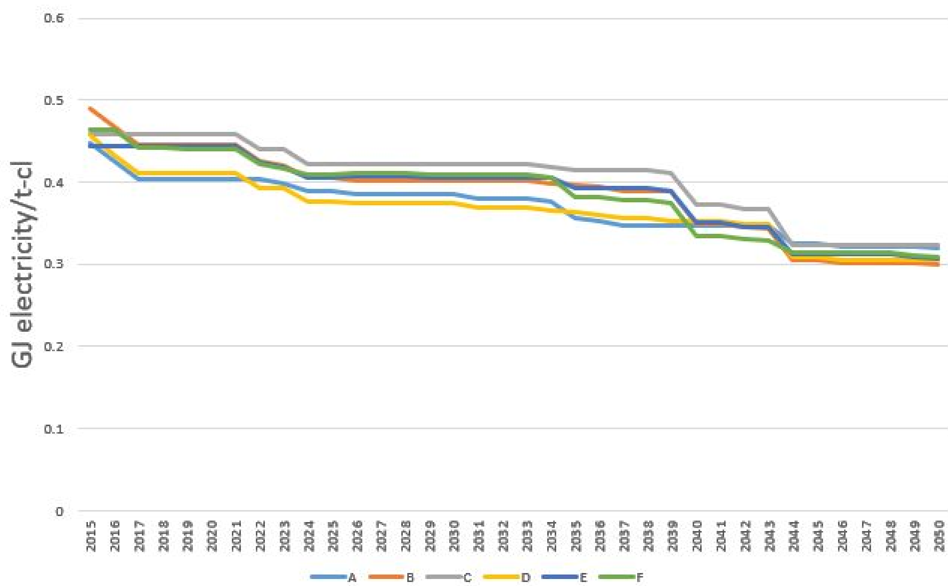

Figure 6: Electricity consumption. High CO_2 tax scenario

story relates to the fuel and electricity consumption: we see the spikes in 2033 (see Figure 11 and Figure 12).

