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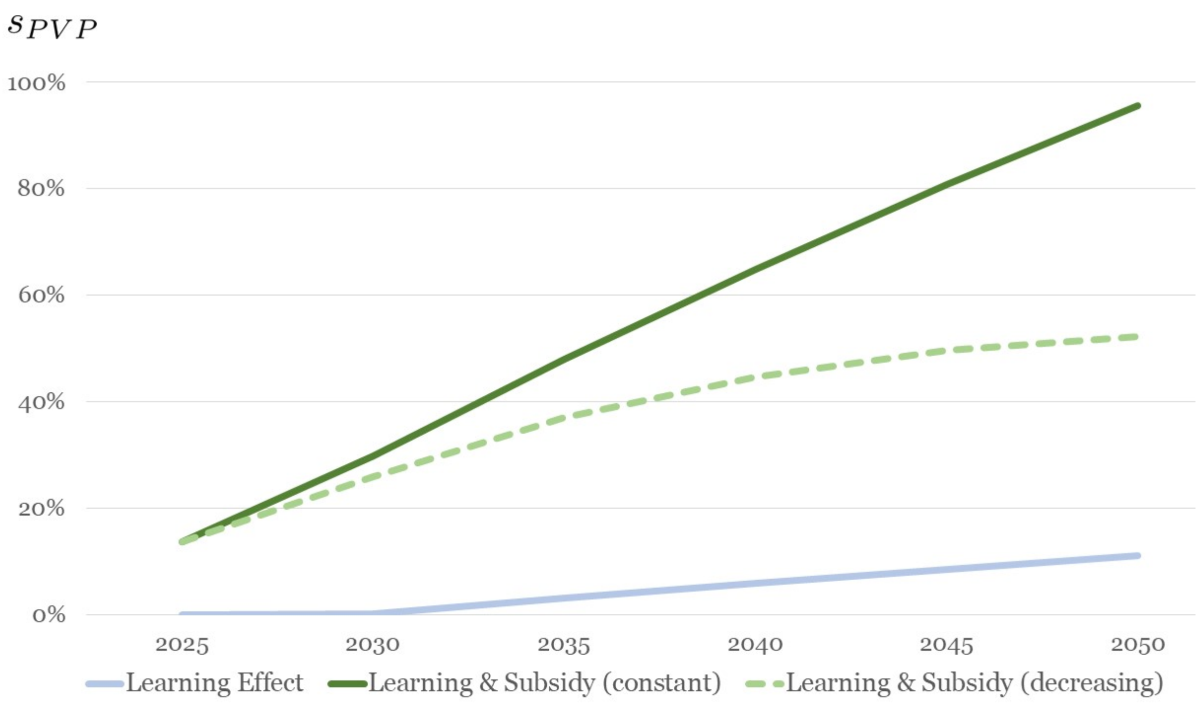
Optimal energy policy mix in the light of induced innovation and endogenous growth



Source: Authors’ simulations showing the learning factor (s_{PVP}) for solar energy with a constant and decreasing output subsidy profile, assuming that the Swiss economy is fully decarbonized by 2050.

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Zusammenfassung

Das Projekt untersucht eine Reihe von markt- und technologiebasierten Politikinstrumenten, um einen optimalen Politikmix für die Dekarbonisierung der Schweizer Wirtschaft zu identifizieren. Besonderes Augenmerk wird dabei auf die Rolle von Innovationen gelegt. Zu diesem Zweck untersuchen wir das Konzept des politikinduzierten technologischen Wandels in einem quantitativen allgemeinen Gleichgewichtsmodell. Wir erweitern diesen Modellrahmen um drei zusätzliche Kanäle, die mit politischen Instrumenten gezielt gefördert werden können, wodurch die Dekarbonisierung der Schweizer Wirtschaft beschleunigt wird. Zu diesen Kanälen gehören die verbesserte Substituierbarkeit fossiler Energien durch erneuerbare Energien, Lern- und Skaleneffekte bei der Erzeugung erneuerbarer Energien sowie Effizienzsteigerungen beim Gesamtenergieverbrauch. Werden diese Mechanismen in einem makroökonomischen allgemeinen Gleichgewichtsrahmen implementiert, ergeben sich vielfältige Effekte, die sich gegenseitig verstärken können. Dabei stehen drei separat identifizierbare Zusammenhänge im Vordergrund. Erstens erhöhen strenge klimapolitische Maßnahmen die Substituierbarkeit zwischen sauberen und schmutzigen Inputs in der Wirtschaft, was die Energiewende beschleunigt und die Gesamtkosten der Emissionsreduzierung erheblich senkt. Zweitens führt die Politik zu Lern- und Skaleneffekten, die den Ausbau erneuerbarer Energien beschleunigen. Drittens kann die Politik Investitionen in energiesparende Technologien anregen und so die Effizienz der Energienutzung verbessern.

Wir kommen zu dem Ergebnis, dass die CO_2 Abgabe ein effizientes Instrument zur Erreichung des Netto-Null-Emissionsziels darstellt. Die Resultate des Projekts machen aber deutlich, dass die nötigen Abgabesätze wesentlich reduziert werden können, wenn die genannten Einflusskanäle voll berücksichtigt werden. Denn die Abgabe reduziert nicht nur den Einsatz fossiler Brennstoffe direkt, sondern fördert gleichzeitig indirekt die Investitionstätigkeit über die drei oben genannten Kanäle. Subventionen für erneuerbare Energien stellen ein weiteres wirksames Instrument dar, um Innovationen in diesen Sektoren zu fördern und ihren Ausbau zu beschleunigen. Obwohl Subventionen allein nicht ausreichen, um den Ausstieg aus der Nutzung fossiler Brennstoffe zu bewerkstelligen, fördern sie in Kombination mit einer CO_2 Abgabe die Nutzung sauberer Energien und senken die Kosten der Klimaschutzmaßnahmen. Unsere Simulationen zeigen, wie die Politik die vorgenannten Kanäle stimulieren kann, um den Übergang zu einer emissionsarmen Wirtschaft zu erleichtern.

Die Ergebnisse des Projekts wurden auf internationalen Konferenzen vorgestellt und führten zu vier Arbeitspapieren, die eingereicht und schließlich in hochrangigen Fachzeitschriften veröffentlicht werden sollen.

Résumé

Le projet examine la variété des instruments politiques basés sur le marché et la technologie afin de trouver une combinaison optimale de mesures politiques pour décarboniser l'économie suisse. Il met particulièrement l'accent sur le rôle de l'innovation dans la réalisation de cet objectif politique ambitieux. Pour atteindre les objectifs de ce projet, nous explorons le concept de changement technologique induit par les politiques dans un cadre d'équilibre général quantitatif. Nous étendons ce cadre pour inclure trois canaux supplémentaires par lesquels les instruments politiques pourraient stimuler l'innovation sur la voie de la décarbonisation de l'économie. Ces canaux comprennent l'amélioration de la substituabilité de l'énergie fossile par l'énergie renouvelable, l'effet d'apprentissage et d'économie d'échelle dans la production d'énergie renouvelable, et les améliorations de l'efficacité dans l'utilisation globale de l'énergie. Lorsqu'ils sont mis en œuvre dans un cadre d'équilibre général macroéconomique, ces mécanismes révèlent des effets politiques autrement indétectables. Tout

d'abord, une politique climatique stricte renforce la substituabilité entre les intrants écologiques et polluants dans l'économie, ce qui accélère la transition énergétique et réduit considérablement tous les coûts liés à la réduction des émissions. Deuxièmement, les mesures politiques entraînent des effets d'apprentissage et d'économie d'échelle, ce qui accélèrent l'expansion des énergies renouvelables. Troisièmement, les mesures politiques peuvent stimuler les investissements envers les technologies écoenergétiques et améliorer ainsi l'efficacité de l'utilisation de l'énergie.

Nous constatons que la taxe carbone est un instrument essentiel pour atteindre l'objectif du zéro émission nette. Cet instrument permet à la fois de réduire l'utilisation des énergies fossiles et d'encourager l'innovation par les trois canaux susmentionnés. La subvention accordée aux secteurs des énergies renouvelables est un autre instrument puissant qui peut cibler l'innovation dans ces secteurs et faciliter leur expansion. Même si une subvention en soi n'est pas assez forte pour éliminer progressivement les combustibles fossiles, en combinaison avec une taxe carbone, elle encourage l'utilisation d'énergies propres et réduit davantage les coûts d'atténuation. Nos simulations révèlent comment les mesures politiques peuvent stimuler les canaux d'innovation pour faciliter la transition vers une économie à faible émission de carbone.

Les résultats du projet ont été présentés lors de conférences internationales et ont donné lieu à quatre documents de travail, qui seront soumis et éventuellement publiés dans des revues réputées à comité de lecture.

Summary

The project examines the variety of market-based and technology-based policy instruments to find an optimal policy mix for decarbonizing the Swiss economy. It places a special emphasis on the role of innovation in successful achievement of this stringent policy target. To achieve the project’s goals, we explore the concept of policy-induced technological change in a quantitative general equilibrium framework. We extend this framework to include three additional channels through which policy instruments might stimulate innovation on the economy’s way to decarbonization. These channels include improved substitutability of fossil energy with renewable energy, learning and scale effects in renewable energy generation, and efficiency improvements in overall energy use. When implemented in a macroeconomic general equilibrium framework, these mechanisms reveal otherwise undetectable policy effects. First of all, stringent climate policy increases the substitutability between clean and dirty inputs in the economy, which accelerates energy transition and substantially lowers the overall costs of mitigation. Second, policy induces learning and scale effects, accelerating the expansion of renewable energy. Third, policies can spur investment in energy saving technologies and thereby improve the efficiency of energy use.

We find that carbon tax is an essential instrument for achieving the net-zero emissions target. This instrument both reduces the use of fossil energy and incentivizes innovation via the three channels. Subsidy to renewable energy sectors is another powerful instrument that can target innovation in these sectors and facilitate their expansion. Even though a subsidy by itself is not strong enough to phase out fossil fuels, in combination with a carbon tax it promotes clean energy use and further reduces the costs of mitigation. Our simulations reveal the ways policy can stimulate the innovation channels to ease the transition to a low-carbon economy.

The results of the project have been presented at international conferences and resulted in four working papers, to be submitted and eventually published in high-rank peer-reviewed journals.

Main findings

- We present three innovative mechanisms that hold empirical foundation yet are often overlooked in macroeconomic analyses of climate policy: endogenous substitution, induced learning, and fostered efficiency. Our findings indicate their substantial influence on policy outcomes, optimal policy design, and the costs associated with greenhouse gas mitigation efforts.

- With an endogenous substitution elasticity between clean and dirty energies, the required carbon tax level for achieving net-zero targets emerges notably lower compared to cases with a constant elasticity of substitution. By incorporating all three mechanisms, i.e. substitution, learning, and efficiency, the optimal carbon tax under a net-zero goal decreases significantly from 400 CHF in the reference scenario to a reduced rate of 221 CHF per ton of CO_2.

- By considering all three mechanisms collectively, the adverse impact on welfare stemming from climate policy can be curtailed by over half, transitioning from -1.01% to a more favorable -0.047%. A significant portion of this improvement is attributable to the endogenous elasticity mechanism, while the influence of the remaining two channels on overall welfare remains more modest. An ideal policy combination harnesses distinct innovation and learning channels to expedite the decarbonization process within the Swiss economy.

- The learning effects induced by a carbon tax exhibit moderation; however, the introduction of targeted subsidies to the solar and wind sectors elevates learning rates to 52.3% and 38.7% respectively, utilizing diminishing subsidy profiles, or even higher at 95.6% and 71.3% with a uniform profile. Notably, learning substantially magnifies the impact of subsidies, with this effect enduring beyond the subsidy phase-out.

- An intriguing synergy emerges between endogenous substitutability and learning. Notably, learning rates experience marked elevation when substitutability levels are endogenously determined. This reinforcement effect between policy and learning holds potential to expedite the shift towards a low-carbon economy, proving indispensable for growth and capital accumulation in the renewable energy sectors.

- Our analysis reveals that while a carbon tax can incentivize improvements in energy efficiency, the magnitude of this effect remains relatively moderate, remaining under 1% across sectors even within a net-zero scenario.

- Furthermore, we explore the potential of efficiency standards, which prescribe reduced energy consumption per unit of output, to stimulate innovation in energy efficiency. Interestingly, while such standards marginally decrease the requisite carbon tax for achieving net-zero goals, they simultaneously elevate the overall policy costs in terms of consumer welfare.

