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The Rebound Effects from Industrial Energy Efficiency Improvements

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par

Michel ZIMMERMANN

Acceptée sur proposition du jury

Prof. J.-L. Scartezzini, président du jury
Prof. Ph. Thalmann, Dr V. Moreau, directeurs de thèse
Prof. A. Löschel, rapporteur
Prof. R. Madlener, rapporteur
Prof. F. Maréchal, rapporteur

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Für dich Mami

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Zürich, 14 January 2022 Michel Zimmermann

Abstract

In energy policy, energy efficiency constitutes a central element in reducing domestic and, specifically, industrial energy use. Unfortunately, the effectiveness of energy efficiency improvements in achieving its targets is known to be limited by rebound effects. Rebound effects follow from economic and behavioral adjustments to the efficiency improvements themselves. This thesis investigates such rebound effects in the case of annual industrial energy efficiency improvements in Switzerland. To this end, we develop a recursively dynamic computable general equilibrium model, which takes special account of the relationship between energy and capital in perpetuating rebound effects.

Chapter 2 provides the first assessment of economy-wide rebound effects for Switzerland. We show that industrial energy efficiency improvements are only partially effective in reducing energy use, as we find substantial rebound effects, both domestically and for all non-energy good sectors. The sector-specific results crucially depend on the energy and capital intensities of the respective sectors. Moreover, we find that our more sophisticated representation of capital lowers the simulated rebound effects. Conversely, existing traditional rebound assessments with a homogenous capital stock may overestimate rebound effects.

Chapter 3 adds to the scarce knowledge on the rebound mechanisms that actually cause energy efficiency to be less efficient than anticipated. It illustrates that industrial energy efficiency improvements in Switzerland lead to economy-wide rebound effects in equal parts via partial equilibrium and general equilibrium channels. We find this by undertaking a decomposition analysis of rebound effects. We show composition and trade effects (i.e. general equilibrium effects) to be the main rebound mechanisms for energy-intensive industries. Sectors with a high share of value added, however, primarily rebound due to substitution away from capital towards energy.

Chapter 4 analyses the mitigation of rebound effects with economic instruments in order to maximize the energy savings from efficiency improvements. We explore the suitability of uniform taxes to increase the efficacy of energy efficiency in reducing energy use and investigate the economic impact of such taxes. The tax rates are endogenously determined to fully offset economy-wide rebound effects in Switzerland. We demonstrate that the economic gains from the energy efficiency improvements still outweigh the costs of the taxation if revenue is recycled by reducing pre-existing taxes. The more energy carriers are taxed simultaneously, the more efficient the tax scheme is, as unwanted substitution effects can be avoided. We demonstrate that rewarding energy-reducing sectors in a bonus-malus scheme proves the most efficient way to mitigate rebound effects, as it retains most of the economic gains of the energy efficiency improvements.

In conclusion, we show that it is essential to evaluate the expected rebound effects and to compensate for them with complementary policies, such as energy taxes. Such economic policy instruments could mitigate rebound effects for sectors with strong partial equilibrium rebound mechanisms, while for energy-intensive sectors a more holistic approach using multiple policy instruments needs to be pursued. Finally, we highlight the potential for rebound mitigation to increase energy savings from energy efficiency improvements.

Keywords: Rebound effects, energy efficiency, capital-energy substitutability, decomposition analysis, computable general equilibrium modelling, rebound mitigation, energy taxation, revenue recycling

Zusammenfassung

In der Energiepolitik ist die Energieeffizienz ein zentrales Element zur Verringerung des Energieverbrauchs in Haushalten und Industrie. Leider ist die Wirksamkeit von Energieeffizienzverbesserungen bei der Erreichung ihrer Ziele durch Rebound-Effekte begrenzt. Rebound-Effekte ergeben sich aus wirtschaftlichen und Verhaltens-Anpassungen aufgrund der Effizienzsteigerungen selbst. In dieser Arbeit wird die Existenz solcher Rebound-Effekte am Beispiel jährlicher Energieeffizienzverbesserungen in der Schweizer Wirtschaft untersucht. Ein rekursiv-dynamisches, allgemeines Gleichgewichtsmodell wird dazu entwickelt, das die spezielle Beziehung zwischen Energie und Kapital in der Entstehung von Rebound-Effekten berücksichtigt.

Kapitel 2 liefert die erste Schätzung der gesamtwirtschaftlichen Rebound-Effekte für die Schweiz. Wir zeigen, dass Energieeffizienzverbesserungen in der Industrie nur teilweise wirksam sind, um den Energieverbrauch zu senken und finden erhebliche Rebound-Effekte. Die sektorspezifischen Ergebnisse hängen entscheidend von den Energie- und Kapitalintensitäten der jeweiligen Sektoren ab. Darüber hinaus stellen wir fest, dass unsere differenziertere Darstellung von Kapital die simulierten Rebound-Effekte reduziert und herkömmliche Rebound Analysen mit einem homogenen Kapitalstock die Rebound-Effekte potenziell überbewerten.

Kapitel 3 zeigt auf, welche Rebound-Mechanismen tatsächlich dazu führen, dass Energieeffizienz weniger effektiv ist als erwartet. Es demonstriert, dass Verbesserungen der industriellen Energieeffizienz in der Schweiz in gleichen Teilen durch partielle und allgemeine Gleichgewichtseffekte zu gesamtwirtschaftlichen Rebound-Effekten führen. Wir finden dies, indem wir eine Dekompositionsanalyse der Rebound-Effekte durchführen. Wir stellen fest, dass Struktur- und Handelseffekte (d. h. allgemeine Gleichgewichtseffekte) die wichtigsten Rebound-Mechanismen für energieintensive Industrien sind. Rebound-Effekte in Sektoren mit einem hohen Wertschöpfungsanteil sind in erster Linie durch Substitution von Kapital durch Energie verursacht.

In Kapitel 4 wird die Eignung von ökonomischen Instrumenten analysiert, um Rebound-Effekte zu minimieren. Konkret wird untersucht, wie sich Steuern auf die Verwendung verschiedener Energieträger in der Produktion auf den Energieverbrauch und die Wirtschaft auswirken. Die Steuersätze werden endogen so bestimmt, damit die gesamtwirtschaftlichen Rebound-Effekte in der Schweiz gleich null sind. Wir zeigen, dass die wirtschaftlichen Gewinne der Energieeffizienzverbesserungen die Kosten der Besteuerung immer noch überwiegen, wenn die Einnahmen zur Senkung bestehender Steuern verwendet werden. Wir zeigen, dass die Belohnung energiesparender Sektoren in einem Bonus-Malus-System der effizienteste Weg ist, um Rebound-Effekte abzuschwächen, da so der größte Teil der wirtschaftlichen Gewinne aus den Energieeffizienzverbesserungen erhalten bleibt.

Abschließend zeigen wir, dass es von entscheidender Bedeutung ist, Rebound-Effekte zu schätzen und sie durch ergänzende Maßnahmen wie Energiesteuern zu verhindern. Solche Instrumente können die Rebound-Effekte für Sektoren mit starken partiellen Gleichgewichtseffekten abschwächen, während für energieintensive Sektoren ein ganzheitlicherer Ansatz mit mehreren Instrumenten verfolgt werden muss. Zudem weisen wir auf das Potenzial für eine Rebound-Minderung hin, um die Energieersparnisse von Energieeffizienzverbesserungen zu erhöhen.

Schlüsselwörter: Rebound-Effekte, Energieeffizienz, Kapital-Energie-Substitution, Dekompositionsanalyse, allgemeine Gleichgewichtsmodelle, Rebound-Minderung, Energiesteuern, Steuereinnahmenverwendung

Résumé

L'efficacité énergétique constitue un pilier de la réduction de la consommation d'énergie, en particulier industrielle. Le potentiel de l'efficacité énergétique pour atteindre ces objectifs de réduction est pourtant limité par les effets rebond. Ceux-ci découlent d'ajustements économiques aux améliorations de l'efficacité elles-mêmes. Cette thèse étudie ces effets rebond suite à une amélioration annuelle de l'efficacité énergétique dans l'industrie en Suisse. A cette fin, nous développons un modèle d'équilibre général calculable dynamique, qui détaille la relation entre capital et énergie dans l'analyse des effets rebond.

Le chapitre 2 fournit la première évaluation des effets rebond à l'échelle de l'économie pour la Suisse. Nous montrons que l'amélioration de l'efficacité énergétique ne permet de réduire la consommation d'énergie que partiellement. Les effets rebond sont substantiels, tant au niveau national que pour tous les secteurs de biens non énergétiques. Les résultats sectoriels dépendent essentiellement de leurs intensités énergétiques et en capital. En outre, nous constatons que notre représentation plus sophistiquée du capital réduit les effets rebond simulés. Inversement, les estimations existantes avec un stock de capital homogène peuvent surestimer ces effets.

Le chapitre 3 ajoute aux connaissances limitées sur les mécanismes de rebond qui font que le potentiel d'efficacité n'est pas atteint. Les améliorations de l'efficacité entraînent des effets rebond pour l'industrie et l'ensemble de l'économie, à parts égales, via des canaux d'équilibre partiel et général. Nous montrons que les effets de composition et d'équilibre général sont les principaux mécanismes de rebond pour les industries à forte intensité énergétique. Les secteurs dont la part de la valeur ajoutée est élevée rebondissent principalement en raison de la substitution du capital par l'énergie.

Le chapitre 4 analyse les possibilités d'atténuer les effets rebond par des taxes, dans le but de maximiser les économies d'énergie. Plus précisément, nous explorons l'impact de taxes uniformes sur l'utilisation de différents vecteurs énergétiques par secteur sur la consommation d'énergie et l'économie. Les taux d'imposition sont déterminés de manière endogène afin de compenser entièrement les effets rebond. Nous démontrons que les gains économiques résultant des améliorations de l'efficacité énergétique dépassent toujours les coûts de la taxation, si les recettes sont recyclées sous forme de réduction des taxes existantes. Plus les vecteurs énergétiques sont taxés simultanément, plus le système fiscal est efficace, car les effets de substitution indésirables peuvent être évités. En comparant les différents modes de recyclage des recettes, nous montrons qu'un système récompensant les secteurs qui réduisent leur consommation d'énergie, est économiquement plus avantageux.

En conclusion, il est essentiel d'évaluer les effets rebond et de les neutraliser par des politiques complémentaires, telles que des taxes sur l'énergie. Ces instruments de politique économique pourraient atténuer les effets rebond pour les secteurs soumis à des mécanismes de rebond de type équilibre partiel, tandis que pour les secteurs à forte intensité énergétique, une approche plus globale doit être adoptée. Enfin, nous soulignons le potentiel de l'atténuation par rebond pour augmenter les économies d'énergie réalisées grâce aux améliorations de l'efficacité énergétique.

Mots-clés : Effets rebond, efficacité énergétique, substituabilité capital-énergie, analyse de décomposition, modèle d'équilibre général calculable, atténuation des effets rebond, taxation de l'énergie, recyclage des recettes.

Contents

List of Abbreviations

CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CHF	Swiss Franc
EEI	Energy efficiency improvement
EEIWR	Energy efficiency improvement without rebound effect
ESC	Energy system capital
GAMS	General Algebraic Modeling System
GDP	Gross domestic product
GE	General equilibrium
GTAP	Global Trade Analysis Project
IDA	Index decomposition analysis
IO	Input-output
kWh	Kilowatt-hour
MCP	Mixed complementarity problem
ME	Marshall-Edgeworth
MPSGE	Mathematical programming system for general equilibrium analysis
OC	Other capital
OECD	Organization for Economic Co-operation and Development
PE	Partial equilibrium
PJ	Petajoule
R-EEI	Rebound effects from energy efficiency improvements
SAM	Social accounting matrix
SDA	Structural decomposition analysis
SEEM	Swiss Energy Efficiency Model
SS	steady-state
TJ	Terajoule
TWC	Tradable White Certificate

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Chapter 1 Introduction

Climate change poses an imminent threat to biodiversity and human life across the globe. Deep economic and societal changes are needed to avoid a catastrophic temperature rise. Political initiatives, such as the Paris Agreement, demand efforts across all activities to sharply reduce anthropogenic greenhouse gas emissions and present governments and economic actors with substantial challenges. Wealthy nations such as Switzerland have a particular responsibility in driving and facilitating the urgent transition to a low-carbon economy. A central element of this endeavor is understanding the way energy is used, both in production and consumption, and especially how energy can be used more efficiently.

Energy efficiency thus plays a very important role in national energy policy and energy efficiency policies and measures are systematically advocated for and promoted to reduce society's dependence on energy. The European Union only recently doubled down on its commitment to energy efficiency as a vital part of its European Green Deal (EC, 2021). And for Switzerland, the case study for the thesis presented here, energy efficiency is similarly a centerpiece of its national energy strategy, with several policies in place addressing the housing sector and mobility and productive processes (SFOE, 2021b).

This, however, relies on the premise that energy efficiency is actually capable of delivering the reductions in energy use that are necessary and expected. Swiss production is particularly reliant on energy efficiency, as it already has one of the lowest energy intensities in Europe (Odyssee, 2021) and still uses more than a third of total final energy use in Switzerland and even more when commercial transport is included (SFOE, 2020a). The effectiveness of energy efficiency in achieving its targets has, however, been frequently challenged.

Energy efficiency commonly refers to "using less energy to produce the same amount of services or useful output" (Patterson, 1996, p. 377). For an aggregated analysis of energy efficiency (e.g. at the industry-, economy- or even global level), it is common to use the measure of energy productivity as a proxy for energy efficiency. This is defined by measuring useful output in economic terms per energy input (e.g. $\frac{GDP\ [mCHF]}{total\ final\ energy\ use\ [TJ]}$) and allows a comparison across processes and industries. In its essence, energy efficiency reduces the effective price of an energy service, as the same level of service can be obtained with fewer energy inputs. At the same time, the lower price triggers a wide range of behavioral and economic adjustments, which may cause energy use to be higher than anticipated from the energy efficiency improvement (EEI). The difference between the potential energy savings and the actual energy savings is often explained by the occurrence of rebound effects.

Rebound effects have been the subject of frequent debate ever since the 1980s (Khazzoom, 1980; Brookes, 1990) and are now commonly recognized to be a direct consequence from EEIs. The response to the decrease in the effective price of energy manifests via different channels and may depend on the temporal dynamics considered (Lange et al., 2021). At the micro-level, the most commonly described mechanisms that cause energy use to rebound are the substitution effect (i.e. the substitution of production factors for the now cheaper energy service) and the income effect (i.e. due to increased disposable income). EEI, however, do not only affect the actors experiencing the stimuli, but also perpetuate across the economy and other actors via the meso- and macro-level. Consequently, rebound effects similarly occur at more aggregate levels, with definitions, classifications and estimations abound. All rebound effects within an economy can be summarized as economy-wide rebound effects.

While there is still much uncertainty about the exact magnitude of these economy-wide rebound effects (Stern, 2020), there exists a consensus that they are non-trivial (Colmenares et al., 2020) and thus require more attention. Yet, an assessment of economy-wide rebound effects in Switzerland is still lacking. The thesis presented here seeks to remedy this. Moreover, we add to the sparse and conflicting knowledge on the underlying rebound mechanisms causing the rebound effects to occur in the first place. Finally, we investigate how energy policy could deal with the existence of rebound effects and what the economic implications of rebound mitigation are.

1.1 The assessment of rebound effects

The rebound effect literature contains assessments of economy-wide rebound effects from EEI in both production and consumption for a host of different countries. Research thereby mainly relies on three overarching methodologies: econometric analysis, macroeconomic models, and computable general equilibrium (CGE) models (Colmenares et al., 2020). In this thesis, we use CGE modeling as its ability to analyze system-wide effects over time ideally suits our purpose of assessing the rebound effects of continuous industrial EEIs.[1] Notwithstanding the methodology's suitability for such an analysis, CGE modelers need to account for additional elements when assessing rebound effects. CGE models often rely on constant elasticity of substitution (CES) functions, which are known to crucially influence the achieved energy savings as a result of energy efficiency. This is the case both with respect to its exact functional form and the size of the elasticity parameters. We account for this in developing a new recursively dynamic CGE model for Switzerland, designed specifically for the assessment of industrial EEI over time: The Swiss Energy Efficiency Model (SEEM). A special focus thereby also lies on how we model the relationship between capital and energy, which we assume to be partly substitutable and partly complementary and thus provides a more accurate representation of real-world conditions.

In using the SEEM CGE model, we provide an assessment of Swiss rebound effects, which complements the various rebound assessments of other countries. There is, however, great variation in the exact focus, the chosen assumption and specifications, and consequently the rebound effects estimated within the plethora of studies in the literature. Simulations of economy-wide rebound effects have, for instance, been undertaken for the UK and Scotland (Allan et al., 2007b; Hanley et al., 2009; Turner, 2009), Sweden (Broberg et al., 2015), and Germany (Koesler et al., 2016). The overwhelming majority of studies analyses one-off EEI, such as Garau and Mandras (2015) or Figus et al. (2020). CGE simulations often undertake sensitivity analyses of nesting structures and the chosen elasticities of substitution. However, there appears to exist no study that reflects the unclear relationship between energy and capital in a differentiated manner, even though this relationship is frequently highlighted as the crucial determinant of rebound effects (Broadstock et al., 2007; Lecca et al., 2014). The assessment of continuous industrial EEI with a novel focus on the energy-capital relationship in Switzerland thus constitutes a clear research gap and contribution of this thesis.

A further commonality between the majority of economy-wide rebound assessments lies in the fact that there is little to no quantification of the underlying mechanisms that cause the rebound effect. Such decompositions of rebound mechanisms can mainly be found in analytical GE models as in Böhringer and Rivers (2021), Fullerton and Ta (2020), or Lemoine (2020). While theoretically valuable, these assessments do not have the level of detail or temporal dynamics of CGE models. Decomposing rebound effects with a CGE model thus offers numerous novel and valuable insights, such as the assessment of sectoral differences, the impact of economic adjustments in driving the different mechanisms, and how this changes over time.

There exists a broad consensus on the negative impact of rebound effects on the effectiveness of energy efficiency in reducing energy use. This raises the question of how to respond to energy savings being lost. A relatively new strand of literature looking into this concerns the mitigation of rebound effects and the ways to increase the efficacy of policies and measures designed to make the use of energy more efficient. A few authors qualitatively study the suitability of complementary policies to increase energy savings from energy efficiency and identify (energy) taxation as a potential tool (e.g. Font Vivanco et al., 2016; Freire-González, 2021). This is underlined by two studies by Saunders (2018) and Freire-González (2020), who quantify the impact of rebound-offsetting energy taxation on energy use and the economy with distinctively different conclusions. While the former highlights the need to consider revenue recycling to absorb the (mainly) negative economic impacts of the new tax, Freire-González (2020) finds the mitigation of rebound effects to be cost-effective and advisable even without explicitly redistributing the tax revenue. More research on the mitigation of rebound and the subsequent economic consequences is needed, as well as on the impact of different modes of revenue recycling.

1.2 Objectives of thesis

With the thesis presented here, we aim to investigate the effectiveness of industrial energy efficiency as a tool for reducing energy use. We study the case of Switzerland. In Switzerland, energy efficiency plays a crucially important role in its national energy strategy. Moreover, a recent study shows a clear need for high energy savings from energy efficiency in Switzerland,

[1] For a detailed review of CGE models in rebound assessments, see Allan et al. (2007a).

and specifically in production to achieve the necessary reductions in energy use (Bhadbhade et al., 2020). High efficacy of energy efficiency is thus paramount. Finally, Switzerland has recently pledged to move away from nuclear energy (SFOE, 2021b), which will lead to greater dependency on intermittent renewables and energy imports. This decreases national energy security, which can, inter alia, be mitigated through the means of energy efficiency.

As our first main objective, we intend to quantify rebound effects in Switzerland, at the aggregate national and industry-wide level and for individual sectors. In doing so, we can thoroughly assess the potential contribution of energy efficiency in Swiss energy policy for the first time, as the combined consideration of energy efficiency and rebound effects thus far presents a blind spot in Swiss energy policy-making. On a methodological level, and as a secondary objective, our newly developed CGE model with a heterogeneous capital stock adds to the ongoing debate on the complementarity/substitutability between energy and capital. This has regularly been characterized as a crucial determinant of rebound effects simulated with CGE models. We account for the reality of energy efficiency policy as an ongoing process and thus model energy efficiency as continuous rather than one-off improvements. Finally, in focusing on energy efficiency in production, we highlight how industries and their interplay with households are crucial in perpetuating rebound effects and add to a research area that so far has been comparatively overlooked (Santarius, 2016).

The assessment of the rebound effects with SEEM provides important insights into the effectiveness of energy efficiency and its impact on energy use and the economy. However, it does not allow to give clear-cut answers about the underlying rebound mechanisms that cause energy savings to be lost in the first place. Identifying the mechanisms of rebound effects from industrial EEI constitutes the second main objective of the thesis. We aim to achieve this by developing and applying a decomposition analysis. We establish a simple and tractable methodology to quantify the individual contributions of selected rebound mechanisms, which creates a better understanding of what perpetuates rebound effects in the different production sectors and Switzerland, overall. Such an understanding is paramount to increase the effectiveness of energy efficiency policies and to illustrate how policies may have to vary between different sectors. It also enables to better estimate what kind of rebound effects may follow from future energy efficiency policies.

The third main objective relates to the question of how to respond to the existence of rebound effects in Switzerland and consequently to the analysis of ways to increase the effectiveness of industrial energy efficiency in reducing energy use. We investigate economic instruments to mitigate rebound effects and thus add an element to the rebound literature that has so far received little attention. We specifically focus on the impact uniform unit taxes on energy carriers have on the economy to examine the economic consequences of offsetting the efficiency-induced reduction in the effective price of energy. Moreover, we compare several tax revenue recycling schemes to assess how complementary energy policies could be designed to both increase the efficacy of energy efficiency while retaining its economic benefits. This allows us to better inform policy-makers on how to deal with the expected rebound effects and to propose new energy (efficiency) policies, which provide greater energy savings.

1.3 Outline of thesis

Chapter 2 provides the first assessment of the economy-wide rebound effects that occur as a result of costless annual industrial EEI in Switzerland from 2020 to 2050. We introduce the newly developed SEEM, which is specifically designed to investigate the effectiveness of energy efficiency and the system-wide impacts on energy use and the economy. We depart from traditional rebound assessments in focusing on continuous EEI rather than a one-off increase. Another novel element in our new approach constitutes the way we model the capital stock, which is heterogeneous. One part of the capital stock is assumed to be substitutable with energy (energy system capital), while the other part is assumed to be complementary (other capital). In doing so, we present a more accurate representation of real-world conditions and shed light on how the relationship between energy and capital influences rebound effects.

We demonstrate that rebound effects cause a significant amount of energy savings to be lost. We show this at the economy-wide level - encompassing both production and households -, as well as at the industry-wide level, which focuses on energy use by production. Consequently, this is also mirrored in the sectoral rebound effects, which we find to be positive for all non-energy good sectors. Rebound effects were particularly high for the energy-intensive manufacturing industry and the services sector. Energy supply sectors see a much lower erosion of energy savings due to rebound effects, with the fossil fuel sectors (refined oil and natural gas) even exhibiting negative rebound effects. The efficiency-induced reductions in the sectoral costs of production positively impact production and consumption on aggregate, even though the economic gains are not evenly distributed across the sectors.

With an elaborate sensitivity analysis, we analyse the importance of certain assumptions modeled in SEEM in perpetuating rebound effects. We show that the elasticity of substitution between the energy composite and energy system capital is elementary for the size of rebound effects, both on aggregate and sectorally. Increasing this elasticity has the potential to substantially augment the amount of energy savings lost from efficiency stimuli. Moreover, we find that varying the chosen share of energy system capital is less influential on the results than the differentiation of the capital stock, which has a lowering impact on rebound effects. As a corollary, we hypothesize that traditional rebound assessments simulating economy-wide rebound effects with a homogenous capital stock may overestimate rebound effects.

Chapter 3 uses SEEM to investigate the underlying rebound mechanisms that lead to the energy savings lost as a result of continuous EEI in production. Specifically, we decompose sectoral, industry-wide, and economy-wide rebound effects in Switzerland into a partial equilibrium (PE) component and a general equilibrium (GE) component. The former concerns the direct substitution between the energy composite and energy system capital, while the GE component is divided into two effects: a multiplier effect (i.e. the impact of increased spending and investment) and a residual component. The latter is further analysed with complementary decomposition techniques.

In decomposing rebound effects in Switzerland, we can identify that direct substitution effects and GE effects are in equal parts responsible for the erosion of total domestic energy savings following annual EEIs. The analysis of the rebound effects in the different sectors of SEEM further highlights the importance of accounting for sectoral heterogeneity when trying to understand rebound effects. For sectors with high energy intensity, efficiency-induced trade and composition effects are the main drivers of rebound effects, which are part of the residual component. Conversely, sectors with a high share of value added experience rebound effects primarily due to direct substitution between the energy composite and energy system capital. This emphasizes the importance of more diligent sectoral analyses when investigating rebound effects. Underlining the findings from Chapter 2, the sensitivity analysis presented in this chapter additionally highlights the need for a solid (empirical) understanding of key elasticities in CGE models, as they ultimately prescribe the policies best able to mitigate rebound effects. While imposing a tax on energy may suffice to neutralize rebound mechanisms via the PE channel, more comprehensive economy-wide considerations are needed for rebound effects caused by GE channels.

Finally, Chapter 4 investigates the question of how domestic energy policy should respond to the existence of significant rebound effects and what the economic impact of such a response would be. To this end, we endogenously determine the tax rates needed to fully offset economy-wide rebound effects in each year of the time horizon considered. This is tantamount to a cap on the industrial use of the different energy carriers (refined oil, natural gas, and electricity). We only levy the taxes on production, as households do not experience any efficiency improvements. We simulate individual uniform unit taxes for each energy carrier and impose them in both individual scenarios and as part of a comprehensive tax scheme, encompassing all energy carriers. In addition, we analyse how recycling the tax revenue influences the economic impact of energy taxation for the mitigation of rebound effects by comparing four different modes of utilizing the additional tax revenue.

We demonstrate that the mitigation of rebound effects through complementary energy taxation can substantially increase the efficacy of energy efficiency in reducing energy use. While some of the economic benefits from the efficiency stimuli are retained in all simulations, significant tax rates are nonetheless required and the increased costs in production consequently hamper economic activity, as well as welfare. This is particularly accentuated in the case of a comprehensive tax scheme covering all energy carriers, which is nevertheless the most efficient scheme as unwanted substitution effects between energy carriers can be prevented. For economic welfare, we show that the reduction of pre-existing taxes with the new tax revenue is preferable to both increased government purchases and to a lump-sum transfer of the revenue to households. Finally, we also examine a bonus-malus scheme, in which sectors are rewarded for energy use reductions below their historical benchmark energy use and penalised if they remain above. This recycling scheme delivers the most efficient outcome and the largest absorption of the negative economic impact and leads to an almost similar economic outcome than if rebound was not mitigated, albeit with much higher energy savings.

1.4 Structure of thesis

The thesis presented here consists of three connected, yet individual, papers, as illustrated in Figure 1.1. All papers are entirely based on the work I have done over the last four years as part of the current thesis.

Chapter 2 presents a paper assessing rebound effects in Switzerland with a newly developed CGE model. The paper is titled "Do Rebound Effects Matter for Switzerland? Assessing the Effectiveness of Industrial Energy Efficiency Improvements?" and was written by Michel Zimmermann, Frank Vöhringer, Philippe Thalmann, and Vincent Moreau - submitted to *Energy Economics*.

Chapter 3 presents a decomposition analysis of Swiss rebound effects as part of an amended version of the paper "Identifying the Mechanisms of Rebound Effects from Annual Industrial Energy Efficiency Improvements: A Decomposition Analysis". This paper was written by Michel Zimmermann, Frank Vöhringer, Philippe Thalmann, and Vincent Moreau - not yet submitted.

Chapter 4 presents an amended version of a paper investigating the mitigation of rebound effects. The paper titled "The Mitigation of Rebound Effects from Industrial Energy Efficiency: A Computable General Equilibrium Analysis for Switzerland" was written by Michel Zimmermann, Frank Vöhringer, Philippe Thalmann, and Vincent Moreau - not yet submitted.

In order to avoid repetition, the descriptions of the Swiss Energy Efficiency Model in the methodology sections in Chapter 3 and Chapter 4 have been removed. Moreover, the references and the appendices of the individual papers were moved to the end of the thesis.

Figure 1.1: A graphical representation of the structure of the thesis

Chapter 2 Do Rebound Effects Matter for Switzerland? Assessing the Effectiveness of Industrial Energy Efficiency Improvements

Abstract

In energy policy, efficiency improvements are conventional means for reducing industrial energy use as well as related environmental and climate externalities. Unfortunately, the effectiveness of energy efficiency improvements in reducing energy use is known to be limited by rebound effects. These rebound effects arise from economic and behavioral responses to the energy efficiency improvements themselves. In this paper, we show that their magnitude critically depends on the substitutability (or complementarity) of energy with different types of capital. These relationships between energy and capital must, hence, be carefully modeled in the context of rebound assessments. To this end, we develop a new, recursively dynamic computable general equilibrium model for Switzerland, which differentiates the capital stock into capital that is substitutable and capital that is complementary with energy. With this model, we simulate average economy-wide rebound effects of 38%; Sector-specific average rebound effects range from negative rebound effects for energy supply sectors to 48% for the energy-intensive manufacturing industry. The sector-specific results crucially depend on the energy and capital intensities of the respective sectors. A sensitivity analysis shows that our more sophisticated representation of capital lowers the simulated rebound effects. Conversely, existing rebound assessments with a homogenous capital stock may overestimate rebound effects. Nonetheless, both economy-wide and industrial rebound effects in Switzerland remain substantial. When devising energy efficiency policies, it is thus essential to evaluate the expected rebound effects and to compensate for them with complementary policies, such as energy and carbon taxes.

