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List of abbreviations

AC	Air conditioning
ADF	Augmented Dicky-Fuller
BAU	Business as usual
BAT	Best available technique
BFE	Bundesamt für Energie
BFS	Bundesamt für Statistik
BIP	Bruttoinlandsprodukt
CC	CO_2 Cap
CCUS	CO_2 Capture Utilisation and Storage
CE	Cambridge Econometrics
CHP	Combined Heat and Power
CO_2	Carbon dioxide
COP	Coefficient of Performance
CREST	Competence Center for Research in Energy, Society and Transition
ECM	Error Correction Model
EE	Energy Efficiency
EIP	Efficiency of Industrial Processes
ENTSOE	European Network of Transmission System Operators for Electricity
EQ	Electrical and ICT equipment
ESD	Energy Service Demand
ETS	Emission Trading Scheme
ETSAP	Energy Technology Systems Analysis Program (Technology Collaboration Programme of the International Energy Agency)
EU	European Union
FA	Floor area for heating and lighting
GDP	Gross Domestic Product
GHG	Greenhouse gas
GMM	Generalized Method of Moments
GVA	Gross Value Added
IEA	International Energy Agency
IFTP	Industry Food, Textile, Pulp and Paper
IBMT	Industry Basic metals (Iron and steel and non-ferrous metals)
ICHM	Industry Chemicals
ICMN	Industry Cement and non-ferrous minerals
ICNS	Industry Construction
ICT	Information and communications technology
IMMO	Industry Metal tools, machinery, other industries
IO	Input Output
LR	Long-run
LS	Long time series
LT	Lighting
MD	Mechanical drive

NOGA	General Classification of Economic Activities
OECD	Organisation for Economic Co-operation and Development
ORC	Organic Rankine Cycle
OT	Others
PDL	Polynomial Distributed Lag
PH	High temperature process heat
PI	Production Index
PIB	Produit Intérieur Brut
ppt	percentage points
PSI	Paul Scherrer Institute
R&D	Research and Development
SCCER	Swiss Competence Center for Energy Research
SES	Swiss Energy Strategy
SFOE	Swiss Federal Office of Energy
SH	Space heating
SR	Short-run
SS	Short time series
STEM	Swiss TIMES Energy systems Model
TIMES	The Integrated MARKAL EFOM System
TT	Inclusion of time trend
TYNDP	Ten-Year National Development Plan
WH	Water heating
WP	Work Package

Summary

In this project price elasticities of natural gas and electricity consumption for Swiss industry are investigated based on historic time series. In addition, future long-term developments of the Swiss industries' energy demands are analysed by employing an energy-econometric accounting framework combined with a techno-economic modelling approach. Therefore, a combination of the global macro-economic model E3ME and the Swiss energy system model STEM has been applied to conduct a multi-scenario analysis scoping on the Swiss industry.

The analysis of the price elasticities for electricity and gas, suggest that most Swiss industries do not reduce energy consumption in the years immediately following an increase in energy prices. However, in the longer term (i.e. around 5 years after any initial shock), we identify statistically significant price elasticities, suggesting that, in most cases, it takes time to adjust and adapt manufacturing processes and procedures or to invest in more energy-efficient equipment, following a price signal. The results also suggest considerable heterogeneity in estimated price elasticities among industry sectors. One of the sectors that is least responsive to a change in energy prices is 'Iron & steel', where our estimates indicate a 0.14% reduction in energy demand in the long run for a 1% increase in energy prices. By contrast, in the 'Non-metallic minerals' and 'Paper and pulp' sectors, we find that energy demand in more elastic as firms in these sectors are more responsive to a change in energy price, with an estimated price elasticity of -0.7 implying that firms in these sectors, on average, will reduce energy demand by 0.7% for a 1% increase in relative energy prices.

The scenario analysis of long-term developments of energy consumption of the Swiss industry and related energy policies reveals that the combination of general energy efficiency improvements alongside a reduction of the per-capita electricity consumption is a less cost-effective way to promote energy efficiency and to reduce CO_2 emissions in industry. This leads to the conclusion that promoting an efficient use of electricity is beneficial while incentives to switch from fossil fuels to electricity-based technologies should retain. A broader roll-out of electricity-based technologies such as e-mobility, deployment of heat pumps is essential for decarbonisation of the Swiss energy system. Limiting the total amount of electricity consumed could be counter-productive and may lead to less cost-optimal emission mitigation solutions.

If a deep decarbonisation of the energy sector is achieved, the industry sector remains one of the challenging sectors for mitigation and may increase its share of the total CO_2 emissions in the energy system in the long run (2050). This statement even holds if only energy-related CO_2 emissions are considered, while abatement of process-related CO_2 emissions depends on the availability and adaptation of some emerging technologies, such as CO_2 capture technologies in the cement industry or waste incineration plants.

Electricity becomes a key energy carrier under a decarbonisation strategy, not only in industry but also in other energy end-use sectors. This not only requires a timely commissioning of new renewable energy in Switzerland but also to deploy the option of increased electricity imports. In industry, oil-products can be phased out and partly substituted by biogenic liquids and other low-carbon energy carriers as well as electricity-based heating, for instance with low temperature heat pumps in selected subsectors (especially food, and paper industries). The share of the energy intensive branches of total industrial energy consumption increases over time which indicates better opportunities to unlock energy efficiency improvements in non-energy-intensive sectors. Where possible, biogenic waste product streams should be used as an energy carrier, which not only helps to close material/product circles but also to provide low carbon fuel substitutes, as our results indicate for the food industry.

