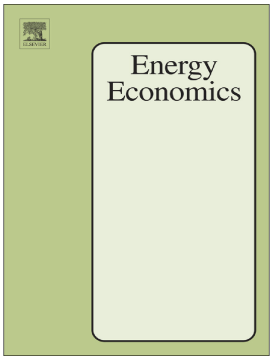

Do rebound effects matter for Switzerland? Assessing the effectiveness of industrial energy efficiency improvements

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

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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

Declaration of interest: None

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; European Commission, 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 1:

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

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 (Madlener and Turner, 2016)[1]. At its core, an energy efficiency improvement reduces the costs for a given energy service when constant energy prices are assumed (e.g. reduced fuel expenses per kilometer travelled, 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, energy efficiency improvements can also depress world energy prices, which potentially spur energy use and cause additional rebound effects (Förster 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 (2001, 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 in order 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, 2021). Moreover, energy efficiency plays a crucial role in the Energy Strategy 2050, in which Switzerland has set additional ambitious energy 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 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, 2020). At the same time, Switzerland already has one of the lowest energy intensities in Europe (Oddyssee, 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 energy efficiency improvements 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 energy efficiency improvements in production. The Swiss industry and services sectors account for roughly a third of the total final energy use in Switzerland (SFOE, 2020) 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 the 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 modelling the different interactions between economic actors as a result of energy efficiency improvements. We

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

implement annual energy efficiency improvements 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 energy efficiency improvements 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 modelled as weak substitutes, which purports that energy efficiency measures lead firms to decrease their capital use in substituting towards energy. 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 labelled "other capital"), it is assumed to be complementary with energy. As a consequence, increased energy demand after an energy efficiency improvement 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 energy efficiency improvements. In summary, we aim to, for the first time, assess economy-wide rebound effects from annual industrial energy efficiency improvements 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 discusses the existing work on (industrial) rebound effect assessments with a particular focus on dynamic CGE analyses. Section 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 4 shows the results from the implementation of annual energy efficiency improvements 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 5 discusses the findings from the main simulation and the sensitivity analyses. Finally, Section 6 offers a conclusion and some policy recommendations.

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 actually 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 are similarly uncertain. In an extensive literature review, Stern (2020, p. 5.) asks the question 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 disaggregating 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., 2007). Koesler et al. (2016) use a static, multi-regional, multi-sectoral CGE model to investigate the impact of a 10%, one-time, energy efficiency improvement 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.

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 energy efficiency improvements, 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 energy efficiency improvements 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 energy efficiency improvement 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 energy efficiency improvements influence trade and how this relates to rebound effects. These improvements are usually modelled as occurring exclusively in the domestic economy, under a *ceteris paribus* condition. The effect of this on rebound 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 provides 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 modelled 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 energy efficiency improvements. 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., 2007).

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. 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 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).

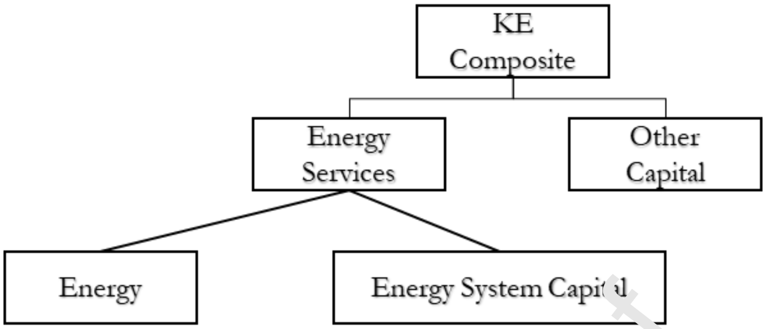
Firms are assumed to be profit-maximizing with all markets being perfectly competitive and without possibilities for economies of scale. The output (Y) for each sector *i* is produced by combining the production factors capital (K), labor (L), energy (E) and intermediate commodities and materials (M), 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 energy efficiency improvements. 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 modelled as nested constant elasticity of substitution 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 modelled 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 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 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 gas imports, respectively. The full nesting tree of the production function in SEEM is shown in the Appendix.