Highlights

- Industrial energy efficiency improvements lead to significant rebound effects
- Sectoral rebound effects largely depend on capital intensity
- The relationship between capital and energy essentially influences rebound effects
- A more differentiated representation of capital lowers rebound effects

Keywords
Rebound effects, energy efficiency, capital-energy substitutability, computable general equilibrium modelling

2.1 Introduction

National energy transition strategies place high expectations on energy efficiency and technological change in order to move towards a low-carbon economy (DETEC 2017; EC, 2019). This relies on the premise that energy efficiency, and thereby the more efficient use of energy, actually leads to absolute reductions of energy use and emissions. However, the notion that increased energy efficiency is as successful as intended in reducing energy use has been frequently challenged, particularly as the evidence for absolute decoupling of economic growth and energy use is relatively sparse. If at all, absolute decoupling has so far been limited to brief time spells, both globally (Brockway et al., 2021) and for countries such as Switzerland (Moreau and Vuille, 2018). One of the reasons for this lies in the existence of rebound effects. Rebound effects occur when there is a difference between actually achieved and the expected energy savings, that is the potential energy savings based on engineering estimates (Kazzoom, 1980; Brookes 1990). By comparing these potential and actual energy savings, the rebound effects (in %) can be calculated, as described in Equation 2.1:

<u>Equation 2.1: The calculation of rebound effects</u>

$$Rebound\ Effect = \left(1 - \frac{Actual\ Energy\ Savings}{Potential\ Energy\ Savings}\right) * 100$$

Introduction

Rebound effects have been frequently studied and discussed ever since the 1980s and are now commonly recognized to be a direct consequence from energy efficiency improvements (EEIs) (Madlener and Turner, 2016)[2]. At its core, an EEI reduces the costs for a given energy service when constant energy prices are assumed (e.g. reduced fuel expenses per kilometer traveled, in the case of a more fuel-efficient vehicle). This leads to direct rebound effects through increased demand for said energy service (e.g. more trips with the new vehicle) and indirect rebound effects via an increase in demand for other goods, which further stimulates energy use. Both direct and indirect rebound effects can consist of substitution effects (i.e. substitution towards the now more efficient energy service) and income effects (i.e. due to the increased disposable income).

Additionally, there exist meso- and macroeconomic rebound effects, which describe economic adjustments that perpetuate rebound effects at higher levels of aggregation: Composition effects (i.e. changes in factor use and the economic structure), market price effects via changes in domestic energy prices, output effects, and (efficiency-induced) growth effects (Santarius, 2016). Finally, at a global level, EEI can also depress world energy prices, which potentially spur energy use and cause additional rebound effects (Fölster and Nyström, 2010). From an economic perspective, rebound effects can be viewed as a positive effect that naturally occurs after technical change (Broberg et al., 2015). Birol and Keppler (2000, p. 462) even describe it as the very thing "that translates technological efficiency improvements into economic growth". Rebound effects thus are only an issue when seeking to reduce energy use or emissions and it subsequently becomes a trade-off between economic growth and the necessity to limit resource use.

This study focuses on Switzerland, which is an interesting case study for the assessment of rebound effects for various reasons: Energy efficiency policies have been widely used to reduce energy demand in a range of areas, such as buildings (via a subsidy/rebate scheme), mobility (via standards) and electricity saving measures (e.g. ProKilowatt; SFOE, 2021c). Moreover, energy efficiency plays a crucial role in the Energy Strategy 2050, in which Switzerland has set additional ambitious energy use reduction targets for households and industrial production. Consequently, it is important to identify potential rebound effects as a consequence of energy efficiency measures to determine the effectiveness and success of energy efficiency in reducing energy use. If energy efficiency measures in Switzerland lead to substantially lower actual energy savings than predicted by ex-ante engineering estimates, this could greatly hinder the efforts of Swiss energy efficiency policies in reducing energy use and emissions. Large rebound effects could thus make more stringent or alternative energy policy schemes necessary. The need for a successful reduction in energy demand is further highlighted by the fact that the Swiss energy supply is characterized by a great dependence on fossil fuels from abroad with almost all natural gas and oil (either as refined oil or crude oil) being imported (SFOE, 2020a). At the same time, Switzerland already has one of the lowest energy intensities in Europe (Odyssee, 2021), which underlines the importance of effective energy efficiency policies.

The possibility of economy-wide rebound effects received no discernible attention in devising the Energy Strategy 2050. Furthermore, no study appears to exist that explicitly measures sector-specific or economy-wide rebound effects as a result of EEIs in Switzerland. This paper intends to fill this research gap. Moreover, we aim to contribute to the debate on the complementarity/substitutability between capital and energy, which has been frequently pointed out as an important determinant of rebound effects (Broadstock et al., 2007). We analyze the rebound effects that occur as a result of EEI in production. The Swiss industry and services sectors account for roughly a third of the total final energy use in Switzerland (SFOE, 2020a) and when transport fuels are included, this share is even larger. It is therefore important to understand how large these rebound effects are at the sector-specific, industry-wide, and economy-wide level, as effective energy efficiency has an important role in reducing this reliance on energy.

The rebound effects for the Swiss economy are measured with the Swiss Energy Efficiency Model (SEEM), which is a newly developed recursive-dynamic computable general equilibrium (CGE) model. It assesses the effectiveness of energy efficiency in Switzerland and tests whether continued efforts in the policy area are worth pursuing by comprehensively modeling the different interactions between economic actors as a result of EEIs. We implement annual EEI contrary to the standard assumption of a one-off increase in energy efficiency, which better reflects the continuous nature of energy efficiency policies. The paper, therefore, adds to the sparse and conflicting understanding in the literature of how annual EEIs impact energy use and, consequently, rebound effects. As aforementioned, the CGE model used here puts special emphasis on the relationship between energy and capital. Traditionally, energy and capital are modeled as weak substitutes, which purports that energy efficiency measures lead firms to decrease their capital use in substituting towards energy.

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[2] For an extensive introduction to rebound effects, see Sorrell (2007).

However, it is our understanding that this is only true for a small share of capital, which is here termed "energy system capital", such as the insulation in a building. For the bulk of capital (subsequently labeled "other capital"), it is assumed to be complementary to energy. As a consequence, increased energy demand after an EEI also induces more demand for "other capital". This provides a more accurate description of real-world conditions and a novel and innovative approach in determining how the relationship between capital and energy perpetuates economy-wide rebound effects as a result of industrial EEIs. In summary, we aim to, for the first time, assess economy-wide rebound effects from annual industrial EEIs in Switzerland with a CGE model that is characterized by its recursively-dynamic nature and a heterogeneous capital stock.

This paper is organized as follows: Section 2.2 discusses the existing work on (industrial) rebound effect assessments with a particular focus on dynamic CGE analyses. Section 2.3 introduces the Swiss Energy Efficiency Model (SEEM), which is a recursive-dynamic CGE model that was designed to measure industrial rebound effects in Switzerland. Section 2.4 shows the results from the implementation of annual EEI over a time horizon from 2020 to 2050, both for key macroeconomic indicators and aggregate and sectoral energy use. It further illustrates some key sensitivities of the model. Section 2.5 discusses the findings from the main simulation and the sensitivity analyses. Finally, Section 2.6 offers a conclusion and some policy recommendations.

2.2 Literature review

Much of the empirical rebound literature has focused on assessing direct and indirect rebound effects from the use of more energy-efficient household appliances. Druckman et al. (2011) and Chitnis et al. (2013; 2014) find that, for UK households, these rebound effects cause the actual energy savings to be much smaller than anticipated or to potentially even backfire. Backfire describes the case when energy consumption increases due to higher energy efficiency. In a similar Swiss study, Mohler et al. (2016) show the direct rebound effects of private transportation to vary between 20% and 60% depending on the empirical approach. These two studies are contrasted by the lack of significant rebound effects that are found in Switzerland for the purchase of more fuel-efficient cars (de Haan et al., 2007). A survey undertaken by Greening et al. (2000) corroborates this and attests direct rebounds to be generally of minor relevance. Meanwhile, moderate direct rebound effects of 20% are found in empirical studies focusing on specific industries such as freight transport (Matos and Silva, 2011) and aviation (Evans and Schäfer, 2013).

For meso- and macroeconomic rebound effects, the magnitude of these effects is similarly uncertain. In an extensive literature review, Stern (2020, p.5.) asks the question of how large are rebound effects at the economy-wide level and concludes that "despite much research on this topic, we do not have a definitive answer". In pursuing this answer, research mainly relies on three overarching methods to evaluate rebound effects (Colmenares et al., 2020): CGE models, macroeconomic models, and econometric analysis. Econometric analysis is used by Brockway et al. (2017), who find large variations in economy-wide rebounds between countries depending on their energy intensity and how export-oriented their economies are. Lemoine (2020) develops a theoretical macroeconomic model with US data to measure and decompose partial and general equilibrium effects. The study shows high rebound effects for energy sectors (80%) and moderate ones for non-energy goods (28%). It further demonstrates that elasticities of substitution are highly critical for these estimates. Rausch and Schwerin (2018) find backfire effects for their macroeconomic model. This model stands out in its vintage capital approach and by its disaggregation of capital into non-energy using capital and energy-using capital, the latter of which is then combined with energy for the production of energy services.

CGE models are frequently used to estimate rebound effects at the economy-wide level, given their ability to analyze the system-wide effects of policy- and non-policy-induced changes at different spatial scales (for a detailed review, see Allan et al., 2007a). Koesler et al. (2016) use a static, multi-regional, multi-sectoral CGE model to investigate the impact of a 10%, one-time, EEI in production for Germany with a special focus on how domestic efficiency stimuli can affect energy use abroad. They apply this in two scenarios – i) in manufacturing only and ii) across all production – and find that domestic rebound effects are substantial, as more than 50% of the potential energy savings are taken back by rebound effects. They also highlight that, when considering the effects in energy use abroad, this leads to a lower global rebound effect. In a comparable static study for the US, Böhringer and Rivers (2018) show even higher economy-wide rebound effects, in which they credit the majority of the rebound effects as resulting from price reductions of energy services (i.e. the direct and indirect rebound effects) and only a small part to be due to economy-wide adjustments.

Literature review

For CGE analyses of rebound effects over time, modelers rely on dynamic models. For instance, Broberg et al (2015) examine the economy-wide rebound effects in Sweden with a dynamic CGE model for an exogenous one-time improvement in energy efficiency. They analyze three different scenarios, in which they vary the number of industries that experience the energy efficiency stimulus, ranging from all industries to only energy-intensive industries. They show that a 5% productivity improvement can lead to economy-wide rebound effects between 40-70%, with particularly high rebound effects among energy-intensive industries. Turner (2009) contrasts these findings by providing evidence for super-conservation (i.e. higher actual energy savings than anticipated and thus negative rebound effects as termed by Saunders, (2008)) in the UK economy after industrial EEI, particularly in the long run. They derive this back to two effects: the negative multiplier effect that stems from a decrease in energy demand and the so-called divestment effect. This effect describes the contraction of domestic energy supply sectors because of a fall in energy prices and a lack of capital accumulation after the improvement. In a fully dynamic analysis of economy-wide rebound effects in Italy, Garau and Mandras (2015) provide some support for the decreasing rebound effects over time found by Turner (2009), particularly in the case of natural gas. The observation of decreasing rebound effects with time directly contradicts the statement by Wei (2007) and Saunders (2008), who argue that rebound effects are always larger in the long run than in the short run as resource availability becomes less constrained in the long term.

Figus et al. (2020) add to this debate by analyzing how the flexibility of energy prices in adjusting to EEI influences the evolution of rebound effects in the long term. They find conditions under which short-term rebounds are larger than in the long run and vice versa, depending on this flexibility. Their study concludes that, ultimately, there is not one single determinant for the evolution of rebounds, and analyses have to holistically interpret rebound effects as a consequence of system-wide macroeconomic effects. What all these CGE analyses have in common is that they limit the introduction of energy efficiency to a one-off improvement. A rare exception to this constitutes Duarte et al. (2018). They use a recursive-dynamic CGE model to investigate the impact of annual EEI that follows a logistic evolution (i.e. an S-shape) for household use of electrical appliances and the use of transport in Spain. Their analysis exhibits strong rebound effects that increase over time to more than 50%.

To our knowledge, Gonseth et al. (2017) is the only study that investigates Swiss rebound effects at the economy-wide level. They investigate the change in energy use from changing heating and cooling needs due to global warming between 2010 and 2060 and whether this change is affected by rebound effects. Their results suggest that there is a sizeable share of total energy savings lost as a consequence of the behavioral and economic adjustments from this change, with economy-wide rebound effects between 35-37% being reported.

Finally, for an export-oriented, small open economy like Switzerland, another potentially important element is how domestic EEIs influence trade and how this relates to rebound effects. These improvements are usually modeled as occurring exclusively in the domestic economy, under a *ceteris paribus* condition. The effect of this on rebound effects is inconclusive: Broberg et al. (2015) purports little sensitivity of rebound effects regarding trade elasticities and subsequently trade flows. Meanwhile, Turner (2008) indicates that the occurrence of rebound effects for the UK and Scotland are strongly influenced by their respective degree of openness, particularly regarding energy trade.

CGE models and their use for the assessment of rebound effects are subject to a number of limitations. Firstly, their calibration oftentimes relies on social accounting matrices (SAM), which usually provide a snapshot of an economy in a given year. An additional issue is the choice of the functional form of both utility and production functions and, in particular, its impact on the rebound effect. In a review of different production functions, Saunders (2008) suggests that certain functional forms, such as the widely used Cobb-Douglas production function, might a priori pre-determine the rebound results (i.e. backfire). Lecca et al. (2011) also champion more sensitivity analysis for CGE models in general, particularly when using nested constant elasticity of substitution (CES) functions. They investigate specifically how the point in which energy enters the production function can influence the simulation results when analyzing exogenous shocks. In rebound assessments, energy is often modeled as a direct substitute to capital. Lecca et al. (2011) show that changing the elasticity of substitution between energy and capital greatly influences both macroeconomic indicators and energy use, indicating a potential key elasticity of substitution when assessing rebound effects. This underlines the fact that the choice of elasticities of substitution in CGE models is particularly important. Yet, they are notoriously challenging to empirically estimate. If models use existing estimates from the literature, they tend to greatly differ, as Broadstock et al. (2007) show.

This thus further warrants sensitivity analyses when analyzing EEIs. Sensitivity analyses have indeed been routinely included in the majority of CGE model simulations that investigate economy-wide rebound effects. The analyses undertaken comprise, inter alia, the assumptions with respect to the labor market (fixed vs. flexible labor supply in the case of Broberg et al., (2015)), the elasticities of substitution for different nests (Turner et al., 2009) or different nestings altogether (Garau and Mandras, 2015), and whether the efficiency stimulus is costless or not (Allan et al., 2007b).

2.3 Method

The Swiss Energy Efficiency Model (SEEM) is a newly developed multi-sectoral recursive-dynamic CGE model of Switzerland with a time horizon from 2020 until 2050.[3] Households are represented by a myopic representative agent, who maximizes utility by consuming goods and services at given prices under a budget constraint. Households choose between labor and leisure, which is determined by an exogenous labor endowment and the endogenous wage rate in each period. In each year, the household's constant marginal propensity to save determines investment. The government collects a range of taxes: an income tax on labor compensation and capital, social security contributions, export and import tariffs, a tax on the use of fossil fuels and electricity, and net commodity taxes (i.e. a collection of output taxes, such as VAT). The benchmark tax rates correspond to current fiscal settings. The tax revenue is used for the procurement and provision of public goods. By endogenous modification of the income taxes, a constant public goods provision is implemented over the time horizon (equal yield assumption).

Firms are assumed to be profit-maximizing with all markets being perfectly competitive and without possibilities for economies of scale. The output (Y) for each sector *i* is produced by combining the production factors capital (K), labor (L), energy (E), and intermediate commodities and materials (M), with exogenously set productivity factors specific to each production factor (γ_i). The sectoral demands for each output or commodity (*c*) by sector (j) are adjusted by changes in the relative factor prices.

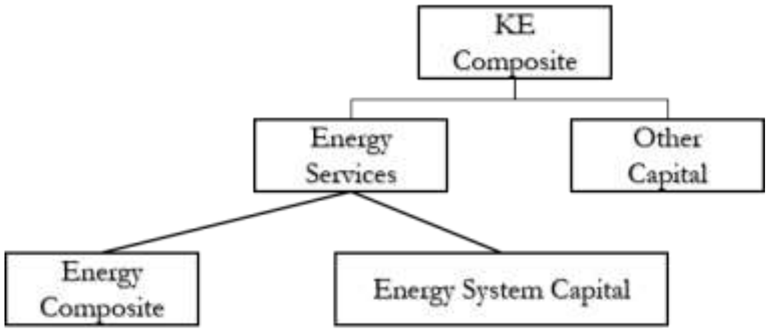
In this research, we differentiate two types of capital: energy system capital (ESC) and "other capital" (OC). ESC represents the part of the capital that turns energy into usable energy (e.g. the internal combustion engine of a truck or the kiln in a cement factory). OC refers to the remaining capital (e.g. the truck itself or the factory the kiln is located in). This accounts for the ongoing and inconclusive debate on whether capital and energy are supposed to be complements or substitutes (Broadstock et al., 2007). By differentiating the two types of capital, the model represents the fact that some capital can effectively be substituted for energy (i.e. the ESC) in the case of EEIs. Meanwhile, certain capital can only be used in a complementary fashion (i.e. OC) and actually increases with the higher demand for energy services as a result of the efficiency stimulus. As data availability on the different types of capital is sparse for Switzerland, it was assumed that ESC makes up 10% of total capital. This seems to be a good approximation since energy systems (e.g. heating systems, insulation or engines) comprise only a small part of buildings, machines, and equipment.

Both the utility function and the production function are modeled as nested CES functions. The nesting structure of the production function follows the GTAP-E model. GTAP-E is an expansion of the well-established GTAP CGE model, which specifically takes into account the possibility of energy substitution. In GTAP-E, energy is modeled as part of the value-added nest (Burniaux and Truong, 2002). To account for the distinction between ESC and OC, some adjustments are made to the nesting tree. As illustrated in Figure 2.1, the energy composite is combined with ESC and turned into an energy service. While the former and energy are assumed to be weakly substitutable, OC is then combined with the energy service in a Leontief function, as a change in the price of the energy service will not induce any substitution with OC.

In Figure 2.1, this Leontief function is represented by the kinked lines. The KE-composite, together with labor, is then used in combination with intermediate goods to produce a good or service. For the refined oil and gas sector, there is an additional input at the top level in a Leontief fashion with crude oil and natural gas imports, respectively. The full nesting tree of the production function in SEEM is shown in the Appendix.

[3] An algebraic representation and a glossary of all variables and parameters of the SEEM model are provided in the appendix

Figure 2.1: Subset of the nesting structure, highlighting the relationship between the energy composite, ESC and OC



Switzerland is modeled as a small open economy in SEEM and thus domestic price changes do not influence world prices. Domestic and foreign goods are considered to be imperfect substitutes governed by Armington elasticities for import. Elasticities of transformation are applied to account for the difference in selling goods domestically or abroad. The trade deficit for Switzerland is used as a closure rule for the balance of trade, which is fixed for each time period of the model simulation. Both imports and exports are further valued via a foreign exchange rate, which is used to clear the trade markets.

Both trade and production elasticities of substitution are taken from the literature. For the Armington elasticities, we use estimates from the GTAP-E model (Burniaux and Truong, 2002), which forms the basis of the nesting structure applied in SEEM. Certain values, however, are adjusted downwards to account for Swiss trade characteristics, such as for the transport and the services sectors. The elasticities of substitution in production in the top nest are from Okagawa and Ban (2008). The authors provide estimates based on data for OECD countries for a nesting structure, in which energy is part of the value added as in SEEM. A crucial parameter concerns the sector-specific elasticities of substitution between ESC and the energy composite, which are shown in Table 2.1. For the primary and secondary sectors, we can rely on specific Swiss estimates from Mohler and Müller (2012) from a data set spanning 12 years. The study by Okagawa and Ban (2008) is the source for the remaining sectors. While a direct comparison is challenging due to our novel nesting approach, the overview of various nesting structures in Van der Werff (2008) indicates that our values are at the lower end. Finally, inter-fuel substitution is governed by elasticities of substitution from the GTAP-E model (Burniaux and Truong, 2002). All consumption elasticities are based on Paltsev et al. (2005). An overview of all elasticities of substitution is provided in the Appendix.

Table 2.1: The elasticities of substitution between ESC and the energy composite for the different sectors in SEEM

Energy-intensive manufacturing industry	Rest-of-industry sector	Transport sector	Services sector	Refined oil sector	Natural gas (distribution) sector	Electricity production, transmission and distribution	*Unweighted mean*
0.34	0.44	0.45	0.5	0.1	0.1	0.5	*0.35*

In SEEM, the Swiss economy is summarized into seven representative sectors (*i*) with four non-energy goods sectors and three energy supply sectors. The four non-energy goods sectors are divided along their reliance on energy as an input for production: The energy-intensive manufacturing industry sector and the transport sector both comprise the most energy-intensive sectors in Switzerland in the first and secondary sector, and the tertiary sector, respectively. The remaining low energy-intensive sectors are summarized in a "rest-of-industry" sector and the services sector. Energy supply in Switzerland is aggregated into three main sectors: the refined oil sector, which encompasses all types of liquid fuels, and the very insignificant Swiss coal production; the natural gas (distribution) sector and the electricity production, transmission and distribution sector. Beyond the industry-specific commodity of each sector, SEEM further contains two additional energy carriers, namely imported crude oil - that is turned into refined oil in the refined oil sector - and natural gas imports, which is the main input for the natural gas (distribution) sector. There is no substantial resource extraction in Switzerland and this is therefore neglected in the analysis. The whole sector aggregation with the corresponding NOGA classifications is shown in the Appendix[4].

The SAM used in SEEM is based on the Swiss energy input-output table of 2014 (Nathani et al., 2019), which is an energy-specific disaggregation of the Swiss input-output table published by the Swiss Federal Statistics Office. Energy supply and use in the energy input-output table are based on official energy flow accounts and transformed to monetary values by multiplying the physical values with estimated energy prices per fuel source for 2014. The same energy prices are used in the subsequent result section to convert monetary model outputs into physical outputs. Finally, all references to energy in this work relate to final energy rather than primary energy to ensure consistency with the data inputs from the energy input-output table.

The recursive-dynamic nature of the CGE model implies that actors take their decisions sequentially at the start of each period over the 30-year time horizon based on the relative prices in each period and the investment of the previous period. SEEM is modeled in the programming language "mathematical programming system for general equilibrium analysis" (MPSGE) in GAMS (Rutherford, 1999), using the PATH solver. In SEEM, capital is modeled with a putty-clay formulation. New capital is invested in the two capital types (putty) and once it is installed, it cannot be changed and used elsewhere (clay). The total capital stock at the beginning of each period is the sum of the newly installed capital based on the investment of the previous period and the existing capital stock, which is depreciated at a constant rate. The supplied labor can move freely across domestic sectors.

As the reference steady-state scenario (SS scenario), the model is run based on the benchmark data, assuming a steady-state of the economy over the entire time horizon. The growth rate is determined by the increase in labor supply, based on the central population growth scenario for Switzerland (FSO, 2020). There are no EEI in the SS scenario. All results shown in the following are compared to the SS scenario. The consumer price index, which refers to the average price of consuming the goods and services available, is used as numeraire and therefore all prices are expressed relative to it.

In the main scenario (the R-EEI scenario), an annual EEI of 2.2% p.a. for all production sectors is implemented. The improvement is assumed to be exogenous and available at no cost. It is modeled as biased technical change $\gamma_{EC,t}$ by increasing the productivity factor of each energy input and hence enabling the same amount of output with less energy, as illustrated in Equation 2.2. Equation 2.2 shows the production function of the goods "energy services", where the energy composite and ESC are combined, with $\alpha_{ES,i}$ describing the value shares at this nest and $\rho_{ES,i}$ the sector-specific constant elasticity of substitution.

<u>Equation 2.2: The production function at the nest between the energy composite and ESC</u>

$$ES_{i,t} = \left[\alpha_{ES,i}\left((1+\gamma_{EC,t}) * EC_{i,t}\right)^{\rho_{ES,i}} + (1-\alpha_{ES,i})\left(ESC_{i,t}\right)^{\rho_{ES,i}}\right]^{\frac{1}{\rho_{ES,i}}}$$

This work aims to specifically investigate industrial rebound effects in Switzerland and how increased industrial energy efficiency impacts energy use and the economy. As a consequence, households do not experience any EEIs, nor do other countries in the rest of the world. For Switzerland to achieve its envisioned final energy use by 2035, a 43% reduction compared to 2000 is required (SFOE, 2020b). This is tantamount to an annual reduction of 2.2%, which corresponds to our chosen annual EEI. As this estimate encompasses all final energy use (incl. households) and is absent of any incorporated rebound effects, the 2.2% is to be interpreted as the lower bound of the yearly improvements needed to achieve the reduction target. Until 2050, simple calculus suggests that this amounts to an industry-wide improvement of energy efficiency of roughly 50% compared to 2020. Since industrial energy demand only accounts for 56% of total energy demand (with households using the remaining 44%), the annual domestic shock reduces to 1.23%. Any deviation from these values in the simulation results will be due to rebound effects.

The industry-specific, industry-wide and economy-wide rebound effects are calculated with Equation 2.3 below, where $\dot{E}_t^i$ represents the change in physical energy use of a sector i relative to the SS scenario for a given year, and $\gamma_{EC,t}$ the cumulative

[4] NOGA is the general classification of Economic Activities for Switzerland (Nomenclature générale des activités économiques NOGA).

EEI in year t. Similarly, the industry-wide and the economy-wide rebound effects are calculated by comparing the percentage response of the total industrial physical energy use $\dot{E}_t$ to the EEI $\gamma_{EC,t}$. For economy-wide rebound effects, we compare the total change in energy use (i.e. production + consumption) and the corresponding cumulative annual domestic shock (i.e. based on the aforementioned 1.23%).

Equation 2.3: The calculation of sector-specific rebound effects

$$R_t^i = \left(1 + \frac{\dot{E}_t^i}{\gamma_{EC,t}}\right) x\ 100$$

2.4 Results

2.4.1 The rebound effects from annual industrial energy efficiency improvements

The physical energy savings from annual industrial EEIs in Switzerland fall short of what is suggested from the engineering estimates. This is illustrated in Table 2.2, which shows the short-, mid- and long-term rebound effects. The table further indicates the share of each sector of total final physical energy use in production and the value share of final energy use as a production input. The energy-intensive manufacturing sector and the services sector have the highest sectoral rebound effects of almost 60% and 40%, respectively, after the introduction of the first improvement, indicating a relatively low efficacy of energy efficiency. For both sectors, the rebound effects in the mid- and long-term then gradually decrease, which hints at decreasing substitution, the more efficiently energy is used. This is particularly pronounced for the energy-intensive manufacturing industry, for which the annual sector-specific rebound effects drop to almost 50% of the initial level. Meanwhile, the annual improvements are more effective in reducing energy use for the transport sector and the rest-of-industry sector. But even for the rest-of-industry sector, almost 20% of all energy savings are offset by economic adjustments in 2050, following the efficiency stimulus.

The energy supply sectors show a different picture. The electricity sector with a relatively low reliance on intermediate inputs results in marginally higher energy use than anticipated. The share of eroded energy savings grows over time, which diverges from the evolution of the non-energy goods sectors. The refined oil sector and the gas sector experience super-conservation. This super-conservation and the resulting reduction in energy use beyond what was expected from the engineering estimates mainly stems from the fact that their production is heavily reliant on imports of crude oil and gas, respectively. These inputs are bought at world prices independent of domestic price changes and are thus unaffected by domestic EEIs. Overall, energy inputs constitute only a small share of the energy supply sectors' input mix. Hence, the impact of the positive rebound for the electricity sector and super-conservation for the fossil fuel sectors of their energy use is negligible in absolute terms.

The weighted sum of these sectoral rebound effects equals 38% overall rebound effect in the first period after the first EEI, which gradually decreases over time to below 30% in 2050. The industry-wide rebound effects in a given year thus decrease with each additional EEI. The total rebound effects, which include the change in final energy use, are larger and amount to roughly 34% in 2050. Households benefit from the price adjustments that occur due to the increased efficiency stimulating consumption, which is further amplified via an income effect. In Switzerland, rebound effects thus significantly erode absolute energy savings from increased energy efficiency.

Table 2.2: The rebound effects after annual improvements of 2.2% in industrial energy efficiency for the short-, mid- and long-term (in %)

Sectors			Annual improvement of 2.2% p.a.		
	Share in total physical final energy use	Value share of final energy of each sector	2021	2035	2050
Energy-intensive manufacturing industry	23.6%	5.5%	57.3%	48.2%	39.6%
Rest-of-industry sector	11.2%	1.1%	19.7%	19.1%	18.3%
Transport sector	25.3%	7.7%	29.1%	25.1%	21.2%
Services sector	38.4%	1.4%	37.5%	35.0%	32.1%
Refined oil sector	<0.1%	0.4%	-24.9%	-19.0%	-14.2%
Natural gas (distribution) sector	<0.1%	<0.1%	-19.5%	-15.2%	-11.6%
Electricity production, transmission and distribution	1.5%	1.0%	4.6%	6.0%	6.9%
Industry-wide rebound effect			**37.5%**	**33.3%**	**29.2%**
Economy-wide rebound effect			**40.8%**	**37.3%**	**33.9%**

These rebound effects are a direct consequence of economic and behavioral adjustments to EEIs. Table 2.3 gives an overview of several key aggregate macroeconomic indicators in 2050. The impact on the aggregate economic activity remains relatively small, even though industrial energy efficiency increases by 2.2% p.a. and a total of 47% in 2050. This lowers costs of production and increases competitiveness and thus GDP grows by an additional 1.7% in 2050, relative to the steady-state. This is partially reflected in an increase in production output, as well as stronger demand for domestically produced goods. The expansion of the economy and the strengthened competitiveness of its industries further leads to higher aggregate demand from abroad, as well as an increase in imported goods.