- Quantitative examination discloses that the presence of negative emissions technologies and carbon capture and storage technologies (NET/CCS) dampens improvements in efficiency, thereby discouraging ongoing innovation in energy usage. In scenarios devoid of NET/CCS, efficiency enhancements demonstrate notable growth across sectors, reaching levels as high as

12%. Policy endeavors should prioritize incentivizing investments in energy-saving and emission-reducing technologies. The inclusion of NET/CCS somewhat mitigates these incentives and should be viewed as a final recourse.

Executive Summary

1. *Overview of the project*

An increasing number of countries are committing to achieve a net-zero emissions goal by mid-century. These ambitious commitments, however, rarely translate to actual policy measures that would ensure the achievement of the targets. Currently implemented policies are estimated to fall short of what is required to achieve carbon neutrality. Switzerland has joined the pledge to decarbonize the economy by the year 2050. However, it is far from clear whether the outlined policy measures are sufficient to achieve this goal. Given the wide variety of policy instruments that differ in their costs, efficiency, and public acceptance, selecting an optimal combination of them can be a daunting task for policymakers.

This project examines the variety of policy instruments available and highlights those that would help the Swiss economy achieve its net zero target. To accomplish this task, we examine three mechanisms that emerge endogenously during decarbonization and can facilitate the transition to a zero-carbon economy.[1] These mechanisms include the expansion of renewable energy use, learning in renewable energy generation, and efficiency improvements in overall energy use. We explore whether and to which extent different policy instruments can exploit these mechanisms to accelerate the transition.

To analyze which policy instruments would be the most effective in decarbonizing the Swiss economy, we use an advanced modeling framework of the CITE model. In this dynamic computable general equilibrium model economic growth does not occur by default but rather stems from intentional investments in R&D, which enables studying innovation-driven processes in the economy. We extend the framework to include the above mechanisms, which act as additional channels of innovation:

- The degree of substitutability between clean and dirty inputs increases endogenously with the expansion of renewable energies.
- The costs of generating renewable (solar and wind) energy decreases endogenously with cumulative experience in these sectors.
- Energy efficiency in economic sectors increases endogenously through sector-specific investments in energy-saving technologies

Our results suggest that a carbon tax[2] is a key instrument for reaching a climate policy target. Not only does it directly discourage the use of fossil fuels, but it also stimulates innovation through the three internal channels mentioned above. Among these channels, endogenous substitution has the strongest impact on the costs of mitigation and the economy's growth path. Notably, this impact can be governed solely by carbon tax.

[1] In our analysis, we depart from the formal net-zero target that addresses all greenhouse gas emissions and focus on net-zero CO_2 emissions.

[2] By a carbon tax we refer to a market-based policy of charging a price per ton of emitted CO_2, which could take a form of taxation or carbon allowances traded at ETS.

Combining a carbon tax with a subsidy to renewable energy can further reduce the costs of mitigation. In this case, a decreasing subsidy profile is welfare-superior to a constant profile: initially, a subsidy notably facilitates the expansion of renewable energy but as the economy approaches the net-zero target, the subsidy loses its relevance.

Subsidizing renewable energy also facilitates learning in these sectors. Even a subsidy that diminishes over time can amplify the learning effect by a factor of five in comparison to using carbon tax as an only policy. We also find a dynamic positive feedback from learning to policy, in that it amplifies the effect of the subsidy on sectoral growth and maintains this effect even when the subsidy is gradually phased out.

Our results suggest that a carbon tax can stimulate investment in energy-saving technologies and thereby increase energy efficiency in the corresponding sectors, but the magnitude of this effect is rather moderate. The producers can be further incentivized to invest in energy-saving technologies by direct subsidies to R&D. We also consider efficiency standards for the transportation and construction sectors and find that they can slightly increase the efficiency of energy use. However, the additional costs associated with this directive instrument outweigh the associated reduction in carbon tax.

Over the course of the project, we modeled three novel mechanisms that are commonly overlooked in macroeconomic analyses of climate policy but can have a strong impact on policy outcomes and the associated costs of mitigation. In what follows, their main features and roles for climate policies are summarized.

2. *Endogenous Substitution Mechanism*

Any macroeconomic analysis studying the transition to a carbon-free economy has to make an assumption on the degree of substitutability between fossil and renewable energy. This assumption has been shown to strongly influence the predictions for sustainable growth and optimal designs of climate policy. Despite the decisive role of this parameter in climate policy analysis, up to now it has been considered constant and exogenous by most macroeconomic studies. However, the growing integration of clean energy strongly suggests that this substitutability is likely to have improved over time. Accounting for this observation, we study dynamic elasticity of substitution that improves with expansion of renewable energy. We first empirically document the presence of intertemporal variation in the substitutability: our estimate of the elasticity of substitution almost doubles from around 2.8 in the 1990s to 5.2 in the 2010s. We further show the empirical relevance of a variable elasticity of substitution that depends on the share of clean inputs. Given the strong empirical evidence, we extend the numerical framework of the CITE model to include dynamic elasticity of substitution that evolves endogenously with the relative share of clean energy in the economy. A crucial feature of this new endogenous mechanism is the possibility to stimulate it using policy instruments: Any measure that facilitates clean energy expansion would also implicitly ease its substitution for fossil energy. Indeed, we find that, under the net-zero target, the elasticity of substitution can rise up from the modest value of 3 to as high as 10. This higher substitutability eases the path to energy transition and substantially lowers the economic costs of climate change mitigation, creating a positive feedback loop from policy to substitutability.

The most notable finding of this exercise is that a carbon tax alone can drive the substitutability high enough to ease reaching the net-zero target. Additional measures, such as subsidies to clean energy, might prove beneficial in that they lower the overall costs of mitigation. The latter effect, however, is driven purely by the synergy between the two policy instruments, and not by the presence of the endogenous substitutability mechanism. We also find that a decreasing subsidy profile is preferred to a constant one — as the share of renewable energy goes up, the subsidy loses its relevance and becomes too costly for the economy.

3. *Learning Mechanism*

It is a well-known fact that the costs of producing renewable energy have been declining with the development of technology and increasing installed capacity. This decline in costs of a technology with accumulated experience is referred to as learning. Newer and cleaner energy technologies are usually found to have relatively high learning rates compared to mature fossil-based energy technologies. As a result, the competitiveness of renewable energy and its potential to substitute for fossil energy might increase over time — even though initially it might have to rely on governmental support to survive on the market. Hence, the two essential elements for an insightful modeling of the energy transition within an economy are 1) a dynamic (as opposed to static) perspective and 2) a mechanism to represent learning from experience. To study the potential paths for decarbonizing the Swiss economy, we integrate a learning mechanism into the dynamic framework of the CITE model. Because the expansion of production in renewable energy sectors follows a highly nonlinear process that includes tipping points and disruptive changes, we use a flexible function that features nonlinearity.

The mechanism applies to the solar and wind energy sectors — which are expected to take on the major share of the expansion of renewables in the upcoming energy transition in Switzerland. Higher output in these sectors improves their investment efficiency. In other words, with increasing experience (represented by the excess cumulative sectoral output), the efficiency of investments is enhanced, resulting in more capital accumulated in subsequent periods.

In the presence of this mechanism, a policy that promotes renewable energy production may implicitly stimulate learning. Our simulations suggest that the learning effect induced by a carbon tax is rather moderate in the two energy sectors, about 10% in the net-zero scenario. However, adding a targeted subsidy to the solar (wind) sector raises the learning rates to 52.3% (38.7%) or even 95.6% (71.3%) corresponding to decreasing and constant subsidy profiles. Learning, in turn, can greatly amplify the effect of a subsidy and retain this effect even if the subsidy is phased out. This reinforcement effect between policy and learning might accelerate the transition to a low-carbon economy. The learning mechanism *per se* does not seem to significantly impact the aggregate costs of mitigation or the overall economy's growth. However, it appears essential for the growth and capital accumulation in the renewable energy sectors.

We also find a strong synergy between the two mechanisms of endogenous substitutability and learning, in that the learning rates are substantially higher when the degree of substitutability is determined endogenously.

4. *Energy Efficiency (EE) mechanism*

A carbon tax on fossil fuels makes them relatively more expensive and increases the incentives to substitute fossil energy sources with other inputs. In their effort to reduce the tax burden, producers may choose either to move away from dirty energy and use clean energy or to try to lower their overall energy consumption. The latter option usually requires additional investments in energy-saving technologies that would increase the efficiency of energy use in production. This effect of increasing energy efficiency induced by a climate policy has been broadly documented but rarely taken into account when modeling climate policy outcome. We integrate this potentially important channel of mitigation to the CITE model and introduce energy efficiency improvements that arise endogenously through sector–specific investment activities.

We find that a carbon tax can indeed incentivize energy efficiency improvements. However, even in the net-zero scenario the magnitude of this effect is quite moderate - under 1% for all sectors. We further examine whether efficiency standards that prescribe lower energy use per unit of output can spur innovation in energy efficiency. The standards apply to two sectors — transportation and construction — typically targeted by policies that directly regulate their energy use. As a policy instrument, efficiency standards are known to be less cost-efficient than the instruments that act through market prices. In our case, too, the standards slightly lower the carbon tax required to reach the net-zero target but at the same time they increase the overall policy costs in terms of consumers' welfare.

The simulations also reveal an unexpected insight that the availability of the negative emissions technologies and carbon capture and storage technologies (NET/CCS) restrains efficiency improvement. Intuitively, NET/CCS offer an alternative for producers, who can decide between the two options based on the marginal costs of emission reduction: to stick to the existing technology and compensate for the emissions using the NET/CCS or to invest in energy-saving technology and reduce the emissions in the first place. Depending on the availability and the costs of NET/CCS, they might discourage innovation in energy use. In the absence of the NETs and CCS technologies, efficiency improvements could increase for most of the sectors and reach up to 12%.

5. *Putting it all together*

Our findings suggest that the costs for reaching the net-zero target do not have to be prohibitively high when policy instruments are used in an efficient combination. Innovation and technological progress are critical processes to consider when evaluating these costs. When the three channels are taken into account, the total policy costs over the whole modelled period can be reduced by more than half, from -1.01% to -0.047% of the total welfare. A large part of this reduction is attributable to the endogenous elasticity mechanism, while the impact of the other two channels on aggregate welfare is much smaller.

When a carbon tax is used to reach the net-zero target, it might still have to increase to 221 CHF per ton CO_2 by mid-century. However, without considering the ways the tax spurs innovation, the estimated cost could be as high as 400 CHF/tCO_2. Combining the carbon tax with renewable energy subsidies facilitates learning in these sectors and accelerates the adoption of clean energy sources across the economy, further reducing the cost of mitigating climate change.

Contents

Abbreviations

AGR	Agriculture
AEEI	Additional Energy Efficiency Improvement
BNK	Banking
CCS	Carbon capture and storage
CGE	Computable General Equilibrium
CHM	Chemical Industry
CITE	Computable Induced Technical Change and Energy
CON	Construction
ENEFF	Energy Efficiency
HEA	Health
INS	Insurance
MCH	Machinery Industry
NET	Negative Emission Technology
OIN	Other Industries
OSE	Other Service Sectors
TRN	Transportation
R&D	Research and Development

1 Introduction

1.1 Background information and current situation

The goal of net-zero emissions of greenhouse gases by 2050 was adopted by the Swiss Federal Council in August 2019 and requires that Switzerland should not emit more greenhouse gases into the atmosphere than can be captured and stored in natural and technological sinks ("net zero target"). This net-zero target is also the subject of the "Climate and Innovation Act", which was approved by the people in the referendum of June 18, 2023 with 59.1 percent in favour and is thus enshrined in law. Achieving net-zero emissions by 2050 will require significant reductions in emissions from the buildings sector, transportation, and industry, which opened a prolonged debate on an efficient, feasible, and otherwise optimal set of policies that would ensure compliance with the net-zero target. The main challenge in designing such a package is to assess the specific impact of individual policy instruments and their synergies when implemented in the real economy.

The recent climate economics literature concludes that ambitious policy goals require a combination of policy instruments that regulate market prices with those that promote technological progress (Popp, 2019). Additional, innovation-enhancing measures prove to be a necessary supplement to the prevalent uniform carbon taxation (Acemoglu et al., 2012). Such theoretical conclusions, while insightful, are too generalised to derive concrete policy recommendations. The economic mechanisms and the overall outcome for a highly developed real economy like Switzerland remain unclear.