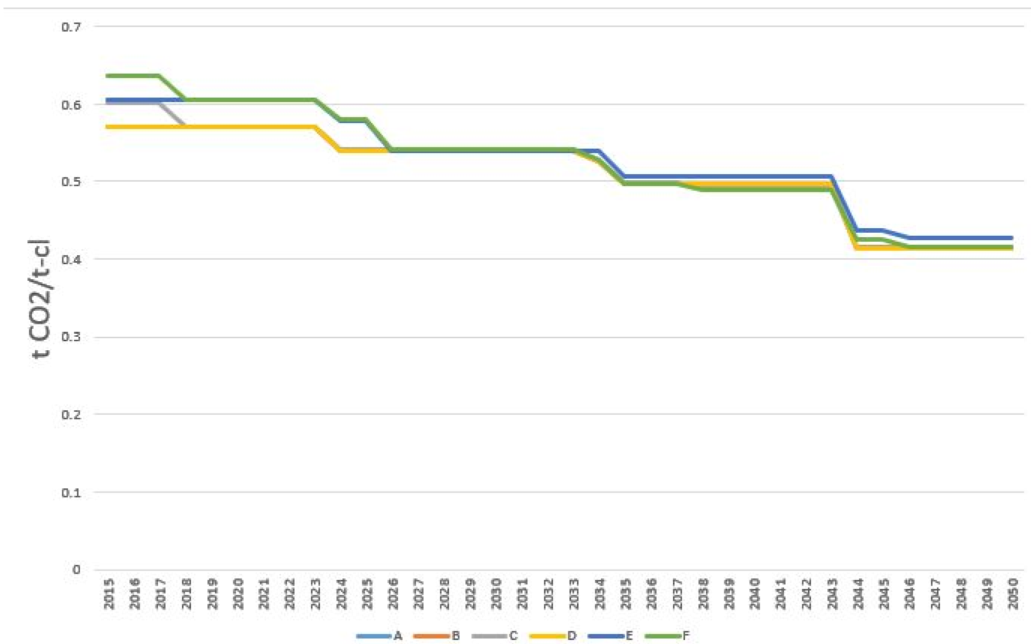

Figure 7: CO_2 emissions. High CO_2 tax scenario

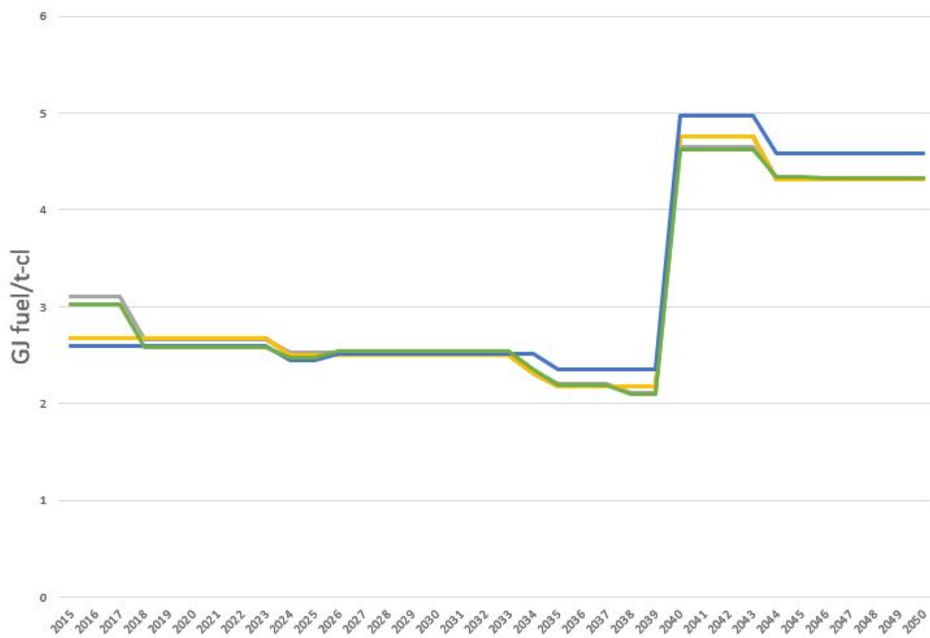

Figure 8: Fossil Fuel consumption. The CCS measure available in 2040 scenario

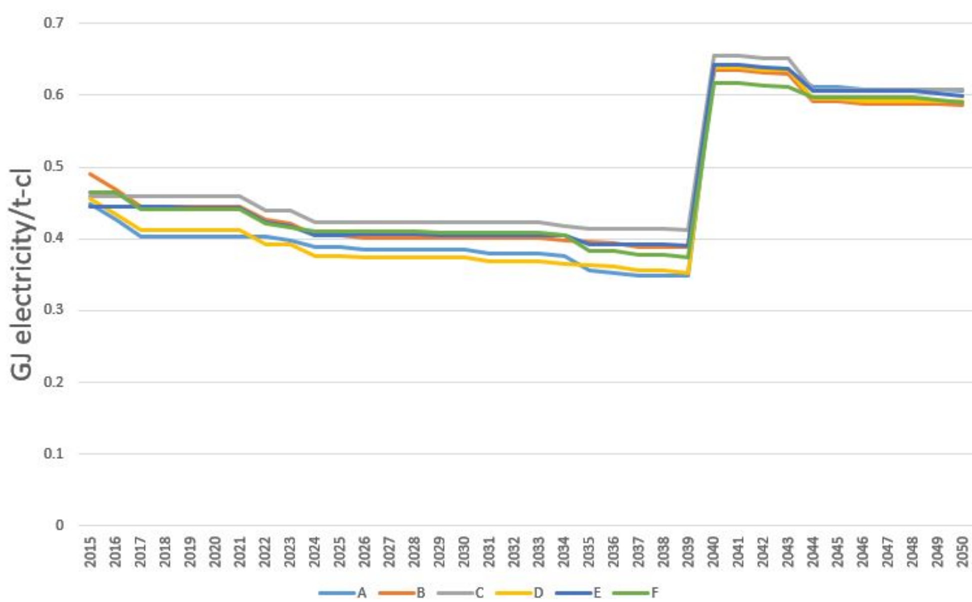

Figure 9: Electricity consumption. The CCS measure available in 2040 scenario