EEIs also improve the productivity of each worker and therefore the real wage rate increases by almost 1.9% in the long-run. Higher wages incentivize households to forgo leisure and instead increase the labor supplied to the economy. These positive income effects induce higher consumption by households and households' savings, which stimulates growth in annual investment. The total capital stock increases in line with the expansion of the economy, although there is a clear shift away from ESC towards OC. Overall, EEIs positively impact total welfare, which is 1.54% higher than in the SS scenario without energy efficiency. Welfare here entails consumption and leisure. Ancillary benefits such as (positive) externalities are not included.

Table 2.3 also indicates the effect of energy efficiency on household, industry-wide and domestic physical energy use. Benefitting from income effects and cheaper oil prices, household energy use increases by 2.9% more in 2050 than without any EEIs. Meanwhile, industrial energy use is reduced by roughly a third compared to the SS scenario. On average, final domestic energy use falls by 17.9%.

Results

Table 2.3: Overview of aggregate macroeconomic indicators for 2050, relative to the steady-state scenario (in percentage changes)

Indicator	*2050*
GDP (expenditure approach)	1.6%
Domestic Production	0.7%
Domestic Demand	0.7%
Exports	0.6%
Imports	0.7%
Private Consumption	2.8%
Investments (public + private)	1.5%
Working hours	0.04%
Real Wage	1.9%
Total OC supply	1.6%
Total ESC supply	-7.7%
Rental Rate of capital	1.4%
Hicksian Welfare Index	1.5%
Household energy use	2.9%
Industrial energy use	-34.0%
Domestic energy use	-17.8%

The year-on-year rise in energy efficiency does reduce total energy use and positively impacts the economy as a whole. The different sectors in SEEM have, however, varying input mixes and are thus expected to respond quite differently to the industrial energy efficiency stimulus. Table 2.4 reveals great sectoral differences in how producer prices (relative to consumer price index) and production are affected. These changes largely correspond to the respective energy intensities of the sectors. As a result, the strengthened competitiveness and subsequent positive output effects are heavily concentrated in the two most energy-intensive sectors. Both the energy-intensive manufacturing industry and the transport sector are capable of capitalizing on the decreased marginal cost of production and expanding their production, which lowers the prices of their outputs through supply and demand adjustments in the model. This is particularly pronounced for the manufacturing sector (-6% in 2050). Being a very trade-dependent sector, its domestic products gain a price advantage over their foreign competitors and the sector consequently experiences an increase in exports of more than 25%.

Table 2.4: Percentage change in producer prices, output (sold domestically and exported) and imports, relative to the steady-state scenario in 2050

	Producer prices	**Output**	**Output to domestic market**	**Exports**	**Imports**
Energy intensive manufacturing industry	-6.1%	22.6%	12.2%	25.3%	-2.2%
Rest-of-industry sector	1.8%	-6.0%	-2.5%	-7.5%	4.2%
Transport sector	-3.9%	6.6%	4.8%	11.6%	3.0%
Services sector	0.7%	0.5%	1.3%	-1.9%	2.5%
Refined oil sector	-1.1%	-16.2%	-16.3%	-16.0%	-16.7%
Natural gas (distribution) sector	0.03%	-16.3%	-16.3%	n/a	-16.3%
Electricity production, transmission and distribution	0.5%	-18.5%	-18.0%	-20.2%	-17.3%

The effect on the much less energy-intensive rest-of-industry sector is essentially the opposite. The domestic sector shows signs of a contraction in sales, both in the domestic market and abroad, due to its comparative disadvantage to benefit from the stimulus in energy efficiency. This puts upward pressure on its price and leads intermediate and final demand to be satisfied by imported goods. Moreover, given the price increase, other sectors that use rest-of-industry goods as intermediate inputs also substitute away towards more alternative intermediate goods, leading to additional demand reductions. The effects on the services sector are more ambiguous. Capital and labor inputs constitute 80% of its production mix, which becomes more expensive as a result of the EEI. Therefore, the sector's cost of production and domestic output price increase. However, its goods and services constitute an important input for consumption and other sectors, particularly the transport and energy-intensive manufacturing sector, which increases domestic demand nonetheless. Given the weak substitutability between domestically produced and imported services, both indicators increase relative to the SS scenario to satisfy this demand.

Generally, less tradable goods exhibit smaller changes. For instance, even though the transport sector has the highest energy intensity of all sectors, its adjustments are subtler than in the manufacturing sector. Production by the three energy sectors drastically shrinks in size, although there are some differences between them, which mainly stem from their input mix. The electricity sector mainly relies on domestic inputs, which increases its exposure to price changes and thus drives up costs of production and output prices. Meanwhile, the main inputs for the gas and refined oil sector are imported natural gas and crude oil, the price of which are primarily determined by the foreign exchange rate *PFX*. This is particularly pronounced for the refined oil sector. As imports get comparatively less expensive than other factor inputs, their sectoral output decreases less.

The yearly economy-wide rebound effects are on average 37%. If expressed in physical units, the cumulative total energy not saved due to rebound effects amounts to roughly 1900 PJ over the 30 years, which is more than twice the total final energy used in Switzerland in 2019 (SFOE, 2020a). The comparison of GDP and domestic energy use (i.e. the degree of decoupling) further reveals an average annual decrease in energy intensity (TJ/mCHF) of -0.7%, which would have been significantly higher if no rebound effects occurred (-1.1%). In summary, the rebound effects in Switzerland estimated in this work are substantial and it can thus be concluded that energy efficiency in Switzerland is only partially effective in reducing industrial energy use.

2.4.2 Sensitivity analysis: altering the relationship between energy and capital

The relationship between energy and capital is an important element in assessing rebound effects. The disaggregation of the capital stock, into substitutable ESC and complementary OC, in this analysis aims to better represent how these two production factors relate to each other to gauge how this decision and the chosen elasticities of substitution ultimately affect the result. In order to achieve this, a sensitivity analysis is undertaken. We simulate individually: a doubling of the sector-specific elasticities of substitution between the energy composite and ESC; a doubling of the previously 10% share of ESC in total capital supply; dropping the assumption that energy services and OC are complementary by assigning the same substitution elasticity as nested with energy and ESC. The results are illustrated in Table 2.5.

The doubling of the energy-ESC substitution elasticities substantially increases both the industry-wide and total economy-wide rebound effects, compared to the R-EEI scenario. This is particularly pronounced in the service sector, which is now the sector with the most potential energy savings eroded in 2050, both in relative and absolute terms. Higher elasticities of substitution significantly augment the sensitivity of factor allocation to price changes and thus allow the economic actors to take better advantage of the reduction in the effective price of energy due to the EEI. The greater ease with which production factors can be (re-)allocated strengthens GDP growth and allows industries to expand their production in comparison with the R-EEI scenario. This expansion is also aided by a significantly lesser contraction of the energy supply sector due to the higher energy demand, particularly for the electricity sector. Larger rebound effects also lead to more energy used per worker and thus increase labor productivity. Real wages and income consequently rise, which induces higher consumption and more investment. The rental rate of capital is lower in this simulation, as higher elasticities lead to more substitution away from capital. The positive impact on production and energy use from an increase in the elasticity of substitution between capital and energy is corroborated by Lecca et al. (2011). Moreover, it brings the modeled elasticities of substitution and thus the measured aggregate rebound effects more in line with comparable rebound assessments, as an overview of sensitivity analyses by CGE rebound assessments in Brockway et al. (2021) demonstrates.

Results

Table 2.5: Change in key macroeconomic indicators and aggregate rebound effects for changing assumptions regarding the relationship between energy and capital in 2050, relative to the steady-state scenario

	EEI scenario	**Doubling the elasticity between energy composite and ESC**	**Doubling the share of ESC in total capital**	***Removing Leontief assumption between energy services and OC***
GDP	1.7%	2.0%	1.8%	1.9%
Domestic production	0.7%	1.3%	0.8%	1.6%
Private consumption	2.8%	3.5%	3.0%	3.3%
Investment	1.5%	1.8%	1.59%	1.7%
Real wage	1.9%	2.6%	2.0%	2.4%
Rental rate of capital	1.4%	1.0%	1.3%	1.1%
Industry-wide rebound effect	29.2%	51.1%	34.9%	45.9%
Economy-wide rebound effect	33.9%	56.9%	39.9%	51.5%

With a doubling of ESC in the total capital stock, energy system capital becomes a more relevant input and cost factor for the production of goods and services. Consequently, any change in the price of effective energy brings about bigger substitution effects towards energy use away from ESC, as shown for both the industry-wide and the economy-wide rebound effect. As in the case of higher elasticity between the two production factors, the increased rebound effects induce economic growth compared to the R-EEI scenario, as well as income effects. Overall, the results are less sensitive to the choice of the share of ESC than to the choice of the elasticity of substitution between energy and ESC.

Finally, we test the influence of the assumed complementarity between energy services and OC. The previous Leontief function is thereby replaced by a CES nest with elasticities of substitution, which are the same as between energy and ESC. As expected, the increased flexibility in the model allows production to more readily react to price changes. This triggers an increase in rebound effects and macroeconomic indicators in comparison to the R-EEI scenario, which is almost on par with a doubling of the elasticity between energy composite and ESC. The biggest difference between the two sensitivity analyses is the origin of the rebound effect. With a doubling of the energy-ESC substitution elasticity, the rebound effects are largely driven by substitution between energy and ESC. Without the complementarity between the energy service and OC, both ESC and OC grow at a uniform rate. The erosion of energy savings is thus perpetuated at a higher level by replacing OC with additional goods of "energy services" as a result of the stimulus in energy efficiency.

2.4.3 Sensitivity analysis: increasing the elasticities of substitution in production with time

An interesting finding of the R-EEI scenario is that sectoral rebound effect trajectories differ with respect to temporal patterns. For the majority of the sectors and at the aggregate level, annual rebound effects decrease over time, with varying speed. Meanwhile, the energy supply sectors see their rebound effects grow with each annual EEI. In SEEM, the elasticities of substitution are constant and there is no accounting for differences in short- and long-term elasticities. In doing so, we assume that the ease with which factor allocation can be adjusted stays constant in all periods, which is a reasonable assumption for myopic actors as in SEEM. However, in reality, actors are likely to change their factor allocation in the long-run, which is why long-run elasticities tend to be larger than short-run elasticities. We test the impact of this on rebound effects and their evolution by linearly increasing the elasticities of substitution in production so that the final values in 2050 are double the starting values in 2021. In 2050, the unweighted mean average of the elasticity of substitution at the top level is 0.45 and 0.7 between ESC and the energy composite. As Table 2.6 shows, the increasing elasticities of substitution have a profound impact on the evolution of rebound effects over time.

Compared to the R-EEI scenario, the sector-specific rebound effects grow with each additional efficiency stimulus. The only exception constitutes the energy-intensive industry, which stays more or less constant over the mid- and long-term. The increase in rebound effects is particularly pronounced for the services sector, the rest-of-industry sector and the electricity sector. All these sectors exhibit above-average capital intensity. In the case of the electricity sector, the high benchmark capital use in combination with an already comparatively high elasticity of substitution leads to tenfold the rebound effects. The increased flexibility thus induces (very) strong substitution away from ESC towards energy. This is also mirrored in the industry-wide and economy-wide rebound effects in 2050, which almost double in size as opposed to the scenario with constant elasticities of substitution. Garau et al. (2015) similarly find rebound effects twice as large in the long-run after almost doubling the production elasticities of substitution in their CGE model for Italy.

The economic consequences in this scenario are much less pronounced than might be expected given the drastic change in rebound effects. While there is increased economic growth, production, investment and private consumption, the difference between the two scenarios is nowhere of the magnitude of the difference in sectoral rebound effects and mainly stems from the increased activity in the energy supply sectors.

Table 2.6: Rebound effects in 2050 for the main scenario and the sensitivity analysis with a linear increase in the elasticities of substitution in production, relative to the steady-state scenario

Sectors	R-EEI scenario			Doubling of production elasticities in 30 years		
	2021	2035	2050	2021	2035	2050
Energy-intensive manufacturing industry	57.3%	48.2%	39.6%	57.3%	55.5%	57.3%
Rest-of-industry sector	19.5%	19.1%	18.3%	19.5%	30.4%	45.4%
Transport	29.1%	25.1%	21.2%	29.1%	32.7%	38.0%
Service sectors	37.5%	35.0%	32.1%	37.5%	49.4%	69.0%
Refined oil sector	-24.9%	-19.0%	-14.2%	-24.9%	-13.6%	-3.8%
Natural gas (distribution) sector	-19.5%	-15.3%	-11.6%	-19.4%	-7.8%	3.3%
Electricity production, transmission and distribution	4.6%	6.0%	6.9%	4.6%	25.2%	52.7%
Industry-wide rebound effect	**37.5%**	**33.3%**	**29.2%**	**37.5%**	**44.0%**	**55.5%**
Economy-wide rebound effect	**40.8%**	**37.3%**	**33.9%**	**40.8%**	**48.0%**	**60.1%**

2.5 Discussion

The assessment of the rebound effects from continuous industrial EEIs for Switzerland yields several interesting insights. First, the study shows that the efficiency improvements in Switzerland indeed reduce final energy use at both the industry-wide and the economy-wide level, but the effectiveness of these improvements is crucially limited through the occurrence of substantial rebound effects. In the R-EEI scenario and as an average over 30 years, 38% of the annual economy-wide energy savings are lost as a consequence of economic adjustments to energy efficiency measures. These economic adjustments result from lower effective energy prices, which cause substitution towards energy. Moreover, EEIs trigger income effects by reducing the cost of production for firms and by relaxing the budget constraints on households. This stimulates private consumption and leads to an overall expansion of production. The economy-wide rebound effects measured in this work focus more towards the lower end of the estimates collected in a recent review by Brockway et al. (2021). They find a median of economy-wide rebound effects of 60% in a sample of 14 studies assessing industrial EEIs. The overwhelming majority of these studies do not however consider annual increases in efficiency.

Moreover, the direct comparison of rebound assessments with CGE models is difficult, as is underlined by the sensitivity analyses presented here, which exhibit significantly higher rebound effects for modified parameter values and nesting structures. Similarly, readers have to take caution in comparing rebound assessments from CGE models as SEEM with alternative modeling approaches, such as Rausch and Schwerin (2018). They find a backfire effect (>100% rebound effect) from endogenous investment-specific technological change with their macroeconomic model. They lead this back to a cross-price effect, as a result of which capital prices decrease more than energy prices increase, thus inducing more energy use than without energy efficiency improvements altogether. This effect is, however, not present in SEEM.

Second, the effect from the industrial EEIs on the sectors modeled in SEEM differs greatly, both in terms of how their production is affected and how this perpetuates sectoral rebound effects. This can be illustrated for the two sectors for which rebound effects are highest, namely the energy-intensive manufacturing industry and the service sector. The energy-intensive manufacturing industry in Switzerland profits from the increased competitiveness and expands its production.

Discussion

This expansion itself induces an increase in the sector's energy demand, which points at a primarily growth-induced origin of its high rebound effects. Meanwhile, the services sector has a lower-than-average energy intensity, yet nonetheless experiences substantial erosion of its potential energy savings. In Switzerland, the services sector is the sector that has the highest share of value added, which provides more scope for substitution with energy as the effective price of energy decreases with each additional EEI. In addition, the value of its elasticity of substitution between energy and ESC is higher than for other sectors, making the decision to choose between energy and ESC particularly sensitive to price changes. As a result, this is an important driver for this sector's rebound effects. The sensitivity analysis of the relationship between capital and energy confirms the impact of the varying drivers on the rebound effects of the manufacturing sector and the services sector. The services sector and its energy use are greatly influenced by any change in the elasticities between energy and ESC and thus overtakes the energy-intensive manufacturing industry as the sector that rebounds the most. Conversely, the impact of the changed elasticities on sectoral economic performance and, therefore, the rebound effects for the manufacturing sector are less pronounced.

The effects on the other sectors can similarly be explained with the dynamics illustrated above. For instance, the electricity sector has a similar capital intensity and the same elasticity of substitution at the relevant nest as the services sector. Its rebound effects are, however, substantially lower. In this case, demand reductions outweigh the potential substitution effects to increase energy use and rebound effects. It is similar in the transport sector and rest-of-industry sector. Transport is the most energy-intensive sector and experiences growth-induced rebound effects. These effects are however much smaller than in the case of the energy-intensive manufacturing industry since transported goods are traded less internationally. Moreover, it also has a lower capital intensity than other sectors, which restricts possibilities for further substitution. The rest-of-industry sector, in turn, shows clear substitution effects inducing rebounds that are however hamstrung by the contraction of its production. Similarly, reduced fossil fuel demand implies negative rebound effects in the fossil fuel sectors.

Third, the Swiss economy experiences a form of 'Dutch disease', which originated from a situation when existing sectors in a small open economy are adversely affected by asymmetric growth between different industries due to a change in factor endowments (Corden and Neary, 1982). EEIs in SEEM trigger such asymmetries as a result of the varying energy intensities. Specifically, for the two manufacturing sectors: the energy-intensive manufacturing sector experiences a boom and production in the rest-of-industry sector strongly contracts. These tendencies are further amplified by trade effects, which highlights the need to consider trade dynamics when introducing energy efficiency measures. This is true, even if the EEIs introduced here are assumed to be only domestic, while technological progress actually is likely to be a more global phenomenon.

Rebound effects decrease with time both at the aggregate level and for non-energy goods sectors. In SEEM, EEIs are introduced continuously and at a constant rate of 2.2% p.a. As a corollary, the energy-saving gains from each additional EEI decrease in absolute terms, since, for instance, a 2.2% improvement for a vehicle that needs 10l/100km has comparatively more potential to save energy than an already more efficient vehicle. In contrast to our approach, Duarte et al. (2018) introduce EEIs along a sigmoid function and arrive at increasing rebound effects over time. We find that the introduction of constant annual stimuli does not necessarily predetermine that rebound effects decrease, as evidenced by our sensitivity analysis with increasing production elasticities with time. The change in the time path of rebound effects thus shows that greater factor substitutability in the long-run can in fact induce increasing rebound effects. This thus lends some support to findings made by Wei (2007) and Saunders (2008) regarding the potentially greater rebound effects in the long-term due to increased factor flexibility.

Finally, when we drop the assumption that energy services and OCC are complements, rebound effects and the economic effects of EEIs become larger. The literature is clear on the augmenting impact of further substitution possibilities on the erosion of energy savings. Our assumption of identical elasticities of substitution at the two nests, where capital is combined with the energy composite and energy services, respectively, means that the results are identical to a simulation in which there is no disaggregation between ESC and OC in the first place. It can be concluded that our novel representation of the relationship between energy and capital has a lowering effect on the assessment of rebound effects. This results in the corollary that representing capital as a homogenous production factor overstates the rebound effects that occur from EEIs.

2.6 Conclusion

The paper investigates the impact of continuous industrial EEIs on the Swiss economy with a recursive-dynamic CGE model. It puts special emphasis on the relationship between capital and energy by disaggregating the capital stock into energy system capital and "other capital", which are considered substitutes and complements to energy, respectively. Our simulations show that energy efficiency measures are only partially successful in reducing energy use. Industry-wide and economy-wide rebound effects erode more than a third of annual energy savings. The more productive use of energy increases GDP and income. Additional investment further enhances these growth effects. Industrial energy efficiency measures in Switzerland thus have positive economic effects. From an energy policy perspective, however, it is clear that a solid understanding of the resulting rebound effects in Switzerland is paramount, otherwise, the established national energy use reduction targets will likely be missed.

A closer look at the impact of efficiency stimuli on the different sectors modeled in SEEM reveals substantial differences in how sectors benefit. Sectors such as the energy-intensive manufacturing industry or the capital-intensive services sector show large sectoral rebound effects as a result of efficiency-induced growth effects and substitution effects, respectively. The less energy-intensive parts of the primary and secondary sectors contract as a consequence of EEI, which can be led back to a form of the Dutch disease effect. Sensitivity analyses show that both these sectoral differences and the aggregate results crucially depend on the elasticity of substitution between capital and energy. Moreover, the disaggregation of capital in two capital types with differing substitutability with energy lowers rebound effects overall.

In summary, from an economy-wide perspective, energy efficiency policies constitute a solid tool in reducing final energy use in the economy. However, rebound effects need to be taken into consideration when assessing the expected gains from these policies, as rebound effects substantially reduce their effectiveness. In light of the great necessity for energy savings and emission reductions, it seems important to reduce rebound effects. From an economic perspective, this requires counteracting the change in the effective price of energy from the efficiency stimuli via selected policies. Font Vivanco et al. (2016) discuss several policy-oriented approaches and conclude that cap-and-trade systems covering the whole economy, as well as energy and carbon taxes are most suitable for achieving this. However, such policies also bring about other economic impacts, which constitute an important area for future rebound assessments.

A decomposition analysis similar to Böhringer and Rivers (2018) could shed additional light on the different drivers of rebound effects. Future work should also address certain caveats present in this paper. One caveat is the assumption by which EEIs exclusively occur in Switzerland. Compared to global improvements in energy efficiency, this exaggerates the price differentials between Swiss industries and the rest of the world and thus may overstate the terms-of-trade effects and rebound effects. Another caveat is the fact that we compare the main scenario to a simplified steady-state scenario, in which no EEIs take place over time. Finally, it is a strong assumption to model EEIs as entirely costless. There is some evidence in the literature that including costs could significantly lower rebound effects (Broberg et al., 2015). Future work should test alternative specifications to investigate the impact of these three assumptions.

Chapter 3 Identifying the Mechanisms of Rebound Effects from Annual Industrial Energy Efficiency Improvements: A Decomposition Analysis

Abstract

It is commonly accepted that rebound effects significantly reduce the effectiveness of energy efficiency in delivering energy use reductions. The understanding of the underlying rebound mechanisms that cause this ineffectiveness is however scarce. This paper illustrates that industrial energy efficiency improvements in Switzerland lead to rebound effects via both partial equilibrium and general equilibrium channels and that their relative importance depends on the input mix of the sector considered. We find this assessing rebound effects and decomposing them with a recursively dynamic computable general equilibrium model. The decomposition analysis yields three rebound mechanisms: a direct substitution effect, a multiplier effect, and a residual term, the latter of which is further investigated using complementary decomposition techniques. At the domestic level, partial and general equilibrium channels contribute in almost equal parts to the economy-wide rebound effect of 38% in 2050. For sectoral rebound effects, we find composition and trade effects, which form parts of the residual term, to be the main rebound mechanisms for energy-intensive industries. Conversely, sectors with a high share of value added primarily rebound due to substitution away from capital towards energy. A sensitivity analysis underlines both the necessity to have a solid empirical understanding of key elasticities and to consider sector-specific solutions when seeking to improve the effectiveness of energy efficiency. Economic policy instruments could mitigate rebound effects for sectors with strong partial equilibrium rebound mechanisms, while for energy-intensive sectors a more holistic approach needs to be pursued.

Highlights

- Decomposition analysis sheds light on rebound mechanisms to offset energy savings
- Partial and general equilibrium mechanisms similarly drive Swiss rebound effects
- The input mix determines which mechanisms influence sectoral rebound effects most
- Energy-intensive industries lose energy savings via general equilibrium adjustments
- Rebound effects in capital-intensive industries are caused by substitution effects

Keywords
Rebound effects, energy efficiency, decomposition analysis, computable general equilibrium modeling

3.1 Introduction

Energy efficiency policies play an important role in reducing industrial and total energy use. This becomes even more significant as the pressure to reduce emissions keeps growing (Patt et al., 2018). Although energy intensity has steadily decreased in developed economies (Voigt et al., 2014), the picture is less clear for absolute energy use, which across countries remains above what would have been anticipated from the nominal increase in energy efficiency. This depressed effectiveness of energy efficiency measures and policies is (partly) ascribed to the occurrence of rebound effects, which arise as a result of economic and behavioral responses to energy efficiency improvements (EEIs) (Madlener and Turner, 2016).

In the literature, rebound effects are often used as an umbrella term that encompasses a wide range of effects at varying levels of aggregation and across different dimensions. For higher levels of aggregation, rebound effects are measured by comparing the actual energy savings from EEIs and the potential energy savings that are expected from an engineering perspective (Kazzoom, 1980; Brookes, 1990):

Equation 3.1: The calculation of rebound effects

$$Rebound\ Effect = \left(1 - \frac{Actual\ Energy\ Savings}{Potential\ Energy\ Savings}\right) * 100$$

Simply measuring the size of rebound effects does not allow to infer the mechanisms that trigger them. The literature comprises many assessments that investigate the causes for rebound effects in a partial equilibrium (PE) context, considering selected products or markets only. As for example, Greening et al. (2000) point out, there is, however, a need for a better understanding of the origins of rebound effects, particularly in a general equilibrium (GE) setting. We contribute to this by assessing the effectiveness of annual EEIs and by subsequently decomposing the rebound effects in certain underlying mechanisms.

We build on Zimmermann et al. (2021), which is the first assessment of economy-wide rebound effects of industrial EEIs in Switzerland. Again, we use the Swiss Energy Efficiency Model (SEEM), which is a recursively dynamic with computable general equilibrium (CGE) model of the Swiss economy. It differentiates capital into two types: energy system capital (i.e. substitutable with energy) and other capital (i.e. complementary to energy). After assessing the total rebound effects, we conduct a two-part decomposition analysis: First, inspired by Böhringer and Rivers (2021), we use SEEM to decompose rebound effects into a PE component (i.e. micro-level rebound effects) and two GE components (a multiplier channel and a residual channel). Second, we investigate how further meso- and macro-level mechanisms via the GE channel impact rebound effects for Switzerland, using structural and index decomposition analysis of energy use in combination with other economic indicators. We additionally focus on the decomposition at the sectoral level. This allows us to elucidate the rebound mechanisms and effects in the context of energy efficiency (Fullerton and Ta, 2020), thus providing information that can be used to increase the effectiveness of such policies. By shedding more light on the underlying adjustments and effects, we further respond to the black box criticism CGE models often face (Böhringer and Rivers, 2021).

The structure of this paper is as follows: Section 3.2 introduces the rebound mechanisms identified in the literature and how decomposition analysis can be used to identify them. Section 3.3 briefly introduces the decomposition analyses. Section 3.4 shows the result of the model simulations and the decomposition thereof, including an investigation of the most relevant sensitivities. Section 3.5 discusses these results. Section 3.6 concludes and offers some policy recommendations.

3.2 Literature review

For the last thirty years, rebound effects have been subject to continuous scientific scrutiny with definitions, classifications and estimations abound. A recent typology of rebound effects published by Lange et al. (2021) differentiates between *rebound mechanisms* and *rebound effects*. Rebound mechanisms describe the dynamics that cause EEIs to incompletely translate into reduced energy use and thus the occurrence of rebound effects. Moreover, the authors identify that these rebound mechanisms work at different economic levels and may differ depending on the time horizon in question. We now introduce the rebound mechanisms identified by Lange et al. (2021) and illustrate how relevant studies from the literature assess drivers of rebound effects. Some of the studies identify mechanisms that do not perfectly fit into the aforementioned typology. In that case, we provide additional information on what the individual mechanisms refer to in order to ensure a comprehensive overview of the different rebound mechanisms in the literature.

Rebound effects at the micro-level are perpetuated as a result of the decrease in the effective price of energy following EEIs. In addition, households may adjust their consumption behavior and substitute towards now cheaper energy and may experience an income effect, as they have to spend less on energy. Firms benefit from reduced production costs and potentially expand their production, resulting in an output effect. Analogous to households, they may also adjust their production mix through substitution. These microeconomic rebound effects have also been described as direct and indirect rebound effects in other works (Greening et al., 2000; Sorrell, 2007).

Chitnis et al. (2013; 2014) investigate such direct and indirect rebound effects for UK households and find large differences for different energy efficiency measures. These studies acknowledge the impact of both income and substitution effects; however, they refrain from quantifying the respective contributions. Chitnis and Sorrell (2015) present such a quantification in an assessment of rebound effects for three energy services used by households. They attribute the eroded energy savings primarily to substitution effects with income effects only playing a marginal role. In a similar study, Thomas and Azevedo (2013) use an input-output model of the US and contradict the previously illustrated findings that substitution effects dominate income effects. They acknowledge, however, that this may be due to the elasticities of substitution used in their approach and that the individual contribution of the two effects may vary amongst income groups. Finally, Schmitz and Madlener (2020) econometrically estimate direct and indirect rebound effects and – while observing moderate to significant overall rebound effects - even find some negative substitution effects offsetting income rebound effects.

Assessments of rebound effects and the corresponding mechanisms at the meso- and macro-level often rely on CGE models to capture the system-wide changes that stem from price adjustments that follow EEIs. These CGE analyses typically find considerable rebound effects. In a review of rebound effects in energy and climate models, Colmenares et al. (2020) report a mean economy-wide rebound effect of 42.5% for producers when studies use CGE simulations. An example of such an assessment is Broberg et al. (2015), who assess a one-time industrial EEI for Sweden in a fully dynamic setting. This study highlights the great variation in the size of sectoral and economy-wide rebound effects, with the latter varying from 40-70% depending on the scenario analyzed. They attribute rebound effects mainly to substitution and output effects but do not quantify the relative contributions.

When assessing rebound effects in a GE context, adjustments to EEIs at the household- and firm-level inevitably affect the meso-level (Lange et al., 2021). The meso-level concerns all effects that relate to markets or sectors. Due to efficiency-induced reductions in the costs of production of firms and the subsequent micro-level mechanisms, entire sectors can change in size and affect other sectors through changes in output prices. Through supply and demand adjustments, it follows that such changes also impact firms' demand for intermediate goods and final demand. EEIs also lower demand for energy itself, which affects individual energy markets. This in turn changes energy demand and possibly perpetuates further rebound effects at the meso-level. Finally, in the long-run, increased demand of entire sectors resulting from price adjustments can result in economies of scale, as production of selected sectors is expanded.