The scenario results related to the macro-economic impacts show a low to moderate impact until 2030, for both the energy policies and the climate policies analysed in this study. In the longer term, macro-economic impacts are determined significantly by the developments of the energy and carbon prices applicable to consumers. The achievement of the indicative goals of the Swiss energy policy, i.e. improving general energy efficiency while curbing the average per-capita electricity consumption, reduces Swiss GDP by 1 to 4% (2030 and 2050 respectively), equivalent to GDP growth of around

0.1 percentage points (ppt) lower than baseline over this period. Higher consumer prices, for instance as consequence of a deep decarbonisation within Switzerland with limited availability of cost-efficient decarbonisation technologies, would lead to more pronounced GDP impacts of up to 10% lower than baseline by 2050 (equivalent to an annual GDP growth rate 0.3ppt lower than baseline in each year to 2050). Again, the macro-economic impacts are highly dependent on boundary conditions, such as access to wider EU electricity markets and level of successful solar PV deployment in Switzerland. For instance, availability of more imported (low-carbon) electricity could reduce the scale of the negative economic impacts to around 3% to 4% lower than baseline by 2050 (equivalent to a 0.1ppt reduction in the annual GDP growth rate over this period).

Zusammenfassung

Das vorliegende Forschungsprojekt untersucht Preiselastizitäten des Erdgas- und Elektrizitätsverbrauchs im Schweizer Industriesektor basierend auf historischen Zeitreihen. Zusätzlich werden langfristige Entwicklungen der zukünftigen Energienachfrage in der Schweizer Industrie analysiert, indem ein energie-ökonometrisches Konzept mit einem technisch-ökonomischen Modellierungsansatz kombiniert wird. Zu diesem Zweck wird eine Kombination des globalen makroökonomischen Modells E3ME und des Schweizer Energiesystemmodels STEM für eine szenariogestützte Analyse für den Schweizer Industriesektor verwendet. Die Analyse der Preiselastizitäten zeigt, dass die meisten Schweizer Industriebranchen ihren Energieverbrauch in den Jahren unmittelbar nach einem Preisanstieg nicht reduzieren. Es konnten jedoch langfristig (ungefähr fünf Jahre nach Eintritt des Ereignisses) statistisch signifikante Preiselastizitäten festgestellt werden. Diese suggerieren, dass es nach einem Preissignal in den meisten Fällen Zeit braucht, um Produktionsabläufe und Verfahren anzupassen oder in energieeffizientere Ausstattung zu investieren. Die Resultate deuten ebenfalls auf eine auffällige Heterogenität der geschätzten Preiselastizitäten zwischen den Industriesektoren hin. Einer der reaktionsschwächsten Sektoren auf eine Preisänderung ist die Eisen- und Stahlindustrie, wo unsere Abschätzungen eine langfristige Reduktion von 0.14% des Energieverbrauchs auf einen Preisanstieg von 1% zeigen. Auf der anderen Seite beobachten wir, dass der Sektor der «Nichtmetallischen Mineralien»- und die Papier- und Zellstoffindustrie am meisten auf eine Veränderung der Energiepreise reagieren. Die hierfür geschätzte Preiselastizität von -0.7 bedeutet, dass Firmen in diesen Sektoren im Durchschnitt ihre Energienachfrage um 0.7% reduzieren in Folge einer Erhöhung der Energiepreise von 1%.

Die Szenarioanalyse der langfristigen Entwicklung des Energieverbrauchs in der Schweizer Industrie und damit verbundener energiepolitischen Zielsetzungen zeigt, dass die Realisierung allgemeiner Energieeffizienzverbesserungen bei gleichzeitiger Reduktion des pro-Kopf-Stromverbrauchs ein weniger kostengünstiger Weg ist, um Energieeffizienz zu fördern und CO_2-Emissionen zu reduzieren. Daraus lässt sich schlussfolgern, dass eine effiziente Stromnutzung gefördert werden sollte und gleichzeitig Anreize zum Ersatz fossiler Brennstoffe durch strombasierten Technologien beibehalten werden sollten. Ein weiterer Ausbau strombasierter Technologien wie Elektromobilität oder der Einsatz von Wärmepumpen ist erforderlich für eine Dekarbonisierung des Schweizer Energiesystems. Die Beschränkung des Stromverbrauchs könnte sich als kontra-produktiv erweisen und zu einer weniger kostenoptimalen Lösung führen, um Emissionen zu verringern.

Sollte eine tiefgreifende Dekarbonisierung des Energiesektors erreicht werden, so zeigt sich der Industriesektor als einer der anspruchsvollsten Sektoren für eine Verminderung der CO_2 Emissionen. Auf lange Sicht (2050) erhöht sich gegebenenfalls der Anteil des Industriesektor an den Gesamtemissionen. Gemäß den Modellrechnungen trifft dies insbesondere zu, wenn ausschließlich die energiebezogenen CO_2-Emissionen betrachtet werden. Die Senkung der prozessbezogenen Emissionen hängt von der Verfügbarkeit von neuen Technologien, wie zum Beispiel CO_2-Abscheidung im Zementsektor oder bei der Abfallverwertung, ab.