Despite their clear importance for policy outcomes, innovation-stimulating measures are omitted from most of the policy analyses. Traditionally, innovation is modelled as exogenous technological learning, which leaves no room for policy interventions. The endogenous induced innovation framework addresses this weakness and shows how innovation drives economic growth. Yet, it is rather generalised and cannot reflect the innovation channels specific to energy transition.

This project addresses these limitations by incorporating key innovation channels that reflect policies' effects on innovation. The ultimate goal is to combine comprehensive policy analysis with implementation of induced-innovation mechanisms to infer the best policy profile for the Swiss economy. For the purpose of this project, we define the net-zero target as net-zero CO_2 emissions and do not consider other greenhouse gases.

1.2 Purpose of the project

The project aims to explore the mechanisms through which various policy instruments would efficiently direct the Swiss economy towards its stringent climate policy target. We employ the endogenous growth framework to highlight the role of innovation for climate and energy policies. We extend this framework with several mechanisms critical for an adequate assessment of stringent climate and energy policy measures. These mechanisms reflect the changes to the economic processes induced by the policies – namely, rapid energy technology development, easier substitution for carbon-intensive inputs, and higher energy efficiency in the economic sectors.

We intend to find optimal combinations of policy measures for Switzerland that would stimulate the investment in clean energy and ease the transition to a carbon-free economy. The optimality of the design implies a balanced and efficient mixture of price-regulating and innovation-inducing instruments.

1.3 Objectives

The project addresses three general research questions,

1. How can policy coordinate technological investment and, consequently, the economy's growth to promote clean energy use?
2. How does the interplay of innovation-inducing and market-regulating policy instruments affect the economy's welfare and growth?
3. What is the optimal time-profile for the mix of market-based and technology-based policies for the Swiss economy?

Within these general considerations, we aim to explore how both market-based and technology-based policy instruments can work in the Swiss economy through the following extensions of the growth mechanism:

1) The mechanism of improving substitutability between clean and dirty production inputs,

2) The mechanism of higher growth potential (scale effect) for younger technologies as opposed to mature ones,

3) The mechanism of innovation-based increasing energy efficiency in non-energy sectors.

2 Description of facility

Not applicable

3 Procedures and methodology

The project uses the computable general equilibrium model CITE (Bretschger et al., 2011), which features endogenous growth and is calibrated to the Swiss economy. CITE is the first and to date the only general equilibrium model that fully incorporates endogenous, innovation-driven growth in a multi-sector economy. Yet, the ability of the model to reflect the effects of specific policy measures is limited by its structure and a few generalising assumptions. These assumptions include pre-specified CES production functions at all levels of production—including energy generation and the production of intermediate goods.

Before carrying out an analysis of various policy instruments, the model has been extended to include the mechanisms that reveal otherwise undetectable effects of policy measures. Specifically, the mechanism of endogenous substitutability between clean and dirty inputs demonstrates how stringent policies benefit the economy by easing the substitution for dirty inputs. The higher growth potential for selected clean energy sectors (solar and wind) reflects learning and scale effects in the process of capital formation that can be targeted by policy. Finally, the mechanism for potential energy efficiency improvement shows how policies can stimulate R&D for higher energy efficiency.

The inference from the project mainly builds on the numerical analysis of combinations of policy instruments. Whenever necessary and possible, theoretical analysis and empirical estimations corroborate quantitative assessment. For example, our empirical analysis in Jo and Miftakhova (2022) strongly supports the endogenous mechanism for substitution between clean and dirty production inputs. The two theoretical papers produced in the course of the project have increased our understanding of the role of tipping points (as triggers for favourable disruptive technological developments) and of scale and learning effects in the transition to a net-zero economy. The conditions for a successful technology transition from dirty to clean technology as well as the role of learning and scale effects in the process of capital formation are discussed in Bretschger et al. (2022). Furthermore, in Bretschger und Leuthard (2022), we use an integrated formal approach to investigate the importance of tipping dynamics and nonlinearities for sustainable development in different domains such as nature, technology, politics, and society.

Innovation plays a key role in energy transition and the subsequent decarbonization of the economy. The analyses of climate policy that overlook these processes and make projections within the assumed technological process are likely to overestimate the costs of mitigation and underestimate the economy's potential for growth. The analysis below aims at improving the ways innovation processes are considered in climate policy analyses and investigate how policy instruments can stimulate economic growth given stringent policy targets. For that, we consider three channels through which climate policy may, explicitly or implicitly, stimulate innovation.

Endogenous Substitutability

The degree of substitutability between clean and dirty energy plays a central role in leading economic analyses of optimal environmental policy. Despite its importance, assuming a constant and exogenous elasticity of substitution has been a dominant theoretical approach. A lot of attention has been drawn to the value of this parameter; however, its evolution over time and with advances in renewable energy technologies has gone largely unnoticed. The observational data on the growing integration of clean energy strongly suggests that this substitutability is likely to have improved over time. To test this intuition, in the paper Jo and Miftakhova (2022) we examine time variation in the elasticity of substitution from the standard CES specification on a 10-year rolling window. We find substantial time variation and improvement over the last three decades in the estimated energy substitution capacity. The subsequent empirical analysis provides strong evidence for the empirical relevance of the elasticity of substitution between clean and dirty energy that expands with the share of clean inputs in the economy. The theoretical analysis in the paper builds on a dynamic general equilibrium model with an endogenous elasticity of substitution that interacts with the relative share of clean energy in the economy. The analysis reveals strong dynamic feedback effects arising from endogenous substitution capacity that amplifies the impact of directed technical change and accelerates the transition to a green economy. It also suggests the combination of a carbon tax and subsidy being superior to the tax as an only instrument in driving the economy's energy transition.[3]

To integrate the concept of endogenous elasticity of substitution into the CITE modelling framework, we extend the CES formulation for the energy aggregate to allow its elasticity parameter to adjust dynamically,

$$E_{i,t} = \left[\phi_i E_{C,i,t}^{\frac{\sigma_{E,t}-1}{\sigma_{E,t}}} + (1-\phi_i) E_{D,i,t}^{\frac{\sigma_{E,t}-1}{\sigma_{E,t}}} \right]^{\frac{\sigma_{E,t}}{\sigma_{E,t}-1}}.$$

[3] An interested reader is invited to explore further details and results in Jo and Miftakhova (2022).

The possibility to substitute clean energy for dirty grows with the expansion of renewable energy - such that the elasticity of substitution, $\sigma_{E,t}$, is determined by the ratio

$$\sigma_{E,t} = \eta \frac{E_{C,t}}{E_{D,t}} \ .$$

Based on the empirical estimation in Jo and Miftakhova (2022), we set η to 3.076. The elasticity of substitution between clean and dirty energy is therefore an endogenous dynamic variable that essentially reflects the economy's path to clean energy transition. To solve the model, we update the value for the elasticity of substitution iteratively until it converges to the value specified in $\sigma_{E,t}$. The stopping rule for the iterative algorithm is

$$|\sigma^{old}_{E,t} - \sigma^{new}_{E,t}| < \varepsilon,$$

with a tolerance criterion $\varepsilon = 10^{-6}$. We apply the same iterative strategy for the two other mechanisms below.

Learning Effects

Learning is an important driver of the cost reductions in renewable energy sectors. In order to reflect their learning potential, we introduce a learning mechanism for the wind and solar energy sectors (in addition to the existing endogenous growth mechanism based on gains from diversification for all sectors in the CITE model). Under a policy, the cumulative output for these sectors may exceed its benchmark level specified by the balanced growth path. This excess cumulative output represents the stock of additional experience, which increases the productivity of investment in the corresponding sector. This relation is represented via a learning factor *s*, which augments investments in the capital accumulation equation according to:

$$J_{i,t+1} = (1 + s_{i,t}) \left[\upsilon_i I_{P,i,t}^{\frac{\sigma_J - 1}{\sigma_J}} + (1 - \upsilon_i) I_{N,i,t}^{\frac{\sigma_J - 1}{\sigma_J}} \right]^{\frac{\sigma_J}{\sigma_J - 1}} + (1 - \delta_t) J_{i,t},$$

where the subscript *i* refers to the wind or solar sector. The learning factor *s* depends on the (excess) cumulative output in a non-linear fashion:

$$s_{i,t} = \frac{\beta}{1 + \left(\frac{\omega}{x_t}\right)^{\gamma}}, \quad \text{with} \quad x_t = \max \left[0, \frac{Y^{Cum}_{i,t} - \bar{Y}^{Cum}_{i,t}}{\bar{Y}^{Cum}_{i,t}} \right],$$

where $\bar{Y}^{Cum}_{i,t}$ corresponds to the benchmark cumulative output. The nonlinear functional specification for the learning factor *s* (S-shaped curve) is widely used in energy economic models (e.g. Kverndokk & Rosendahl 2007, Kalkuhl et al. 2012 and Mattauch et al. 2015) and reflects the fact that production expansion in the wind and solar industries follows a highly nonlinear process.

Each time the cumulative output exceeds its benchmark level, the corresponding sector can gain additional experience and thereby the efficiency of capital formation in the subsequent periods. This learning mechanism leads to a positive nonlinear deviation from the balanced growth path and thus provides scope for policy interventions that promote the development of clean energy sectors and thereby decrease the costs of mitigation.

It is important to distinguish the learning effect in energy transition in CITE from the already existing endogenous growth mechanism based on gains from specialisation according to the new growth theory (Romer 1990 and Grossmann & Helpmann 1994). Intuitively, the main difference between productivity gains through sector-wise learning and endogenous technological change based on gains from specialisation is that the latter considers technological innovation as an economic activity. The incentives to invest in new varieties stem from the monopoly rent (monopolistic power) and thus the possibility for an inventor to make profit with a new product. In contrast, the learning mechanism in the wind and solar sectors arises as a pure by-product of output production without any costs. The schematic representation in Figure 1 demonstrates the positive feedback loop formed by the two endogenous growth channels. The upper part of the figure represents the already implemented endogenous growth mechanism based on gains from specialization. The lower part displays the newly introduced learning effect in the energy transition. Focusing on the upper part, we can observe that new capital *(J)* is formed by physical (I_P) and non-physical (I_N) investments. The level of accumulated sectoral capital determines the number of intermediates and hence the extent of gains from diversification at the intermediate production level *(Q)*. These gains translate to higher levels of sectoral output *(Y)*.

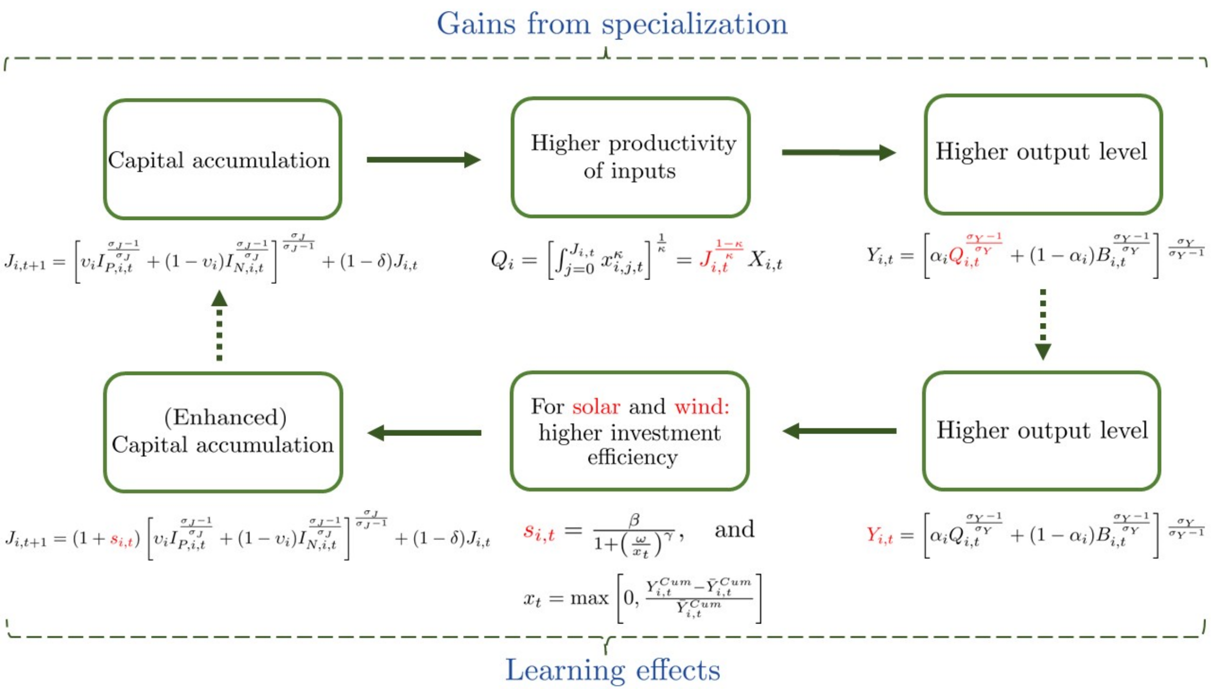


Figure 1: Gains from specialisation and scale effect in energy transition

The lower part of the Figure captures the learning channel in energy transition. For the sectors with high learning potential, i.e., the wind and solar energy sectors, higher output is associated with a learning effect, captured by $s_{i,t}$, which in turn increases investment efficiency for these sectors. In other words, with increasing production experience in the wind and solar sectors, capital is accumulated more efficiently in the subsequent periods. This process repeats itself, establishing a self-reinforcing cycle.