The economic adjustments from energy efficiency also manifest at the macro-level. As different energy sectors adjust their prices, economy-wide energy prices change and possibly induce more energy use and thus higher rebound effects. Similarly, if certain energy-intensive sectors are more capable of accommodating to energy efficiency gains, the demand and the composition of the economy move towards more energy-intensive sectors. There are two additional mechanisms at the macro-level: a multiplier effect, which results from increased spending and investment due to increased incomes and revenues from improved energy efficiency, and a wage effect. The wage effect contributes to rebound effects when employers pass on gains from energy efficiency through higher wages, which stimulates consumption. In the long-run, two macro-level rebound mechanisms possibly work to offset potential energy savings. First, if investment moves towards more energy-intensive production as expected returns on investments are increasing and, second, if energy efficiency induces more innovation. The latter effect can, however, also entice additional energy savings when concentrated in R&D for more energy-efficient technology.

Turner (2009) comprises a qualitative assessment of some of the aforementioned mechanisms for the UK. The author suggests that rebound effects can decrease with time and even become negative, mainly due to a disinvestment effect. The disinvestment effect refers to a contraction in domestic energy supply, as a result of falling prices and a lack of capital accumulation following the efficiency stimuli. This contraction increases energy prices in the long-run, which in turn hinder micro- (i.e. income, output, and substitution effects) and meso-level mechanisms (i.e. composition effects) to induce rebound effects.

For the quantitative decomposition of rebound effects in a GE setting, no universally accepted methodology has yet been established and different studies cover different rebound mechanisms. Rausch and Schwerin (2018) use an analytical GE growth model and find very high rebound effects of more than 100%, which is generally referred to as a backfire effect (i.e. higher energy use than if no EEIs had taken place). They also investigate the drivers of this growth in energy use. The authors conclude that growth effects due to increased investment and thus long-run macro-level mechanisms are primarily responsible for this dynamic in their model.

Using a static analytical GE model, Da Rocha and De Almeida (2021) decompose economy-wide rebound effects into six mechanisms, such as a direct substitution, a direct output effect, and a cross-price effect, which describes how a price change for one energy service changes the demand for alternative energy services. For each mechanism, they illustrate under what conditions it limits or amplifies rebound effects. The model lacks empirical data and an analysis of temporal dynamics. Lemoine (2020) similarly decomposes rebound effects into multiple mechanisms with an analytical GE model. Additionally, the author then applies the model to US data, using only sectoral input use and elasticities of substitution as parameters. The analysis focuses on the differences in the underlying mechanisms for consumption good sectors and energy supply. It shows that for consumption good sectors, GE mechanisms reduce overall rebound effects, compared to a PE setting. The opposite is true for the energy supply sectors. Next to the static nature of the model, the model is also limited in its representation of the production factors that can react to price changes caused by EEI, as only labor and a production factor *energy resource* enters the production function.

A third example of an analytical general equilibrium model for the analysis of rebound mechanisms is Fullerton and Ta (2020). They use a linearized version of their model to investigate how rebound effects differ between costless EEI and costly energy efficiency standards. The authors decompose the rebound effect into income and substitution effects both for the energy service that experiences EEI (i.e. the direct rebound effect) and for other goods (indirect meso-economic rebound effects). They show that the consideration of costs suppresses rebound effects because the (negative) income effects can counteract the substitution effects.

All these analytical general equilibrium models have in common that they are static and limited in the complexity in which economies and especially production are represented. Specifically, they often represent a limited amount of production factors and are thus less capable of demonstrating substitution between production factors due to price changes amongst sectors. This thus hinders the possibilities to find the origin of the mechanisms perpetuating rebound effects, particularly at a sectoral level, as well as the interpretation thereof.

The three studies closest to this paper are Lecca et al. (2014), Zhou et al. (2018) and Böhringer and Rivers (2021). Lecca et al. (2014) apply an input-output (IO) model and a CGE model to investigate how rebound effects from an EEI for households change when including general equilibrium effects. First, they make use of the fixed prices and incomes in the IO model to determine the substitution effect. Subsequently, they show that endogenous price adjustments and endogenous incomes have a significant impact on total rebound effects. The analysis is undertaken for both the short- and the long-run. Zhou et al. (2018) apply a CGE model to decompose rebound effects for China in a static setting. They demonstrate that for the overwhelming majority of sectors in China, the substitution effect far outweighs the output effect as the main rebound mechanism.

Böhringer and Rivers (2021) analytically decompose the rebound effect into two PE and four GE channels. Their application with US data yields an economy-wide rebound effect of approximately 60%. They find that the PE component, encompassing a substitution and an income channel, dominates the GE effect, which is mainly due to the substitution effects. The GE component accounts for roughly a third of the total rebound effect. Of the four mechanisms, the energy price channel has the strongest impact. The composition channel, the growth channel and the labor supply channel are found to be of marginal importance. The analysis builds on a 2-sector model and a simulation of a one-time EEI, leaving scope for exploring the relative importance of rebound mechanisms in more disaggregated and more dynamic settings.

3.3 Method

3.3.1 Scenarios and Rebound Calculation

As a reference scenario, SEEM assumes a steady state of the economy over time (the SS scenario). Estimated population growth for Switzerland determines the increase in labor supply and thus the growth rate of the model (FSO, 2020). No EEIs are implemented in the SS scenario. The consumer price index is used as a numeraire.

The main scenario (the R-EEI scenario) assumes annual EEIs of 2.31% in production, which are exogenous and costless. These improvements are modeled as biased technical change, enabling more production of output with less energy. In SEEM, only production in Switzerland experiences energy efficiency stimuli. The implemented rate of 2.31% is based on the Swiss Energy Perspectives 2050+ (Prognos AG, TEP Zürich, Infras and Ecoplan, 2020), which assesses possible pathways to net-zero emissions by 2050 while ensuring energy security[5].

In the results section of this paper, sectoral and industrial rebound effects are calculated with Equation 3.2. $\dot{E}_t^i$ represents the yearly change in physical energy use of a sector i or the total industry relative to the reference scenario (i.e. the actual

[5] In the Swiss Energy Perspectives' Zero Basis scenario, an annual final energy use reduction of 1.53% for Switzerland (excl. household) is needed to achieve net-zero emissions by 2050 (Prognos AG, TEP Zürich, Infras and Ecoplan, 2020). Assuming an average rebound effect of roughly 33.6% for Switzerland (Zimmermann et al., 2021), the necessary improvement in energy efficiency increases to the 2.31% of the R-EEI scenario. This estimate thus serves as a lower-bound approximation of the required reduction in energy use.

energy savings). In the denominator, $\gamma_{EC,t}$ shows the cumulative EEI in year t (i.e. the potential energy savings). This denominator is equivalent to the change in physical energy use for a hypothetical scenario, in which EEIs are perfectly effective and no rebound occurs. We term this scenario EEIWR (Energy Efficiency Improvements Without Rebound Effects). Rebound effects at the economy-wide level are calculated by comparing the percentage response of the domestic physical energy use $\dot{E}_t$ to the EEI $\gamma_{EC,t}$ multiplied with the share of industrial energy use in total domestic energy use in the benchmark.

Equation 3.2: The calculation of sector-specific rebound effects

$$R_t^i = \left(1 + \frac{\dot{E}_t^i}{\gamma_{EC,t}}\right) x\ 100$$

3.3.2 Decomposition analysis with SEEM

An EEI reduces the effective price of energy. This reduction entices economic actors benefitting from the improvement (i.e. the firms in SEEM) to substitute production factors for energy. We solve SEEM under PE conditions to determine the level of substitution that occurs between the energy composite and the production factor within the same nest (i.e. ESC). We thereby hold incomes and all prices but the price of the energy composite $PEC_{i,t}$ fixed. For the energy composite, the EEI in a given year is passed on as a one-to-one reduction in the price.

To calculate the reduction in energy use with SEEM under PE conditions, three equations are relevant: the price of the energy composite (Equation 3.3); the sector-specific market clearance of the energy composite good (Equation 3.4), in which supply equals demand; and the sector-specific zero profit conditions of the energy service, which is produced by combining the energy composite and ESC (Equation 3.5)[6]:

Equation 3.3: The price of the energy composite

$$PEC_{i,t} = \left(\frac{1}{(1+\gamma_{EC})^t}\right)$$

Equation 3.4: The sector-specific market clearance of the energy composite good

$$ec0_i * (1+\gamma_{EC})^t * EC_{i,t} = ec0_i * ES_{i,t} * \left(\frac{\partial \prod_{i,t}^{ES}}{\partial PEC_{i,t}}\right)^{\sigma_{ES,i}}$$

Equation 3.5: The sector-specific zero profit condition of the energy service nest

$$\prod_{i,t}^{ES} = PES_{i,t} = \left(\theta_{ES,i} * RK_{ESC,t}{}^{1-\sigma_{ES,i}} + \left(1-\theta_{ES,i}\right) * PEC_{i,t}{}^{1-\sigma_{ES,i}}\right)^{\frac{1}{(1-\sigma_{ES,i})}}$$

$ec0_i$ corresponds to the reference quantity of the energy composite in sector *i*; $EC_{i,t}$ and $ES_{i,t}$ refer to the sector-specific activity levels of the energy composite and the energy services at time *t*, respectively; $\theta_{ES,i}$ is the sectoral benchmark value share of ESC for the production of energy services and $\sigma_{ES,i}$ the sectoral elasticity of substitution between ESC and the energy composite. $RK_{ESC,t}$ is the rental rate of ESC.

Under PE conditions, only the price of the energy composite is allowed to change (i.e. $RK_{ESC,t} = 1$) and thus the first term of the RHS of Equation 3.5 reduces to $\theta_{ES,i}$. The now reduced version of Equation 3.5 is plugged in Equation 3.4, giving Equation 3.6. This equation determines the change in energy use $\Delta E_{i,t}$ in monetary terms that occurs in PE if only the price of the energy composite changes:

[6] For a detailed description of all parameter, please refer to the Appendix.

Equation 3.6: The calculation of the change in energy use in monetary terms

$$\Delta E_{i,t} = ec0_i * \left(1+\gamma_{EC,t}\right)^t * EC_{i,t} - ec0_i * ES_{i,t} * \left(\frac{\left(\theta_{ES,i} * 1 + \left(1-\theta_{ES,i}\right) * \left(PEC_{i,t}\right)^{1-\sigma_{ES,i}}\right)^{\frac{1}{(1-\sigma_{ES,i})}}}{PEC_{i,t}}\right)^{\sigma_{ES,i}}$$

To arrive at the amount of energy savings in monetary units lost due to the substitution towards the energy composite, we calculate the difference between the energy savings from Equation 6 and the engineering savings, which correspond to the potential energy savings if no rebound effects occur altogether. Finally, we can use the benchmark energy intensity (TJ/mCHF) to determine the total physical actual energy savings from the direct PE substitution effect[7].

In order to identify the contribution of the GE rebound mechanisms, we allow all variables to be determined endogenously. First, the model is run to determine the absolute change in physical energy use as a consequence of the EEIs. To isolate the GE component ($\boldsymbol{Rebound_{i,t}^{GE}}$), the actual energy savings from the R-EEI scenario and the energy savings offset under PE conditions ($\boldsymbol{Rebound_{i,t}^{PE}}$) are subtracted from the potential energy savings, as shown in Equation 3.7. The individual rebound components $\boldsymbol{R_{i,t}^{PE}}$ and $\boldsymbol{R_{i,t}^{GE}}$ in percentages follow from that in Equation 3.8 and 3.9. The illustrated equations are all sector-specific. Industry-wide and economy-wide rebound effects are calculated with the same logic.

Equation 3.7: The calculation of the GE component (in energy terms) of the total rebound effect

$$Rebound_{i,t}^{GE} = PotentialEnergySavings_{i,t} - ActualEnergySavings_{i,t}^{Total} - Rebound_{i,t}^{PE}$$

Equation 3.8: The calculation of the rebound effect component under PE conditions

$$R_{i,t}^{PE} = \left(\frac{Rebound_{i,t}^{PE}}{PotentialEnergySavings_{i,t}}\right) * 100$$

Equation 3.9: The calculation of the rebound effect component under GE conditions

$$R_{i,t}^{GE} = \left(\frac{Rebound_{i,t}^{GE}}{PotentialEnergySavings_{i,t}}\right) * 100$$

We further decompose the GE component of the total rebound effect into two mechanisms. At the macro-level, EEIs increase household income and thus spending, which translates into higher sectoral activity levels and more investment. Lange et al. (2021) term this the multiplier effect. The multiplier effect can be controlled for by running a simulation in SEEM in which we impose a steady-state growth path for aggregate consumption (excl. leisure) and investment, as illustrated in Equation 3.10. Analogous to Equation 3.8 and 3.9, we calculate the savings that are accumulated and the rebound effects, absent any multiplier dynamics. The contribution to the overall rebound effect by the multiplier mechanism is determined via Equation 3.11. $R_{i,t}^{GE|Mult}$ thereby corresponding to the GE component of the overall rebound effect, while imposing Equation 3.10.

Equation 3.10: The condition under which the multiplier effect is controlled for

$$\frac{(Investment_t + Consumption_t)}{(Investment_0 + Consumption_0)} = (1 + GrowthRate)^t$$

Equation 3.11: The contribution of the multiplier effect to the total rebound effect

$$R_{i,t}^{Mult} = R_{i,t}^{GE} - R_{i,t}^{GE|Mult}$$

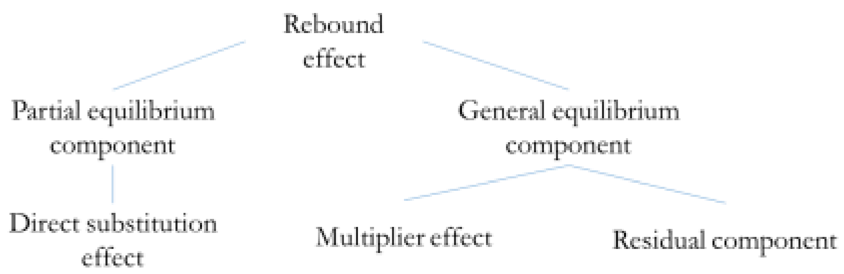
[7] In GAMS/MPSGE, the simulation of SEEM under PE condition is done by solving SEEM with zero iterations, therefore disallowing any price adjustments. Moreover, we implement the annual energy efficiency improvements in combination with an analogous price reduction in the price of the energy composite (i.e. Equation 3.3). The change in energy use under PE conditions is then shown in the marginal column of the solution report, which indicates how much lower energy use would have been if prices had been able to change.

Equation 3.12: The contribution of the residual effect to the total rebound effect

$$R_{i,t}^{Residual} = R_{i,t}^{GE} - R_{i,t}^{Mult}$$

The residual between the total contribution of the GE mechanisms and the multiplier mechanisms to total rebound encompasses a wide range of effects, such as various structural changes in the economy, including, for example, indirect substitution effects or trade effects. This is calculated with Equation 3.12. Figure 3.1. presents a graphical overview of the three identified mechanisms that we decompose the rebound effects into.

Figure 3.1: An overview of the decomposition of total rebound effects in three rebound mechanisms within SEEM



3.3.3 Structural Decomposition Analysis and Index Decomposition Analysis

Rebound mechanisms via the GE channels can take many forms and thereby affect energy use. To better understand the residual component, we additionally apply two related but distinct decomposition analyses: index decomposition analysis (IDA) and structural decomposition analysis (SDA). These analyses are regularly used to gain a better understanding of how energy use changes over time. In SEEM, changes in energy use are a direct result of EEIs, and decomposing these changes allows to infer which rebound mechanisms contributed most. Specifically, we are interested in how energy use is different between the R-EEI scenario and the SS scenario in 2050.

For both the SDA and the IDA, we apply an additive decomposition[8]. The SDA is based on input-output data. We, therefore, construct the 2050 IO tables for the R-EEI and the SS scenario based on model outputs from SEEM. We decompose the change in energy use into five factors with the Marshall-Edgeworth Method (ME). The ME method is a commonly used index approach, which exhibits time reversal, is zero-value robust, and only has small residuals. It is thus well suited for this type of analysis. It weighs the change for a respective indicator with the mean of the base and the terminal year (Hoekstra and Van den Bergh, 2003).

Equation 3.13: The structural decomposition analysis of total energy use

$$E = eLy = eL\varphi\delta Y = e(I-A)^{-1}\varphi\delta Y$$

Equation 3.14: The calculation of the contribution of each indicator to a change in energy use

$$\Delta E = E^{2050,R-EEI} - E^{2050,SS} = \Delta e + \Delta L + \Delta\varphi + \Delta\delta + \Delta Y$$

Equation 3.13 illustrates how total energy use can be decomposed into the relevant individual components. e is a vector of the energy intensity; L shows in the production recipe of the economy (i.e. the Leontief matrix); and y is the final demand vector. Final demand can further be decomposed into three separate indicators: φ is a matrix indicating the spending pattern within each final demand category (i.e. in households, investment, government, and exports); δ is a vector of the destination of total final demand (i.e. the share of an individual final demand category of total final demand); and

[8] See Hoekstra and van den Bergh (2003) for a comparison of the two approaches and the difference between a multiplicative and an additive decomposition.

ΔY, which measures total final demand. Applying the ME method and thus calculating the weighted change of the individual indicators between the two scenarios, we arrive at the contribution of each indicator to a change in energy use, shown in Equation 3.14.

While the SDA relies on input-output data, the IDA requires only aggregate sectoral data. The IDA decomposes the change in sectoral energy use in 2050 between the R-EEI scenario and the SS scenario into three effects: an activity effect ΔE_{act}, a structure effect ΔE_{str} and an intensity effect ΔE_{int}. The three indicators illustrate how changes in overall economic activity (ΔE_{act}), changes in the output composition of the economy (ΔE_{str}) and changes in the energy intensity (ΔE_{int}) affect sectoral energy use, respectively. By applying the Logarithmic Mean Divisa Index (Ang, 2005), we decompose the impact of the three effects without residual.

In the hypothetical EEIWR scenario, the change in energy use relative to the SS scenario is equal to the potential energy savings anticipated by the engineering estimates. This change is entirely due to the intensity effect, as neither overall economic activity nor the composition of the economy changes in EEIWR (i.e. ΔE_{act}=0, $\Delta E_{str} = 0$). By comparing this change with the IDA between the SS and the R-EEI scenario, we identify the individual contribution of the three factors to the total rebound effect. The exact application and calculation of the different indicators for both IDA and SDA are given in the Appendix.

3.4 Results

3.4.1 The decomposition of rebound effects

Annual EEIs in production in Switzerland lead to substantial rebound effects. Domestically, there is a total rebound effect of 34% in 2050, which corresponds to lost energy savings of almost 115 PJ. Figure 3.2 provides a graphical representation of the differences in energy use for the three scenarios in 2050. In the SS scenario, domestic energy use (i.e. energy used by firms and households) reaches roughly 1240 PJ. If energy efficiency was perfectly effective (i.e. the "energy efficiency improvements without rebound (EEIWR)" scenario), energy use would decrease to below 900 PJ. Yet, actual energy savings in the "energy efficiency improvement (R-EEI)" scenario only amount to 225 PJ instead of 345 PJ. When focusing on production, industry-wide rebound effects are lower than the economy-wide rebound effects and average 33% over the 30 years simulated. This is because income effects stimulate the representative household's energy use and thus increase overall economy-wide rebound effects.

Figure 3.2: Index of domestic energy use in the R-EEI (red line), SS (turquoise line) and EEIWR (black line) scenario

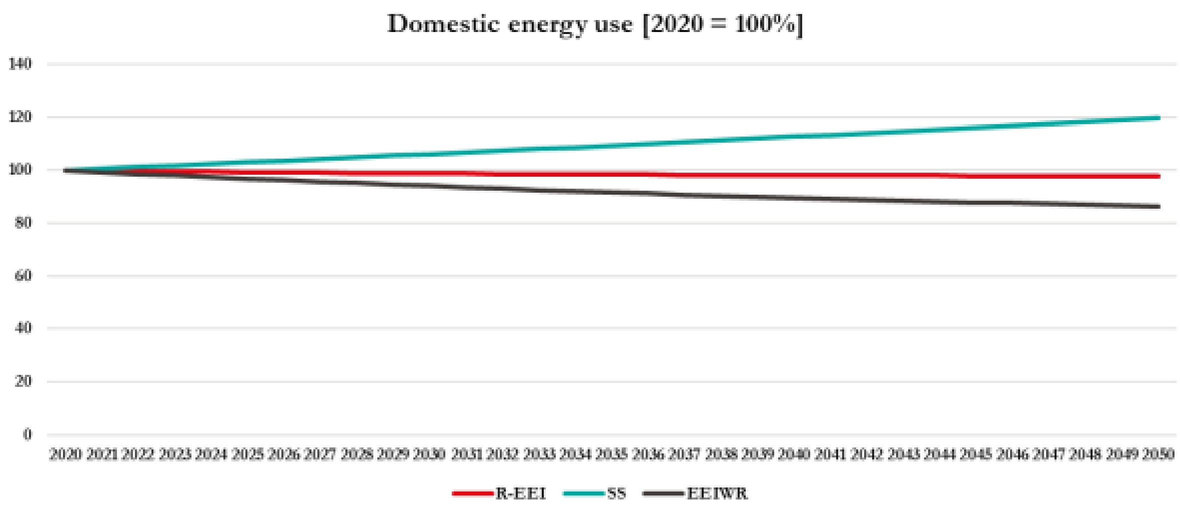
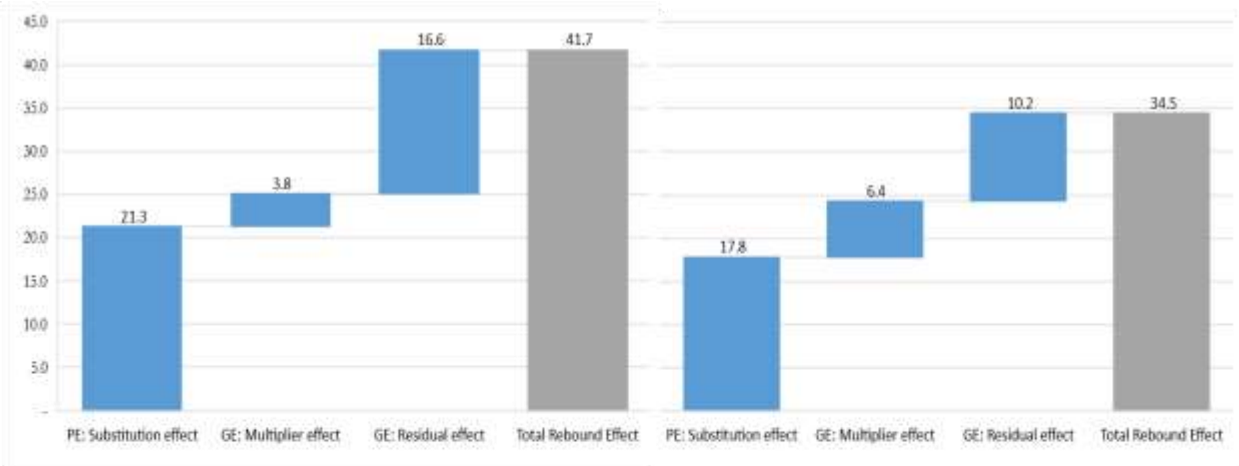


Figure 3.3 shows the results of the rebound decomposition for the first period after energy efficiency improves and for 2050. Slightly more than 50% of the lost energy savings stem from substitution effects, as the lower price of the energy composite causes substitution from ESC towards the energy composite. If we allow for all prices, wages and incomes to adjust and thus incorporate GE effects, economy-wide rebound effects almost double. The respective contribution of the

multiplier effect and the residual effect greatly differ between 2021 and 2050. Initially, the multiplier effect is hardly responsible for the offset of energy savings, which are primarily eroded through other GE rebound mechanisms. With each additional EEI, however, household income and thus consumption increase, which stimulates production and investment. Therefore, the contribution of the multiplier effect to the economy-wide rebound effect grows. In 2050, the multiplier effect causes 40% of the GE component.

Figure 3.3: Contribution of the three rebound mechanisms (in blue) towards total economy-wide rebound effect (in grey) for 2021 (left) and 2050 (right) as a result of industrial EEIs (in % points)



Overall, the GE component of the rebound effect is predominantly caused by the residual term. To investigate this residual term, we refer to the SDA illustrated in Table 3.1. The SDA decomposes the change in energy use due to the energy efficiency stimulus for different indicators. As expected, the change in energy intensity (TJ/mCHF) resulting from EEIs plays by far the biggest part in reducing energy use. On aggregate, changes in the industrial composition of the economy only affect energy use slightly, as the decrease in energy intensity offsets the higher demand for products of energy-intensive sectors benefitting from EEIs.

An opposite trend applies to the final demand categories (i.e. households, investment, government, and exports). Overall, spending within the different categories moves towards more energy-intensive goods, as the efficiency stimuli make them cheaper and thus more attractive. This works to increase energy use by 27 PJ. Within households, this shift is further supported by an increase in real wages and capital remuneration, which increases private consumption by more than 2.8%. Meanwhile, as Table 3.1 indicates, the overall change in total final demand has contributed to an increase in energy use and subsequently to the GE component of the rebound effects. The relative importance of the individual final demand categories, however, barely changes (-0.18 PJ).

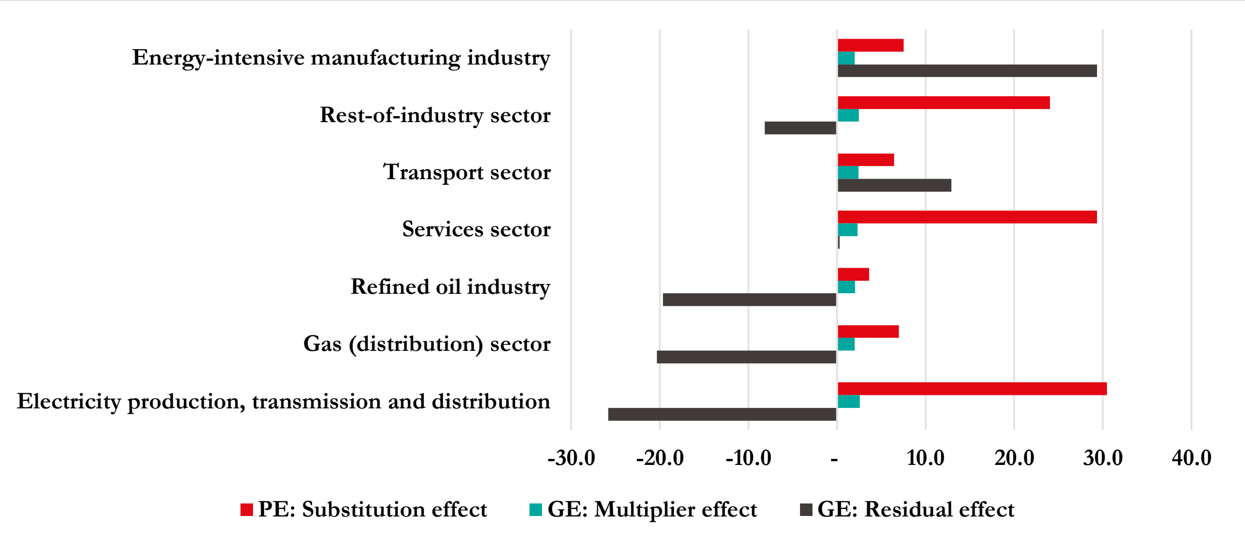
Table 3.1: Structural decomposition of changes in energy use between the R-EEI and the SS scenario in 2050 in PJ

Additive structural decomposition analysis (Marshall-Edgeworth approach)						
Change in energy use in PJ	Change in energy intensity	Change in industrial structure	Change in spending patterns within the final demand categories	Change in the relative importance of the individual final demand categories	Change in total final demand	Residual
-245.2	-280.1	-1.0	27.0	-0.2	9.1	-0.03

At the aggregate level, substitution effects and GE effects play an equally significant role in perpetuating rebound effects. Figure 3.4 however reveals a different picture for individual sectors. The energy-intensive manufacturing industry and the transport sector exhibit a considerably higher energy intensity than all the other sectors. As a consequence, these two sectors strengthen their relative competitiveness from the energy efficiency stimuli, which translates into strong rebound mechanisms covered by the residual component. This component is responsible for 75 % and 60% of their sectoral rebound effects in 2050, respectively.

Conversely, the rest-of-industry sector and the services sector, in particular, have a high share of value added. This provides them with more scope for replacing ESC with the energy composite, as energy becomes cheaper and capital costs increase with the rental rate of capital. The decomposition analysis corroborates this and shows strong substitution effects for both sectors. Their low reliance on energy puts them at a comparative economic disadvantage in responding to EEIs. As these changes are sector-specific, they affect the GE channel via the residual component rather than via the aggregate multiplier effect. In the case of the services sector, the impact on the residual GE component is negligible, whereas for the rest-of-industry sector it is even negative due to a contraction in its production.

Figure 3.4: The contribution of each rebound mechanism for each sector in 2050 in percentage points



This is even more accentuated for the energy supply sectors, as the demand for their goods collapses due to the annually increasing energy efficiency in the economy. The size of the substitution effect varies for the three sectors. Natural gas and crude oil constitute the main input for the natural gas (distribution) sector and the refined oil sector, respectively, whereas the electricity sector is much more reliant on capital and labor. Consequently, only electricity exhibits strong substitution effects. The size of the multiplier effect is very similar across all sectors. As already indicated, the reason for this lies in the fact that it is an aggregate macro-level mechanism, which affects all sectors in comparatively equal measures.