Strom erweist sich als wichtiger Energieträger in Dekarbonisierungsstrategien, nicht nur in der Industrie, sondern auch in anderen Endenergieverbrauchssektoren. Dies erfordert sowohl den rechtzeitigen Ausbau von erneuerbarer Energie in der Schweiz, als auch die Nutzung von Stromimporten. In der Industrie können Erdölprodukte reduziert und teilweise ersetzt werden, insbesondere durch biogene Treibstoffe oder andere kohlenstoffarme Brennstoffe, beziehungsweise in ausgewählten Industrie-bereichen (Nahrungsmittelbranche und Papierindustrie) durch strombasierte Wärmeerzeugung, zum Beispiel mit Wärmepumpen im industriellen Niedertemperaturbereich. Der Anteil der energieintensiven Branchen am industriellen Gesamtenergieverbrauch erhöht sich mit der Zeit, was bedeutet, dass die nicht energieintensiven Sektoren die besseren Möglichkeiten haben, um ihre Energieeffizient zu

verbessern. Wo immer möglich, sollten biogene Abfälle eine Wiederverwendung als Energieträger finden. Wie unsere Resultate für die Nahrungsmittelbranche zeigen schließt dies nicht nur die Stoffkreisläufe, sondern stellt auch CO_2-emissionsarme Ersatzbrennstoffe zur Verfügung.

Die Resultate zu den makroökonomischen Auswirkungen der in dieser Studie analysierten Klima- und Energiepolitiken zeigen geringe bis mäßige Auswirkungen bis 2030. Auf lange Sicht gesehen werden die makroökonomische Auswirkungen signifikant von der Entwicklung der Preise für Energie- und CO_2 Emissionszertifikate bei den Endverbrauchern bestimmt. Das Erreichen der Zielvorgaben der Schweizer Energiepolitik, die Energieeffizient zu verbessern und gleichzeitig den Stromverbrauch pro Kopf zu senken, würde das Schweizer Bruttoinlandsprodukt (BIP) um 1% in 2030 und 4% in 2050, senken. Dies entspricht einem verringerten Wachstum des BIP um 0.1 Prozentpunkte in der gleichen Periode im Vergleich zum Referenzszenario. Höhere Konsumentenpreise, beispielsweise als Folge einer tiefgreifenden Dekarbonisierung des Schweizer Energiesystems mit begrenzten Möglichkeiten des Ausbaus kostengünstiger Minderungstechnologien, würden sich signifikant auf das BIP auswirken mit einem bis zu 10% tieferen BIP in 2050 verglichen mit dem Referenzszenario (entspricht einem um 0.3 Prozentpunkte niedrigeren jährlichen BIP-Wachstum gegenüber dem Referenzszenario). Auch hier sind die makroökonomischen Auswirkungen stark von den Randbedingungen abhängig, wie dem Zugang zum EU-Strommarkt und dem Ausbaugrad der Photovoltaik in der Schweiz. Zum Beispiel könnte eine Verfügbarkeit von höheren (weitestgehend CO_2-freien) Stromimporten die negativen wirtschaftlichen Auswirkungen auf ein um 3% bis 4% tieferes BIP in 2050 gegenüber dem Referenzszenario reduzieren, was einer um 0.1 Prozentpunkte tieferen jährlichen BIP-Wachstumsrate in derselben Periode entspricht.

Résumé

Le présent projet de recherche examine, sur la base de séries chronologiques historiques, les élasticités-prix de la consommation de gaz naturel et d'électricité dans le secteur industriel suisse. L'évolution à long terme de la demande énergétique dans l'industrie suisse est également analysée en conjuguant un concept énergétique-économétrique avec une approche de modélisation technico-économique. A cet effet, le modèle macroéconomique global E3ME et le modèle du système énergétique suisse STEM sont combinés pour procéder à une analyse basée sur des scénarios pour le secteur industriel suisse. L'analyse des élasticités-prix montrent que la plupart des branches de l'industrie suisse ne réduisent pas leur consommation d'énergie dans les années qui suivent immédiatement une augmentation des prix. Cependant, à long terme (environ cinq ans après la survenance de l'événement), des élasticités-prix statistiquement significatives peuvent être constatées. Celles-ci suggèrent que, dans la plupart des cas, il faut du temps après un signal lié aux prix pour adapter les cycles et les procédés de production, ou encore investir dans un équipement présentant une meilleure efficacité énergétique. Les résultats indiquent également une hétérogénéité frappante des estimations des élasticités-prix entre les différents secteurs industriels. La sidérurgie est l'un des secteurs qui réagit le moins à une modification des prix: nos estimations mettent en évidence une réduction à long terme de 0,14% de la consommation d'énergie après une augmentation de prix de 1%. A l'autre bout, nous observons que ce sont le secteur des produits minéraux non métalliques et l'industrie du papier et de la pâte à papier qui réagissent le plus à une modification des prix de l'énergie. L'élasticité-prix estimée ici est de -0,7, ce qui signifie que les entreprises de ce secteur réduisent en moyenne leur demande énergétique de 0,7% après une augmentation de 1% des prix de l'énergie.