The extent to which the investment efficiency can be improved depends on three parameters - the curvature of learning curve, γ, scaling parameter, ω, and maximal productivity, β. Table 1 summarises the values for the three parameters for solar and wind technologies, based on the existing literature (Mattauch et al., 2015).

Parameters:	PVP	Wind
Maximal productivity, β	9	7
Scaling parameter, ω	250	250
Curvature of learning curve, γ	0.2	0.27

Table 1: Parameters' values for the learning effects in the solar and wind energy sectors (based on Mattauch et al., 2015)

Energy Efficiency Improvement

A carbon tax on fossil fuels increases the incentives to substitute fossil energy sources with other inputs. In addition to this substitution effect, intermediate firms invest in energy-augmenting technical progress - they redirect their investment activities in favour of energy-saving technologies. In the literature, energy-augmenting technical progress is usually modelled by the so-called additional energy efficiency improvement (AEEI), which reduces energy use depending on the assumed (exogenous) sectoral energy intensity improvements. We develop this idea further and introduce energy efficiency improvements that arise endogenously through sector–specific investment activities.

As energy enters sectoral production at the level of the intermediate varieties in CITE, we measure the energy intensity by the share of energy used in the production at this level. Using labour *(L)* and energy *(E)* as inputs, intermediate goods *(X)* are now produced according to the following CES production function:

$$X_{i,t} = \left[\nu_i L_{i,t}^{\frac{\sigma_x - 1}{\sigma_x}} + (1 - \nu_i) \left[(1 + f_{i,t}) E_{i,t} \right]^{\frac{\sigma_x - 1}{\sigma_x}} \right]^{\frac{\sigma_x}{\sigma_x - 1}},$$

where the factor $f_{i,t}$ represents the novel efficiency improvement mechanism; the subscript *i* refers to the corresponding sector.[4] We assume that energy efficiency increases endogenously with excess sectoral investment (on top of the benchmark level), such that

$$f_{i,t} = \max \left[0, k_i \cdot \frac{I_{i,t}^{Cum} - \bar{I}_{i,t}^{Cum}}{\bar{I}_{i,t}^{Cum}} \right],$$

where $k_{i,}$ is a sector-specific parameter that measures the intensity of efficiency improvements. For this parameter we use the values estimated by Bhadbhade et al. (2020) and Bhadbhade et al. (2021) and their projections for the Swiss economy up to 2050 (see Table 2).

[4] The energy-saving mechanism applies to all sectors in the economy except energy-producing sectors.

Sector:	Projected Phyical EE (p.a):
Machinery industry (MCH):	1.4%
Chemical industry (CHM):	1.4%
Other industry (OIN):	1.4%
Construction (CON):	1.4%
Agriculture (AGR):	1.7%
Other Services (OSE):	2%
Health (HEA):	2%
Banking & financial services (BNK):	2%
Transport (TRN):	1.6%
Insurance (INS):	2%

Table 2: Projected sector-specific values for k based on Bhadbhade et al., 2020 and Bhadbhade et al., 2021. The projected physical energy efficiency (EE) measure represents the contribution (per annum) of technical progress to EE improvement and is calculated based on the energy efficiency index (ODEX) (see Bosseboeuf et al., 2005 for a detailed description).

When cumulative sectoral investment exceeds its benchmark level, i.e., $I_{i,t}^{Cum} > \bar{I}_{i,t}^{Cum}$, energy efficiency increases in the respective sector. The magnitude of this improvement depends on both the excess sectoral investment activity and the strength of the efficiency improvement determined by the sector-specific rate k_i. Investments thus entail positive spillover effects that are not internalised by policy.

The detailed description of the methodology is provided in Bretschger et al. (2023).

4 Results and discussion

Simulated Scenarios

The following simulations explore the interplay of the three innovation mechanisms and various policy instruments. In most cases, the results are compared to the baseline scenario. The baseline scenario includes a policy target and a carbon tax that ensures reaching this target. Policy targets are defined as the amount of CO_2 emissions allowed in 2050 in percent of the initial emissions level in 2025. For example, a baseline scenario with a 40% target implies that only 40% of the initial emissions level can be emitted in 2050 (that is, the emissions are reduced by 60%). The carbon tax increases gradually over time until the given target is reached. Most of the figures below present the results across different policy targets, but we keep our focus on the net-zero case.[5] By definition, none of the three mechanisms is considered in the baseline scenario. Instead, the effects of each of the mechanisms and the impacts of additional policy instruments are compared to the baseline outcomes.

To obtain realistic predictions for the transformation of the Swiss energy sector, all simulated scenarios include the nuclear phase-out as planned by the Swiss government. In accordance with the schedule in the Energy Perspectives 2050+ (SFOE, 2020), the availability of nuclear energy is gradually reduced to zero by 2035.

[5]Note that we do not use a business-as-usual scenario that would have no policy in place. Instead, all simulations are compared to the baseline scenario where none of the three mechanisms are in place and carbon tax is the only policy instrument.

Furthermore, in all simulated scenarios, negative emission technologies and carbon capture and storage technologies (NET/CCS) are assumed to be available starting in 2035. The availability is again specified according to the schedule in the Energy Perspectives 2050+ (SFOE, 2020). Arguably, the assumption on the costs of these technologies is highly speculative due to the absence of reliable estimates or projections. Nevertheless, we assume the costs to be 300 CHF/tCO_2. In a sensitivity analysis, we find that the level of these costs affect the optimal values for the carbon tax required to achieve the reduction targets. However, they do not affect qualitative conclusions of our study.

Endogenous Substitutability Mechanism

As explained above, in our modified model, the elasticity of substitution between clean and dirty energy is an endogenous dynamic variable. Because it is determined by the relative share of clean energy in the economy, it essentially reflects the economy's path to decarbonization.

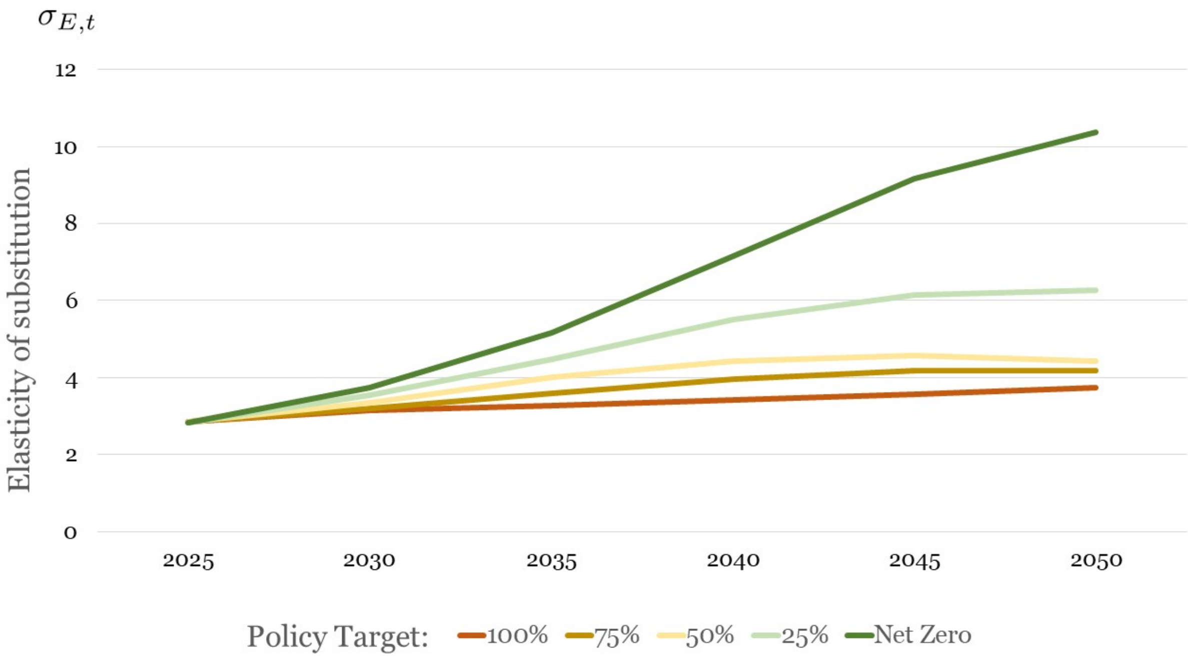


Figure 2: Dynamics of the endogenous elasticity of substitution under policies of increasing stringency. Policy stringency corresponds to the CO_2 emissions target in 2050 as a percentage of the emissions level in 2025.

Figure 2 shows the resulting dynamics for the endogenous elasticity of substitution under the policies of increasing stringency. Starting from the initial value of slightly below 3 in 2025, the elasticity of substitution only moderately increases in the first five years. However, already by 2035 the differences in its dynamics across policy targets become apparent — the values range from just above 3 for moderate policies to 5 for the case of full decarbonization. Given the net-zero target, the value for the elasticity of substitution will exceed 10 by mid-century. Even the mildest policy target of non-increasing emissions (i.e., policy stringency of 100%) increases the elasticity of substitution slightly, raising it to a value of almost 4 by 2050.

More aggressive carbon policy, apart from being more costly, ensures a steeper substitutability profile — which in turn enables faster and *less* costly decarbonization. To demonstrate this positive feedback effect, Figure 3 compares the policy costs in terms of welfare between a constant and a dynamic energy substitution elasticity.

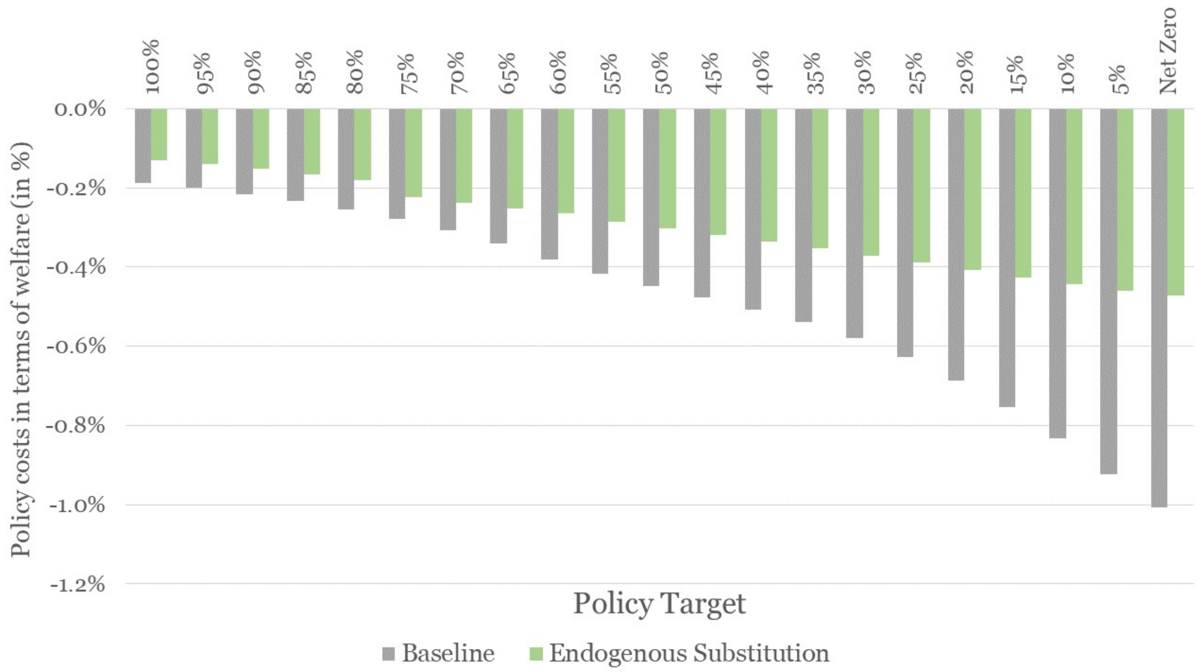


Figure 3: Policy costs in terms of welfare in the cases of constant and dynamic (endogenous) elasticity of substitution, in percentages of the baseline welfare level.