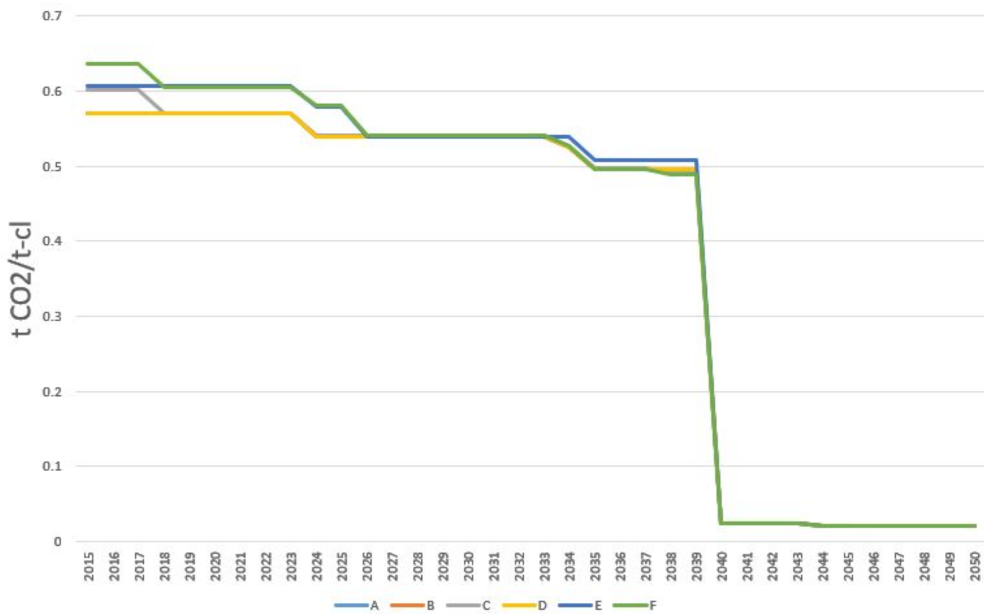

Figure 10: CO_2 emissions after sequestration. The CCS measure available in 2040 scenario

Figure 11: Fossil Fuel consumption. The CCS measure available when profitable scenario

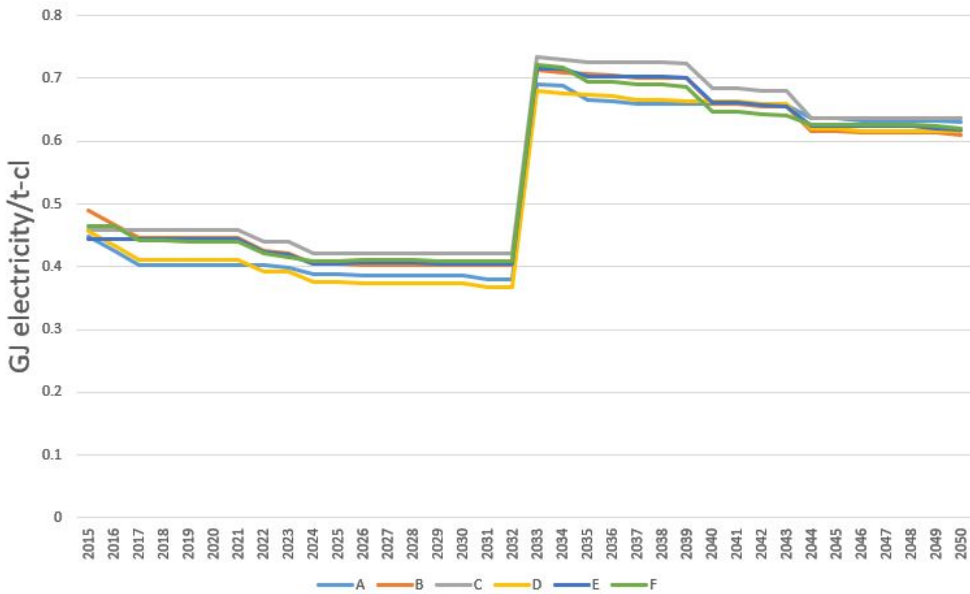

Figure 12: Electricity consumption. The CCS measure available when profitable scenario