L'analyse de scénarios pour l'évolution à long terme de la consommation d'énergie dans l'industrie suisse et des objectifs de politique énergétique qui y sont liés montre que réaliser des améliorations générales en termes d'efficacité énergétique tout en réduisant la consommation d'électricité par tête représente une voie moins économique pour encourager l'efficacité énergétique et réduire les émissions de CO_2. On peut donc en déduire qu'il faudrait encourager une utilisation plus efficace de l'électricité tout en maintenant des incitatifs pour remplacer les combustibles fossiles par des technologies électriques. Pour décarboniser le système énergétique suisse, il faut continuer à développer des technologies électriques comme la mobilité électrique ou l'emploi de pompes à chaleur. Limiter la consommation d'électricité pourrait s'avérer contre-productif et entraîner une solution moins optimale en termes de coûts pour la réduction des émissions.

Dans l'objectif d'une décarbonisation profonde du secteur de l'énergie, le secteur industriel apparaît comme l'un des plus exigeants pour une réduction des émissions de CO_2. Le cas échéant, la part du secteur industriel dans l'ensemble des émissions augmente à long terme (2050). D'après les calculs sur modèle, ce constat vaut tout particulièrement si l'on considère exclusivement les émissions de CO_2 liées à l'énergie. La réduction des émissions liées aux processus dépend de la disponibilité de nouvelles technologies comme la capture du CO_2 dans le secteur du ciment ou lors du traitement des déchets.

L'électricité est une importante source d'énergie dans des stratégies de décarbonisation, non seulement dans l'industrie, mais aussi dans d'autres secteurs de consommation d'énergie finale. Cela nécessite aussi bien le développement d'énergies renouvelables en Suisse que le recours aux importations d'électricité. Dans l'industrie, la part de produits pétroliers peut être réduite et ils peuvent être partiellement remplacés, notamment par des biocarburants ou d'autres combustibles à faible teneur en carbone; dans certains secteurs industriels ciblés (industrie alimentaire et industrie du papier), une production de chaleur d'origine électrique, par exemple au moyen de pompes à chaleur basse température, peut se substituer. La part des secteurs à haute consommation d'énergie dans la consommation énergétique globale de l'industrie augmente avec le temps, ce qui signifie que les secteurs qui ne sont pas à haute consommation d'énergie ont de meilleures opportunités pour améliorer leur efficacité énergétique. Partout où c'est possible, les déchets biogènes devraient être utilisés comme source d'énergie. Comme le montrent nos résultats pour l'industrie alimentaire, en plus de boucler le cycle des matières, cela met à disposition des combustibles de remplacement peu émetteurs de CO_2.

En termes d'impact macroéconomique, les résultats des politiques climatiques et énergétiques analysées dans cette étude montrent un effet faible à modéré d'ici 2030. Dans une perspective à long terme, l'impact macroéconomique est déterminé de manière significative par l'évolution des prix des certificats énergétiques et des émissions de CO_2 chez les utilisateurs finaux. Si les objectifs de la politique énergétique suisse devaient être atteints – amélioration de l'efficacité énergétique couplée à une réduction de la consommation d'électricité par tête – le Produit Intérieur Brut (PIB) suisse diminuerait de 1% en 2030 et de 4% en 2050. Cela correspond à une réduction de 0,1 point de pourcentage de la croissance du PIB par rapport au scénario de référence pendant la même période. Des prix à la consommation plus élevés, comme conséquence par exemple d'une décarbonisation profonde du système énergétique suisse avec des possibilités limitées de développement de technologies de réduction abordables, auraient un impact significatif sur le PIB avec, en 2050, un PIB jusqu'à 10% inférieur par rapport au scénario de référence (ce qui correspond à une croissance annuelle du PIB inférieure de 0,3 point de pourcentage par rapport au scénario de référence). Là aussi, l'impact macroéconomique dépend largement des conditions cadres, comme l'accès au marché de l'électricité de l'UE et le degré de développement du photovoltaïque en Suisse. La possibilité de disposer d'importations d'électricité (autant que possible non émettrice de CO_2) pourrait par exemple réduire l'impact économique négatif avec, en 2050, un PIB de 3% à 4% inférieur par rapport au scénario de référence, ce qui correspond dans la même période à une croissance annuelle du PIB inférieure de 0,1 point de pourcentage.

1 Project goals and project set-up

The objective of this project is 1) to conduct an empirical analysis of the price elasticities of natural gas and electricity consumption for Swiss industry (including sub-sectoral detail) based on historical time series, and 2) to investigate future long-term developments of the industry sector's energy demand patterns under different policy frameworks by considering demand elasticities, fuel and technology substitutions, and energy efficiency improvement measures.

The proposed project consists of two work packages (WPs) as illustrated in Figure 1. In the first work package, historic price demand elasticities for electricity and natural gas consumption are estimated by each industrial sub sector for Switzerland, while in WP2 features a forward-looking analysis (until 2050) to investigate long-term final energy consumption of Swiss industry. The research builds on analytical frameworks and tools developed by Cambridge Econometrics (CE) and the Paul Scherrer Institute (PSI), for which the existing methods and modelling tools have been advanced. The forward-looking part of the project benefits from improved modelling tools, which have been jointly applied in a scenario analysis to address major energy policy questions.