In the presence of the endogenous substitutability mechanism, the welfare losses do increase with stricter emissions targets, but they stay below 0.5% of the aggregate welfare level even in the case of net-zero scenario. In the absence of this mechanism, i.e., in the baseline scenario, these costs can be up to 2 times higher.

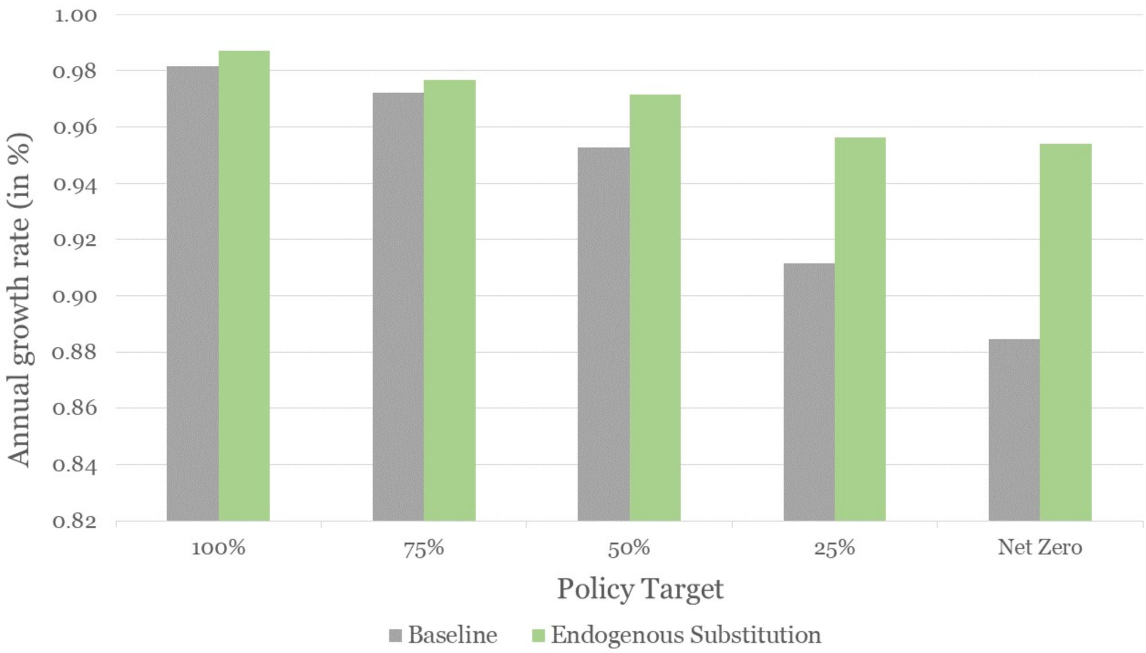


Figure 4: Annual aggregate growth rates of economy in the cases of constant and dynamic (endogenous) elasticity of substitution under policies of increasing stringency.

Figure 4 translates these results into the economy's growth rates. Stringent carbon policies expectedly lead to slower growth for the economy. This effect, however, can be offset to a large extent by higher energy substitutability. In the extreme case of the net-zero target, this offset amounts to almost seven percentage points of difference in the economy’s annual growth rate.

Notably, the pronounced effect of endogenous substitutability on the economy’s decarbonization path is driven solely by carbon tax. To stimulate this mechanism further, a policy maker might consider a direct subsidy to renewable energy. We model two types of output subsidies to the solar and wind sectors — one with constant and one with decreasing profile. The constant subsidy of 30% is given to the producers in the two sectors throughout the modelled period, whereas the decreasing subsidy also starts at the level of 30% but is gradually phased out by 2050. Figure 5 shows the resulting costs of mitigation in terms of the aggregate welfare.

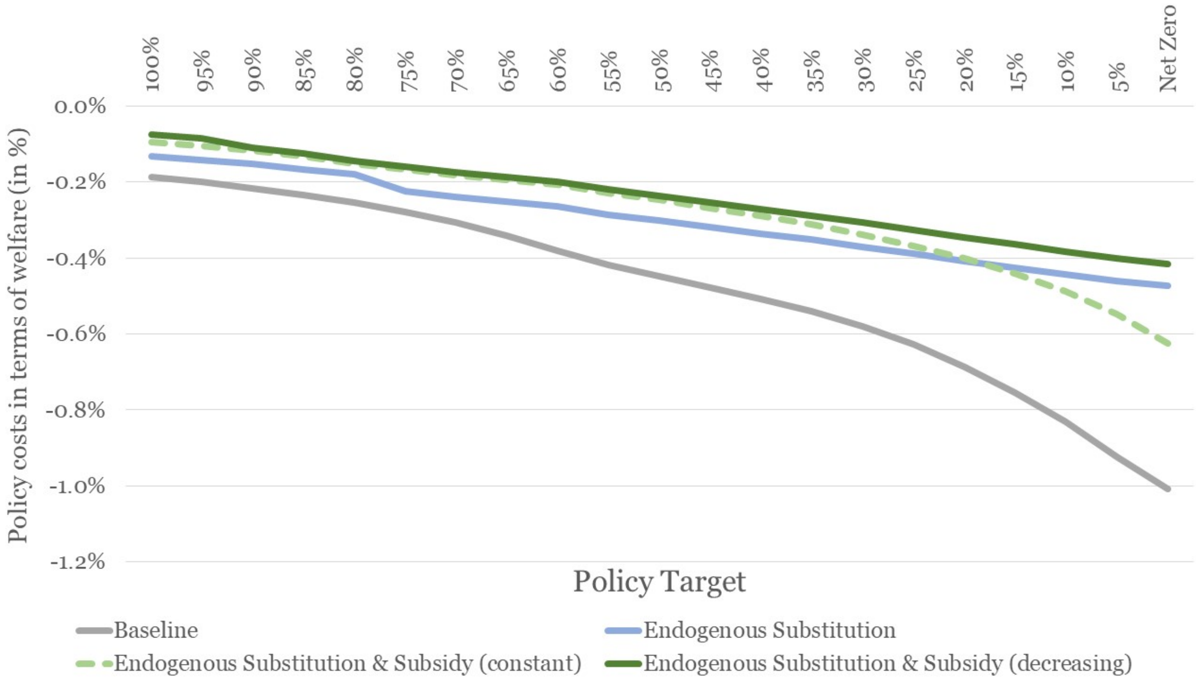


Figure 5: The effect of output subsidies on the policy costs when the elasticity of substitution is endogenous (in percentages of the benchmark welfare level).

When combined with moderate levels of carbon tax (corresponding to up to 60% reduction in CO_2 emissions), both types of subsidies appear welfare-improving. However, under stringent policy targets, they have opposite outcomes: decreasing subsidy stays beneficial, while the constant subsidy is not cost-efficient anymore. Even though it stimulates the transition to renewable energy, the subsidy loses its relevance once the economy starts approaching the policy target indicating that only a temporary subsidy is needed to decarbonize the economy.

Learning effects in renewable energy

The potential for learning in the solar and wind sectors is represented by the learning factor *s*, which depends on the additional output in these sectors under a climate policy. As shown in the previous section, this learning factor directly increases the productivity of investment in these sectors. Figure 6 shows the evolution of the learning factor paths for wind (s_{Wind}) and solar (s_{PVP}) energy under the assumption that the Swiss economy reaches the net-zero target by 2050.

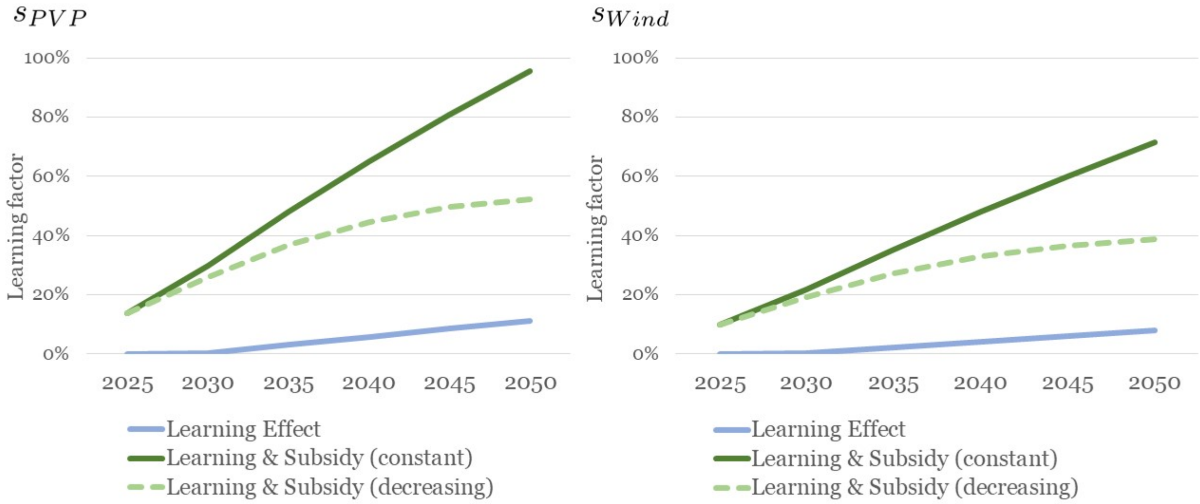
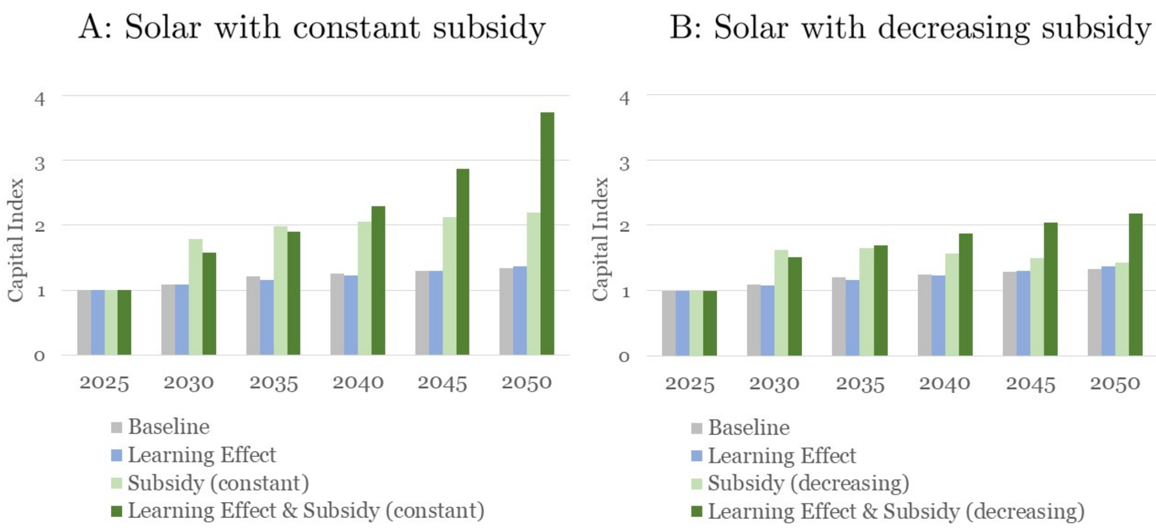


Figure 6: Implemented learning effect in energy transition for solar (left) and wind (right) sectors and the effect of output subsidies (with constant and decreasing profiles) on learning. Learning is measured in percentage increase in the productivity of investment in the corresponding sector.