Figure 1: Subset of the nesting structure, highlighting the relationship between the energy composite, ESC and OC



Switzerland is modelled 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 production and trade elasticities of substitution are taken from the literature. Where no Swiss sources are available, alternative established sources are used and adjusted to account for the Swiss production and trade characteristics, if needed. A crucial parameter concerns the elasticity substitution between ESC and the energy composite, which are shown in Table 1. 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. All consumption elasticities are based on Paltsev et al. (2005). An overview of all elasticities of substitution is provided in the Appendix.

Table 1: The elasticities of substitution between ESC and the energy composite for the different sectors in SEEM

Energy-intensive manufacturing industry	Rest of industry	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[2].

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

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

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, after adjusting them with the simulated price changes. 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 modelled in the programming language "mathematical programming system for general equilibrium analysis" (MPSGE) in GAMS (Rutherford, 1999), using the PATH solver. In SEEM, capital is modelled 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 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 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 energy efficiency improvements 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 a numeraire and therefore all prices are expressed relative to it.

In the main scenario (the EEI scenario), an annual energy efficiency improvement 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 modelled as biased technical change $\gamma_{EC,t}$ by increasing the productivity factor of each energy input and hence enables the same amount of output with less energy, as illustrated in Equation 2. Equation 2 shows the production function of the goods "energy services", where the energy composite and ESC is combined, with α_{ES} describing the value shares at this nest and $\rho_{i,ES}$ the sector-specific constant elasticity of substitution.

$$ES_{i,t} = \left[\alpha_{ES}\left(\gamma_{EC,t} * EC_{i,t}\right)^{\rho_{EC,ES}} + (1-\alpha_{ES})\left(ESC_{i,t}\right)^{\rho_{EC,ESC}}\right]^{\frac{1}{\rho_{EC,ESC}}} \quad (2)$$

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 energy efficiency improvement, 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, 2020). This is tantamount to an annual reduction of 2.2%, which corresponds to our chosen annual energy efficiency improvement. 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 3 below, where $\dot{E}_t^i$ represents the change in physical energy use of a sector i relative to the business as usual case for a given year, and $\gamma_{EC,t}$ the cumulative energy efficiency improvement 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 energy efficiency improvement $\gamma_{EC,t}$. For economy-wide rebound effects, we compare total change in energy use (i.e. production + consumption) and the corresponding cumulative annual domestic shock (i.e. based on the aforementioned 1.23%).

$$R_t^i = \left(1 + \frac{\dot{E}_t^i}{\gamma_{EC,t}}\right) x\ 100 \quad (3)$$

4. Results

4.1 The rebound effects from annual industrial energy efficiency improvements

The physical energy savings from annual industrial energy efficiency improvements in Switzerland fall short of what is suggested from the engineering estimates. This is illustrated in Table 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 high energy-intensive 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 for 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 energy efficiency improvements. 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 are negligible in absolute terms

The weighted sum of these sectoral rebound effects equals 38% overall rebound effect in the first period after the first energy efficiency improvement, which gradually decreases over time to below 30% in 2050. The industry-wide rebound effects in a given year thus decrease with each additional energy efficiency improvement. The total rebound effects, which includes the change in final energy use, are larger and amounts 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: The rebound effects after annual improvements of 2.2% in industrial energy efficiency for the short, medium 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%	57.32	48.18	39.58
Rest of industry	11.2%	1.1%	19.46	19.10	18.34
Transport sector	25.3%	7.7%	29.12	25.10	21.22
Services sector	38.4%	1.4%	37.54	34.97	32.12
Refined oil sector	<0.1%	0.4%	-24.87	-19.04	-14.15
Natural gas (distribution) sector	<0.1%	<0.1%	-19.45	-15.28	-11.63
Electricity production, transmission and distribution	1.5%	1.0%	4.57	5.97	6.87
Industry-wide rebound effect			**37.49**	**33.33**	**29.16**
Economy-wide rebound effect			**40.81**	**37.33**	**33.85**

These rebound effects are a direct consequence of economic and behavioral adjustments to the energy efficiency improvements. Table 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 a stronger demand for domestically produced goods. The expansion of the economy and the strengthened competitiveness of its industries further leads to a higher aggregate demand from abroad, as well as an increase in imported goods.