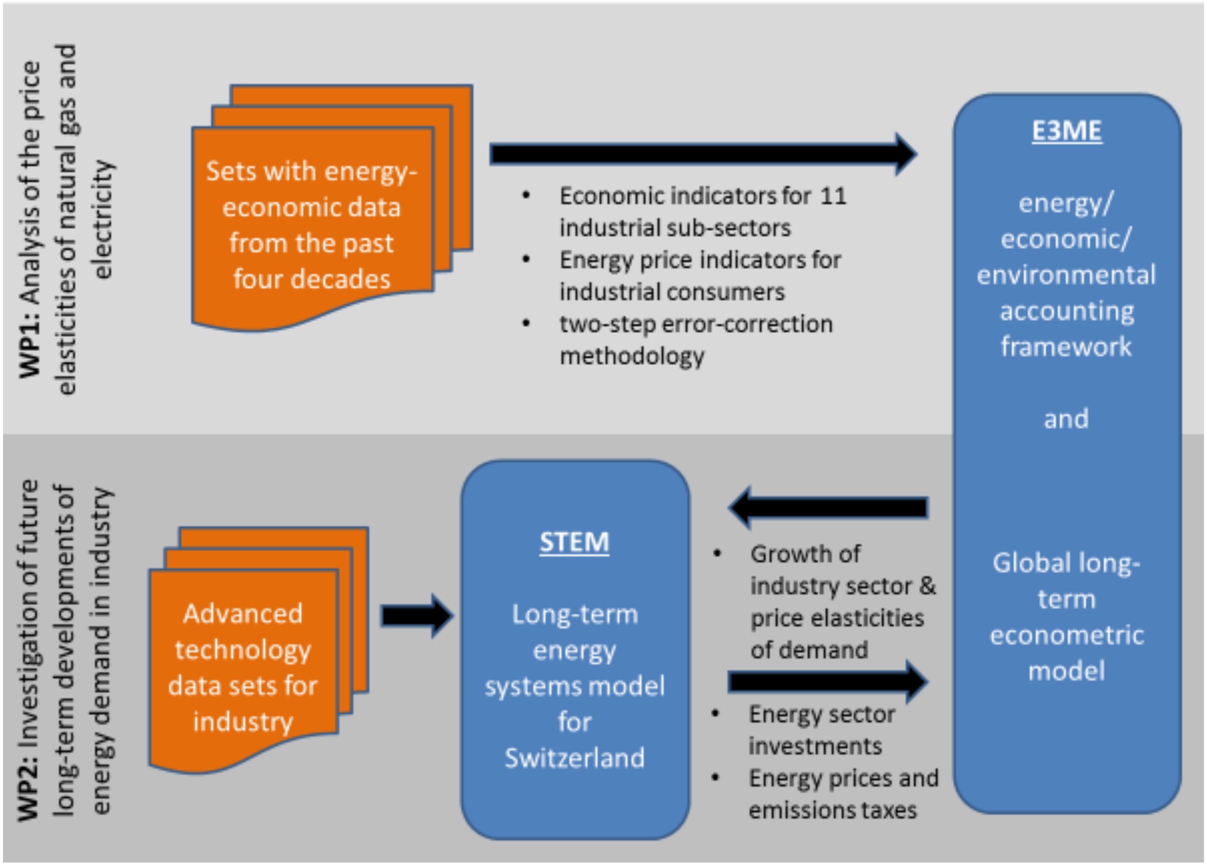

Figure 1: Project methodology and model linkage

The E3ME model is a macro-econometric model based on the system of national accounts with a bottom-up sectoral disaggregation. Identity relationships, such as gross output and GDP are fixed as the sum of their component parts; behavioural relationships estimated for the model. The latest input-output (IO) tables from the OECD and Eurostat are included and complemented with Swiss national data. IO coefficients are projected forwards through dynamic logistic trends. Technical progress is endogenous, defined as a function of investment enhanced by R&D spending. Central to E3ME are the two-way linkages between the energy system and the wider economy including environmental implications.

STEM is a technology-rich bottom up energy systems model for Switzerland which operates under a cost-optimisation paradigm with a long-term perspective. STEM distinguishes seven industrial subsectors, for which differences with regards to their consumption patterns (e.g. energy intensity; process heat requirements; fuel options; temporal energy demand patterns; future economic growth) are considered. For the production of heat (process heat and space/water heating), the model has a range of options including various technology (e.g. boilers, heat pump, CHPs) and fuel combinations (e.g. coal, natural gas, oil, biomass, waste, electricity, solar).

2 Work undertaken and findings obtained

The project consists of two work packages which are relatively independent from each other.

2.1 WP1: Empirical analysis of the price elasticities of industrial energy consumption

The aim of the first work package is to estimate price demand elasticities for electricity and natural gas consumption by each industrial sub-sector for Switzerland (see Table 22 and Table 23 in the appendix).

The industrial energy price elasticities are key parameters for the modelling of future energy pathways for industry in Switzerland, to determine how industry is likely to respond following the introduction of market-based instruments, such as an energy tax, carbon tax or carbon price. In a simple modelling framework, increases in energy prices (e.g. due to a carbon tax) would have a direct impact on energy demand, as higher costs of energy would drive firms to invest in more energy-efficient equipment or to adopt more energy-efficient behaviors. Higher energy prices would also have indirect impacts, reducing the relative competitiveness of domestic industry, leading to a squeeze in production and a further knock-on impact on energy demand. Our combined E3ME-TIMES modelling approach captures both these direct and indirect channels by which energy prices impact on energy demand. The aim of this work package is to derive price elasticities of energy demand, that can ultimately be used in our combined modelling framework.