Consistent with the literature on learning rates for renewable energy technologies (see e.g. Rubin et al., 2015), our results suggest that the learning factor for wind energy is lower than for solar energy. The learning effect driven purely by the decarbonization target is relatively low — about 10% in both sectors. However, these sectors benefit from a remarkable increase in their learning factors when output subsidies are used as additional policy instruments. A decreasing subsidy profile leads to learning factors of up to 50% for the solar sector and up to 40% for the wind sector. Maintaining a constant subsidy profile over the model period under consideration, the learning factor of the solar (wind) sector increases to almost 100% (70%) by 2050. Targeted policies in the form of output subsidies can therefore have a significant impact on sectoral learning by exploiting the learning potential of the two energy sectors.

The presence of the learning mechanism, in turn, reinforces and sustains the effect of subsidies even when the policy itself expires. This is shown by Figure 7, which depicts the impact of the learning effect on capital formation in the solar and wind sector assuming that the Swiss economy reaches the net-zero target by 2050.



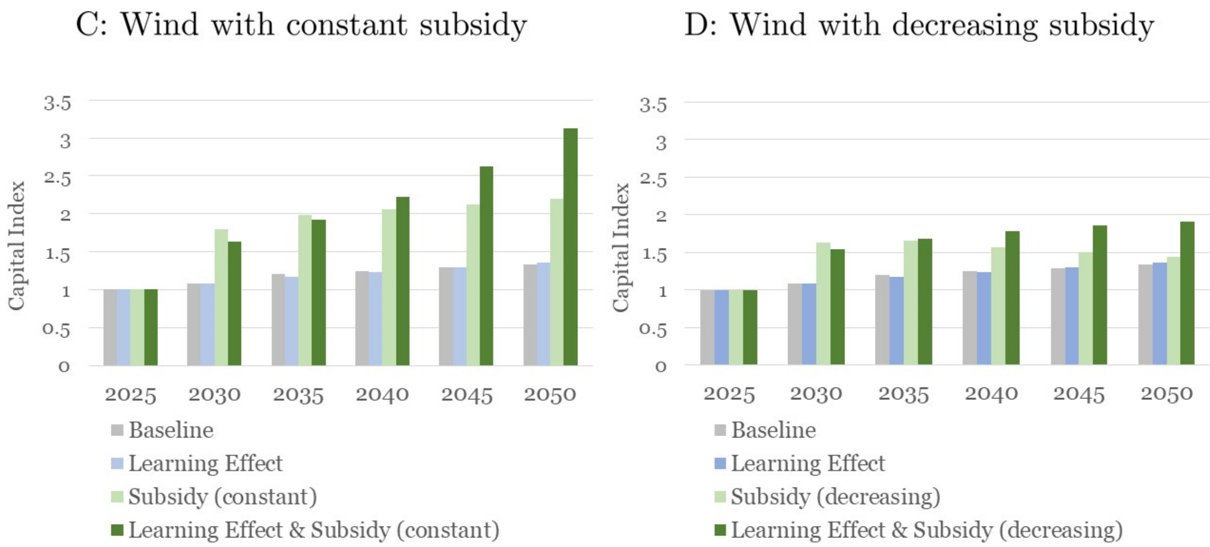


Figure 7: Capital accumulation in solar (top) and wind (bottom) sectors under the baseline scenario, scenario with the learning mechanism, and under constant (left) and decreasing (right) subsidy profiles for the net-zero policy target. The amount of capital is measured as index normalized to 1 in the initial year 2025.

The amount of accumulated capital increases slightly due to the sole learning effect in the two sectors. In both sectors, a constant subsidy policy (left) can boost capital accumulation by up to 70% by 2050, even when learning is not taken into account. What is striking, however, is the extent of synergy between the constant subsidy policy and learning, which increases the capital index by another 70% (solar) and 45% (wind). Even in the case of a declining subsidy profile (right), a strong synergy effect persists once triggered by policy. Therefore, we conclude that a targeted policy can reinforce the learning mechanism and thereby accelerate the energy transition.

Another prominent synergy effect we found occurs between the learning and endogenous substitution mechanisms. As Figure 8 shows, learning factors are up to three times higher by 2050 when energy substitution is endogenous. Intuitively, an increasing substitutability profile facilitates the expansion of production in the two energy sectors, allowing more experience to be gained, which in turn translates into higher learning rates.

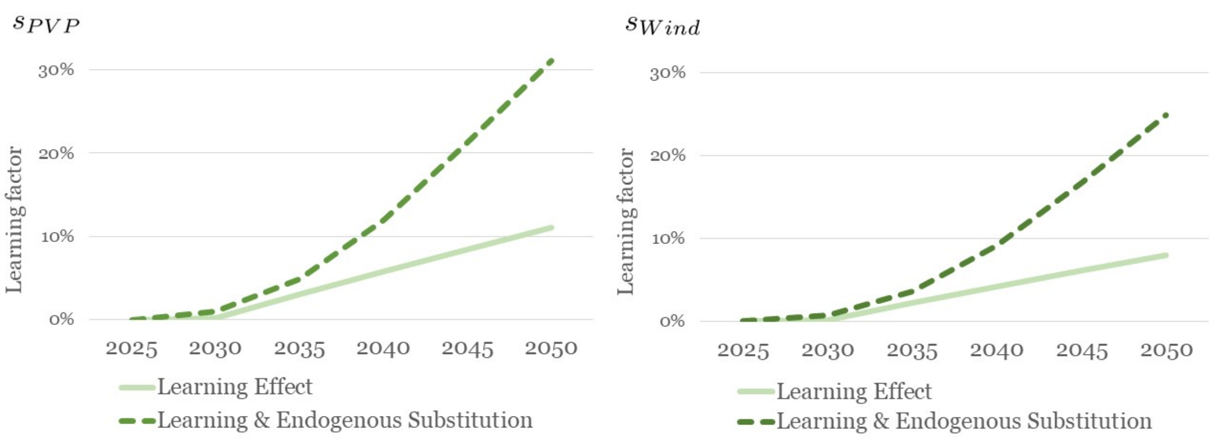


Figure 8: The synergy between the learning effect and the endogenous elasticity of substitution mechanism for the wind and solar sectors under the net-zero target.

At the aggregate level, the learning mechanism has a very modest impact on the overall economy's path to the net-zero target: In our simulations, the optimal carbon tax remains almost unchanged (less than 1% difference) when learning effects are taken into account, even in the net-zero scenario. Moreover, the cost of policy in terms of welfare can only be reduced by a negligible amount. However, learning seems to be essential for growth and capital accumulation in the renewable energy sectors.

Energy Efficiency Improvement

As explained in the previous section, for every sector (except energy producing sectors) the potential for more efficient energy use is reflected in the efficiency factor *f*. Figure 9 shows the trajectories of the efficiency improvement effect for the economic sectors in the CITE model under the assumption that the Swiss economy reaches its net-zero target by 2050.[6]

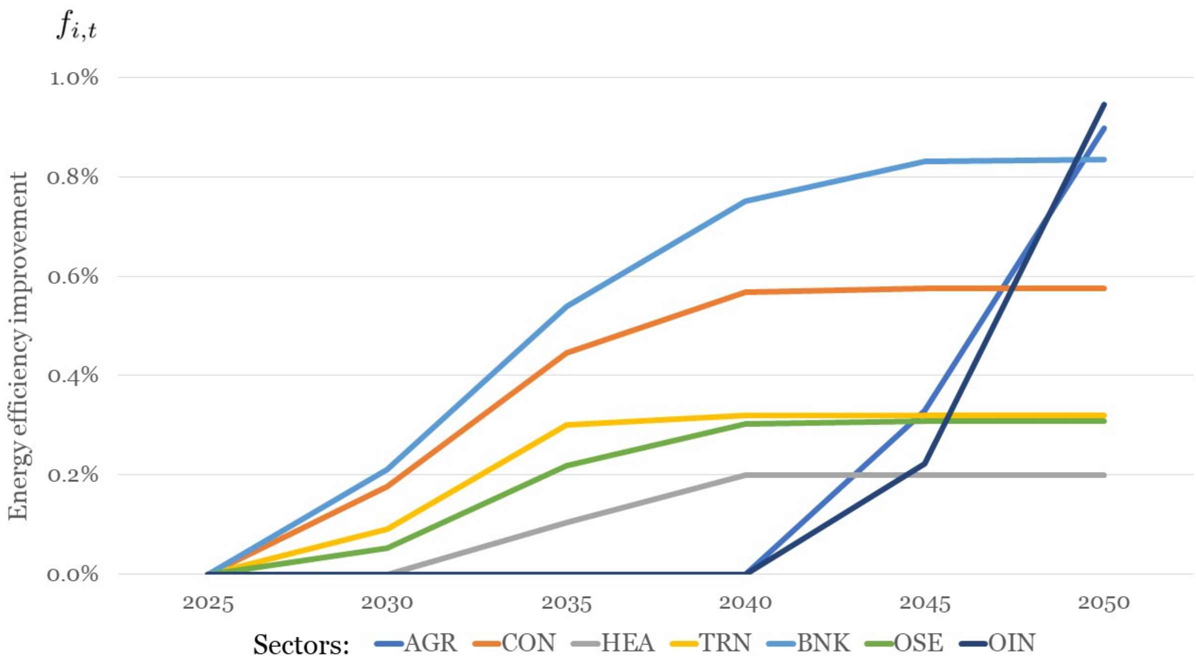


Figure 9: Trajectories of the energy efficiency effect for different sectors given the net zero target by 2050.

In fact, stringent climate policy creates incentives for most sectors to reduce their energy use through additional investment in energy-saving technologies — their improvements in energy efficiency gradually build up, reaching levels between 0.2% and 1% by 2050.

Given the moderate magnitude of the effect, it is worth exploring how complementary policies can stimulate this particular mechanism. First, we consider an energy-efficiency standard for the transportation and construction sectors (SFOE, 2020). Specifically, the two sectors must reduce their energy intensity by 40% and 50%, respectively, by 2050. As shown in Figure 10, the standards lead to additional energy efficiency improvements in the two sectors considered, but at a low level. The higher the standard, the higher the induced efficiency improvements.

[6] Note that the effect is zero for the remaining sectors.

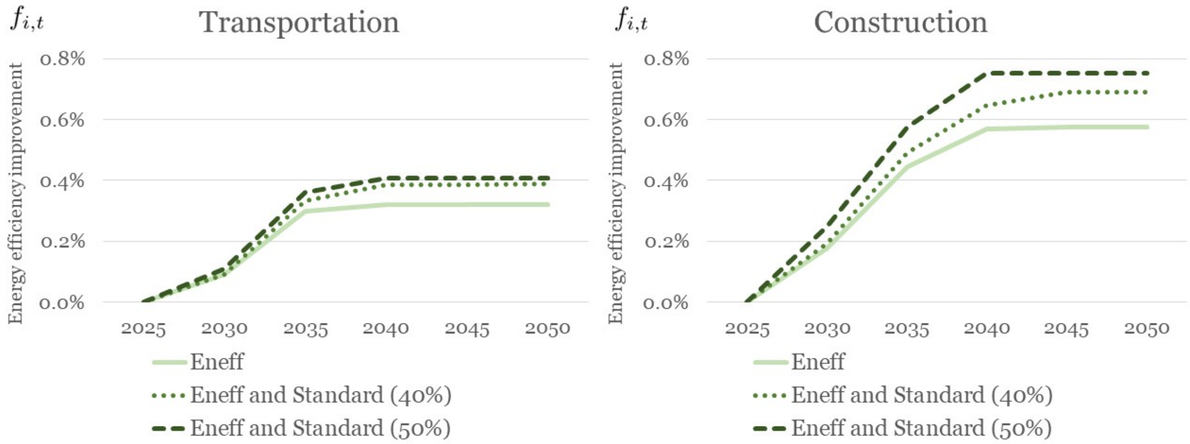


Figure 10: Trajectories for the energy efficiency effect for the transport and construction sectors with an emission standard of 40% and 50%, assuming that the Swiss economy reaches the net-zero target by 2050.

Figure 11 shows that the presence of an efficiency standard slightly lowers the level of carbon tax required to achieve the net zero target. Specifically, an efficiency standard of 50% in the transportation and construction sectors reduces the carbon price in 2050 from 400 CHF/tCO_2 to 380 CHf/tCO_2. The higher the standard, the lower the carbon tax needed to reach the net-zero target by mid century.