The specific comparison of the rest-of-industry sector and the energy-intensive manufacturing industry yields additional insights. Table 3.2 gives an overview of the rebound mechanisms in the short-, mid- and long-run for the two sectors. Specifically, it illustrates the contribution of the substitution effect, the multiplier effect, and the residual effect to the total rebound effect. As aforementioned, the PE substitution effect for the energy-intensive manufacturing sector plays only a minor role, as this sector exhibits low elasticity of substitution between ESC and the energy composite. This contrasts with the very high GE effect. This sector's capability in accommodating to EEIs leads to significant reductions in the cost of production. These cost reductions directly translate into a strong decrease in the producer price of its output by 6.3% in 2050. Consequently, demand for this sector's outputs grows by 23.4%. As a very export-oriented sector, 90% of this increase comes from abroad. The sector, therefore, experiences strong meso-level rebound mechanisms, which are responsible for the bulk of the residual GE effect. In 2050, the residual GE effect contributes 30 percentage points to the overall rebound effect of 39%. The contribution of the multiplier effect for this sector is negligible over the entire time horizon.

Table 3.2: Comparison of the contribution of the three rebound mechanisms between the energy-intensive manufacturing sector and the rest-of-industry sector over time

Rebound mechanisms	**Energy-intensive manufacturing sector**			**Rest-of-industry sector**		
	2021	2035	2050	2021	2035	2050
PE channel: Substitution effect	8.7%	8.1%	7.5%	29.0%	26.5%	24.0%
GE channel: Multiplier effect	2.8%	2.3%	2.0%	0.5%	2.0%	2.4%
GE channel: Residual effect	46.0%	37.56%	29.6%	-10.2%	-9.6%	-8.3
Total rebound effect	**57.6%**	**48.0%**	**39.0%**	**19.3%**	**18.9%**	**18.1%**

These adjustments can also be seen in the IDA shown in Table 3.3. The structure effect measures how much a change in the share of a sector's output of total economic activity impacts energy use. For the energy-intensive manufacturing sector, this effect causes a rebound of 28 PJ or more than 89% of the total energy savings lost due to rebound effects. Additional GE mechanisms are also at play. Domestic demand is also increasingly satisfied by locally produced goods instead of imports, which stimulates production and thus sectoral energy demand. Moreover, we can observe that the growth in domestic production of this sector outpaces the growth in demand for both intermediate inputs and labor supply, indicating increased substitution away from these inputs towards energy.

The respective contributions for the rest-of-industry sector look markedly different. The main rebound mechanism for this sector is the direct substitution of ESC for energy, which is larger than the total rebound effect in 2050 (24% for the PE channel vs. 18% overall). As a matter of fact, the sector's demand for ESC in 2050 decreases by more than 13% relative to the SS scenario, which is by far the biggest change in its input mix. This reduction is twice as large as the reduction in its output. Its production contracts by 6%, which is caused by a price-driven decrease in domestic and foreign demand. This is mirrored in the GE component of the sector in Table 3.2. Rebound mechanisms via the GE channel contribute negatively to the overall sectoral rebound effect, as the replacement of domestic supply by imports suppresses energy demand more than if only PE effects were considered. As in the case of the higher energy-intensive manufacturing sector, the multiplier effect does not significantly impact the total rebound effect.

Table 3.3: Index decomposition analysis for the energy-intensive manufacturing sector and the rest-of-industry sector for 2050 in PJ

Index decomposition analysis	**Energy-intensive manufacturing sector**			**Rest-of-industry sector**		
	R-EEI vs. SS	EEIWR vs. SS	Rebound effect	R-EEI vs. SS	EEIWR vs. SS	Rebound effect
Activity effect (Y)	0.9	0	0.9	0.4	0	0.4
Structure effect (Y_i/Y)	28.2	0	28.2	-4.3	0	-4.3
Intensity effect (E_i/Y_i)	-78.6	-81.1	2.5	-27.67	-38.6	10.9
Total effect (change in PJ)	**-49.5**	**-81.1**	**31.6**	**-31.5**	**-38.6**	**7.0**

The decrease in economic activity of the rest-of-industry sector also reduces its share of total GDP (Yi/Y) and thus its economic importance relative to the SS scenario. It does however positively contribute to more energy savings, as evidenced by the negative structure effect in the IDA. The only element of the IDA that puts upward pressure on energy use in the R-EEI scenario relative to the SS scenario is the activity effect, albeit marginally. In line with the CGE decomposition, the negative structure effect illustrates that the sector's lower output reduces the rebound effect.

3.4.2 Sensitivity analysis

We test several elasticities of substitution in production to examine how different elasticities influence the PE and the GE component. Moreover, our novel assumption regarding the complementarity of OC and the choice of assigning 10% of total capital to ESC similarly warrants an analysis of how this influences the rebound mechanisms. Based on Equation 3.6, there are two main determinants of the substitution effect: 1) the elasticity of substitution between ESC and the energy composite and 2) the benchmark value share of ESC relative to the energy composite. We, therefore, run two simulations to see how separately doubling the elasticity and the share of ESC (i.e. to 20%) for all sectors affects overall energy use. Table 3.4 shows the result of all tested sensitivities.

Table 3.4: Overview of the impact of the different sensitivity analyses on economy-wide rebound effects and the respective contributions of the rebound mechanisms in 2050 (% change relative to R-EEI scenario in brackets)

Rebound mechanisms	**Economy-wide rebound effects**				
	R-EEI scenario	**Doubling the elasticity between energy composite and ESC**	**Doubling the share of ESC in total capital**	**Removing Leontief assumption between energy services and OC**	**Doubling of production elasticities in 30 years**
PE channel: Substitution effect	17.8%	37.2% (+109%)	22.4% (+26)	17.8% (+0%)	37.2% (+109%)
GE channel: Multiplier effect	6.4%	8.1% (+28%)	6.8% (+7%)	7.7% (+21%)	7.0% (+9%)
GE channel: Residual effect	9.4%	11.2% (+19%)	10.3% (+9%)	25.7% (+174%)	15.5% (+65%)
Total rebound effect	**33.5%**	**56.5% (+68%)**	**39.5% (+18%)**	**51.1% (+53%)**	**59.6% (+78%)**

As expected, both simulations increase sectoral, industry-wide, and economy-wide rebound effects. The higher elasticity between ESC and the energy composite affects all three rebound mechanisms. However, the impact is heavily concentrated in the PE component, which is responsible for more than four-fifths of the 68% increase in economy-wide rebound effects in 2050. The analysis also indicates that the share of ESC of total capital is less impactful than the choice of the elasticity parameter when assessing rebound effects. This is particularly because the PE channel is much less sensitive regarding the value share. For the GE component, the opposite is the case, albeit to a relatively moderate extent.

In SEEM, we assume complementarity between OC and energy services. Given the large share of OC and its position in the nesting tree, this assumption significantly hinders further substitution effects and a priori limits the erosion of energy savings from EEIs. We can simulate how large this limitation is by replacing the complementarity with a setup, in which the elasticity of substitution between the OC and energy services is the same as in the lower nest between ESC and the energy composite. As the elasticity of substitution between OC and energy services does not enter Equation 3.6, the PE channel is not affected by this sensitivity. Therefore, only GE components are affected by the new flexibility, adjusting the size of OC in sectors' input mixes.

This is particularly accentuated for the two energy-intensive sectors: the transport sector and the energy-intensive manufacturing industry. The transport sector's residual component grows by more than 190% in 2050 relative to the R-EEI scenario. This is overwhelmingly due to substitution away from OC towards energy services. The demand for OC decreases from +13% in the R-EEI scenario to +5%, even though overall sectoral production is now larger. More flexibility further reduces production costs of the transport sector and thus the prices for transport services. It follows that demand for transport services increases, inducing additional rebound effects. Overall, the lack of complementarity between OC and energy services leads GE mechanisms to dominate the PE component, as shown in Table 3.4.

Finally, we test how rebound mechanisms respond to a yearly increase in the elasticities of substitution in production, which allows firms to more easily change their factor allocation in the long-run. Specifically, we assume a linear increase in the elasticities to double their starting values by 2050. As expected, there is an increase in rebound effects from the short- to the long-run in almost all sectors. More flexibility in responding to relative price changes induces greater substitution and thus greater rebound effects. The simulation results in Table 4 indicate that this rise in rebound effect particularly manifests through substitution effects between ESC and energy. All non-energy good sectors almost double their substitution effect over time. Meanwhile, the impact of increased elasticities on the GE channels is much more subdued. Nonetheless, it can be observed that the contribution of the residual channel no longer decreases over time. For the transport sector, there is even a reversal of the trend. It thus becomes clear that the elasticity of substitution between ESC and energy is the key elasticity in perpetuating rebounds effect in SEEM.

3.5 Discussion

The decomposition analysis of rebound effects provides important insights into the mechanisms that cause EEIs to be only partially effective in reducing energy demand, as evidenced by the substantial rebound effects found in our CGE simulation in Switzerland. In 2050, economy-wide rebound effects are caused in almost equal parts by direct substitution away from ESC towards the energy composite (i.e. the PE channel) and by GE adjustments. The multiplier effect – i.e. increased energy use due to increased spending, revenues, and investment – only plays a minor role. The main GE adjustments occur via the residual component, encompassing sectoral composition effects, factor reallocation, and demand-driven trade effects.

The strong impact of GE adjustments contradicts the results of the static GE analysis by Böhringer and Rivers (2021), who show the PE channel to dominate the GE channel. Particularly surprising is that they find the composition effect to be of minor importance, whereas our simulation results indicate a clear shift towards more energy-intensive sectors. A possible explanation is that the authors only implement a one-time EEI in only one sector in their two-sector model. Consequently, there are fewer adjustments between the different sectors and less scope for rebound mechanisms via the GE channel. Moreover, we find in our results that trade substantially contributes to these composition effects, particularly in the case of the energy-intensive manufacturing industry. This dynamic is new compared to the closed-economy analysis of Böhringer and Rivers (2021). This points to the importance of considering trade when assessing the effectiveness of exclusively domestic EEIs.

The fact that the GE channel significantly drives rebound effects exemplifies the need to holistically assess rebound effects with system-wide CGE models, as otherwise important rebound-inducing mechanisms are missed. This is not the whole story, however. The sensitivity analysis also shows that assuming all capital to be weakly substitutable with energy significantly increases overall rebound and the contribution of the residual channel. This underlines the fact that when CGE rebound assessments do not differentiate between capital types, they likely overestimate the amount of energy savings lost through GE adjustments.

The GE channel is also more sensitive to the complementarity assumption than to changes in the elasticity of substitution between the energy composite and the ESC. Doubling this elasticity, however, has a significant impact on the contribution of the PE channel, in which case the results are in line with the findings of Böhringer and Rivers (2021). It is thus paramount to have solid empirical estimates of the relevant elasticities of substitution in assessing rebound effects, particularly when it comes to the substitutability (or complementarity) between capital and energy. The sensitivity analysis has also shown that this is much more important than the individual value shares of the two types of capital.

When we increase the flexibility with which factors can be allocated in the long-run, we see a reversal of the temporal dynamics of rebound effects, which now grow with each new annual improvement. The impact on the importance of the individual components is similar to doubling the elasticity of the ESC-energy composite. The substitution effect contributes more than 60% to the total rebound effect. For a one-time EEI in consumption, Lecca et al. (2014) similarly decompose rebound effects into a PE component and a GE component and implement larger elasticities of substitution in the long-run. They observe an increased contribution from the PE channel over time, which matches our findings. We can therefore conclude that direct substitution possibilities for energy are the most significant parameter when assessing rebound effects in the long-run. It highlights the need to account for temporal characteristics when choosing elasticity parameters.

Sectoral rebound effects in SEEM materialise for different reasons. For sectors with a comparatively high value share of energy as an input, the GE channel is more important than direct substitution between ESC and the energy composite. This is true for R-EEI scenario, as well as the different sensitivities that we test. This concurs with the findings of Lemoine (2020), who demonstrate the importance of the GE channels in causing rebound effects for energy-intensive sectors in the US. Our results however show that the initial energy value share is not the only, and not even the strongest determinant for dominant GE channels. The benchmark energy intensity of the transport sector is almost 60% higher than for the energy-intensive manufacturing sector. Nonetheless, rebound effects, as well as the contribution of the GE channels, are significantly higher for the latter. We attribute this to the stronger trade exposure of the manufacturing sector compared to the transport sector. Following efficiency-induced price reductions, the increased demand from abroad leads to a strong expansion of its production and energy needs, which Zimmermann et al. (2021) recognize as a variant of the Dutch Disease effect. This effect induces strong composition effects and consequently, the energy-intensive manufacturing industry exhibits the strongest rebound effects.

Sectors with a higher value share of capital and higher elasticities of substitution between ESC and the energy composite experience much stronger PE effects, as they take advantage of the decrease in the effective price of energy due to the efficiency stimuli. For the services sector, this mechanism is responsible for the lion's share of the sectoral rebound effects with GE effects playing almost no role at all. Meanwhile, the rest-of-industry sector and the energy supply sectors all exhibit a negative contribution of the GE channels. This corroborates the findings by Lemoine (2020), which indicate that the GE channel can reduce rebound effects for some sectors. For the rest-of-industry sector, and under the assumption of purely domestic EEI, this is due to negative composition effects that are caused by the Dutch Disease effect. The energy supply sectors face a strong drop in demand from other sectors due to the increased energy efficiency. The sectors, therefore, adjust their output level downwards and thus require less energy themselves, which leads to negative rebound effects.

Most rebound assessments focus on economy-wide rebound effects. Our analysis illustrates that more attention has to be brought to sectoral rebound effects and the diverse underlying mechanisms that perpetuate them. Only this way, the effectiveness of EEIs can ultimately be understood. Rebound effects in energy-intensive sectors overwhelmingly manifest via GE channels. Consequently, if the goal is to mitigate rebound effects and thus increase the efficacy of energy efficiency, it would require an approach that considers the impacts of various policies on the economic structure. Meanwhile, for sectors with a higher share of value added, mitigation can focus on offsetting the price differential between the energy composite and capital that arises after energy efficiency is improved, as this is the underlying cause for rebound effects via the PE channel.

3.6 Conclusion

Annual industrial EEIs bring about a reduction in the effective price of energy and trigger a wide range of economic adjustments, leading to higher energy use than anticipated. The measurement of these economy-wide rebound effects is well established in the literature and has recently been undertaken for Switzerland for the first time (Zimmermann et al., 2021). This study builds on this CGE assessment and decomposes rebound effects into three rebound mechanisms: a direct substitution effect; a multiplier effect; and a residual term, encompassing, inter alia, composition effects, indirect substitution effects, and trade effects. Moreover, we employ index and structural decomposition analysis to gain a better understanding of the drivers of the residual term.

The average rebound effects at the economy-wide level of 35% are both caused by the direct substitution of energy system capital for energy (i.e. the PE channel) and rebound mechanisms that occur via GE adjustments. We find that the composition effect and demand-driven trade effects are particularly significant to explain the large contribution of the GE channel for Switzerland. This is underlined by the substantial expansion of the energy-intensive sectors of the economy, which reap the economic gains from EEIs. As a result, their rebound effects mainly occur through GE adjustments. For more capital-intensive sectors, the direct substitution effect is by far the most relevant rebound mechanism. Our sensitivity analysis highlights the importance of the elasticity of substitution between energy system capital and the energy composite. Moreover, it shows that the differentiation between two capital types limits rebound mechanisms via the GE channel. Rebound assessments in a CGE context traditionally assume a homogenous capital stock. We can therefore hypothesize that the consensus of high rebound effects in the literature may be influenced by exaggerated estimates.

It is nonetheless recommended for policy-makers to have a better understanding of the causes of rebound effects if energy efficiency policies are to effectively reduce energy use. As our findings indicate great sectoral heterogeneity concerning the underlying rebound mechanisms, the policy lessons vary between sectors. We show that the price differential between energy system capital and the energy composite following EEIs leads to direct substitution away from capital. For sectors with high capital and labor use, this effect is the primary mechanism causing rebound effects. Policy-makers can thus aim to neutralize this PE channel by implementing a tax on energy carriers in the size of the annual EEI and thus removing the incentive to substitute (Freire-González, 2020).

Generally, an energy tax is often named as the key policy tool to counteract rebound effects not only at the micro-level but also at the economy-wide level (Font Vivanco et al., 2016). Policy-makers should also think about how revenues are recycled and what the implications for individual sectors are to avoid additional rebound effects (Freire-González and Puig-Ventosa, 2015). For more energy-intensive sectors like the transport sector or the energy-intensive manufacturing sector, the large contribution of the GE channel indicates that simply increasing the price of energy carriers through a tax may not suffice to reduce rebound effects. Policy-makers thus should account for the economy-wide impact of rebound-mitigating policies in a more comprehensive manner and consider how rebound effects via composition or trade effects could be prevented when designing emission trading schemes or border tax adjustments.

Assessing policies that maximize the effectiveness of energy efficiency presents an important avenue for future research. Future work should also address the great residual component of our decomposition analysis, which constitutes a caveat present in this paper. Of particular importance is the contribution of the change in the structure of the economy and trade. A better understanding of the latter effect is further crucial to better gauge the impact of an additional caveat: we assume EEI to occur exclusively in Switzerland. Technological change is, however, likely to be a global phenomenon and thus possibly impacts trade less than observed in this study. Finally, we assume costless EEIs, which is rarely the case in the real world. To include such costs in rebound assessments is likely to depress rebound effects (Broberg et al., 2015).

Chapter 4 The Mitigation of Rebound Effects from Industrial Energy Efficiency: A Computable General Equilibrium Analysis

Abstract

Rebound effects significantly limit the effectiveness of (industrial) energy efficiency policies and measures in reducing industrial and domestic energy use. A still relatively unexplored solution to this ineffectiveness constitutes the mitigation of rebound effects with economic instruments. This paper explores the suitability of uniform taxes to increase the efficacy of energy efficiency in reducing energy use and investigates the economic impact of such taxes. With a recursively dynamic computable general equilibrium model, the taxation of different energy carriers is tested. The tax rates are endogenously set to fully offset economy-wide rebound effects in Switzerland. Moreover, four different modes of recycling and spending the tax revenue are compared. The analysis of revenue recycling as reductions of preexisting taxes demonstrates that the economic gains from energy efficiency improvements still outweigh the costs the taxation incurs. When all energy carriers are taxed simultaneously, the highest reduction in energy savings is achieved, as unwanted substitution between energy carriers can be avoided. Rewarding energy-reducing sectors in a bonus-malus scheme proves the most efficient way to mitigate rebound effects, as it retains most of the economic gains of the energy efficiency improvements. Conversely, lump-sum transfers to households and increased government purchases are less conducive to economic activity and welfare. Rebound mitigation thus presents a suitable policy tool to increase the effectiveness of energy efficiency in reducing energy use and a more routine consideration of its merits in energy policy-making is necessary.

Highlights

- Rebound mitigation can increase energy savings from industrial energy efficiency
- Uniform energy taxation constitutes a promising tool for rebound mitigation
- All energy carriers should be targeted by taxation to avoid unwanted substitution
- The choice of how tax revenue is used influences the taxes' economic impact

Keywords
Rebound effects, energy efficiency, rebound mitigation, energy taxation, revenue recycling, computable general equilibrium modeling

4.1 Introduction and review of literature

In the face of increasing pressures to reduce emissions from fossil fuels, energy efficiency policies and measures constitute central elements of industrial and national energy strategies around the world. For instance, the European Union recently reconfirmed its commitment to energy efficiency as a vital part of its European Green Deal (EC, 2021). Moreover, the European Commission considers a significant part of the estimated 275 billion euros of investment for the Green Deal to go into energy efficiency (EC, 2020). Energy efficiency is also a central pillar of the energy strategy in Switzerland (SFOE, 2021b), where concerns over energy security as a result of the nuclear phase-out add to the need to reduce emissions. To bridge the energy efficiency gap that prevents cost-effective energy efficiency measures from being implemented (Gillingham and Parker, 2014), Switzerland has similarly financed significant investments in energy efficiency in the industry and services sectors (ProKilowatt: SFOE, 2021c) and the housing sector. For the housing sector alone, subsidies of 2.3 billion CHF were distributed over the last decade (SFOE, 2021a).

Given the substantial commitments to and investments in energy efficiency, it is thus important for energy efficiency policies to be as effective as possible in achieving their energy savings targets. Ineffective energy efficiency policies would further involve potentially high opportunity costs, particularly when they are introduced instead of alternative competing energy policies, such as the increased diffusion of renewable energy sources (Patt et al., 2018). And indeed, the effectiveness of energy efficiency is oftentimes found to be jeopardized by so-called rebound effects, also in the case of Switzerland (Zimmermann et al., 2021). This is troubling, as a recent study shows a clear need for higher energy savings from energy efficiency in Switzerland, and specifically in production, to achieve the necessary reductions in energy use (Bhadbhade et al., 2020). To this end, this paper investigates the potential to increase the effectiveness of energy efficiency in Switzerland by mitigating rebound effects with economic instruments.

Rebound effects are a consequence of the reduced effective price in the use of energy as a result of energy efficiency improvements (EEIs). This leads to a differential between the actual and the potential energy savings, because of price-induced economic and behavioral adjustments. As a typology by Lange et al. (2021) shows, there are a considerable number of potential rebound mechanisms that can offset energy savings. They occur at different levels of aggregation and in the short- and the long-run. These mechanisms encompass micro-level effects, such as the substitution of production factors for energy, and meso-level effects (e.g. efficiency-induced changes of sectoral demands for intermediate goods). The possible move of the economy towards more energy-intensive production following an EEI (i.e. the composition effect) constitutes one of many macro-level rebound mechanisms.

It is now commonly accepted in the literature that rebound effects partially offset energy savings from EEIs (Madlener and Turner, 2016). Considerable rebound effects have been found in the case of more energy-efficient household appliances (Druckman et al., 2011; Chitnis et al., 2013; 2014) and for industries (Anson and Turner, 2009; Matos and Silva, 2011; Evans and Schäfer, 2013). Assessments of the more aggregate economy-wide rebound effects produce varying results and the question on their magnitude is still considered to miss "a definitive answer" (Stern, 2020, p.5.) A recent review of climate and energy models assessing economy-wide rebound effects puts the mean at 42.5%, indicating the extent of energy savings lost due to rebound effects (Colmenares et al., 2020). Computable general equilibrium models have been used to estimate these aggregate rebound effects for a myriad of countries, including the US (Böhringer and Rivers, 2018), the UK and Scotland (Allan et al., 2007b; Hanley et al., 2009; Turner, 2009), Sweden (Broberg et al., 2015), Germany (Koesler et al., 2016) and Switzerland (Zimmermann et al., 2021):

While the assessment of rebound effects is thus relatively well established, a strand of literature that has received much less scrutiny concerns the (policy) response to rebound effects. Font Vivanco et al. (2018) underline the need for a better understanding of the mitigation of rebound effects with complementary policies, both in the case of costless and policy-induced EEIs. Nonetheless, only a limited number of studies investigate possible ways to minimise the energy savings being lost. Given the prevalence of these rebound effects, this appears as a missed opportunity.

Freire-González and Puig-Ventosa (2015) similarly criticize this in their study of the most suitable policy measures to control and mitigate rebound effects in households. They identify measures in three main areas: First, through improved information and awareness, policy-makers can attempt to change consumer behavior to avoid the savings from energy being spent on energy-intensive goods and services. Secondly, legal instruments may support this by enforcing clear standards and limits or better labelling for the energy use of products and services. Finally, the authors illustrate that policy-makers can rely on economic policy instruments to counteract the decrease in the effective price of energy and thus mitigate rebound effects. They consider energy taxation the most promising instrument, although they highlight the need to consider the way related tax revenues are used. Only if designed appropriately, re-spending effects that involuntarily induce further energy use can be prevented, which several studies underline (Alfredsson, 2004; Druckman et al., 2011; Freire-González, 2011).

Freire-González (2021) argues that a certain level of rebound effects may not be avoided in the current economic system. He nonetheless ascribes potential to energy taxation to counteract rebound effects. The author further introduces cap-and-trade systems as a means to overcome concerns of rebound effects. Specifically, he highlights its main advantage of attaining a pre-defined policy target at the expense of possibly higher costs and a more challenging implementation. Bonus-malus schemes constitute an additional instrument at policy-makers' disposal. In such schemes, the revenue from (energy) taxation is earmarked to reward actors' sustainable behavior. Finally, rebates and subsidies are further economic instruments that could be used to mitigate rebound effects, even though their suitability has remained largely unexplored (Font Vivanco et al., 2016). Freire-González and Puig-Ventosa (2015) point out that it is ultimately a political question whether to prioritize energy savings or economic growth from increased energy efficiency, as this dictates the decision to mitigate rebound effects or not. Finally, rebound mitigation as a policy instrument also raises certain distributional questions, as it has the potential of disproportionally affecting low-income households (Saunders et al., 2020).

The limited research on rebound mitigation is also mirrored in the attention rebound effects tend to receive in the policy-making process. Font Vivanco et al. (2016) assess whether and how rebound mitigation has entered the policy agenda in the European Union and find limited traction for the issue. In Switzerland, to our knowledge, the existence of rebound effects has neither played a discernible role in the design of energy efficiency policies nor have policies capable of mitigating rebound effects been considered in that regard. Levett (2009) sees this inaction as a corollary to the very nature of rebound effects, which are inherently complex effects that permeate across the entire economic system and are difficult to foresee, assess and, subsequently, counteract. The author prescribes holistic approaches such as the combination of energy efficiency policies and (energy) taxes to promote sustainable behavior and discourage unsustainable one at the same time.

In addition to the selected qualitative and theoretical discussion of potential mitigation tools, a few studies have started to quantitatively analyse the suitability of energy policies to offset rebound effects and the impact these policies have on the economy. Freire Gonzalez and Ho (2021) use a CGE model to assess the (carbon) rebound effects from voluntary actions to reduce households' energy consumption and demonstrate that considerable carbon taxes are needed to offset them. Giraudet and Quirion (2008) compare the suitability of Tradable White Certificates (TWC) for the mitigation of rebound effects to other policies such as energy taxes. TWCs force energy suppliers to increase energy efficiency to a certain level or to purchase certificates from other suppliers, who manage to do more. The authors find TWC a valid alternative to energy taxes, as long as the amount of energy use is fixed. Based on an econometric model, Kratena et al. (2010) simulate the necessary energy taxation to fully compensate rebound effects from an EEI in households' use of transport services, housing and electricity. They find very different tax rates needed for the three types of fuel use, with transport-related fuel prices only requiring an increase of 7% relative to baseline compared to 80% for heating fuel. The authors highlight the potential of complementing energy efficiency with taxation when designed carefully. However, none of these studies considered the possible impact of the redistribution of tax revenues.

Ahmann et al. (2021) employ a macro-econometric model for the analysis of energy efficiency paired with four different policies to reduce rebound effects in the German industry sector: (1) mandatory reinvestments of the energy savings; (2) a CO_2 tax with redistribution; (3) an equal yield tax reform that introduces an energy tax and reduces income taxes; and (4) a reduction of working hours. The CO_2 tax with subsequent redistribution of the tax revenue is the most successful in mitigating rebound effects, even though the effects greatly vary across sectors. In terms of the economic effect of the scenarios, the overall impact is rather small with the reduction of working hours being the sole exception. Specifically, reducing working hours has a comparatively strong negative impact on GDP.

As Font Vivanco et al. (2016) point out, the literature differentiates two types of energy taxation: uniform and sector-specific. Saunders (2018) focuses on the latter and determines the sectoral ad valorem energy taxes necessary to offset historically measured direct rebound effects in the US between 1980-2000. The mitigation of rebound effects in this study requires substantial tax rates around 50% for most sectors, with some estimates even reaching 350%. Moreover, it is demonstrated that certain sectors with high rebound effects only require low energy taxes and vice versa. The author, therefore, concludes that sectoral taxes should be prioritized over uniform rates across the economy for successful rebound mitigation. This also limits the negative economic impact. Even with sectoral taxes, however, the mitigation of rebound effects reduces economic activity relative to no rebound mitigation, with output, employment and profits decreasing for the majority of the sectors. A remedy to this provides the recycling of tax revenues via the reduction of an existing (distortionary) payroll tax, in the case of which Saunders (2018) finds positive effects for economic welfare when mitigating rebound effects.

Freire-González (2020) uses a dynamic CGE model to assess a global 5% one-time energy efficiency stimulus and to test how different levels of ad valorem taxes on the output from energy industries impact rebound effects. Specifically, the study implements these tax rates concurrently to an EEI to equalize the actually achieved and the potential energy savings. The economy-wide rebound effects of approximately 83% are found to be completely mitigated by a tax rate of 3.76%, with which the EEI still yields a positive change in GDP. The study shows that complementing energy efficiency with a uniform energy tax may lead to a double benefit by simultaneously increasing economic welfare and reducing energy use, even when tax revenue is used for increased government spending. It thus contradicts the finding by Saunders (2018) that revenue recycling via a substantial payroll tax is necessary to offset the negative economic impact of rebound mitigation.

There is thus some evidence that energy taxation has the potential to successfully mitigate rebound effects and increase the effectiveness of an EEI in reducing energy use. Evidence is, however, less clear concerning the rate and design of such a tax. Moreover, there have been conflicting findings regarding the impact of such complementary policies on production and the economy as a whole. We contribute to improving the understanding of rebound mitigation by assessing taxes on industrial energy use for Switzerland alongside annual industrial EEIs. As we are interested in mitigating economy-wide rebound effects, we focus on energy carrier taxes, which are uniform across sectors, rather than sector-specific taxes. We use the Swiss Energy Efficiency Model (SEEM) developed in Zimmermann et al. (2021), a recursively-dynamic CGE model of the Swiss economy. CGE models such as SEEM are well suited for this type of analysis, as they enable the assessment of system-wide effects of policy-induced changes (Allan et al., 2007a).