The energy efficiency improvement also improves 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, the energy efficiency improvements positively impact total welfare, which is 1.54% higher than in the SS scenario without energy efficiency. Table 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 energy efficiency improvements. 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%.

Table 3: Overview of aggregate macroeconomic indicators for 2050 relative to the steady-state scenario (in percentage changes)

Indicator	2050
GDP (expenditure approach)	1.64%
Domestic Production	0.66%
Domestic Demand	0.73%
Exports	0.55%
Imports	0.68%
Private Consumption	2.78%
Investments (public + private)	1.54%
Working hours	0.04%
Real Wage	1.88%
Total OC supply	1.63%
Total ESC supply	-7.71%
Rental Rate of capital	1.39%
Hicksian Welfare Index	1.54%
Household energy use	2.90%
Industrial energy use	-33.96%
Domestic energy use	-17.87%

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

	Producer prices	**Output**	**Output to domestic market**	**Exports**	**Imports**
Energy intensive manufacturing industry	-6.14%	22.58%	12.23%	25.25%	-2.17%
Rest-of-industry	1.80%	-5.98%	-2.47%	-7.47%	4.17%
Transport sector	-3.93%	6.55%	4.75%	11.61%	2.29%
Services sector	0.73%	0.51%	1.25%	-1.88%	2.45%
Refined oil sector	-1.05%	-16.17%	-16.33%	-15.97%	-16.67%
Natural gas (distribution) sector	0.03%	-16.33%	-16.33%	n/a	-16.33%
Electricity production, transmission and distribution	0.49%	-18.46%	-18.07%	-20.23%	-17.25%

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 become more expensive as a result of the energy efficiency improvement. Therefore, the sector's cost of production and domestic output price increases. However, its goods and services constitute an important input for consumption and other sectors, particularly the transport and high-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 more subtle 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 the 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 37.3%. 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, 2020). 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.

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 5.

The doubling of the energy-ESC substitution elasticities substantially increases both the industry-wide and total economy-wide rebound effects, compared to the 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 allows the economic actors to take better advantage of the reduction in the effective price of energy due to the energy efficiency improvement. 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 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 modelled 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.

Table 5: Change in key macroeconomic indicators and aggregate rebound effects for changing assumptions regarding the relationship between energy and capital in 2050, compared 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	1.67%	2.01%	1.76%	1.93%
Domestic production	0.66%	1.33%	0.83%	1.15%
Private consumption	2.78%	3.45%	2.96%	3.29%
Investment	1.54%	1.75%	1.59%	1.70%
Real wage	1.88%	2.59%	2.07%	2.41%
Rental rate of capital	1.39%	0.99%	1.28%	1.09%
Industry-wide rebound effect	29.16	51.10	34.87	45.92
Economy-wide rebound effect	33.85	56.88	39.85	51.45

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 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 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 a substitution of energy and ESC. Without complementarity in capital, 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.

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

An interesting finding of the 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 energy efficiency improvement. 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 6 shows, the increasing elasticities of substitution have a profound impact on the evolution of rebound effects over time.

Compared to the EEI scenario, the sector-specific rebound effects grow with each additional efficiency stimulus. The only exception constitutes the energy-intensive industry, which more or less stays constant over 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 6: Rebound effects in 2050 for the main scenario and the sensitivity analysis with a linear increase in the elasticities of substitution in production, compared to the steady state scenario

Sectors	**EEI scenario**			**Doubling of production elasticities in 30 years**		
	2021	2035	2050	2021	2035	2050
Energy intensive industry	57.32	48.18	39.58	57.32	55.49	57.29
Rest-of-industry	19.46	19.10	18.34	19.46	30.39	45.41
Transport	29.12	25.10	21.22	29.12	32.69	38.04
Service sectors	37.54	34.97	32.12	37.54	49.40	68.99
Refined oil sector	-24.87	-19.04	-14.15	-24.87	-13.61	-3.77
Natural gas (distribution) sector	-19.45	-15.28	-11.63	-19.45	-7.79	3.30
Electricity production, transmission and distribution	4.57	5.97	6.87	4.57	25.15	52.66
Industry-wide rebound effect	**37.49**	**33.33**	**29.16**	**37.49**	**44.06**	**55.45**
Economy-wide rebound effect	**40.81**	**37.33**	**33.85**	**40.81**	**47.98**	**60.10**