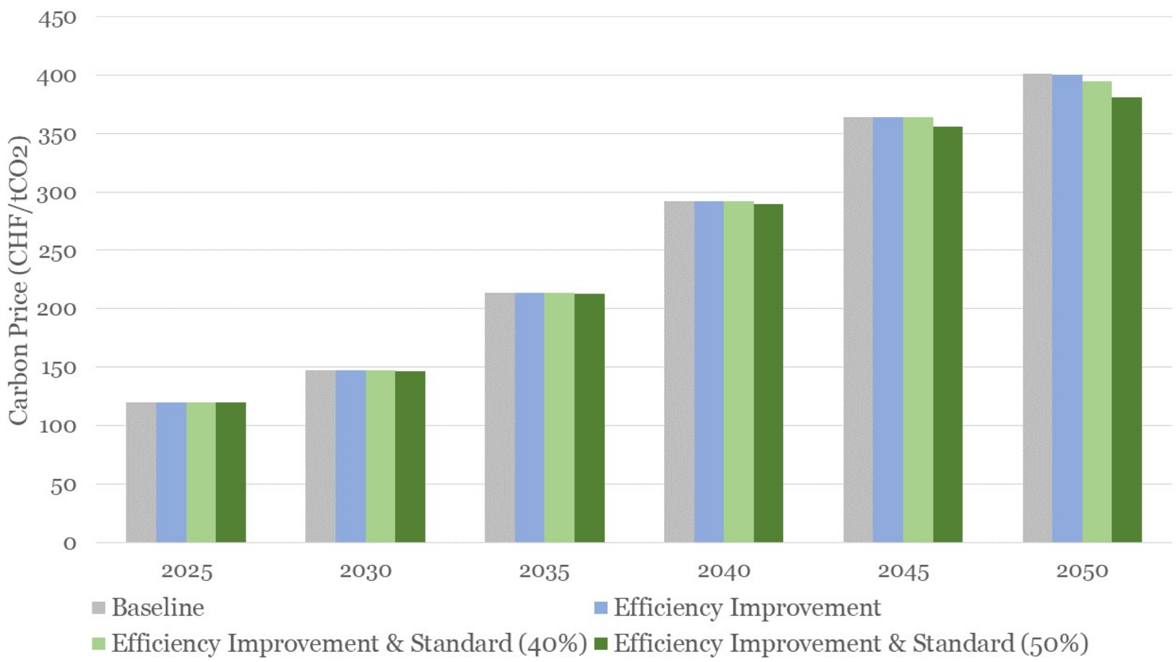


Figure 11: Optimal carbon tax with the mechanism of increasing energy efficiency and efficiency standards of 40% and 50%, assuming that the Swiss economy reaches the net-zero target by 2050.

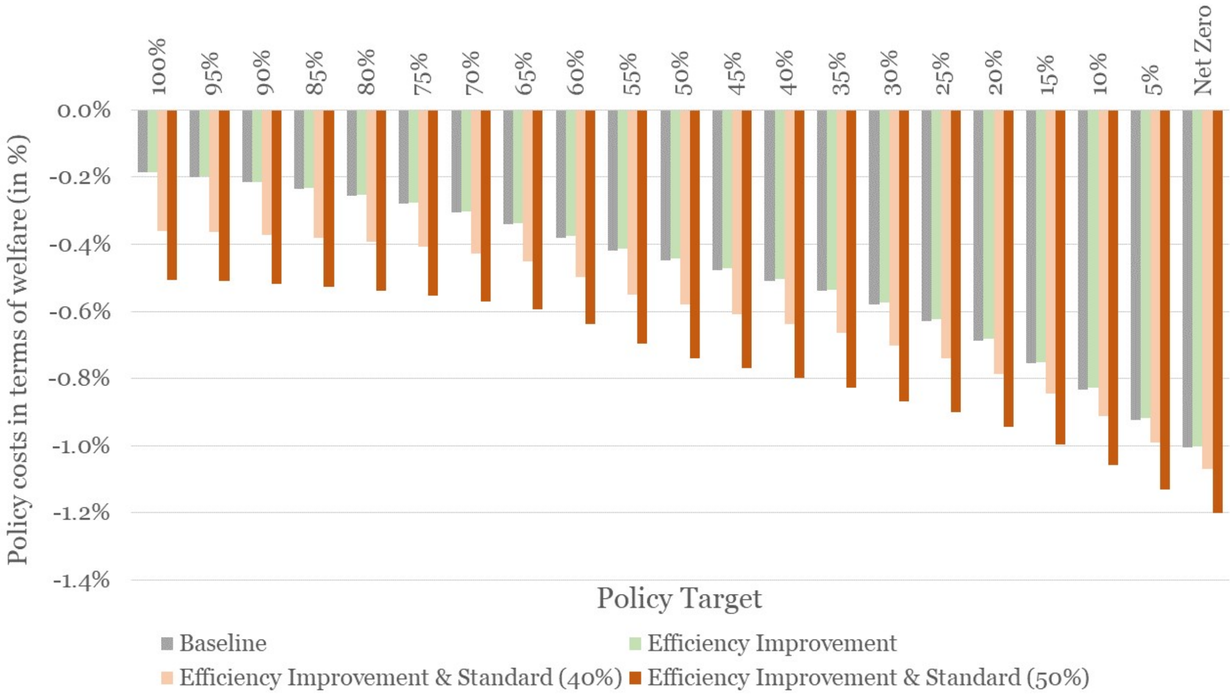


Figure 12: The overall costs of climate policy in terms of welfare across policies of increasing stringency in the baseline scenario, with the energy efficiency improvement mechanism, and efficiency standards.

However, Figure 12 shows that efficiency standards in fact increase the overall cost of climate policy. The higher the efficiency standard, the higher the costs of the policy in terms of welfare. While in the baseline scenario the estimated policy costs are about 1%, they increase to 1.2% if an efficiency standard of 50% is introduced for both sectors. These findings are consistent with a common conclusion in the literature that command-and-control instruments (such as standards) are less cost-efficient than market-based instruments (such as carbon tax), in that they take away the flexibility from the producers in their choice of mitigation strategies.[7]

Because a sector's energy efficiency depends on its innovation activity, we also examined whether innovation subsidies can spur additional energy efficiency improvements. Thus, as an alternative complementary policy, we introduce an R&D subsidy for all sectors in the amount of 30%. Figure 13 illustrates that R&D subsidies can trigger additional innovations that improve energy efficiency in the respective sectors, but the scale of these improvements stays moderate.

[7]Landis (2019b) provides a comprehensive overview and comparison of the two types of policy instruments and finds that taxing energy is about five times more cost-effective than promoting energy savings by mandates.

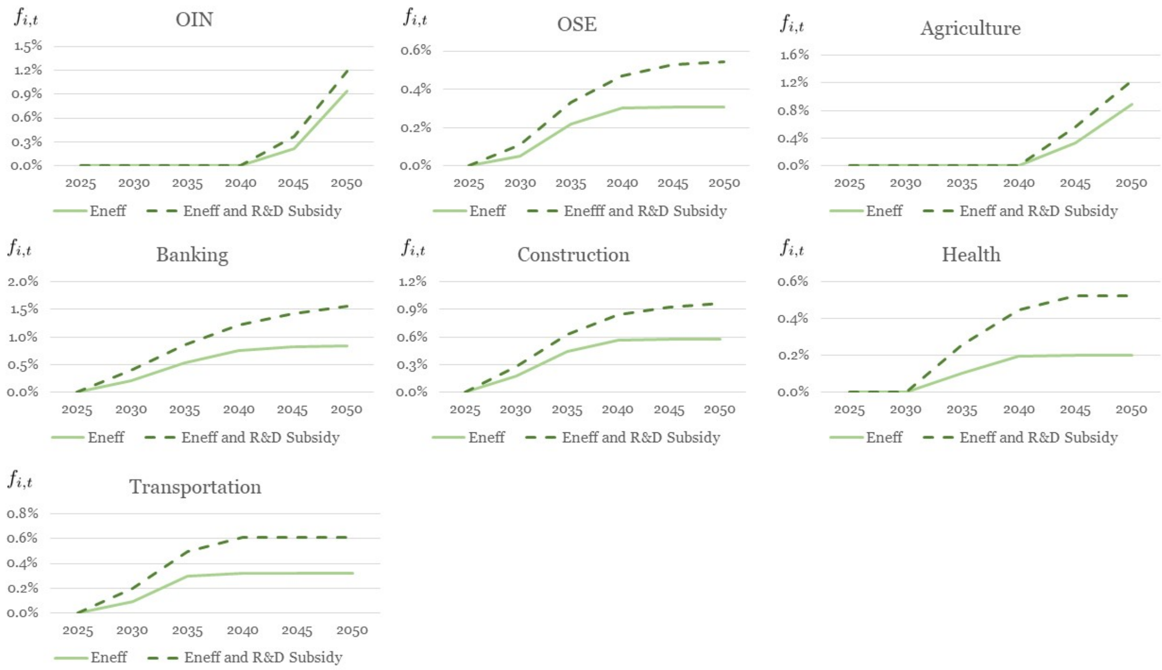


Figure 13: Trajectories for the energy efficiency effect for different sectors with and without R&D subsidies in the net-zero scenario.

In the course of this exercise, we find that the presence of NET/CCS technologies affects the potential impact of the energy efficiency mechanism. As an alternative option to reach the net-zero target, the CCS technologies curb the emissions in the production process and thus the carbon tax to be paid, which largely eliminates the incentives to invest in energy-saving technologies.

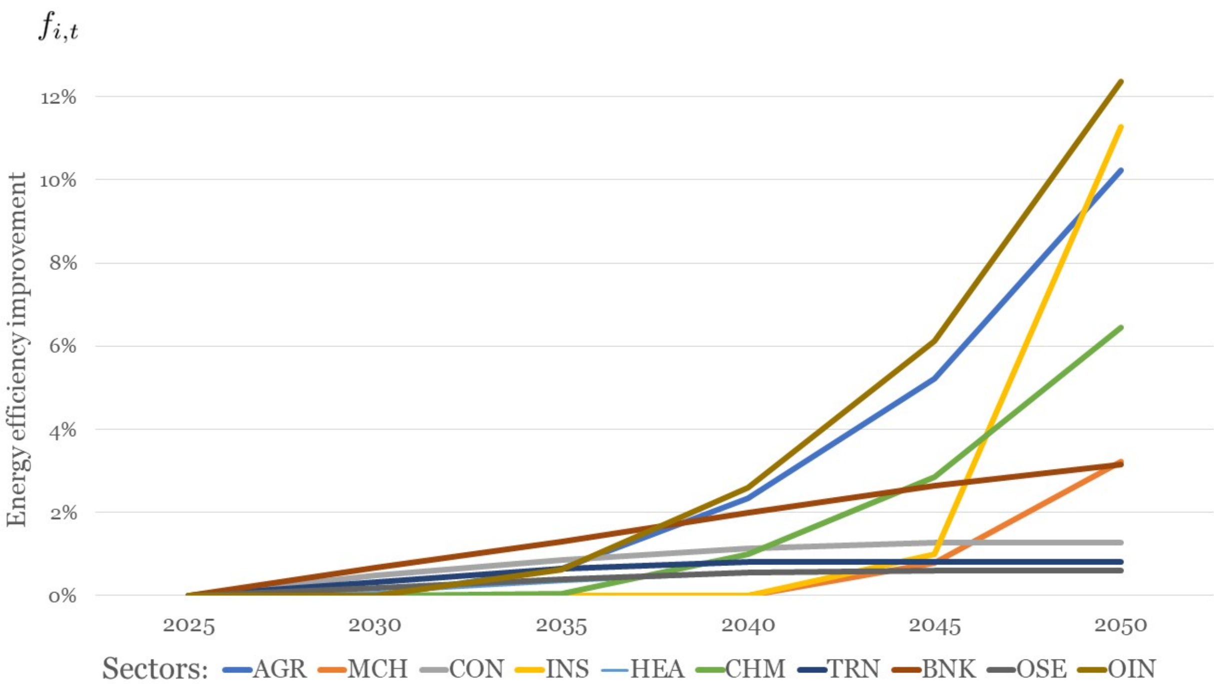


Figure 14: Trajectories of the energy efficiency effect for different sectors in the net-zero scenario without NET/CCS.