EEIs lower the cost of production and can thus be expected to positively influence (economic) welfare. It also likely results in a reduction in the use of fossil fuels and thus leads to positive externalities from a decrease in fossil energy-related emissions. The impact of ensuing rebound effects on welfare is more ambiguous, both at the micro-level and more aggregate levels. As Chan and Gillingham (2015) point out, change in welfare from micro-level rebound effects depends on the definition of the welfare measure – that is, if externalities and congestion costs are included – and the relationship between different types of energy and energy services. It follows that the mitigation of rebound effects also warrants close examination of its implications for welfare.

In the underlying analysis, we assume a narrow definition of welfare based on the Hicksian equivalent variation, which is a commonly used measure of economic welfare in CGE models. Ancillary effects such as externalities and congestions costs are not included. In doing so, the welfare analysis should in the following be interpreted as a lower bound of the expected total changes in actual welfare. The rebound assessment in this research further constitutes a "what-if" analysis, in which we seek to determine possible outcomes of substantial rebound mitigation as a policy target. Specifically, we investigate the normative goal of maximizing energy savings from energy efficiency (i.e. rebound effect equal to zero) rather than maximizing welfare. While this may not be a policy that may likely be pursued in reality, it allows us to gauge the maximum extent to which rebound mitigation as an energy-saving instrument impacts welfare and production.

To this end, we endogenously determine the tax rates to fully offset economy-wide rebound effects from efficiency improvements in refined oil, natural gas and electricity use, thus implementing a cap on energy use. We simulate a separate scenario for the rebound mitigation for each energy carrier individually and discuss the implications of these three scenarios for the economy and welfare. Moreover, we analyse a scenario, in which all three energy carriers are taxed simultaneously, thus completely offsetting economy-wide rebound effects. For this scenario, we additionally investigate how different modes of utilizing the revenues of the newly imposed taxes impact economic welfare and the tax level necessary to offset rebound effects. Revenue recycling is critical, not only because it affects efficiency and distribution, but also because it often triggers further rebound effects. We test the introduction of a bonus-malus scheme, which rewards sectors for the reduction in energy use via bonus payments. We further compare the impact of using the tax revenue either as a lump-sum transfer to households, to reduce existing distortionary taxes and as increased government purchases. This allows us to better understand how to deal with rebound effects from EEIs in the future and helps policy-makers to increase the effectiveness of energy efficiency policies to achieve their targets.

Section 4.2 presents the tax policies and tax revenue recycling and spending schemes we simulate. Section 4.3 provides an overview of the results. In the penultimate section, we interpret and discuss the implications of these results. We conclude with Section 4.5 and elaborate on potential ways forward for energy efficiency policies in Switzerland.

4.2 Method

4.2.1 Description of main scenario and rebound calculation

As a reference scenario, SEEM assumes a steady state of the economy over time (the SS scenario). Estimated population growth for Switzerland determines the increase in labor supply and thus the growth rate of the model (FSO, 2020). No EEIs are implemented in the SS scenario. The consumer price index is used as a numeraire. The main scenario (the R-EEI scenario) assumes annual EEIs of 2.31% in production, which are exogenous and costless. These improvements are modeled as biased technical change, enabling more production of output with less energy. Only production in Switzerland experiences energy efficiency stimuli. All energy carriers (refined oil, gas, and electricity) are equally affected by EEIs. The implemented rate of 2.31% is based on the Swiss Energy Perspectives 2050+ (Prognos AG, TEP Zürich, Infras and Ecoplan, 2020), which assesses possible pathways to net-zero emissions by 2050 while ensuring energy security.

In the results section of this paper, sectoral and industrial rebound effects are calculated with Equation 4.1. $\dot{E}_t^i$ represents the yearly change in physical energy use of a sector i or the total industry relative to the reference scenario (i.e. the actual energy savings). In the denominator, $\gamma_{EC,t}$ shows the cumulative EEI in year t (i.e. the potential energy savings). This is equivalent to the change in physical energy use for a hypothetical scenario, in which EEIs have been perfectly effective and no rebound effects occur.

Rebound effects at the economy-wide level (i.e. production plus households) are calculated by comparing the percentage response of the domestic physical energy use $\dot{E}_t^i$ to the EEI $\gamma_{EC,t}$ multiplied with the share of industrial energy use in total domestic energy use in the benchmark. Rebound effects can also be calculated at the individual energy carrier level when the energy use change of a specific energy carrier is used instead of the change in total physical energy use. In the following, the standalone term "rebound effects" refers to energy rebound effects. If we investigate rebound effects for specific energy carriers, it is preceded by the corresponding designation, e.g. "oil rebound effects".

Equation 4.1: The calculation of rebound effects

$$R_t^i = \left(1 + \frac{\dot{E}_t^i}{\gamma_{EC,t}}\right) x\ 100$$

4.2.2 Tax scenarios and the recycling of the tax revenue

The annual EEIs modeled in the R-EEI scenario bring about a reduction in the effective price in energy, which triggers economic and behavioral adjustments leading to rebound effects. To mitigate these rebound effects, these price-induced responses need to be discouraged. We undertake this by introducing new taxes on energy use, thereby aiming to reduce economy-wide refined oil, natural gas, and electricity rebound effects to zero. We implement three taxes in SEEM, which are energy carrier-specific and uniformly apply to all sectors as a mark-up to the price of refined oil, natural gas, and electricity, respectively. All taxes are levied as unit taxes, that is per unit of physical energy. These taxes are limited to the production sectors; households do not pay them directly.

First, we simulate three scenarios: RM-Oil, RM-Gas, and RM-Elec. For all these scenarios, the R-EEI scenario forms the basis, and only the relevant tax is levied (e.g. in the RM-Oil scenario, only the industrial use of refined oil is taxed). SEEM endogenously determines the annual tax rate for the complete mitigation of economy-wide rebound effects for each energy carrier, by ensuring that the year-on-year reduction in energy use is equal to the potential energy savings (i.e. a decrease in energy use by 2.31% per year). This is tantamount to a cap on energy use. In doing so, we can compare how rebound mitigation differs across energy carriers, as well as what the implications of such mitigation are for welfare, consumption, and production.

The RM-Ene scenario constitutes an additional simulation we undertake, in which all energy carriers are taxed simultaneously. The tax rates are again determined endogenously to fully mitigate the economy-wide energy rebound effects following industrial EEIs. Given the broader tax base, the tax rates are expected to differ from the previous tax scenarios. This allows us to analyze how the simultaneous taxation of multiple energy carriers affects the tax rates necessary for successful rebound mitigation and their impact on households and industries.

The new taxes generate additional revenue. As evidenced in the literature review in Section 4.1, the use of this tax revenue has important economic implications. For the R-EEI scenario, we assume an equal yield assumption, which ensures constant public goods provision through an endogenous adjustment of the capital and labor income tax rate. The equal yield assumption is also retained for the four tax scenarios displayed in Table 4.1. Any additional tax revenue from these scenarios is therefore used to reduce pre-existing capital and labor income taxes.

Next to pure tax reforms, we simulate other recycling and spending options when economy-wide rebound effects for all energy carriers are mitigated. In one recycling variant (RM-BM), we introduce a bonus-malus system, in which the tax revenue is used to reward sectoral energy use reductions. In this recycling mode, the tax is only paid if energy use exceeds the historical benchmark energy use and sectors below this threshold receive a bonus funded from the tax revenue.[9] Moreover, we investigate a lump-sum transfer of the tax revenue to the representative household (RM-LS) and a scenario in which the additional tax revenue is used to increase government public goods provision (RM-GP).

[9] In the model, bonuses are paid as output subsidies.

Table 4.1: Overview of the scenarios simulated in SEEM

Scenario name	Description of scenario
SS	Steady-state reference scenario
R-EEI	EEI of 2.31% p.a.
RM-Oil	R-EEI scenario with an endogenous tax on industrial oil use to completely mitigate economy-wide oil rebound effects
RM-Gas	R-EEI scenario with an endogenous tax on industrial gas use to completely mitigate economy-wide natural gas rebound effects
RM-Elec	R-EEI scenario with an endogenous tax on industrial electricity use to completely mitigate economy-wide electricity rebound effects
RM-Ene	R-EEI scenario with taxes on the industrial use of all energy carriers to completely mitigate economy-wide rebound effects. All tax rates are determined endogenously
RM-LS	RM-Ene scenario with recycling of tax revenue as a lump-sum transfer to the representative household
RM-GP	RM-Ene scenario with increased government spending
RM-BM	A bonus-malus scenario that completely mitigates economy-wide rebound effects for all three energy carriers

4.3 Results

The annual industrial EEIs modeled in the R-EEI scenario lead to substantial industry-wide and economy-wide rebound effects, as Table 4.2 indicates. Instead of an expected 49.6% reduction in industrial energy use in 2050, the estimated energy use in production only decreases by 35%, resulting in industry-wide rebound effects of roughly 30%. This loss in energy savings is mainly driven by increased energy use in the energy-intensive manufacturing industry and the services sector, which exhibit sectoral rebound effects in the last period of 39% and 32%, respectively. The erosion of domestic energy savings is even larger with economy-wide rebound effects of 35%, as households increase their energy use due to efficiency-induced income gains.

While the potential energy savings from the efficiency stimuli do not materialize in full, the more efficient use of energy nonetheless positively impacts the economy. GDP is 1.7% higher in 2050 than in the SS scenario, in which no EEIs take place. Domestic production benefits from the efficiency-induced reduction in the costs of production, which is particularly accentuated in the most energy-intensive industries. This translates into the strengthened competitiveness of the economy and increased domestic economic activity, as well as higher exports. Wages and capital remuneration also increase. The higher income leads to consumption gaining almost three percentage points compared to the SS scenario and welfare follows with an increase of 1.6%. In the definition used here, welfare entails consumption and leisure. Ancillary benefits such as positive externalities or reduced negative externalities and congestions costs are not included. The difference between consumption and welfare thus stems from the fact that households choose labor over leisure, as a result of higher wages.

4.3.1 The mitigation of economy-wide rebound effects

In the following, we impose uniform energy carrier-specific taxes to increase the actual savings achieved with EEIs in the use of refined oil, natural gas, and electricity, respectively. The necessary taxes for each scenario are given in the bottom three rows of Table 4.2. While all taxes are denoted in CHF/kWh for the sake of comparison, we convert the unit tax rates for refined oil and natural gas in liter and m^3, respectively, in the subsequent discussion, as they are the conventional price units for these two energy carriers. For refined oil, the endogenously determined unit tax rate needed to offset the respective economy-wide rebound effects (RM-Oil scenario) amounts to 0.95 CHF per liter in 2050. This roughly corresponds to a CO_2 tax of 385 CHF/tCO_2. Comparing the industry-wide and economy-wide rebound effects, two things become apparent for the RM-Oil scenario: First, industry-wide refined oil rebound effects are negative. To achieve full mitigation of economy-wide rebound effects, production has to compensate for increased energy use by households, stemming from efficiency-induced income effects. Secondly, because of the increased user costs for refined oil, there is strong substitution towards natural gas, and the economy-wide natural gas rebound effects more than double. Albeit smaller, this is also the case for electricity. Consequently, there are still significant economy-wide energy rebound effects, even as oil rebound effects from production are entirely offset.

These effects are largely mirrored in the RM-Gas and the RM-Elec scenario. As electricity is the most used energy carrier in production, the tax on industrial electricity use has the strongest impact on the overall rebound effects of all three scenarios. The RM-Elec scenario also requires the highest tax rate in 2050, slightly higher than the tax on refined oil in the RM-Oil scenario. For both scenarios, the price of the respective energy carrier relative to the numeraire more than doubles with the imposed tax. These changes are much larger than for the price of natural gas in the RM-Gas scenario, which increases by 51%, corresponding to a CO_2 tax of approximately 195 CHF/tCO_2.

We further test a more comprehensive tax scheme in the RM-Ene scenario, in which we impose differentiated unit taxes on all energy carriers to exactly offset economy-wide rebound effects for all of them. Compared to offsetting rebound effects for each energy carrier individually (RM-Oil, RM-Gas, and RM-Elec), significantly higher unit tax rates are required, especially for refined oil and natural gas (1.36 CHF/L instead of 0.95 CHF/L in RM-Oil for refined oil and 0.97 CHF/m3 instead of 0.39 CHF/m3 in RM-Gas for natural gas). Indeed, the mitigation of rebound effects for one energy carrier is of course relatively easy when energy users can simply replace it with another energy carrier. Reducing energy use as a whole is a more challenging task.

In the RM-Ene scenario, the additional energy taxes are not levied on the representative household. At the same time, the representative household enjoys a higher income level due to the benefits from the industrial EEIs. This raises the households' expenditure level, including energy use. For total economy-wide rebound effects to be fully suppressed, the sectors need to additionally decrease their energy use to counteract the increasing energy use by households. Consequently, the industry-wide rebound effects have to be negative, as shown in Table 4.2.

Table 4.2: Overview of industry-wide and economy-wide rebound effects (in %) and the corresponding rebound-offsetting unit tax rates for the four tax scenarios in 2050

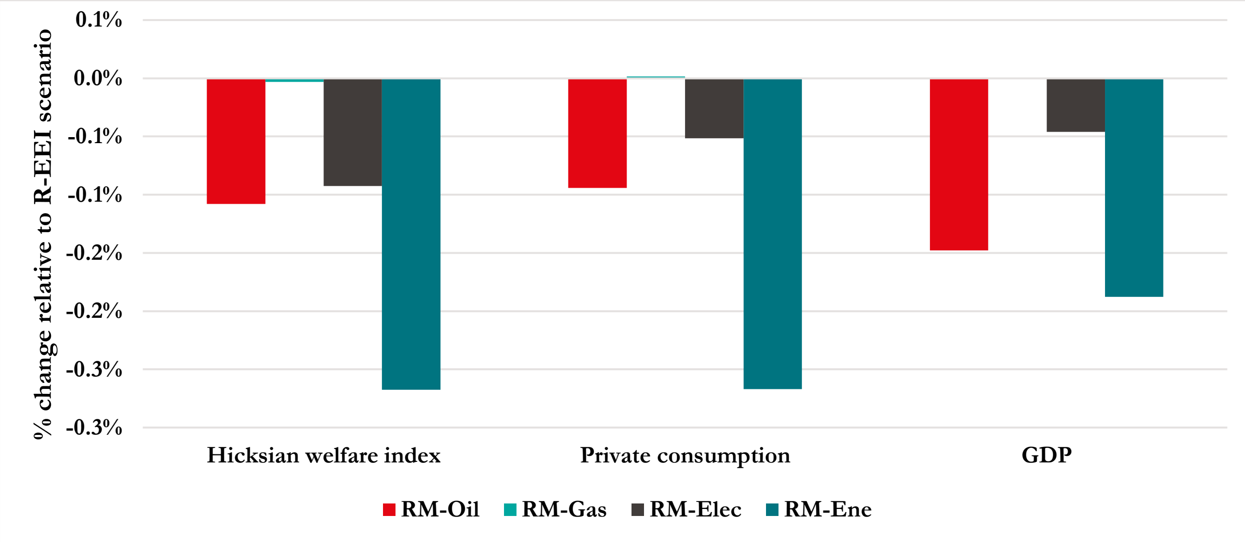
	R-EEI	RM-Oil	RM-Gas	RM-Elec	RM-Ene
Industry-wide refined oil rebound effects	26.1%	-6.3%	30.3%	32.2%	-5.3%
Industry-wide gas rebound effects	30.5%	64.5%	-3.8%	35.8%	-3.6%
Industry-wide electricity rebound effects	30.7%	34.5%	31.2%	-3.5%	-3.2%
Industry-wide rebound effect	**28.8%**	**21.4%**	**26.3%**	**16.4%**	**-4.1%**
Economy-wide refined oil rebound effects	34.3%	**0**	36.9%	38.2%	**0**
Economy-wide gas rebound effects	32.8%	68.1%	**0**	39.6%	**0**
Economy-wide electricity rebound effects	34.0%	37.6%	34.4%	**0**	**0**
Economy-wide rebound effect	**33.5%**	**25.9%**	**31.0%**	**21.0%**	**0**
Oil tax rate	**n/a**	**0.10 CHF/kWh**	**n/a**	**n/a**	**0.14 CHF/kWh**
Gas tax rate	**n/a**	**n/a**	**0.04 CHF/kWh**	**n/a**	**0.09 CHF/kWh**
Electricity tax rate	**n/a**	**n/a**	**n/a**	**0.15 CHF/kWh**	**0.17 CHF/kWh**

Results

We now turn to the analysis of the economic impacts of the different tax scenarios. In each of the three tax scenarios on individual energy carriers, a new tax is introduced, while pre-existing taxes are reduced according to the equal yield assumption. The results are given in Figure 4.1 relative to the R-EEI scenario. Rebound mitigation increases the excess burden of the total tax system for the RM-Oil scenario and the RM-Elec scenario and welfare thus comparatively decreases in both cases. Meanwhile, the impact of the tax on natural gas in the RM-Gas scenario is relatively marginal. The reasons for this are twofold: first, production relies significantly more on refined oil and electricity than on natural gas. Hence, taxing refined oil (i.e. the RM-Oil scenario) or electricity (i.e. the RM-Elec scenario) leads to a larger increase in the tax base than taxing natural gas. And secondly, the much higher tax rates needed to offset rebound effects in the RM-Oil and RM-Elec scenario lead to a larger overall tax burden. Nonetheless, welfare is still higher than in the case of no EEIs (the SS scenario) for all three scenarios.

These findings are largely mirrored in the change in overall consumption in households for the three scenarios, as taxation leads to higher costs of production and subsequently to higher prices for consumers. The enhanced energy savings thus come at an economic cost, as evidenced by the other economic indicators in Figure 4.1. For the RM-Oil and the RM-Elec scenario, the change in GDP decreases relative to the R-EEI scenarios, while economic activity in the RM-Gas scenario is relatively unaffected by the tax on natural gas. The indicators for domestically sold output, exports and imports show a similar picture. In conclusion, the taxation of individual energy carriers manages to offset the respective economy-wide rebound effects, while still reaping some of the efficiency-induced economic benefits. Because of the substitution effects in the case of individual taxation of each energy carrier, the actual energy savings at the economy-wide level are, however, still far from the potential energy savings.

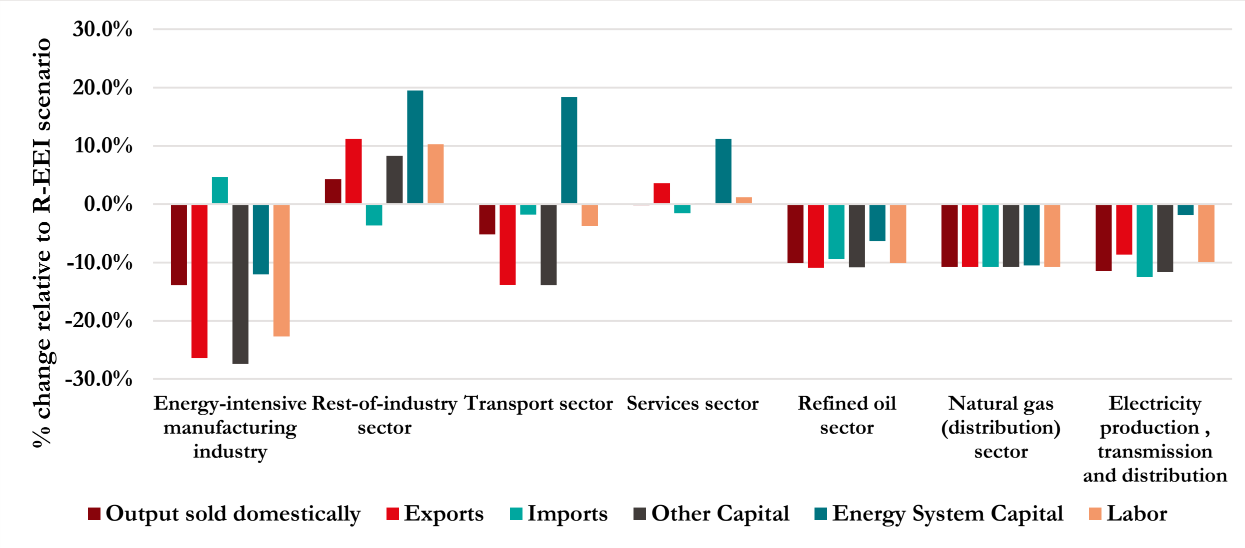
Figure 4.1: An overview of aggregate macroeconomic indicators for the four tax scenarios in 2050, relative to the R-EEI scenario (in %)



In the RM-Ene scenario, the impact on welfare and consumption is much more accentuated, as illustrated in Figure 4.2. Welfare decreases by 0.27%, relative to the R-EEI scenario. This thus indicates an increase in the excess tax burden from broadening the tax base to all energy carriers, even though the pre-existing taxes on capital and labor income in 2050 are reduced to almost 80% of its 2020 levels. The significantly higher taxes rates further add to this decrease in welfare, which can also be found in the change in households' consumption. The broader tax base and the higher tax rates in the RM-Ene scenario also negatively affect GDP, relative to the R-EEI scenario. The impact on GDP is, however, more subdued than on welfare.

The simultaneous taxation of all three energy carriers in combination with an equal yield tax reform changes the relative competitiveness of the different sectors. This warrants a closer look at how the different industries are affected by the complete mitigation of economy-wide rebound effects in the RM-Ene scenario, which we provide in Figure 4.3. For the most energy-intensive sectors - the energy-intensive manufacturing industry and the transport sector -, the taxation has a depressing effect on both the number of goods sold domestically and sold abroad. This is a direct consequence of the higher costs of production and thus higher prices of its goods. For the manufacturing industry, this is so pronounced that its demand for both capital and labor decreases, and domestic demand is increasingly satisfied by imported goods. For the less trade-exposed transport sector, the impact of the tax is not as strong. In fact, the sector even increases its demand for ESC. Its relatively high elasticity of substitution between ESC and the energy composite allows it to respond more readily to the higher energy user costs than the energy-intensive manufacturing sector.

Figure 4.2: The sectoral changes in output, export, import, and in the demand of capital and labor for the RM-Ene scenario, relative to the R-EEI scenario (in %)



Compared to the energy-intensive manufacturing industry and the transport sector, the less energy-intensive rest-of-industry sector and services sector relatively benefit from the taxation of all energy carriers in two overarching ways: First, they experience a relative increase in their competitiveness as they are less affected by the increased user costs for energy. This is additionally accentuated by the strong substitution away from energy towards ESC, indicated in Figure 3. And secondly, as sectors with a relatively large share of value added, they disproportionately benefit from the uniform decrease in the tax rates of the pre-existing capital and labor income tax, resulting from the equal yield tax reform. The rest-of-industry sector particularly gains from this relative increase in competitiveness, as it is the only sector increasing its economic activity relative to the R-EEI scenario. As can be expected, all three energy supply sectors experience a decrease relative to the R-EEI Scenario across all presented indicators.

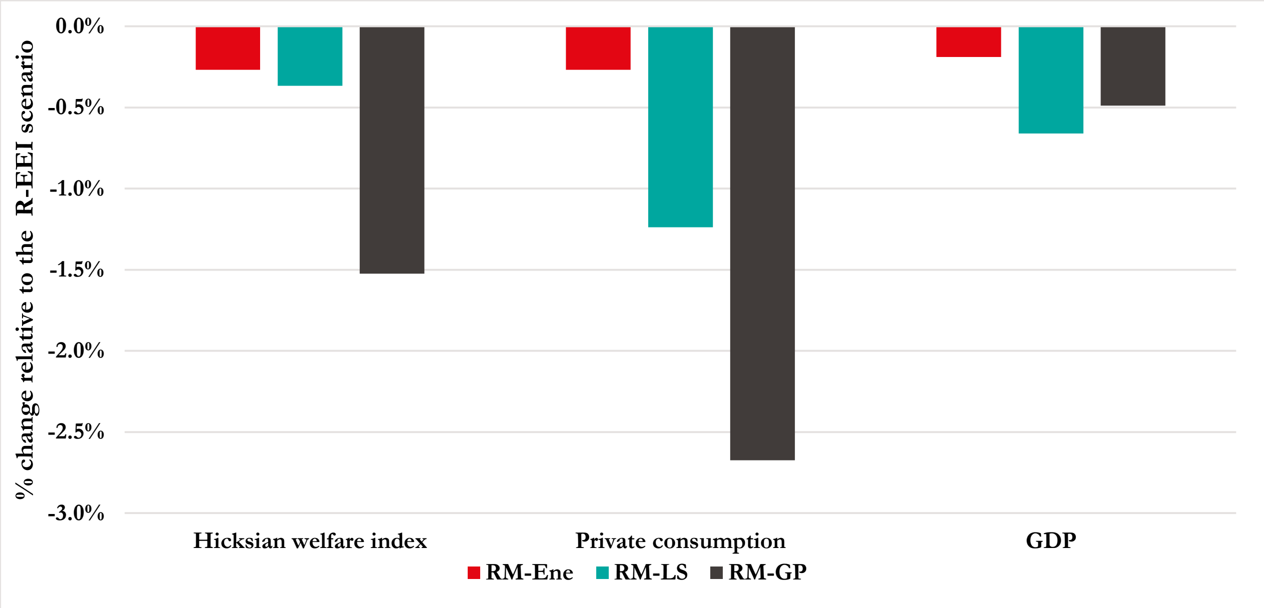
4.3.2 Lump-sum tax recycling (RM-LS) and increased government spending (RM-GP)

In order to better gauge the impact of the equal yield tax reform when mitigating economy-wide rebound effects, we test a scenario in which the additional tax revenue is instead recycled via direct lump-sum transfers to the representative household: the RM-LS scenario. We also simulate the case, in which the tax revenue is used by the government to increase the supply of public goods (the RM-GP scenario). Figure 4.3 juxtaposes the impact of these scenarios with a reduction of preexisting taxes for when economy-wide rebound effects are mitigated for all energy carriers (i.e. the RM-Ene scenario), relative to the R-EEI scenario.

The lump-sum transfer in the RM-LS scenario leads to a less efficient outcome of the tax system than the RM-Ene scenario, as the additional tax revenue here is not used for the reduction of pre-existing distortionary taxes. Rebound mitigation thus creates a larger excess burden, even though the tax rates necessary for successful mitigation are lower in the RM-LS scenario than in the RM-Ene scenario. It is, however, worth mentioning that in SEEM, there is only one representative household. Hence, no results can be presented regarding the distributional implications of lump-sum transfers on different household groups, relative to pure tax reforms.

The impact of this tax variant on consumption is even larger, with households' consuming roughly 1.2% fewer goods and services relative to the R-EEI scenario. This drop in demand is particularly driven by a decrease in the demand for output from the services sector, as the sector's relative competitive edge is lessened by the higher excess burden of existing taxes. Overall, the direct lump-sum transfer translates into lower economic gains for production from EEIs than the equal yield tax reform.

Figure 4.3: A comparison of macroeconomic indicators for the RM-Ene, the RM-LS, and the RM-GP scenario in 2050, relative to the R-EEI scenario



In the RM-GP scenario, the additional tax revenue from rebound mitigation is used towards the increased provision of public goods. While households are affected by higher public goods provision via ancillary benefits, we do not measure this as part of the welfare. As a consequence, the impact on welfare by mitigation economy-wide rebound effects of all energy carriers is largest in this scenario, decreasing by 1.5% relative to the R-EEI scenario. Household consumption is similarly stifled in the RM-GP scenario. The reason for this lies in a price increase of goods and services from the services sector. All additional tax revenue is now used for an increased procurement of public goods, which overwhelmingly consists of output from the services sector. Consequently, this drives up the purchasers' price of the services sector, crowding out demand from households. As the significantly higher government spending (+6%) positively contributes to GDP, GDP decreases less than private consumption relative to the R-EEI scenario.

4.3.3 The bonus-malus scheme (RM-BM)

Finally, we investigate an additional rebound mitigation policy: a bonus-malus scheme (RM-BM scenario). Table 4.3 displays the changes in macroeconomic indicators of this scenario and the RM-Ene scenario, relative to the R-EEI scenario. In the RM-BM scenario, sectors are rewarded with subsidies from the tax revenue for energy use reductions and as such, there is no additional tax revenue on aggregate. Nonetheless, the bonus-malus scheme economically outperforms the pure tax reform, with the decrease in welfare being slightly lower in 2050 for the RM-BM scenario compared to the RM-Ene scenario. The total efficiency of this mitigation policy in terms of welfare is thus highest of all the scenarios simulated, even though both the excess tax burden of pre-existing taxes remains and the respective unit tax rates are higher in the RM-BM scenario than in the RM-Ene scenario. This highlights the positive impact of the bonus payments.

The bonus payments lead to comparatively higher wages and capital remuneration in the RM-BM scenario, which increases income, stimulates private consumption, and induces households to forgo leisure. The bonus-malus scheme further positively impacts production, which fares better in the RM-BM scenario than in the RM-Ene scenario, while economy-wide rebound effects are fully mitigated.

Table 4.3: Comparison of aggregate macroeconomic indicators for the RM-Ene scenario and the RM-BM scenario in 2050, relative to the R-EEI scenario

	RM-Ene	RM-BM
Hicksian welfare index	-0.3%	-0.3%
Private consumption	-0.3%	-0.1%
GDP	-0.2%	-0.1%
Output sold domestically	-0.8%	-0.5%
Working hours	0.2%	0.3%
Leisure	-0.3%	-0.4%
Real wage	0.003%	0.2%
Rental rate of capital	-0.7%	-0.6%

Finally, we analyze how the different industries are affected by the implementation of the RM-BM scenario. As can be expected, energy-intensive sectors benefit most from switching from an equal yield tax reform to a bonus-malus scheme. Even though both the energy-intensive manufacturing industry and the transport sector still have significantly lower economic activity than in the R-EEI scenario, the rewards from the bonus-malus scheme are able to stave off some of the negative economic impacts from mitigating rebound effects. This is contrasted by the less energy-intensive rest-of-industry sector and services sectors, which lose their relative competitive advantage as the excess burden of pre-existing taxes is no longer reduced.