Discussion

The assessment of the rebound effects from continuous industrial energy efficiency improvements for Switzerland yields several interesting insights. First, the study shows that the efficiency improvements in Switzerland indeed reduce final energy use at, both, the production and the economy-wide level, but the effectiveness of these improvements is crucially limited through the occurrence of substantial rebound effects. In the 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, the energy efficiency improvements 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 median economy-wide rebound effects of 60% in a sample of 14 studies assessing industrial energy efficiency improvements. 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.

Second, the effect from the industrial energy efficiency improvement on the sectors modelled 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. 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 energy efficiency improvement. 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 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 than 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. Rest-of-industry, 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). The energy efficiency improvements 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 energy efficiency improvements 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, energy efficiency improvements are introduced continuously and at a constant rate of 2.2% p.a. As a corollary, the energy savings gain from each additional energy efficiency improvement, decreases 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. (2015) introduce energy efficiency improvements 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 energy efficiency improvements 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 energy efficiency improvements.

Conclusion

The paper investigates the impact of continuous industrial energy efficiency improvements for 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 reduction targets will likely be missed.

A closer look at the impact of efficiency stimuli on the different sectors modelled 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 the energy efficiency improvements, 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 for this 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 the energy efficiency improvements 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 energy efficiency improvements take place over time. Finally, it is a strong assumption to model energy efficiency improvement 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.

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References

Allan, G., Gilmartin, M., Turner, K., McGregor, P.G. and Swales, J.K., 2007. UKERC Review of Evidence for the Rebound Effect: Technical Report 4: Computable general equilibrium modelling studies. http://hdl.handle.net/1893/10850

Birol, F. and Keppler, J.H., 2000. Prices, technology development and the rebound effect. Energy Policy 28, 457–469. https://doi.org/10.1016/S0301-4215(00)00020-3

Bohringer, C. and Rivers, N., 2018. The Energy Efficiency Rebound Effect in General Equilibrium (June 26, 2018). CESifo Working Paper Series No. 7116, Available at SSRN: https://ssrn.com/abstract=3235208 [Accessed on 20.05.2021]

Broberg, T., Berg, C. and Samakovlis, E., 2015. The economy-wide rebound effect from improved energy efficiency in Swedish industries–A general equilibrium analysis. Energy Policy 83, 26–37. https://doi.org/10.1016/j.enpol.2015.03.026

Broadstock, D., Hunt, L and Sorrell, S., 2007. UKERC Review of evidence for the rebound effect: Technical report 3: Elasticity of substitution studies. http://sro.sussex.ac.uk/id/eprint/53999 [Accessed on 27.05.21]

Brockway, P. E., Saunders, H., Heun, M. K., Foxon, T. J., Steinberger, J. K., Barrett, J. R., and Sorrell, S. 2017., Energy rebound as a potential threat to a low-carbon future: Findings from a new exergy-based national-level rebound approach. Energies, 10(1), 51. https://doi.org/10.3390/en10010051

Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K., & Court, V., 2021. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. Renewable and Sustainable Energy Reviews, 110781. https://doi.org/10.1016/j.rser.2021.110781

Brookes, L., 1990. The greenhouse effect: the fallacies in the energy efficiency solution. Energy Policy 18, 199–201. https://doi.org/10.1016/0301-4215(90)90145-T

Burniaux, J.-M. and Truong, T., 2002. GTAP-E: An Energy-Environmental Version of the GTAP Model. GTAP Technical Papers. https://docs.lib.purdue.edu/gtaptp/18/ [Accessed on 20.05.2021]

Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K., and Jackson, T., 2013. Turning lights into flights: Estimating direct and indirect rebound effects for UK households. Energy policy, 55, 234-250. https://doi.org/10.1016/j.enpol.2012.12.008

Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K., and Jackson, T., 2014. Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. Ecological Economics, 106, 12-32. https://doi.org/10.1016/j.ecolecon.2014.07.003

Colmenares, G., Löschel, A., and Madlener, R., 2020. The rebound effect representation in climate and energy models. Environmental Research Letters, 15(12), 123010. https://doi.org/10.1088/1748-9326/abc214

Corden, W. M., and Neary, J. P., 1982. Booming sector and de-industrialisation in a small open economy. The economic journal, 92(368), 825-848. https://doi.org/10.2307/2232670

Department of the Environment, Transport, Energy and Communications (DETEC), 2017: Faktenblatt "Energie sparen und Energieeffizienz erhöhen" https://www.uvek.admin.ch/dam/uvek/de/dokumente/energie/faktenblatt3-energiegesetz-effizienz.pdf.download.pdf/04_Faktenblatt_3_Energie_sparen_und_Energieeffizienz_erh%C3%B6hen.pdf [Accessed on 20.05.2021]

De Haan, P., Peters, A., and Scholz, R. W., 2007. Reducing energy consumption in road transport through hybrid vehicles: investigation of rebound effects, and possible effects of tax rebates. Journal of Cleaner Production, 15(11-12), 1076-1084. https://doi.org/10.1016/j.jclepro.2006.05.025

Druckman, A., Chitnis, M., Sorrell, S. and Jackson, T., 2011. Missing carbon reductions? Exploring rebound and backfire effects in UK households. Energy Policy 39, 3572–3581. https://doi.org/10.1016/j.enpol.2011.03.058

Duarte, R., Sánchez-Chóliz, J., and Sarasa, C., 2018. Consumer-side actions in a low-carbon economy: A dynamic CGE analysis for Spain. Energy Policy, 118, 199-210. https://doi.org/10.1016/j.enpol.2018.03.065

European Commission, 2019. The revised energy efficiency directive. https://ec.europa.eu/energy/sites/default/files/documents/energy_efficiency_factsheet.pdf [Accessed on 20.05.2021]

Evans, A., and Schäfer, A., 2013. The rebound effect in the aviation sector. Energy economics, 36, 158-165. https://doi.org/10.1016/j.eneco.2012.12.005

Federal Statistics Office (FSO), 2020. Szenarien zur Bevölkerungsentwicklung der Schweiz und der Kantone 2020-2050. https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/zukuenftige-entwicklung/schweiz-szenarien.assetdetail.14963221.html [Accessed on 20.05.2021]

Figus, G., McGregor, P. G., Swales, J. K., and Turner, K., 2020. Do sticky energy prices impact the time paths of rebound effects associated with energy efficiency actions?. Energy Economics, 86, 104657. https://doi.org/10.1016/j.eneco.2019.104657

Fölster, S., & Nyström, J., 2010. Climate policy to defeat the green paradox. Ambio, 39(3), 223-235. https://doi.org/10.1007/s13280-010-0030-7

Garau, G., and Mandras, G., 2015. Economy-wide rebound effects from an increase in efficiency in the use of energy: the Italian case. https://crenos.unica.it/crenos/sites/default/files/WP15-20_0.pdf [Accessed on 20.05.2021]

Gonseth, C., Thalmann, P., and Vielle, M., 2017. Impacts of global warming on energy use for heating and cooling with full rebound effects in Switzerland. Swiss Journal of Economics and Statistics, 153(4), 341-369. https://doi.org/10.1007/BF03399511

Greening, L.A., Greene, D.L., and Difiglio, C., 2000. Energy efficiency and consumption - the rebound effect - a survey. Energy Policy 13. https://doi.org/10.1016/S0301-4215(00)00021-5

Khazzoom, J.D., 1980. Economic Implications of Mandated Efficiency in Standards for Household Appliances. The Energy Journal 1, 21–40. https://www.iaee.org/energyjournal/article/1472 [Accessed on 20.05.2021]

Koesler, S., Swales, K., and Turner, K., 2016. International spillover and rebound effects from increased energy efficiency in Germany. Energy Economics, 54, 444-452. https://doi.org/10.1016/j.eneco.2015.12.011