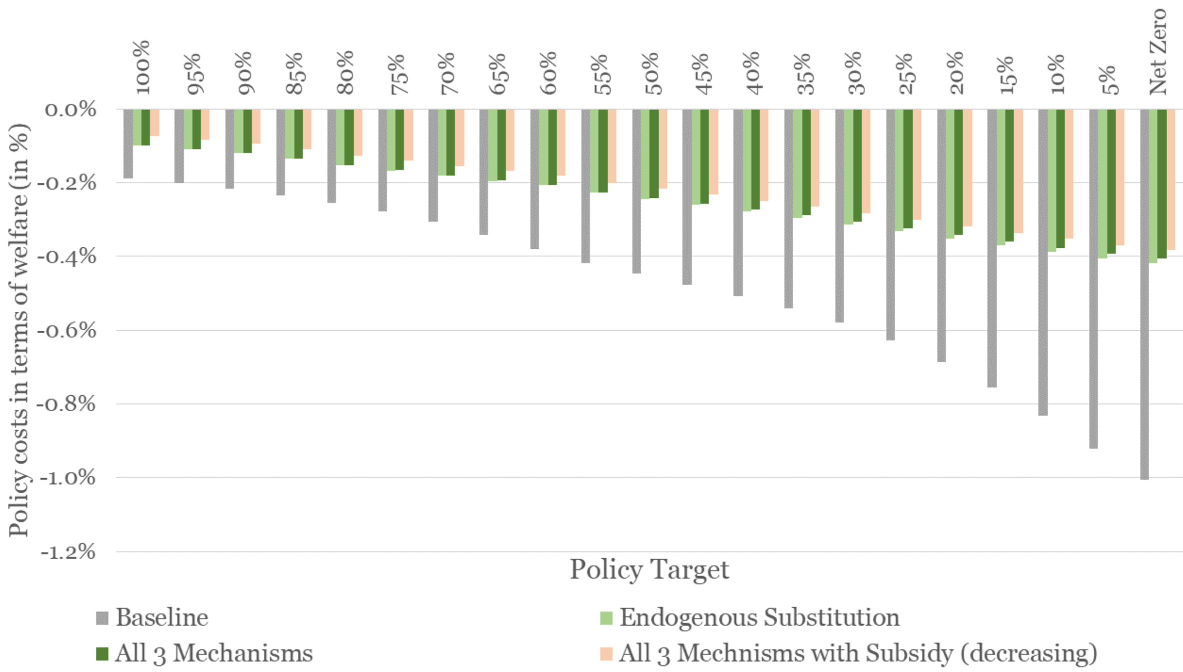
For illustration, Figure 14 shows the efficiency factor, f , for the case where no NET/CCS are present. Depending on the sector, the efficiency improvements resulting from the additional triggered investments can now reach up to 12.5% by 2050. This result opens a discussion on the use of negative emission technologies as a means to reach an emissions target. On the one hand, the future availability of such technologies helps to achieve the ambitious emission reduction targets; on the other hand, our results indicate that the presence of such technologies weakens the incentives to invest in energy-saving innovations.[8]

Putting it all together

The previous sections have highlighted the importance of each of the three mechanisms that can directly or indirectly promote climate policy. Not only can these mechanisms strongly affect the economy's path to the policy target, but they might also have nontrivial synergy effects when enabled jointly.

In fact, when all three feedback channels are taken into account, the cost of the policy in terms of welfare can be reduced by more than a half, as shown in Figure 15. A large part of this reduction is driven by the endogenous elasticity mechanism, whereas the role of other two effects in the aggregate economy's dynamics is much smaller. Notably, the introduction of subsidies as an additional policy instrument slightly lowers the costs further.

Figure 16 demonstrates that the presence of all feedback channels lowers the level of carbon tax required to reach the net-zero target by 2050. More precisely, with all mechanisms in place, the carbon price only increases to 221 CHF/tCO_2, while in the baseline scenario a carbon price of 400 CHF/tCO_2 is required to reach the net-zero target for the Swiss economy. Subsidies to renewable energy, even though beneficial in terms of welfare, leave the carbon price unchanged.



[8] Note that the agents in CITE have perfect foresight and anticipate the availability of the NET/CCS technologies.

Figure 15: The overall costs of climate policy in terms of welfare across policies of increasing stringency in the baseline scenario, with endogenous elasticity of substitution, with all three mechanisms in place, and with decreasing subsidies to renewable energy.

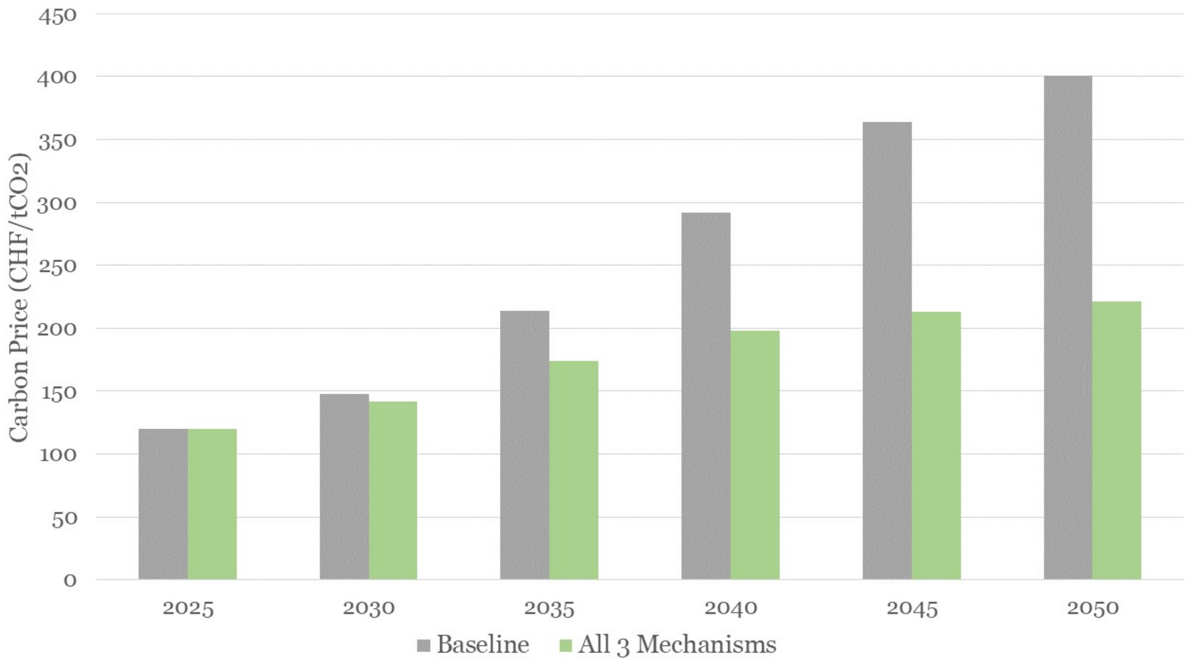


Figure 16: Optimal carbon tax under a net-zero target in the baseline scenario and with all three feedback channels in place.

5 Conclusions

In this project, we analyze how individual policy instruments as well as their combinations can engage innovation to facilitate economic growth while reaching stringent policy targets. We analyze three different effects that develop endogenously during decarbonization and amplify current policies: increasing substitutability of dirty inputs by clean inputs, learning effects in renewable energy, and efficiency improvements in the application of energy. We explore theoretical and empirical questions that arise when studying these effects. For numerical simulations, we use the CITE model, a computable general equilibrium model with endogenous growth dynamics, to represent the macroeconomic framework of climate policy. We implement all three mechanisms in this framework and obtain quantitative results for the Swiss economy on its way to decarbonization.

The first part of the project extends the important literature on endogenous growth and climate change in a novel way by analyzing the three channels that are directly and indirectly affected by policy instruments and reinforcing these instruments in a virtuous cycle. To the best of our knowledge, this project is the first to make advances on this front by investigating the implications of these mechanisms in a macroeconomic analysis of optimal environmental policy. The broad acceptance and positive feedback at the conference presentations suggest that we address a topic highly relevant in the field. The findings from this research project bear importance both for academic researchers and practitioners.

6 Outlook and next steps

The findings of the research project clearly demonstrate that the innovation channels play a significant role in shaping the path to an economy's decarbonization. While the outlined research questions have been extensively addressed within this project from theoretical, empirical, and especially numerical perspectives, there are still multiple insights to be followed up and investigated. In particular, we believe it would be of high theoretical and practical importance to investigate further the trade-off between the presence of NET/CCS and innovation in energy use. Also, due to time constraints, the investigation of distributional effects of the applied policy instruments stayed outside the scope of the project. We believe it is essential to analyze the potential impact of policy instruments on the welfare of various groups of population before recommending a particular combination of policies for implementation.

7 National and international cooperation

Not applicable

8 Communication

The findings of the project have been presented at the internal seminars at ETH Zurich throughout the course of the project.

The results have been further presented at the following conferences:

26th Annual Conference of the European Association of Environmental and Resource Economists, 2021 (online).

10th Annual Conference on Sustainable Resource Use and Economic Dynamics (SURED), 2022 (Ascona, Switzerland)

27th Annual Conference of the European Association of Environmental and Resource Economists, 2022 (Rimini, Italy)

The Annual Conference of the Royal Economic Society (RES), 2022 (online)

Summer Conference of Association of Environmental and Resource Economists (AERE), 2022 (Miami, USA)

28th Annual Conference of the European Association of Environmental and Resource Economists, 2023 (Limassol, Cyprus)

The Annual Congress of the Swiss Society of Economics and Statistics, 2023 (Neuchatel, Switzerland)

9 Publications

Bretschger, Leuthard & Miftakhova (2023): Boosting sluggish climate policy: Endogenous substitution, learning effects and energy efficiency improvements. To be openly published as a working paper in *CER-ETH Economics Working Paper Series*

Jo & Miftakhova (2022): How Constant is Constant Elasticity of Substitution? Endogenous Substitution between Clean and Dirty Energy. Under revision in the *Journal of Environmental Economics and Management*

Bretschger, Komarov & Leuthard (2022): Overcoming the Carbon Trap: Climate Policy and Technology Tipping. To be openly published as a working paper in *CER-ETH Economics Working Paper Series*

Bretschger & Leuthard (2022): Die Bedeutung von Kipppunkten für eine nachhaltige Entwicklung. *Perspektiven der Wirtschaftspolitik.*

10 References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American economic review*, *102*(1), 131-166.

Bhadbhade, N., Fouiteh, I., Yilmaz, S., Patel, M. K., Boogen, N., & Betz, R. (2021). Energy efficiency Trends and Policies in Switzerland (2000-2019/2020).

Bhadbhade, N., Yilmaz, S., Zuberi, J. S., Eichammer, W., & Patel, M. K. (2020). The evolution of energy efficiency in Switzerland in the period 2000-2016. *Energy*, 191, 116526.

Bosseboeuf, D., Lapillonne, B., & Eichhammer, W. (2005). Measuring energy efficiency progress in the EU: the energy efficiency index ODEX. *Proceedings of the 2005 European Council for an Energy Efficient Economy Summer Study, Stockholm, Sweden*, 1127–1135.

Bretschger, L., Ramer, R., & Schwark, F. (2011). Growth effects of carbon policies: applying a fully dynamic CGE model with heterogeneous capital. *Resource and Energy Economics*, *33*(4), 963-980.

SFOE (2020). Energieperspektiven 2050+. Zusammenfassung der wichtigsten Ergebnisse, Federal Office of Energy.

Grossman, G.M., Helpman, E. (1991).In: Innovation and Growth. The MIT Press, Cambridge, USA.

Jo, A., & Miftakhova, A. (2022). How constant is constant elasticity of substitution? Economics *Working Paper Series.*

Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics, 34*(1),1–23.

Kverndokk, S., & Rosendahl, K. E. (2007). Climate policies and learning by doing: Impacts and timing of technology subsidies. *Resource and Energy Economics*, *29*(1), 58-82.

Landis, F., Rausch, S., Kosch, M., & Böhringer, C. (2019). Efficient and equitable policy design: taxing energy use or promoting energy savings? *The Energy Journal,40(1).*

Mattauch, L., Creutzig, F., & Edenhofer, O. (2015). Avoiding carbon lock-in: policy options for advancing structural change. *Economic modelling*, 50, 49–63.

McDonald, A., & Schrattenholzer, L. (2001). Learning rates for energy technologies. *Energy policy*, *29*(4), 255-261.

Popp, D. (2019). Environmental policy and innovation: a decade of research (No. w25631). *National Bureau of Economic Research.*

Romer, P. M. (1990). Endogenous technological change. *Journal of political Economy*, *98*(5, Part 2), S71-S102.

Rubin, E. S., Azevedo, I. M., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy*, *86*, 198-218.

11 Appendix

Not applicable