4.4 Discussion

The results of the mitigation of the economy-wide rebound effects show that there is indeed scope to increase the energy savings from energy efficiency in a manner that still retains some of the economic welfare induced by EEIs. Under partial equilibrium (PE) conditions, EEIs translate one-to-one into a price reduction of the energy service. As such, it would have required an equally large tax to mitigate the resulting rebound effects. Meanwhile, in our simulation of the RM-Ene scenario, the average annual tax rates increases are 3.18%, 2.70%, and 2.71% for refined oil, natural gas, and electricity, respectively. All of these tax rate increases are thus above the annual 2.31% increase in energy efficiency assumed in SEEM. This points to the fact that general equilibrium (GE) effects induce additional energy use and thus work to increase the necessary tax rates.

One GE effect causing higher tax rates in RM-Ene is the limited inter-fuel substitution, which drives up tax rates since all energy carriers are taxed in RM-Ene. This is exemplified by the refined oil tax rate. The sectors that rely most on refined oil also have a comparatively large demand for electricity, which in the RM-Ene scenario, they can no longer substitute towards without also facing higher costs. This is underlined by the fact that in the individual tax scenarios the necessary average annual tax rates are significantly lower.

The tax rates determined in the RM-Ene scenarios contrast the findings from Freire-González (2020), who finds a tax rate of 3.4% to be necessary to counteract the economy-wide rebound effects from the one-time 5% EEI modeled in his study. An explanation for the differences with Freire-González (2020) lies in the author's modelling assumptions, which define much higher elasticities of substitution (i.e. Cobb-Douglas) between production factors. This enables factor re-allocation due to the tax-induced increase in user costs more readily. Consequently, a lower tax rate is needed to discourage energy use.

Our findings in the different recycling and spending modes underline the potential of using the tax revenue to absorb some of the negative impacts of rebound mitigation. When the tax revenue is retained as part of the government's budget (i.e. the RM-GP scenario) and thus not recycled, welfare is decreasing and production is seriously hampered by the mitigation of rebound effects. This corroborates the findings of Saunders (2018), who also emphasises the negative economic impacts on production and employment when mitigating historical direct rebound effects and no specific revenue recycling is considered. Conversely, he highlights the positive impact of reducing payroll taxes with the tax revenue, as the author finds that the negative economic consequences for producers, GDP, and employment are significantly subdued and on average even reversed.

Conclusion

When we use the additional tax revenue to reduce pre-existing taxes as in the RM-Ene scenario rather than increasing public goods provision, the more efficient tax system raises welfare and the economic gains from EEIs are larger. The impact of the equal yield tax reform in the RM-Ene scenario is, however, somewhat less positive overall than in Saunders (2018). This is likely to be a result of our simulation targeting a more comprehensive assessment of rebound effects. Moreover, there are methodological differences between the two studies (simulation-based vs. historical ex-post analysis).

As can be expected, the overall excess tax burden in the RM-LS scenario is greater than in the RM-Ene scenario and, therefore, an equal yield tax reform could be prioritized by the households from a welfare perspective. However, there is also some evidence in the literature that considering different income groups as opposed to the one representative household in SEEM would make a lump-sum transfer more beneficial in terms of its distributional implications (Imhof, 2012).

The relative inability to mitigate the negative effect on welfare and economic activity from the mitigation for rebound effects is a common theme for all recycling and spending schemes we simulated. Amongst them, the RM-BM scenario is the most successful in reducing the excess tax burden. In this scenario, sectors are rewarded for the reduction of industrial energy use by providing subsidies in a revenue-neutral manner, using the target level as a benchmark for a bonus-malus scheme. Bonus payments for reductions in industrial energy use thus provide a potentially beneficial alternative to the more widespread assumption of reducing pre-existing taxes. A necessary condition for this, however, is that the domestic target energy use is predefined and enforced by the taxes, as otherwise, the bonus payments would risk additional rebound effects. This condition assigns challenging tasks to real-world politics, as projecting, imposing, and possibly readjusting the tax rates can only be done as a part of a demanding policy process, and such policy processes tend to be influenced by conflicting interests and industry lobbying. This is, however, not only true for the bonus-malus system, but for all scenarios with rebound mitigation discussed in this paper. In fact, an effective bonus-malus scheme is likely to face less opposition from industries than pure tax reforms. This comes at the expense of potentially difficult negotiations about the benchmarks that are to be applied to each industry and each energy carrier.

In summary, the analysis has shown that the mitigation of economy-wide rebound effects is possible without significantly destroying the economic gains from EEIs. Compared to a world without EEIs (the SS scenario), all seven simulations show higher welfare, higher consumption, and higher GDP in 2050, as well as significantly lower energy use. This is true even for the relatively narrow definition of welfare assumed in this research, without incorporating any ancillary benefits from lower fossil energy use. However, industrial economic activity is negatively impacted by mitigation, as all simulations increase the total excess tax burden and increase costs of production. If economy-wide rebound effects are mitigated through a bonus-malus scheme or in an equal yield tax reform, in which the additional tax revenue is used to lower pre-existing taxes, this negative impact can significantly be reduced. The fact that there is only a limited negative impact on (economic) welfare for certain recycling modes is an encouraging sign for rebound mitigation as a policy tool. This is especially the case, as we study the very ambitious research objective of maximizing energy savings from EEI (i.e. zero rebound effects). If policy-makers sought to only mitigate some of the rebound effects, positive welfare impacts can most likely be expected. But even for such a case, it is important to thoroughly consider the design of the rebound mitigation and what to do with any additional tax revenue.

4.5 Conclusion

The mitigation of economy-wide rebound effects from energy efficiency policies and measures in production substantially increases the level of energy savings, while retaining some of the efficiency-induced economic welfare. Using a CGE model designed to assess rebound effects from EEIs in Switzerland (Zimmermann et al., 2021), we endogenously determine the taxation necessary to offset economy-wide and energy carrier-specific rebound effects. Substantial tax rates are needed to comply with the exogenously defined energy use targets. While increasing the excess tax burden and thus production costs, energy taxation nonetheless allows retaining some of the economic and welfare benefits from EEIs. This highlights its potential to increase the efficacy of energy efficiency in reducing energy use, as long as the tax scheme is comprehensive to avoid unwanted substitution effects between the energy carriers.

We further compare four different modes to recycle or spend the additional tax revenue: (1) lowering pre-existing capital and labor income taxes; (2) paying a lump-sum transfer to households; (3) increasing government spending on public goods, and (4) bonus-malus scheme, rewarding industries for energy use reductions beyond a targeted threshold. While none of these can completely mitigate the negative efficiency impacts of the respective scheme, the bonus-malus scheme is able to significantly retain the economic gains from EEIs.

Energy efficiency constitutes a central policy tool in reducing industry- and economy-wide energy use and ways to increase the efficacy of such policies should be more routinely considered in the policy-making process. The findings presented here demonstrate that certain economic instruments not only enable this successfully but also do so without significantly destroying the economic gains from EEIs. While finding the exact tax rates which counteract rebound effects may prove prohibitively challenging in reality, our results suggest that an average tax rate corresponding to the annual improvement in energy efficiency is a good first approximation for successful rebound mitigation effects. However, the higher the economic reliance on a given energy carrier, the more the tax rate will deviate upwards. Finally, we provide evidence for the possibilities to partially offset the negative economic consequences of rebound mitigation by recycling the tax revenue by reducing pre-existing taxes or by bonus-malus schemes. Bonus-malus schemes are also described as relatively uncontentious in a study on the public acceptability of policies in the EU (Bicket and Vanner, 2016). In a similar study for Switzerland, Thalmann (2004) finds energy policies to have a particularly high public acceptance when the revenue from taxation is earmarked towards encouraging additional energy use reduction. We can thus hypothesize that bonus-malus schemes would also present a policy tool worth considering for Swiss energy policy.

This paper demonstrates the suitability of rebound mitigation in Switzerland to increase energy savings from EEIs and lies the foundation for future work, in which existing economic instruments such as the Swiss CO_2 levy can be investigated to explore their potential in increasing the effectiveness of existing energy efficiency policies. Future research should also juxtapose energy taxation against alternative complementary policies, such as cap-and-trade systems. Moreover, certain caveats present here ought to be addressed. These include the assumption of the relatively crude disaggregation of Swiss production in only seven homogenous sectors, as well as the lack of sufficient disaggregation of households, which potentially obfuscates the impact lump-sum transfers have on different income groups. Finally, analysing the impact of different sensitivities of the model on rebound mitigation would further improve the understanding of the mechanisms by which energy taxation influences the efficacy of energy efficiency policies.

Chapter 5 General conclusion

The current thesis presents the first assessment of economy-wide rebound effects from industrial EEIs in Switzerland. We develop a new recursively dynamic computable general equilibrium model that enables the analysis of the effectiveness of energy efficiency and takes into account the relationship between energy and capital in perpetuating rebound effects. Specifically, we differentiate between two types of capital: one share of capital, which we term energy system capital, is assumed to be substitutable with energy, while the rest of capital ("Other Capital") is considered complementary to energy.

We show that economy-wide rebound effects substantially reduce the efficacy of energy efficiency by causing substantial amounts of potential energy savings to be lost. This highlights the need to consider rebound effects when devising energy efficiency policies more routinely to comply with national energy use reduction targets. Moreover, we find that the economic benefits from EEIs are unevenly distributed across sectors, which indicates that all-encompassing energy policies may yield varying results within the economy. The rebound literature puts great emphasis on the importance of the chosen elasticity of substitution in perpetuating rebound effects. Our findings corroborate this. We further illustrate that our novel approach in modelling capital and energy substitutability/ complementarity has a lowering effect on the simulated rebound effects, which informs the hypothesis that traditional rebound assessments with homogenous capital stocks may overestimate economy-wide rebound effects.

Closer examination of the underlying rebound mechanisms causing the erosion of energy savings teaches us more about the origins of rebound effects and how to think about them. Using decomposition analysis, we demonstrate that rebound mechanisms via the partial equilibrium channel and via the general equilibrium channel both contribute in equal measures to aggregate rebound effects in Switzerland. When looking at the different sectors in more detail, we can observe that the production mix of the individual sectors plays a crucial role in determining the most relevant rebound mechanisms. This indicates that sectoral aspects need to be taken into consideration more frequently. For energy-intensive sectors, sector-specific rebound effects are mostly caused by trade and composition effects (i.e. general equilibrium channel effects) due to the sectors' strengthened competitiveness. Sectors with high shares of value added experience an erosion of their energy savings mainly due to the partial equilibrium channel, which is a direct result of the lower effective price of energy and subsequent substitution towards energy.

Finally, we find that the mitigation of rebound effects with economic instruments can increase the effectiveness of EEIs in reducing energy use. We endogenously determine the tax rates needed to fully offset economy-wide rebound effects for different energy carriers and simulate the taxes' impact on welfare and economic activity. The most efficient approach constitutes a comprehensive tax scheme targeting all energy carriers, as this avoids unwanted substitution effects between the different energy carriers. As a corollary, it follows that this tax scheme also requires the highest tax rates to fully offset economy-wide rebound effects and have the largest negative impact on economic activity. When comparing different modes to recycle or spend the additional tax revenue, we demonstrate that a bonus-malus scheme rewarding sectors for energy use reductions have the greatest potential in retaining the economic gains from EEIs.

The work presented here provides key insights for Swiss energy policy. First, policy-makers in Switzerland ought to consider rebound effects more routinely, as they have the potential to significantly reduce the effectiveness of energy efficiency. Secondly, there is a need to account for sectoral heterogeneity when devising such policies, as different rebound mechanisms contribute to sectoral rebound effects, depending on the sector in question. Consequently, rebound-minimizing policy recommendations might look variedly different between sectors. And thirdly, the potential of rebound mitigation should be taken more seriously when thinking about potential rebound effects, since complementary economic policies such as energy taxation enable greater reductions in energy use while still achieving economic gains. Moreover, this can also encourage additional energy efficiency investments. We conclude by answering the question posed in the title of Chapter 1: Rebound effects in Switzerland do matter and urgently require the attention of policy-makers seeking to reduce energy use as part of the fight against climate change.

5.1 Future research

This assessment of economy-wide rebound effects lays the first foundation in understanding the effectiveness of industrial energy efficiency in Switzerland. Future work should pursue four main avenues to broaden our knowledge on what perpetuates rebound effects and how to mitigate them. First, in SEEM, we assume EEIs to be costless and thus “manna from heaven”. Moreover, we model them as exclusively occurring in Switzerland. Both assumptions are overly restrictive and do not necessarily represent real-world conditions. To include the costs of EEIs limits the incentive for substitution, as the impact of the stimuli on the effective price of energy is reduced. Consequently, this may decrease the estimated rebound effects. While some evidence in the literature suggests this hypothesis is true (Broberg et al., 2015; Fullerton and Ta, 2020), it will first have to be corroborated for Switzerland. Our results also indicate a strong impact of trade on the amount of energy savings lost. It thus requires additional analysis with global EEIs to gauge whether these strong trade effects are a Swiss idiosyncrasy or model-driven.

A second important avenue constitutes the assessment of rebound effects for Switzerland following policy-induced EEIs, as opposed to the completely exogenous improvements we model in SEEM. This would be tantamount to endogenizing energy efficiency, which in itself is a relatively well-established strand of literature. The assessment of ensuing rebound effects is, however, much less prevalent. The reason for this lies in the challenge of defining the correct corresponding potential energy savings from the endogenous efficiency stimuli for the calculation of the rebound effects. It is nonetheless an important issue that should be tackled, as it will provide invaluable insights in determining the effectiveness of future energy efficiency policies and the impact of alternative policies, which may stimulate new energy efficiency investments.

Thirdly, future research should investigate the suitability of existing and planned energy policies in Switzerland to mitigate the rebound effects from energy efficiency policies and measures. This could involve analyzing the existing CO_2 levy on heating fuels (including a possible future expansion on transport fuels), the integration of the Swiss emission trading system (ETS) with the EU ETS, or alternative policies, such as border tax adjustments. Such an assessment could indicate a set of policies that would be best suited for the mitigation of rebound effects in addition to achieving the policies’ targets.

Finally, further refinement and testing of SEEM would also improve its reliability and its value as a tool to inform real-world policy decisions. These refinements could include a greater disaggregation of the Swiss economy, a better representation of different income groups for distributional analysis of energy efficiency and rebound effects, and a more realistic reference scenario, which is not solely based on a steady-state scenario. A more empirical assessment of certain important parameters would additionally produce more reliable results, such as the choice of the share of energy system capital of the total capital stock.

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Appendix

5.2 Data, nesting structure and parameters in SEEM

Table 5.1: Sectoral aggregation in SEEM

Abbreviation	*Description of industry*	*NOGA classification*	*List of industries*
1: HIND	Energy-intensive manufacturing industry	01-17, 20, 22-24,26	Products of agriculture; products of forestry; products of fishing; products of mining and quarrying; Food products, beverage and tobacco products; Textiles, wearing apparel, leather products; Wood and products of wood and cork (except furniture), Pulp, paper and paper products; Chemicals and chemical products; Rubber and plastic products; Other non-metallic mineral products; Basic metals; Computer, electronic and optical products
2: RestIND	Rest-of-industry sector	18, 21, 27-33,41-43	Printed matter and recorded media; Pharmaceutical products; Fabricated metal products, except machinery and equipment; Electrical equipment; Machinery and equipment n.e.c; Motor vehicles, trailers and semi-trailers; Other transport equipment; Furniture; other manufactured goods n.e.c.; Repair and installation of machinery and equipment; Construction work
3: TRANS	Transport sector	49-52	Passenger rail transport services; Freight rail transport services; Rail infrastructure services; Other scheduled passenger land transport services; Taxi operation, Other passenger land transport; Freight road transport services; Pipeline transport services; Water transport services; Air transport services; Water transport infrastructure services; Other warehousing and support services for transport; Unspecified transport services
4: SERV	Service sectors	45-47, 53-98	Wholesale and retail trade and repair of motor vehicles and motorcycles; Wholesale trade, except of motor vehicles and motorcycles; Retail trade, except of motor vehicles and motorcycles; Post and telecommunication services; Accommodation services; Food and beverage services; Publishing, video, audio production services etc.; Telecommunications services; IT-Services; Financial services; Insurance and pension funding services; Real estate services; Legal, accounting, management, architecture, engineering services ; Scientific research and development; Other professional, scientific and technical services; Administrative and support services; Road infrastructure services; Other public administration services; Education services; Human health services; Residential care and social work services; Arts, entertainment and recreation services; Other services; Households as employers of domestic personnel; Undifferentiated goods and services of private households for own use
5: ROIL	Refined oil sector	19	Coke and refined petroleum products
6: GAS	Natural gas (distribution) sector	35k	Services of gas supply

7: ELEC	Electricity production, transmission and distribution	35a-35j, 38-39	Electricity from running hydro power plants; Electricity from storage hydro power plants; Electricity and district heat from nuclear power plants; Electricity and district heat from fossil plants; Electricity and district heat from wood plants; Electricity from biogas plants; Electricity from wind power plants; Electricity from PV plants; Services of electricity distribution and trade; Services of steam and hot water supply; Electricity from waste incineration; Heat from waste incineration; Other water supply, sewage and refuse disposal services

Table 5.2: Production, trade and consumption elasticities of substitution in SEEM

	ESUB-ARM	ETRNX	ESUB-TOP	ESUB-INT	ESUB-KEL	ESUB-KE	ESUB-ELE	ESUB-FOSS
Energy–intensive manufacturing industry	2.50	2.00	0.40	1.00	0.45	0.34	0.50	1.00
Rest-of-industry sector	2.50	2.00	0.57	1.00	0.80	0.44	0.50	1.00
Transport sectors	0.75	2.00	0.20	1.00	0.47	0.45	0.50	1.00
Service sectors	0.75	2.00	0.20	1.00	0.50	0.50	0.50	1.00
Refined oil sector	1.90	2.00	0.00	1.00	0.10	0.10	0.50	1.00
Natural gas (distribution) sector	0.00	0.00	0.00	1.00	0.10	0.10	0.50	1.00
Electricity production, transmission and distribution	0.75	2.00	0.20	1.00	1.00	0.50	0.50	1.00
Elasticity between energy goods					0.4			
Elasticity between non-energy goods					0.8			
Elasticity between all goods					0.25			

ESUBARM: Armington elasticities of substitution; ETRNX: elasticities of transformation; ESUBTOP; elasticities of substitution at the top nest; ESUBINT; elasticities of substitution between intermediate goods; ESUBKEL: elasticities of substitution between KE composite and labor; ESUBKE: elasticities of substitution between energy composite and ESC; ESUBELE: elasticities of substitution between electricity and fossil fuel composite; ESUBFOSS: elasticities of substitution between fossil fuels

Sources: Production elasticities of substitution from Mohler and Müller (2012) for the industry sectors and Okagawa and Ban (2008) and Paltsev (Paltsev, 2005; EPPA model) for the rest of the economy; GTAP-E (Burniaux and Truong, 2002) for the Armington elasticities and the elasticities of transformation. Consumption elasticities of substitution from Paltsev (2005).

Figure 5.1: Nesting structure of the SEEM model of non-fossil fuel production

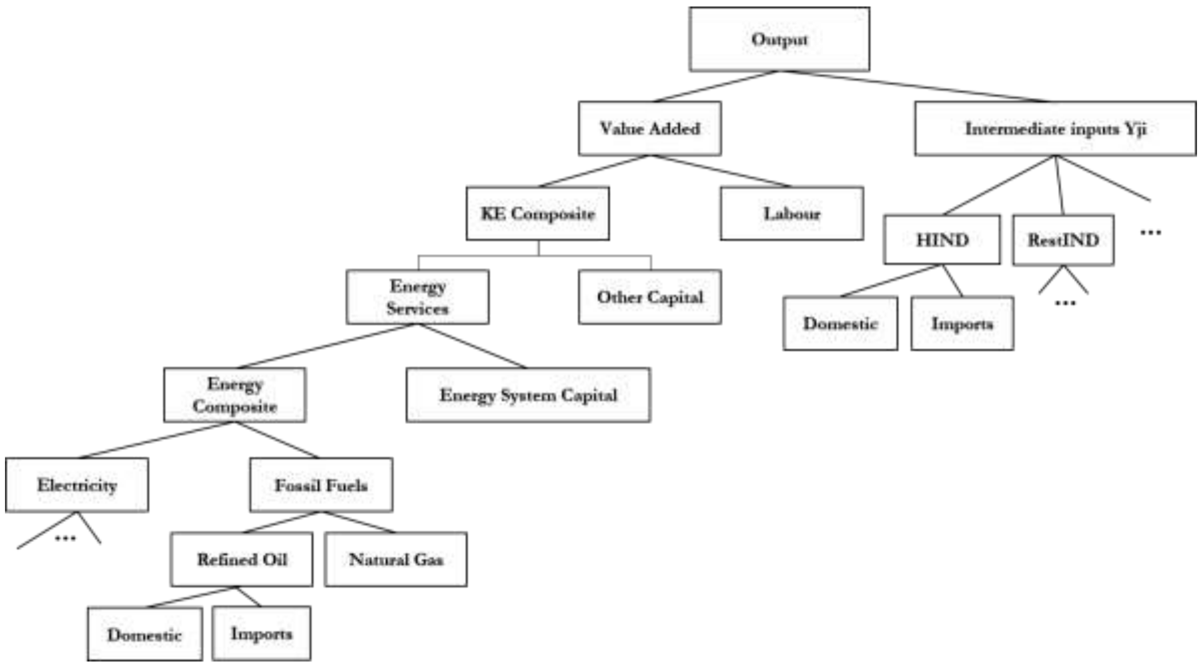
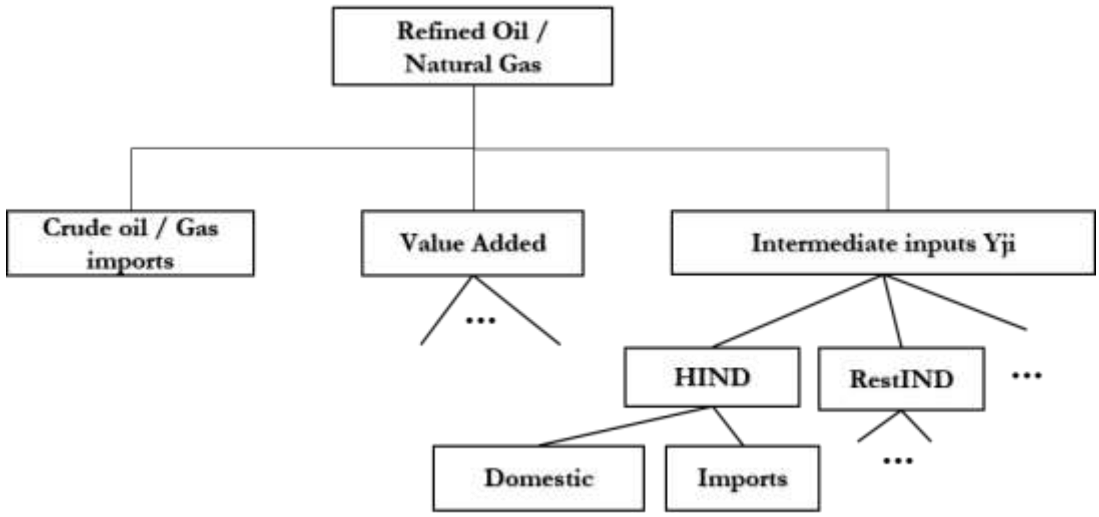
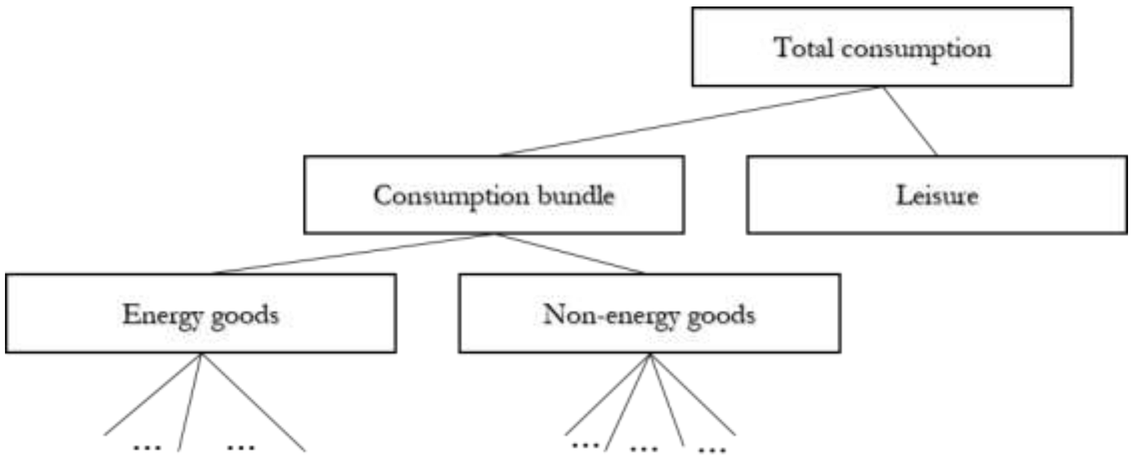


Figure 5.2: Top nest of fossil fuel production of the SEEM model



Data, nesting structure and parameters in SEEM

Figure 5.3: Nesting structure of the SEEM model for household consumption



5.3 Algebraic representation of the Swiss Energy Efficiency Model

The Swiss Energy Efficiency Model is modeled in the programming language MPSGE in GAMS. Algebraically, the computable general equilibrium model is formulated as a mixed complementary problem (MCP) through a system of nonlinear inequalities, which have to be satisfied. When defining the MCP as a nonlinear complementarity problem, it can be written as follows (Rutherford, 1999):

$$Given: f : R^n \rightarrow R^n$$

$$Find: z \in R^n$$

$$s.t. f(z) \geq 0, z \geq 0, z^T f(z) = 0$$

Each inequality corresponds with one of the three following conditions: (1) zero profit conditions for producers, (2) market clearance conditions to ensure supply equals demand for all goods and factors, and (3) and income balance conditions for households and governments. The zero-profit conditions determine the activity levels of the model, while the market clearance conditions determine the price levels. Finally, the income balance determines income. In the case of SEEM, the MCP formulation presented means that either each zero profit condition has to hold or the complementary variable has to be zero. The complementary variables are given in brackets for each equation. For the thesis presented here, in the equilibrium, each equation holds with an equality sign and all variables are positive. Zero profit conditions are shown as unit profit functions ($\prod$). To obtain the compensated demand functions satisfying the market clearance conditions, we use Shephard's Lemma by differentiating each unit profit function by the price of the good demanded or supplied. The following algebraic representation of the SEEM model further contains several constraints. It ends with a glossary, providing an overview of all sets, variables, and parameters of SEEM.