This section outlines our approach and results for estimated price elasticities in industrial energy demand equations. Before estimating industrial energy demand equations, we undertake a literature review to inform our econometric specification and to compare previous estimates of energy price elasticities. In Section 3.1.2 a summary of price elasticity estimates from the literature is presented. In Section 3.1.3 we describe the data sources used for the estimation of Swiss energy demand and energy price elasticities. In Section 3.1.4 we explain our methodological approach and the specification of the econometric equations. Finally, in Section 3.1.5, we present the results from the econometric analysis and discuss the meaning of the results.

2.1.1 Literature Review

The purpose of the literature review is twofold. Firstly, it informs our own econometric specification for energy demand equations and, secondly, it provides a robustness check for the elasticity estimates that we derive for Switzerland. The results from these studies can also be used for benchmarking our price elasticities estimates and, in particular, for comparing our top down macro level estimates to bottom up micro estimates.

There are a number of studies that have sought to estimate the price and income elasticities for household gas and electricity demand in Switzerland (see Filippini et al. (2015), Filippini (1999), Zweifel et al. (1997), Dennerlein (1990), Spierer (1988), Dennerlein and Flaig (1987)). However, we only identify one study by Mohler (2016) that has estimated price elasticities for industrial energy demand in Switzerland. There are large differences in the drivers of energy consumption among households versus industry, due to different time-preferences, energy service uses, consumption patterns and other related factors. Studies that focus on estimating price elasticities of energy demand in households are therefore not included in the scope of the literature review. Instead, we focus on studies that estimate industrial energy demand equations. Because there are limited analyses of industrial energy demand in Switzerland, we conduct a wider search for estimates of industry gas and electricity price elasticities across international sources of energy literature.

The energy studies identified use a variety of different econometric specifications, estimate over different time series, use different data sources and focus on different regions. There is also a difference in the granularity of the industrial energy demand data, with some studies using detailed firm-level data, whilst other studies estimate energy demand equations using data at a broader industry sector level. Drawing on results from the literature review, we can examine the extent to which identified price elasticities are analogous and we can begin to identify a plausible range of values for the price elasticity of industrial energy demand.

As highlighted by Madlener et al. (2011), there are surprisingly few econometric studies of industrial energy demand. Of those studies that do exist, the vast majority estimate energy demand at an aggregate industry sector level, rather than at the industrial sub-sectoral level. In fact, we only identify two studies that provide results for price elasticities at an industry sectoral level[1]. The studies that seek to estimate price elasticities of energy demand broadly fall into two groups:

(i) studies that use logit and translog functions to estimate input factor and fuel substitution (often static in nature)
(ii) studies that use time-series or panel data, to estimate long-run relationships between energy demand, economic activity and energy prices

2.1.1.1 **Economic intuition**

Most of the econometrically estimated energy demand equations include elasticity estimates with respect to economic activity and energy prices (relative to other factor costs).

Economic intuition suggests a positive relationship between economic activity and energy demand: industries will use more energy as production grows. With the existence of economies of scale and cost-efficiency improvements as industries expand, we would expect the magnitude of the elasticity on economic activity to be less than unity, implying that a scale-up in production is met by a less than proportional increase in energy consumption.

We would expect a negative relationship between real energy price and energy demand. If energy prices increase (relative to other factor inputs) then we would expect firms to respond by reducing energy inputs in favor of other factor inputs and to improve energy-efficiency through behavioral and technological measures. The price elasticity for the aggregate energy demand equation effectively captures factor substitution effects. In those industries where it is easier to switch between factor inputs, we would expect the price elasticity of energy demand to be more elastic. In the case where fuel equations are estimated, the fuel price elasticity is dependent on the ease at which it is possible to switch to alternative energy sources for production.

2.1.1.2 **Energy price elasticities from the literature**

The table below shows estimated price elasticities of industry energy demand, as identified in the energy literature. The interpretation of the price elasticities presented here is the percentage change in energy demand for a 1% increase in price. As shown in the table, there are a wide range of energy price elasticities that are estimated in the literature.

Madlener et al (2011) is one of the most comprehensive econometric studies of industry energy demand to date. In this study, electricity demand in Germany is estimated using a panel cointegrating approach, drawing on data over the period 1970-2007, disaggregated by industry sector. The estimated energy price elasticity for industry energy demand using this approach ranges between 0 and -0.57 in the long run[2] (depending on the industry sector), implying that a 1% increase in energy prices could drive up to

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[1] Refer to industry-specific energy price elasticities estimated by Tamminen and Tuomaala (2012), and Madlener et al. (2011), which are presented in Table 13 and Table 14 in the Appendix, for convenience.

[2] The ‘long run’ here refers to the point at which the behaviour of an industry sector reverts to the long term trend, following a shock. It reflects the point at which an industry’s behaviour has fully adjusted to an external shock. Results from the analysis by Madlener suggest that the speed of adjustment to this long term trend is between an annual error correction of about 20% and 77% per year (depending on which sector is considered). This implies that the long run is reached in around fourteen years in the slowest case and around three years in the fastest case. By contrast, the ‘short-term’ captures the instant behavioural response in the immediate years following the shock.

0.57% reduction in electricity demand. To complement and compare to the panel econometric approach, Madlener et al. (2011) also uses a translog function to estimate industry electricity, gas and oil demand at an aggregate industry level, across a selection of five EU Member States but, using the translog specification results are unintuitive and the author concludes that the results obtained from the cointegration analysis are more plausible and robust. For both estimation approaches, a specification is tested with a deterministic time trend to control for technological progress and structural changes and is found to be significant for some industry sectors.