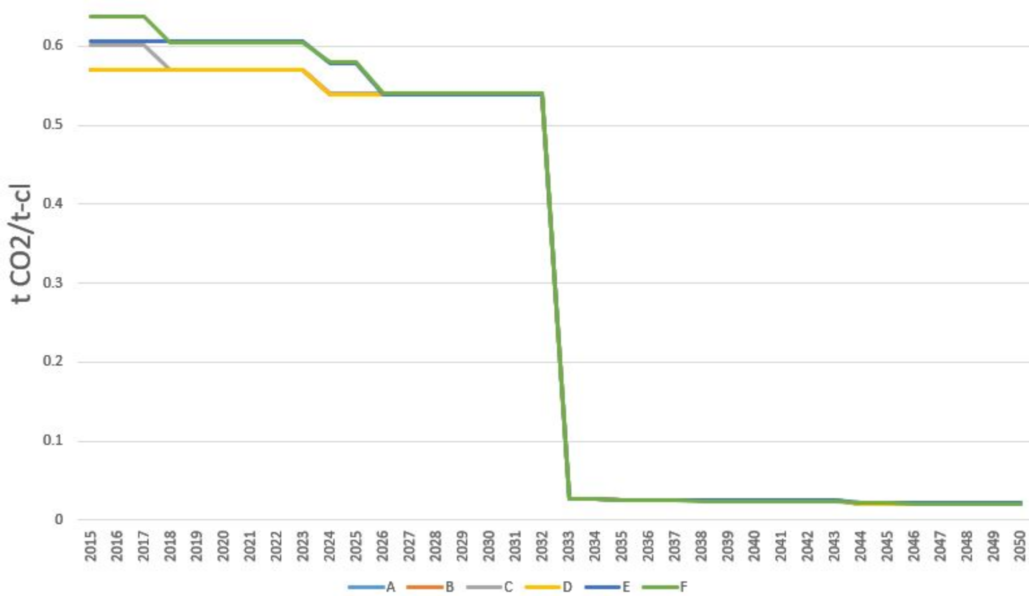

Figure 13: CO_2 emissions after sequestration. The CCS measure available when profitable scenario

4.5. Comparison of scenarios

In the baseline scenario, the CO_2 emissions decrease for all six plants from 2015 to 2050 by around 29.7% (see Table 9). In the high tax, high tax with CCS constrained in 2040 and CCS unconstrained scenarios the difference of CO_2 emissions decrease from 2015 to 2050 by 29.7%, 96.5% and 96.5% respectively. As can be seen from the results the first two scenarios do not have substantial CO_2 emissions decrease because the measure that has a significant CO_2 abatement potential is not implemented in both two scenarios. Contrary, in the following scenarios this technology becomes available (in years 2040 and 2033) which eventually demonstrates considerably higher CO_2 emission reduction potential. It worth mentioning that for the third and fourth scenarios we take into account the CO_2 emissions after sequestration when the CCS measure is already in place.

Moreover, the fuel consumption in the baseline scenario decreases for all six plants from 2015 to 2050 by around 35.7%, the same decrease we can observe in the second scenario (see Table 9). For the rest of the scenarios, due to the implementation of the CCS measure in 2040 and 2033, the fuel consumption from 2015 to 2050 increases by 56.4% and 64.4% respectively. This is explained by the relatively large additional energy demand of CCS.

Furthermore, we observe the electricity consumption decrease in first two scenarios. The results show that in the baseline and high tax scenarios the electricity consumption from 2015 to 2050 decreases by 32.55% in both cases, while in the third and fourth scenarios the consumption increases by 29.7% and 35.1% respectively (see Table 9). Similarly, in this case the CCS measure has additional energy demand, which greatly affects the electricity consumption.

The overview in Table 9 shows that between 2015 and 2050 fuel and electricity consumptions as well as CO2 emissions drop by about 30 to 35% in the scenarios without CCS. Comparing 2050 to 2015 there is no difference between the low and high ETS price scenarios without CCS. The reason is that in each case the later phase is dominated by autonomous technical progress, which makes up for the somewhat slower measure-induced technical progress in earlier phases of the low ETS price scenario. In the scenarios with CCS, CO2 emissions drop by 96% mainly resulting from our assumption that CCS reduces emissions by 95%. Fuels and electricity consumption increase drastically. The increase is higher in the scenario without the technical and legal barriers, because CCS is implemented earlier and thus at a time where the technology is less advanced. Cumulative CO2 emissions relative to the low ETS price scenario are about 1% lower for the high ETS price scenario and between 24% and 44% lower in the scenarios with CCS. This shows the huge importance of the availability of this technology for the cement sector.

Table 9: Comparison of results

Comparison 2050 to 2015	Low ETS price	High ETS price	High ETS price with CCS 2040	High ETS price with CCS
Change in fossil fuels consumption	– 36%	– 36%	– 56%	– 64%
Change in electricity consumption	– 33%	– 33%	+30%	+35%
Change in CO2 emissions	– 30%	– 30%	+96%	+96%
Cumulative CO2 emissions 2015-2050 relative to scenario “Low ETS price”	–	-1.3%	-26%	-44%

5. Sensitivity analysis

1. *Technology improvement*: Technology improvement increase by 1 percentage point a year.
2. *Discount rate change*: Decrease the discount rate twice

3. *Discount rate change*: Increase the discount rate twice

6. Conclusion and outlook

6.1. Conclusion

Given the importance of the cement industry in Switzerland as one of the highest energy-consuming and CO_2-emitting industry, the goal of our study is to understand the potential for energy-efficiency improvement and CO_2 emission reductions. The purpose of the paper was also to show how endogenous energy efficiency improvement could be modelled, which was successfully done. Specifically, our model was constructed for the Swiss cement industry to estimate the energy-efficiency improvements and the potential of decrease of CO_2 emissions by taking into account the costs, lifetime and energy savings of different technologies and measures.