5.3.1 Zero profit conditions

1: Transformation function ($\boldsymbol{Y_{i,t}}$)

$$\prod_{i,t}^{Y} = \left(PY_{i,t} - \left(\theta_{TRX,i} * \left(PY_{i,t} * \frac{(1 - nctax_i)}{pnctax_i} \right)^{1+\sigma_{TRX,i}} + (1 - \theta_{TRX,i}) * \left(PFX_t * \frac{(1 - tx_i)}{pexport_i} \right)^{1+\sigma_{TRX,i}} \right)^{\frac{1}{(1+\sigma_{TRX,i})}} \right) * Y_{i,t} \leq 0$$

2: Top-nest for production of non-fossil fuels ($\boldsymbol{Y_{i,t}}$)

$$\prod_{i,t}^{Y} = \left(\left(\theta_{Y,i} * (PVA_{i,t})^{1-\sigma_{top,i}} + (1 - \theta_{Y,i}) * (PINT_{i,t})^{1-\sigma_{top,i}} \right)^{\frac{1}{(1-\sigma_{top,i})}} - PY_{i,t} \right) * Y_{i,t} \leq 0 \quad i \notin foss$$

3: Top nest for production of fossil fuels ($\boldsymbol{Y_{i,t}}$)

$$\prod_{i,t}^{Y} = \left(\theta_{Y,i} * (PVA_{i,t}) + \theta_{Y,i} * (PINT_{i,t}) + \theta_{Y,i} * PMENERGY_{im,t} - PY_{i,t} \right) * Y_{i,t} \leq 0 \quad i \in foss, \{ROIL \cup COIL\}, \{GAS \cup GASIM\}$$

4: Intermediate material aggregate ($\boldsymbol{INT_{i,t}}$)

$$\prod_{i,t}^{INT} = \left(\prod_{NE} {PA_{NE,t}}^{\theta_{INT,i}} - PINT_{i,t} \right) * INT_{i,t} \leq 0$$

5: Value added aggregate ($\boldsymbol{VA_{i,t}}$)

$$\prod_{i,t}^{VA} = \left(\left(\theta_{VA,i} * \left(PL_t * \frac{(1+\tau_t * ftax_L + SocTax)}{pf_L}\right)^{1-\sigma_{VA,i}} + \left(1-\theta_{VA,i}\right) * \left(PKES_{i,t}\right)^{1-\sigma_{VA,i}}\right)^{\frac{1}{(1-\sigma_{VA,i})}} - PVA_{i,t}\right) * VA_{i,t} \leq 0$$

6: Capital-energy service aggregate ($\boldsymbol{KES_{i,t}}$)

$$\prod_{i,t}^{KES} = \left(\left(\theta_{KES,i} * (RK_{OC,t} * \frac{(1+\tau_t * ftax_K)}{pf_K}) + \left(1-\theta_{KES,i}\right) * PES_{i,t}\right) - PKES_{i,t}\right) * KES_{i,t} \leq 0$$

7: Energy service aggregate ($\boldsymbol{ES_{i,t}}$)

$$\prod_{i,t}^{ES} = \left(\left(\theta_{ES,i} * \left(RK_{ESC,t} * \frac{(1+\tau_t * ftax_K)}{pf_K}\right)^{1-\sigma_{ES,i}} + \left(1-\theta_{ES,i}\right) * \left(PEC_{i,t}\right)^{1-\sigma_{ES,i}}\right)^{\frac{1}{(1-\sigma_{ES,i})}} - PES_{i,t}\right) * ES_{i,t} \leq 0$$

8: Energy composite aggregate ($\boldsymbol{EC_{i,t}}$)

$$\prod_{i,t}^{EC} = \left(\left(\theta_{EC,i} * \left(PA_{Electricity,t} * \frac{(1+fftax_{Electricity})}{pftax_{Electricity}}\right)^{1-\sigma_{ELEC,i}} + \left(1-\theta_{EC,i}\right) * \left(PFOSS_{i,t}\right)^{1-\sigma_{ELEC,i}}\right)^{\frac{1}{(1-\sigma_{ELEC,i})}} - PEC_{i,t}\right) * EC_{i,t} \leq 0$$

9: Fossil fuel aggregate ($\boldsymbol{FOSS_{i,t}}$)

$$\prod_{i,t}^{FOSS} = \left(\left(PA_{Oil,t} * \frac{(1+fftax_{Oil})}{pftax_{Oil}}\right)^{\theta_{FOSS,i}} * \left(PA_{Gas,t} * \frac{(1+fftax_{Gas})}{pftax_{Gas}}\right)^{\theta_{FOSS,i}} - PFOSS_{i,t}\right) * FOSS_{i,t} \leq 0$$

10: Armington aggregate ($\boldsymbol{A_{i,t}}$)

$$\prod_{i,t}^{A} = \left(\left(\theta_{ARM,i} * \left(PY_{i,t}\right)^{1-\sigma_{ARM,i}} + \left(1-\theta_{ARM,i}\right) * \left(PFX_t * \frac{(1+tim_i)}{pimport_i}\right)^{1-\sigma_{ARM,i}}\right)^{\frac{1}{(1-\sigma_{ARM,i})}} - PA_{i,t}\right) A_{i,t} \leq 0$$

11: Energy commodity import aggregate ($\boldsymbol{MENERGY_{im,t}}$)

$$\prod_{im,t}^{MENERGY} = \left(PFX_t * \frac{(1+tim_{im})}{pimport_{im}} - PMENERGY_{im,t}\right) * MENERGY_{im,t} \leq 0$$

12: Capital supply ($K_{cap,t}$)

$$\prod_{cap,t}^{K} = \left(ks_{n_{cap}} * RKNEW_t - RK_{cap,t}\right) * K_{cap,t} \leq 0$$

13: Investment aggregate (INV_t)

$$\prod_{t}^{INV} = \left(\sum_i \theta_{INV,i} * PA_{i,t} - PINV_t\right) * INV_t \leq 0$$

14: Welfare (C_t)

$$\prod_{t}^{C} = \left((\beta_C * (PL_t)^{1-\sigma_{LL}} + (1-\beta_C) * (PCONS_t)^{1-\sigma_{LL}})^{\frac{1}{(1-\sigma_{LL})}} - PC_t\right) * C_t \leq 0$$

15: Consumption good bundle ($CONS_t$)

$$\prod_{t}^{CONS} = \left((\beta_{CONS} * (PEGOODS_t)^{1-\sigma_{CONS}} + (1-\beta_{CONS}) * (PNEGOODS_t)^{1-\sigma_{CONS}})^{\frac{1}{(1-\sigma_{CONS})}} - PCONS_t\right) * CONS_t \leq 0$$

16: Non-energy consumption good bundle ($NEGOODS_t$)

$$\prod_{t}^{NEGOODS} = \left(\left(\sum_{NE} \beta_{NEGOODS} * \left(PA_{NE,t}\right)^{1-\sigma_{NEGoods}}\right)^{\frac{1}{(1-\sigma_{NEGoods})}} - PNEGOODS_t\right) * NEGOODS_t \leq 0$$

17: Energy consumption good bundle ($EGOODS_t$)

$$\prod_{i,t}^{EGOODS} = \left(\left(\sum_{ENE} \beta_{EGOODS} * \left(PA_{ENE,t} * \frac{(1+fftax_{ENE})}{pftax_{ENE}}\right)^{1-\sigma_{EGoods}}\right)^{\frac{1}{1-\sigma_{EGoods}}} - PEGOODS_t\right) * EGOODS_t \leq 0$$

18: Public good (G_t)

$$\prod_{t}^{G} = \left(\sum_{i,t} \theta_{G,i} * PA_{i,t} - PG_t\right) * G_t \leq 0$$

5.3.2 Market clearance conditions

19: Armington good ($A_{i,t}$)

$$A_{i,t} \geq cd0_{NE} * CBUND_t * \frac{\partial \prod_t^{CBUND}}{\partial(PA_{NE,t} * \frac{(1+fftax_{NE})}{pftax_{NE}})} + cd0_E * CENE_t * \frac{\partial \prod_t^{CENE}}{\partial(PA_{ENE,t} * \frac{(1+fftax_{ENE})}{pftax_{ENE}})} + \sum_j yd0_{j,i} * Y_{j,t} * \frac{\partial \prod_{j,t}^{Y}}{\partial(PA_{i,t} * \frac{(1+fftax_i)}{pftax_i})} + i0_i * Inv_t * \frac{\partial \prod_t^{INV}}{\partial(PA_{i,t} * \frac{(1+fftax_i)}{pftax_i})} + g0_i * GVNT_t * \frac{\partial \prod_t^{GVNT}}{\partial(PA_{i,t} * \frac{(1+fftax_i)}{pftax_i})}$$

20: Commodities ($\boldsymbol{PY_{i,t}}$)

$$(y0_i - x0_i) * Y_{i,t} * \frac{\partial \left(PY_{i,t} * \frac{(1 - nctax_i)}{pnctax_i}\right)}{\partial \prod_{i,t}^{Y}} \geq (y0_i - x0_i) * A_{i,t} * \frac{\partial \prod_{i,t}^{A}}{\partial PY_{i,t}}$$

21: Exports ($\boldsymbol{PFX_t}$)

$$x0_i * Y_{i,t} * \frac{\partial \left(PFX_t * \frac{(1 - tx_i)}{pexport_i}\right)}{\partial \prod_{i,t}^{Y}} \geq X_{i,t}$$

22: Imports ($\boldsymbol{PFX_t}$)

$$M_{i,t} \geq \ im0_i * A_{i,t} * \frac{\partial \prod_{i,t}^{A}}{\partial (PFX_t * \frac{(1 + tim_i)}{pimport_i})}$$

23: Energy commodity imports($\boldsymbol{PFX_t}$)

$$Menergy_{im,t} \geq \ energyim0_{im} * Y_{i,t} * \frac{\partial \prod_{i,t}^{Y}}{\partial (PFX_t * \frac{(1 + tim_{im})}{pimport_{im}})} \qquad i \ \in \ foss\,, \{ROIL \cup COIL\}, \{GAS \cup GASIM\}$$

24: Energy services ($\boldsymbol{PES_{i,t}}$)

$$ES_{i,t} \geq \ es0_i * Y_{i,t} * \frac{\partial \prod_{i,t}^{Y}}{\partial PES_{i,t}}$$

25: Energy composite ($\boldsymbol{PEC_{i,t}}$)

$$EC_{i,t} \geq \ ec0_i * ES_{i,t} * \frac{\partial \prod_{i,t}^{ES}}{\partial PEC_{i,t}}$$

26: Fossil fuel composite ($\boldsymbol{PFOSS_{i,t}}$)

$$FOSS_{i,t} \geq \ foss0_i * EC_{i,t} * \frac{\partial \prod_{i,t}^{EC}}{PFOSS_{i,t}}$$

27: Welfare ($\boldsymbol{PC_t}$)

$$C_t \geq \ c0 * \frac{\partial CONS_t}{\partial PC_t}$$

28: Consumption bundle ($\boldsymbol{PCONS_t}$)

$$CBUND_t \geq cbund0 * C_t * \frac{\partial \prod_{t}^{C}}{\partial PCONS_t}$$

29: Energy good consumption composite ($\boldsymbol{PCENE_t}$)

$$CENE_t \geq cene0 * CBUND_t * \frac{\partial \prod_{t}^{CBUND}}{\partial PCENE_t}$$

30: Investment good ($\boldsymbol{PINV_t}$)

$$INV_t \geq \ inv0 * \frac{\partial CONS_t}{\partial PINV_t}$$

31: Public good (PG_t)

$$GVNT_t \geq g0 * \frac{\partial GOV_t}{\partial PG_t}$$

32: Capital supply ($RKNew_t$)

$$K_{cap,t} \geq \; ks_{n0_{cap}} * RKNew_t$$

33: Labor supply (PL_t)

$$e_{L,t} \geq \sum_i fd0_{L,i} * Y_{i,t} * \frac{\partial \prod_{i,t}^{Y}}{\partial (PL_t * \frac{(1 + \tau_t * ftax_L + SocTax)}{pf_L})} + ls0 * C_t * \frac{\partial \prod_t^C}{\partial PL_t}$$

3: Other capital supply ($RK_{OC,t}$)

$$e_{OC,t} \geq \sum_i fd0_{OC,i} * Y_{i,t} * \frac{\partial \prod_{i,t}^{Y}}{\partial (RK_{OC,t} * \frac{(1 + \tau_t * ftax_K)}{pf_K})}$$

35: Energy system capital supply ($RK_{ESC,t}$)

$$e_{ESC,t} \geq \sum_i fd0_{ESC,i} * ES_{i,t} * \frac{\partial \prod_{i,t}^{ES}}{\partial RK_{ESC,t} * \frac{(1 + \tau_t * ftax_K)}{pf_K})}$$

36: Balance of Payment (PFX_t)

$$BOP_t \geq \sum_{im} energyim0_{im*} Menergy_{im,t} * \frac{\partial \prod_{im,t}^{MENERGY}}{\partial (PFX_t * \frac{(1 + tim_{im})}{pimport_{im}})} + \sum_i im0_i * A_{i,t} * \frac{\partial \prod_{i,t}^{A}}{\partial (PFX_t * \frac{(1 + tim_i)}{pimport_i})} - \sum_i x0_i * Y_{i,t} * \frac{\partial (PFX_t * \frac{(1 + tx_i)}{pexport_i})}{\partial \prod_{i,t}^{Y}}$$

5.3.3 Income statements

37: Income statement for households ($CONS_t$)

$$CONS_t = e0_L * PL_t + ks_{s_{cap}} * RK_{cap,t} + ks_{ntot} * RKNEW_t + BOP_t * PFX_t + INV_0 * PINV_t$$

38: Income statement for Government ($\boldsymbol{GOV_t}$)

$$GOV_t = (\tau_t * ftax_L + SocTax) * \sum_i fd0_{L,i} * Y_{i,t} * \frac{\partial \prod_{i,t}^{Y}}{\partial (PL_t * \frac{(1+\tau_t * ftax_L + SocTax)}{pf_L})} + \tau_t$$

$$* ftax_K \left(\sum_i fd0_{OC,i} * Y_{i,t} * \frac{\partial \prod_{i,t}^{Y}}{\partial (RK_{OC,t} * \frac{(1+\tau_t * ftax_K)}{pf_K})} \right.$$

$$\left. + \sum_i fd0_{ESC,i} * ES_{i,t} * \frac{\partial \prod_{i,t}^{ES}}{\partial RK_{ESC,t} * \frac{(1+\tau_t * ftax_K)}{pf_K})} \right)$$

$$+ \sum_i tim_i * q0_i * A_{i,t} * \frac{\partial \prod_{i,t}^{A}}{\partial \left(PFX_t * \frac{(1+tim_i)}{pimport_i} \right)}$$

$$+ \sum_{im} tim_{im} * energyim0_{im} * Menergy_{im,t} * \frac{\partial \prod_{im,t}^{MENERGY}}{\partial \left(PFX_t * \frac{(1+tim_{im})}{pimport_{im}} \right)}$$

$$+ \sum_i tx_i * x0_i * Y_{i,t} * \frac{\partial \left(PFX_t * \frac{(1-tx_i)}{pexport_i} \right)}{\partial \prod_{i,t}^{Y}} + \sum_i fftax_i * CBUND_t * \frac{\partial \prod_{t}^{CBUND}}{\partial (PA_{i,t} * \frac{(1+fftax_i)}{pftax_i})}$$

$$+ \sum_j fftax_j * yd0_{j,i} * Y_{j,t} * \frac{\partial \prod_{j,t}^{Y}}{\partial (PA_{i,t} * \frac{(1+fftax_i)}{pftax_i})}$$

$$+ \sum_i nctax_i * (y0_i - x0_i) * Y_{i,t} * \frac{\partial \left(PY_{i,t} * \frac{(1-nctax_i)}{pnctax_i} \right)}{\partial \prod_{i,t}^{Y}}$$

5.3.4 Auxiliary variables

39: Determination of τ to ensure a steady-state provision of public goods

$$GVNT_t = (1+g)^t$$

40: Determination of rationing multiplier *Const_Inc* to determine the multiplier effect (for decomposition analysis in Chapter 3)

$$\frac{(CBUND_t * CBUND_0 + INV_t * INV_0)}{CBUND_0 + INV_0} = (1+g)^t$$

41: Determination of endogenous refined oil tax (for rebound mitigation in Chapter 4)

$$\sum_i yd0_{Oil,i} * Foss_{i,t} * \frac{\partial \prod_{i,t}^{FOSS}}{\partial \left(PA_{Oil,t} * \frac{1+fftax_{Oil} + (rho1_t * EPRatio_{Oil,i})}{pftax_{Oil}} \right)} * EnergyPrices_{Oil,i} + cd0_{Oil}$$

$$* CENE_t * \frac{\partial \prod_{t}^{CENE}}{\partial (PA_{OIL,t} * \frac{(1+fftax_{Oil})}{pftax_{Oil}})} * EnergyPrices_{Oil,HH} = PotentialRefinedOilUse_t$$

42: Determination of endogenous gas tax (for rebound mitigation in Chapter 4)

$$\sum_i yd0_{Gas,i} * Foss_{i,t} * \frac{\partial \prod_{i,t}^{FOSS}}{\partial\left(PA_{Gas,t} * \frac{1+fftax_{Gas}+\left(rho2_t * EPRatio_{Gas,i}\right)}{pftax_{Gas}}\right)} * EnergyPrices_{Gas,i} + cd0_{Gas} * CENE_t * \frac{\partial \prod_t^{CENE}}{\partial(PA_{GAS,t} * \frac{(1+fftax_{Gas})}{pftax_{Gas}})} * EnergyPrices_{Gas,HH} = PotentialGasUse_t$$

43: Determination of endogenous electricity tax (for rebound mitigation in Chapter 4)

$$\sum_i yd0_{Elec,i} * EC_{i,t} * \frac{\partial \prod_{i,t}^{EC}}{\partial\left(PA_{Elec,t} * \frac{1+fftax_{Elec}+\left(rho3_t * EPRatio_{Elec,i}\right)}{pftax_{Elec}}\right)} * EnergyPrices_{Elec,i} + cd0_{Elec} * CENE_t * \frac{\partial \prod_t^{CENE}}{\partial(PA_{ELEC,t} * \frac{(1+fftax_{Elec})}{pftax_{Elec}})} * EnergyPrices_{Elec,HH} = PotentialElecUse_t$$

44: Determination of the output subsidy rate BMR, if all energy carriers are taxed (for the bonus-malus scheme in Chapter 4)

$$\sum_i yd0_{Oil,i} * Foss_{i,t} * \frac{\partial \prod_{i,t}^{FOSS}}{\partial\left(PA_{Oil,t} * \frac{1+fftax_{Oil}+\left(rho1_t * EPRatio_{Oil,i}\right)}{pftax_{Oil}}\right)} * rho1_t * EPRatio_{Oil,i} + \sum_i yd0_{Gas,i} * Foss_{i,t} * \frac{\partial \prod_{i,t}^{FOSS}}{\partial\left(PA_{Gas,t} * \frac{1+fftax_{Gas}+\left(rho2_t * EPRatio_{Gas,i}\right)}{pftax_{Gas}}\right)} * rho2_t * EPRatio_{Gas,i} + \sum_i yd0_{Elec,i} * EC_{i,t} * \frac{\partial \prod_{i,t}^{EC}}{\partial\left(PA_{Elec,t} * \frac{1+fftax_{Elec}+\left(rho3_t * EPRatio_{Elec,i}\right)}{pftax_{Elec}}\right)} * rho3_t * EPRatio_{Elec,i} = \sum_i Y_{i,t} * \frac{\partial\left(PFX_t * \frac{\left(1-tx_i+(BMR_t * Sub_{XMultiplier_i}\right)}{pexport_i}\right)}{\partial \prod_{i,t}^{Y}} * x0_i * \left(BMR_t * Sub_{XMultiplier_i}\right) + \sum_i Y_{i,t} * \left(\frac{\partial\left(PY_{i,t} * \frac{\left(1-nctax_i+(BMR_t * Sub_{YMultiplier_i}\right)}{pnctax_i}\right)}{\partial \prod_{i,t}^{Y}}\right) * (y0_i - x0_i) * (BMR_t * Sub_{YMultiplier_i})$$

5.3.5 Capital accumulation between periods

45: Capital stock in period t, consisting of depreciated capital stock of period t-1 and investment of period t-1

$$ks\_s_{cap,t} = (1-\delta) * (ks\_s_{cap,t-1} + ks_{n_{cap,t-1}})$$

46: Total new capital equal to the investment of previous period

$$ks\_ntot = (i+\delta) * (INV_t)$$

5.3.6 Evolution over time of variables

In the steady-state (SS) scenario, all activity levels grow with the growth rate between each period. This is also the case for all other scenarios, in which there are additional adjustments taking place due to EEIs and other perturbations.

5.4 Glossary of the Swiss Energy Efficiency Model

5.4.1 Sets

i,j	the set of goods and industries
im	the set of imported energy commodities {COIL,GASIM}
cap	the set of capital types
NE ($\in i$)	the set of non-energy sectors {HIND, RESTIND,TRANS,SERV}
ENE ($\in i$)	the set of energy sectors {ROIL, GAS, ELEC}
Foss ($\in i$)	the set of fossil fuel sectors {ROIL, GAS}

5.4.2 Variables

$PY_{i,t}$	producer price
PFX_t	price of foreign exchange
$PA_{i,t}$	purchaser price
$PVA_{i,t}$	value added price
$PINT_{i,t}$	price of intermediate composite good
$PMENERGY_{im,t}$	domestic price of energy imports
$PKES_{i,t}$	price of capital – energy service composite
$PES_{i,t}$	price of energy service
$PEC_{i,t}$	price of energy composite
$PFOSS_{i,t}$	price of fossil fuel composite
$RK_{cap,t}$	rental rate of sector-specific capital
$RKNEW_t$	rental rate of new capital
PL_t	price of labor
$PINV_t$	price of investment
PC_t	price of consumption
$PCONS_t$	price of consumption bundle
$PNEGOODS_t$	price of non-energy goods consumption bundle
$PEGOODS_t$	price of energy goods consumption bundle
PG_t	price of public good bundle
$CBUND_t$	household consumption bundle

Glossary of the Swiss Energy Efficiency Model

C_t	total household consumption
$CENE_t$	household energy good consumption
$A_{i,t}$	composite good
$Y_{i,t}$	regional supply
$X_{i,t}$	exports
$M_{i,t}$	imports
$Menergy_{im,t}$	energy commodity imports
$ES_{i,t}$	energy service
$EC_{i,t}$	energy composite
$FOSS_{i,t}$	fossil fuel composite
INV_t	investment level
$GVNT_t$	government activity level
$CONS_t$	income level
GOV_t	aggregate government expenditure
$ks_{s_{cap,t}}$	existing capital stock
$ks_{n_{cap,t}}$	new capital per capital type based on the investment of previous period
ks_ntot_t	total new capital based on the investment of previous period
τ_t	multiplier ensuring equal yield assumption
$Const\_INC_t$	rationing multiplier to determine the multiplier effect in Chapter 3
$Rho1_t$	endogenous tax to offset economy-wide rebound effects in the use of refined oil
$Rho2_t$	endogenous tax to offset economy-wide rebound effects in the use of natural gas
$Rho3_t$	endogenous tax to offset economy-wide rebound effects in the use of electricity
BMR_t	bonus payment multiplier for the bonus-malus scheme, if all energy carriers are taxed in Chapter 4

5.4.3 Elasticities

$\sigma_{ARM,i}$	Armington elasticity
$\sigma_{TRX,i}$	elasticity of transformation
$\sigma_{Top,i}$	elasticity of substitution between intermediate inputs and value added composite
$\sigma_{VA,i}$	elasticity of substitution between labor and capital-energy service composite

$\sigma_{ES,i}$	elasticity of substitution between energy composite and energy system capital
$\sigma_{EC,i}$	elasticity of substitution between electricity and fossil fuel composite
σ_{LL}	substitution elasticity between leisure and labor
σ_{CONS}	elasticity of substitution between energy and non-energy goods in consumption
$\sigma_{NEGoods}$	substitution elasticity between non-energy goods in consumption
σ_{EGoods}	substitution elasticity between energy goods in consumption

5.4.4 Parameters

$\theta_{TRX,i}$	share parameter of goods supplied domestically
$\theta_{Y,i}$	share parameter of value added in domestic production
$\theta_{VA,i}$	share parameter of labor inputs in value added
$\theta_{KES,i}$	share parameter of other capital in capital-energy service composite
$\theta_{ES,i}$	share parameter of energy system capital in energy service
$\theta_{ELEC,i}$	share parameter of electricity in energy composite
$\theta_{INT,i}$	share parameter of non-energy goods in intermediate good composite
$\theta_{FOSS,i}$	share parameter of fossil fuel good in fossil fuel composite
$\theta_{ARM,i}$	share parameter of domestically supplied goods in Armington composite
$\theta_{INV,i}$	share parameter of investment goods in investment
$\theta_{G,i}$	share parameter of public goods in public goods provision
β_{C}	share parameter of leisure in household consumption
β_{CONS}	share parameter of non-energy goods in household consumption
$\beta_{NEGOODS}$	share parameter of non-energy goods in non-energy good consumption
β_{EGOODS}	share parameter of energy goods in energy good consumption
$cd0_{i}$	benchmark consumption of good i
$yd0_{j,i}$	benchmark intermediate demand of good j
$i0_{i}$	benchmark investment of good i
$g0_{i}$	benchmark provision of public good i
$x0_{i}$	benchmark export of good i
$im0_{i}$	benchmark imports of good i

$energyim0_{im}$	benchmark imports of energy commodity im
$es0_i$	benchmark energy service i
$ec0_i$	benchmark energy composite i
$foss0_i$	benchmark fossil fuel composite i
$c0$	benchmark welfare
$cbund0$	benchmark consumption
$cene0$	benchmark consumption of energy goods
$inv0$	benchmark investment
$g0$	benchmark public goods provision
$fd0_{L,i}$	benchmark demand for labor by sector i
$fd0_{Cap,i}$	benchmark demand for capital type cap by sector i

5.4.5 Taxes and corresponding benchmark factor prices

$fftax_i$	tax on use and consumption of goods
$ftax_L$	labor income tax
$SocTax$	social security contributions
$ftax_K$	capital income tax
tim_i	import tariffs
tim_{im}	import tariffs on energy commodities
tx_i	export tariffs
$nctax_i$	net commodity tax
$pftax_i$	benchmark gross good price
pf_L	benchmark gross price for labor
pf_K	benchmark gross price for capital
$pimport_i$	benchmark gross price for imports
$pimport_{im}$	benchmark gross price for energy commodity imports
$pexport_i$	benchmark net price for exports
$pnctax_i$	benchmark net price of domestically sold goods

5.4.6 Other parameters

i	interest rate
δ	depreciation rate
g	growth rate
$EnergyPrices_{ENE,i}$	benchmark energy prices for energy carrier ENE for sector i
$EPRatio_{E,i}$	energy price ratio to ensure uniform taxes for rebound mitigation in Chapter 4
$Sub_{YMultiplier_i}$	multiplier to ensure distribution of bonus payments according to benchmark value share of sector i in domestic supply
$Sub_{XMultiplier_i}$	multiplier to ensure distribution of bonus payments according to benchmark value share of sector i in exports

5.5 Decomposition analysis in SEEM

5.5.1 Structural decomposition analysis

$$E = eLy = eL\varphi\delta Y = e(I-A)^{-1}\varphi\delta Y$$

$$\Delta E = E^{2050,R-EEI} - E^{2050,SS} = \Delta e + \Delta L + \Delta\varphi + \Delta\delta + \Delta Y$$

$$\Delta e = (e_{2050} - e_{2020})\frac{(L_{2020}+L_{2050})}{2}\frac{(\varphi_{2020}+\varphi_{2050})}{2}\frac{(\delta_{2020}+\delta_{2050})}{2}\frac{(Y_{2020}+Y_{2050})}{2}$$

5.5.2 Index decomposition analysis

$$E = \sum_i E_i = \sum_i Q\frac{Q_i}{Q}\frac{E_i}{Q_i} = \sum_i QS_iI_i$$

$$\Delta E = \sum_i E_i^{2050,R-EEI} - E_i^{2050,SS} = \Delta E_{act} + \Delta E_{str} + \Delta E_{int}$$

$$\Delta E_{act} = \sum_i \frac{E_i^{2050,R-EEI} - E_i^{2050,SS}}{\ln E_i^{2050,R-EEI} - \ln E_i^{2050,SS}} \ln\left(\frac{Q^{2050,R-EEI}}{Q^{2050,SS}}\right)$$

$$\Delta E_{str} = \sum_i \frac{E_i^{2050,R-EEI} - E_i^{2050,SS}}{\ln E_i^{2050,R-EEI} - \ln E_i^{2050,SS}} \ln\left(\frac{S_i^{2050,R-EEI}}{S_i^{2050,SS}}\right)$$

$$\Delta E_{int} = \sum_i \frac{E_i^{2050,R-EEI} - E_i^{2050,SS}}{\ln E_i^{2050,R-EEI} - \ln E_i^{2050,SS}} \ln\left(\frac{I_i^{2050,R-EEI}}{I_i^{2050,SS}}\right)$$

5.5.3 Glossary of structural and index decomposition analysis

$\boldsymbol{e}$	vector of energy intensity of production n sectors (1xn)
$\boldsymbol{L}$	Leontief inverse matrix (nxn)
$\boldsymbol{I}$	unity matrix (nxn)
$\boldsymbol{A}$	direct requirements matrix (nxn)
$\boldsymbol{\varphi}$	matrix of commodity structure of final demand (nxd)
$\boldsymbol{\delta}$	vector destination structure of final demand (dx1)
$\boldsymbol{Y}$	total final demand (1x1)
E	total energy use
Q	total production output
Q_i	share of output of sector I of total production output
I_i	sectoral energy intensity

Curriculum Vitae

Michel Zimmermann

Address:	Gertrudstrasse 83, 8003 Zürich
Telephone:	+41 (0) 76 496 35 16
E-Mail:	michel.zimmermann@outlook.com
Date of birth:	26 January 1992
Nationality:	Switzerland

Education

01/2018 – 01/2022 **École Polytechnique Fédérale de Lausanne – PhD Program in Environmental and Civil Engineering** (Lausanne, Switzerland)

- Thesis: ”Rebound Effects from Industrial Energy Efficiency Improvements”. Thesis directors: Prof. Philippe Thalmann and Dr. Vincent Moreau

09/2016 – 09/2017 **University College London – Master of Science in Economics and Policy of Energy and the Environment** (London, United Kingdom) - Distinction

- Focus on Policy Analysis, Energy Innovation, Economics of the Environment and Natural Resources and Energy Modelling
- Dissertation: “Inequality in energy and climate policies: Assessing distributional impact consideration in UK policy appraisal”. Supervisor: Dr. Steve Pye

09/2011 – 09/2014 **University of Zurich – Bachelor of Arts in Economics** (Zürich, Switzerland) – magna cum laude: 5.2

- Focus on Microeconomics, Macroeconomics and Finance
- Bachelor’s thesis: “Fiskalpolitik in der Schweiz in den 30er Jahren” which translates to “Fiscal policy in Switzerland during the 1930s”. Supervisor: Prof. Ulrich Woitek
- Exchange semester in Sydney, Australia at University of Technology (UTS), Sydney during Fall term 2014

08/2006 – 09/2010 **Kantonsschule Urdorf – Swiss Federal Maturity** (Zürich, Switzerland)

- Focus on Economics and Law

Professional Experience

01/2018 – 01/2022 **École Polytechnique Fédérale de Lausanne – Doctoral Assistant** (Lausanne, Switzerland)

09/2010 – 09/2016 **Credit Suisse AG – External Asset Managers, Fund Solutions - Junior Supporter** (Zürich, Switzerland)

- Supporting Project Managers in the process of setting up and launching new investment funds
- Preparing offers and pricing proposals for External Asset Managers seeking to establish investment funds

Decomposition analysis in SEEM

Languages and Computer Skills

German	Native
English	Full professional fluency • Master's Degree in the United Kingdom
French	Limited working proficiency • DELF certificate level B1
Spanish	Limited working proficiency • DELE certificate level B1 and 8-month trip in Latin America
Computer Skills	Python, C++, R, GAMS, MS Office

Personal Interest, Activities and Part-time Jobs

Live music, Politics, Activism, Feminism

2019 - ongoing **Die Feministen – Head of regional group ZH**

- A collective that seeks to engage men in the cause for equality of all genders
- Responsible for the regional group in Zurich and the creation of workshops for a critical analysis of masculinity
- www.feministen.ch

08/2015 – 08/2016 **propius GmbH – Amboss Rampe – Barkeeper**

- independent lead of evening shifts & handling of accounting and inventory work