Table 1: Summary of findings from literature review

Study	Country	Energy carrier	Estimation method	Data	Own price elasticity estimates
L Mohler, 2016	Switzerland	All fuels	Linear logit and Translog	1997-2008	-1.03 to -0.56
Tamminen and Tuomaala, 2012	Finland	Electricity, other energy	Translog	2000-2009	Electricity: -0.98 to -1.3 Other energy: -0.83 to -1.0
Madlener et al. 2011	Germany	Electricity	Panel	1970-2007	LR: 0 to -0.5 SR: 0 to -0.57
Madlener et al. 2011	France, Italy, Germany, UK, Spain	Electricity, gas, oil	Translog	1978-2006	Various (many unintuitive)
Arnberg and Bjorner, 2007	Denmark	Electricity, other energy	Linear logit and Translog	1993, 1995-1997	Electricity: -0.19 to -0.21 Other energy: -0.23 to -0.45
Polemis, 2007	Greece	Electricity	Multivariate cointegration	1970–2004	LR: –0.85 SR: –0.35
G. Liu, 2006	OECD countries	Electricity	Dynamic panel	1978 to 1999	LR: -0.044 SR: -0.013
G. Liu, 2006	OECD countries	Natural gas	Dynamic panel	1978 to 1999	LR: -0.243* SR: -0.067*
Kamerschen & Porter, 2004	USA	Electricity	Simultaneous equations	1973–1998	–0.34 to–0.55
Bjørner et al. 2002	Denmark	Energy	Panel cointegration	1983-1997	-0.44
Beenstock et. al. 1999	Israel	Electricity	Cointegration	1975–1994	LR: –0.31 to –0.44
Bose & Shukla, 1999	India	Electricity	Pooled regression	1985/86–1993/94	–0.04 to –0.45

Note(s): LR – 'long run'; SR- 'short run'

In studies by Mohler (2016), Tamminen and Tuomaala (2012), and Arnberg and Bjorner (2007). translog functions are also used to estimate energy price elasticities and to examine the extent to which energy demand and other factor inputs are substitutes or complements. The Mohler (2016) study uses firm-level data covering manufacturing, services and retail sectors in Switzerland over the period 1997-2008. The study estimates a price elasticity of energy demand of -1.03 (for low energy intensity and high energy intensity firms) and an elasticity of -0.56 (for medium energy intensity firms). In Tamminen and Tuomaala (2012), firm-level data covering energy demand in Finland over the period 2000 to 2009 is used to estimate substitution elasticities for factor inputs across 71 sectors. The own-price elasticity of electricity demand is estimated in the range of -0.98 to -1.3, while the own-price elasticity of other energy demand is estimated to be in the range of -0.83 to -1.0 (dependent on sector). Arnberg and Bjorner (2007) use a linear logit specification to estimate price and substitution elasticities using data for 903 firms in Denmark in 1993 and over the period 1995-1997. They estimate own price elasticities in the range of -0.19 to -0.21 for electricity and in the range of -0.23 to -0.45 for other energy use.

Liu (2006) uses a dynamic panel approach (based on Arellano and Bond, one-step GMM) to estimate price elasticities for electricity and natural as using data for OECD countries over the period 1978-1999. The results of the study indicate a long run price elasticity of –0.044 (in the electricity demand equation) and a long run price elasticity of -0.243 (in the gas demand equation). A deterministic time trend was tested as a proxy for technological change but was found to be insignificant. By contrast, Polemis (2007) models aggregate oil and electricity demand for industries in Greece using a multivariate cointegration technique and estimates a long run price elasticity of –0.85, and a short-run price elasticity of –0.35.

2.1.2 Data requirements and data sources

The key data required for our analysis incudes energy demand, economic activity and energy price data for Switzerland. Aggregate energy demand across all industry sectors in Switzerland has remained relatively stable over recent decades, however, this steady trend in energy demand at the aggregate industry level masks more complex trends in energy demand and energy-using behavior at an industry sectoral level. To best capture sector-specific effects, we estimate econometric energy demand equations at an industry sub-sectoral level. This requires data for each of the variables in the regression at the industry sector level.

The quality of the data underpinning an econometric estimation is vital to ensure the reliability and robustness of the elasticity estimates. Before estimating the price and output elasticities for industry gas and electricity demand in Switzerland, we undertook a review of available data. We compared data from alternative sources to test its reliability and credibility.

As well as ensuring good data coverage across industry sectors at the national level for Switzerland, the available time series will also affect the robustness of the econometric estimation. A longer time series increases the sample size and improves the consistency of the elasticity estimates. However, by using data over many decades, we implicitly capture behavioral relationships from far back in history. This raises questions about the appropriateness of applying our estimated energy price elasticities for forward-looking analysis, given expected changes in the relationship between energy prices and demand, due to structural change, technological progress and new policies that target industry energy-using behavior. To mitigate this risk, we consider possible indicators to control for energy-saving technological progress and we test equations using both short and longer time series data. For the forward-looking scenario analysis (in Work Package 2), we apply the more detailed bottom-up STEM model to capture deployment of different energy-saving technologies and their subsequent impact on energy demand.

2.1.2.1 **Energy demand data**

To capture the sector-specific characteristics of industry energy demand in Switzerland, gas demand, electricity demand and total energy demand data is required at an industry sectoral level.