We analyzed around 20 energy efficiency technologies and measures for the cement industry. Using our model, we estimated the potential energy consumption reduction and CO2 emissions abatement potential for the Swiss cement industry for 2015–2050. We also developed two scenarios with CCS measures. In the first scenario, we assume that the CCS measure becomes an available technology in 2040. In the second scenario, we allow the CCS to get implemented as soon as this technology becomes profitable (in the year 2033). We calculated and compared the fuel and electricity consumption decrease as well as CO_2 emissions after the sequestration for both scenarios from 2015 to 2050. The results show that both fuel and electricity saving potentials, as well as CO_2 emissions abatements for the scenario analysis, are higher than in the baseline scenario analysis, in which no CCS technology is implemented during the study period (2015–2050).

It is recommended that further research related to the implementation barriers for the identified cost-effective technologies and measures to be undertaken. An understanding of the existing technologies and barriers of their implementation is an important first step that will lead to developing specific policies and programs to encourage further implementation of energy-efficiency opportunities. Once the barriers of the implementation of new technologies have been identified it is crucial to develop effective programs and policies to overcome the barriers to adoption. This kind of programs and policies might include but not limited to the development of the resources to gather information on energy-efficiency and particular technological assistance which will help to identify and implement energy-efficiency measures. To add, as soon the technologies and measures have been identified the government could form distinctive financing programs of support for the further implementation of these measures.

When looking at our model and trying to interpret the results, one should pay attention to the method and formulas used in the development of the model. In addition to the assumptions used, such as the discount rate, energy prices, lifetime of measures, cost of technologies, fuel and electricity savings, CO_2 abatement, etc. Finally, the approach used in our research can be potentially viewed as a screening tool for helping policymakers, specifically the Swiss government to understand the savings potential of energy-efficiency measures and design appropriate policies to capture the identified savings. Indeed, energy-saving potentials and the cost of energy-efficiency measures and technologies will vary according to country and cement plant-specific conditions.

This study demonstrates that in the Swiss case, an efficiency gap remains in the cement industry. The reason for this is that identified opportune policy and technology measures for energy efficiency improvement still have not been adopted. Hence, effective energy efficiency policies and programs are needed to realize cost-effective energy savings and emission reduction potential.

6.2. *Refinements of the model*

One can use the refinements of the model in future simulations. These refinements might include by are not limited to:

- Technological progress (TP). Constant improvement with time: Investment costs decrease for all the measures by 2% a year.
- Taxes, subsidies on investment
- The efficiency potential depends on how many measures are already implemented (Some measures save a fraction of the total energy consumption and not an absolute value)
- Only one measure per period can be implemented

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7. Acknowledgements

Appendix A Abbreviations

Table 10: Abbreviations

BAT	Best available technology
BAU	Business as usual
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CHF	Swiss franc
CO2	Carbon dioxide
EEI	Energy efficiency improvement
EP2050+	Energy Perspectives 2050+
EPB	ETS price baseline
ERA	Energy reference area
ETC	Endogenous technical change
ETS	Emissions trading system
EUP	Essential unit processes
HSM	Building stock model
SFOE	Swiss Federal Office of Energy
Mt	Megatons
NPV	Net present value
PEEM	Pure energy efficiency measures
toe	Tonnes of oil equivalent

Appendix B Data and calibration of the model

Table 5 from Zuberi and Patel (2017) demonstrates the final energy savings, costs and estimated diffusion data for energy efficiency measures applicable to the Swiss cement industry in 2016.

The paper by Zuberi and Patel (2017) demonstrates a figure that represents the aggregated Energy consumption by the cement industry in Switzerland (Figure 1).

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

We should describe the inefficient (worst/hypothetical) cement plant that does not have any energy-efficient measures implemented. The future worst (illustrative) plant will have today's best plant's specific final energy use of 3.38 GJ/t-cl. The worst illustrative plant does not have any energy-efficient measures. According to the study done by Zuberi and Patel (2017) the current average plant's final energy used in Switzerland today is 3.5 GJ/t-cl for fuel energy while 0.5 GJ/t-cl for electricity. The best cement plant that can possibly achieve the final energy is 3.0 GJ/t-cl for fuel energy and 0.4 GJ/t-cl for electricity.

Additionally, Zuberi and Patel (2017) observe that:

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

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

One can use the refinements of the model in future simulations. These refinements might include by are not limited to:

- Technological progress (TP). Constant improvement with time: Investment costs decrease for all the measures by 2% a year.
- Taxes, subsidies on investment
- The efficiency potential depends on how many measures are already implemented (Some measures save a fraction of the total energy consumption and not an absolute value)
- Only one measure per period can be implemented