Lecca, P., Swales, K. and Turner, K., 2011. An investigation of issues relating to where energy should enter the production function. Economic Modelling 28, 2832–2841. https://doi.org/10.1016/j.econmod.2011.08.014

Lemoine, D., 2020. General equilibrium rebound from energy efficiency innovation. European Economic Review, 125, 103431. https://doi.org/10.1016/j.euroecorev.2020.103431

Madlener, R. and Turner, K., 2016. After 35 Years of Rebound Research in Economics: Where Do We Stand?, in: Santarius, T., Walnum, H.J., Aall, C. (Eds.), Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon. Springer International Publishing, Cham, pp. 17–36. https://doi.org/10.1007/978-3-319-38807-6_2

Matos, F.J.F. and Silva, F.J.F., 2011. The rebound effect on road freight transport: Empirical evidence from Portugal. Energy Policy 39, 2833–2841. https://doi.org/10.1016/j.enpol.2011.02.056

Moreau, V., & Vuille, F., 2018. Decoupling energy use and economic growth: Counter evidence from structural effects and embodied energy in trade. Applied energy, 215, 54-62. https://doi.org/10.1016/j.apenergy.2018.01.044

Mohler, L., and Müller, D., 2012. Substitution elasticities in Swiss manufacturing. Report for the Swiss Federal Office of Energy (SFOE). https://www.aramis.admin.ch/Default?DocumentID=61397&Load=true [Accessed on 20.05.2021]

Mohler, L., Deininger, S., and Müller, D., 2016. Energy Elasticities and the Rebound Effect: A Comprehensive Empirical Analysis. http://edoc.unibas.ch/44162/

Nathani, C., Zandonella, R., van Nieuwkoop, R., Brandes, J., Schwehr, T., Killer, M. and Sutter, D., 2019: Energiebezogene Differenzierung der Schweizerischen Input-Output-Tabelle 2014. Schlussbericht an das Bundesamt für Energie. Rüschlikon/Zürich/Thun. Download: https://www.aramis.admin.ch/Texte/?ProjectID=43188 [Accessed on 20.05.2021]

Okagawa, A., and Ban, K., 2008. Estimation of substitution elasticities for CGE models. Discussion Papers in Economics and Business, 16. http://www2.econ.osaka-u.ac.jp/library/global/dp/0816.pdf [Accessed on 20.05.2021]

Odyssee, 2021. Key Indicators. https://www.indicators.odyssee-mure.eu/online-indicators.html [Accessed on 20.05.2021]

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J. R., Sarofim, M. C., Asadoorian Malcom O. and Babiker, M. H., 2005. The MIT emissions prediction and policy analysis (EPPA) model: version 4. MIT Joint Program on the Science and Policy of Global Change. https://dspace.mit.edu/handle/1721.1/29790 [Accessed on 20.05.2021]

Rausch, S., and Schwerin, H., 2018. Does higher energy efficiency lower economy-wide energy use?. Economics Working Paper Series, 18. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/298513/1/WP-18-299.pdf [Accessed on 20.05.2021]

Rutherford, T. F., 1999. Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. Computational economics, 14(1), 1-46. https://doi.org/10.1023/A:1008655831209

Santarius, T., 2016. Investigating meso-economic rebound effects: production-side effects and feedback loops between the micro and macro level. Journal of Cleaner Production 134, 406–413. https://doi.org/10.1016/j.jclepro.2015.09.055

Saunders, H.D., 2008. Fuel conserving (and using) production functions. Energy Economics 30, 2184–2235. https://doi.org/10.1016/j.eneco.2007.11.006

Sorrell, S., 2007. The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. UK Energy Research Centre: London. https://ukerc.rl.ac.uk/UCAT/PUBLICATIONS/The_Rebound_Effect_An_Assessment_of_the_Evidence_for_Economy-wide_Energy_Savings_from_Improved_Energy_Efficiency.pdf [Accessed on 20.05.2021]

Sorrell, S., 2009. Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy 37, 1456–1469. https://doi.org/10.1016/j.enpol.2008.12.003

Stern, D. I., 2020. How large is the economy-wide rebound effect?. Energy Policy, 147, 111870. https://doi.org/10.1016/j.enpol.2020.111870.

Swiss Federal Office of Energy (SFOE), 2020. Schweizerische Gesamtenergiestatistik 2019. https://www.bfe.admin.ch/bfe/en/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTAxMzg=.html [Accessed on 20.05.2021]

Swiss Federal Office of Energy (SFOE), 2020. What is the Energy Strategy 2050. https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050/what-is-the-energy-strategy-2050.html [Accessed on 20.05.2021]

Swiss Federal Office of Energy (SFOE), 2020 Energy Strategy 2050: Monitoring Report 2020; abridged version https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/monitoring-energy-strategy-2050.html [Accessed on 31.05.2021]

Swiss Federal Office of Energy (SFOE), 2021. Wettbewerbliche Auschreibungen – ProKilowatt https://www.bfe.admin.ch/bfe/de/home/foerderung/energieeffizienz/wettbewerbliche-ausschreibungen-prokilowatt.html [Accessed on 26.05.2021]

Turner, K., 2008. A computable general equilibrium analysis of the relative price sensitivity required to induce rebound effects in response to an improvement in energy efficiency in the UK economy (No. 2008-20). Scottish Institute for Research in Economics (SIRE). https://strathprints.strath.ac.uk/67812/ [Accessed on 20.05.2021]

Turner, K., 2009. Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Economics 31, 648–666. https://doi.org/10.1016/j.eneco.2009.01.008

Van der Werf, E., 2008. Production functions for climate policy modeling: An empirical analysis. Energy economics, 30(6), 2964-2979. https://doi.org/10.1016/j.eneco.2008.05.008

Vivanco, D. F., Kemp, R., and van der Voet, E., 2016. How to deal with the rebound effect? A policy-oriented approach. Energy Policy, 94, 114-125. https://doi.org/10.1016/j.enpol.2016.03.054

Wei, T., 2007. Impact of energy efficiency gains on output and energy use with Cobb–Douglas production function. Energy Policy, 35(4), 2023-2030. https://doi.org/10.1016/j.enpol.2006.08.009

Appendix

Table A1: 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	18, 21, 27-33,41-43	Printed matter and recorded media; Pharmaceutical products; Fabricated metal products, expect 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 A2: Production, trade and consumption elasticities of substitution in SEEM

	ESUBARM	*ETRNX*	*ESUBTOP*	*ESUBINT*	*ESUBKEL*	*ESUBKE*	*ESUBELE*	*ESUBFOSS*
Energy–intensive manufacturing industry	2.50	2.00	0.40	1.00	0.45	0.34	0.50	1.00
Rest of industry	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 top nest; ESUBINT; elasticities of substitution between intermediate goods; ESUBKEL: elasticities of substitution between KE composite and labour; 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 Ban/Okawaga (2008) and Paltsev (Paltsev, 2005; EPPA model) for the rest of the economy; GTAP-E (Burniaux and Truong, 2002) for the trade of substitution. Consumption elasticities of substitution from Paltsev (2005)

Figure A1: Nesting structure of non-fossil fuel production in SEEM

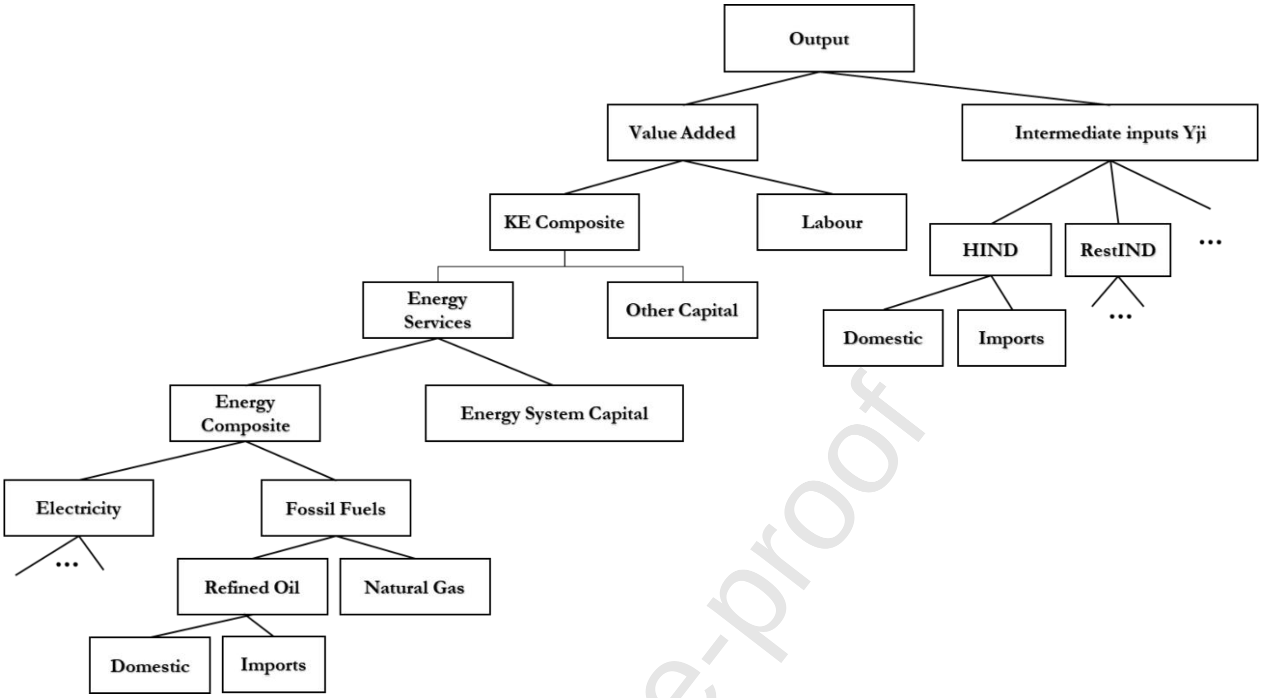
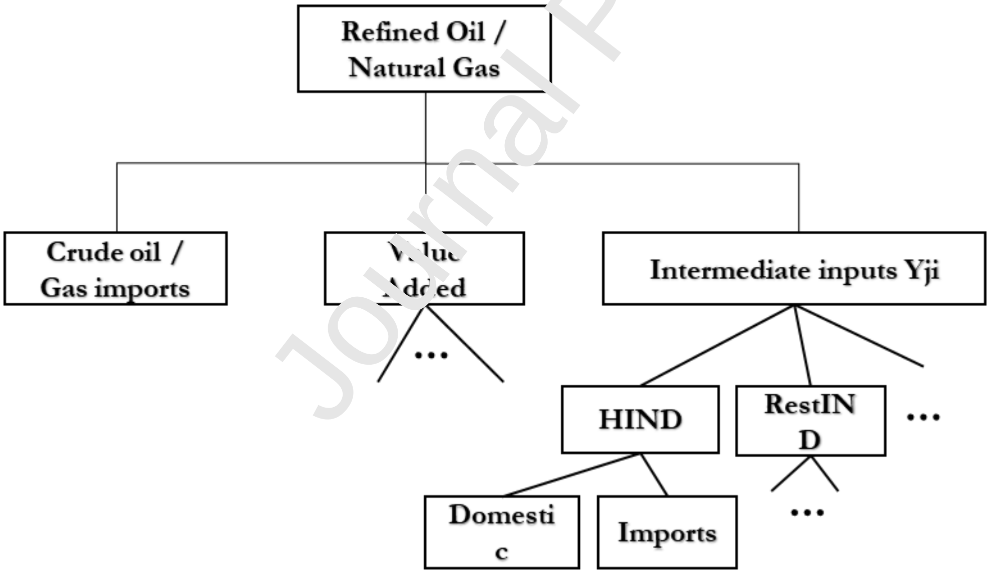


Figure A2: Top nest of fossil fuel production in SEEM



Do rebound effects matter for Switzerland? Assessing the effectiveness of industrial energy efficiency improvements

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Highlights

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