For gas and electricity demand data by industry sector, we identified three key data sources:

- Bundesamt für Energie (BFE), Schweizerische Gesamtenergiestatistik (2018): gas and electricity demand by industry sector over the period 1999-2016 (annual)
- Bundesamt für Energie (BFE), Kantonsstatistik (2018): electricity consumption by canton over the period 2011-2014 (monthly)
- International Energy Agency (IEA), World Energy Balance (2018): gas and electricity demand by industry sector over the period 1960-2015 (annual)

When considering which of these data sources to use, the IEA data has the advantage of a longer time series. The BFE data, however, is more current, including data up to 2016 and some of the data is available on a monthly basis.

The IEA and BFE are both internationally-recognized reputable sources, providing the most reliable energy demand data available for Switzerland. However, there are some differences in the sector-level energy demand trends. IEA and BFE gas and electricity consumption data was compared at the sectoral level and this analysis shows that, in most cases, the two data sources reflect the same trends in energy consumption at a sectoral level (see Annex A) but there are some key differences between the two data sources, which could be due to differences in the way these indicators are measured or in the industry classification.

For this study, we run two alternative regressions. One is a shorter time-series regression which uses the full available series of BFE data (over 1999-2016). We also test a longer time-series regression which uses the IEA industry energy demand data to extend the series from BFE back over the period 1970-1999. By extending the time-series we increase the sample size and improve the consistency of the econometric estimates but also include in data from further back in history, which raises questions about its relevance for capturing current and future energy-using behaviors.

2.1.2.2 Gas and electricity price data

To estimate the price elasticity of energy demand at an aggregate level, we use a weighted average energy price[3]. The energy price term in the aggregate energy demand equation includes all transportation costs, distribution costs and all tax, and so captures the final price faced by industrial end users[4]. The price term used in the aggregate energy demand equation is in real terms, to remove distortionary effects of inflation. By using the real price of energy, it can be thought of as a measure of relative energy prices, implicitly capturing substitution effects between factor inputs. For the gas share equation, the price term reflects the price of gas relative to the weighted average price of all fuels. Similarly, for the electricity share equation, the price term reflects the price of electricity relative to the weighted average price of fuels. The purpose of using a relative fuel price is to capture fuel switching effects.

It is noted that there are likely to be differences in gas and electricity prices faced by different firms and across different industry sectors: those plants that consume particularly large volumes of energy can typically negotiate better deals with energy suppliers. However, due to data limitations, we use the same average industry gas and electricity price series to estimate energy price elasticities for each industry sector. It is expected that, whilst the absolute price of energy might vary slightly across industry sectors, the prices faced at the industry sectoral level should follow similar trends (as they are determined by the same underlying drivers i.e. changes in wholesale prices, distribution costs and tax). Therefore, we do not expect that our use of 'industry average' electricity and gas prices to bias our estimated energy price elasticities.

We identified two sources of data for energy prices:

- Eidgenössische Elektrizitätskommission ElCom, Tarif-Rohdaten der schweizerischen Verteilnetzbetreiber (2018): electricity prices by consumption category and canton over the period 2009-2018 (annual)
- International Energy Agency (IEA), Energy prices and taxes series (2017): industry average gas and electricity prices (with and without tax included) over the period 1978-2016 (annual and quarterly)

In this study, we use the IEA data which covers both gas and electricity prices over a longer time period.

[3] Fuel price weights are calculated based on the share of each fuel in total energy demand.
[4] For more information about the energy price data collection methodology, refer to IEA metadata: http://wds.iea.org/wds/pdf/EPT_countrynotes.pdf

2.1.2.3 **Industry activity**

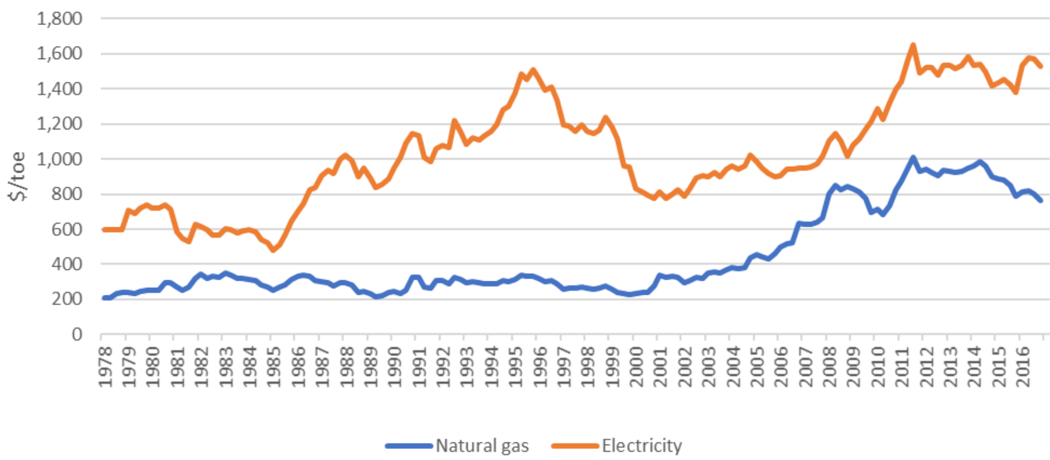


Figure 2: Swiss industry gas and electricity prices incl. tax (IEA, 2017)

An indicator for industrial activity captures and controls for the impact of increased level of industrial production on aggregate energy use. Two possible measures lend themselves to capturing industry activity: sectoral gross value added (GVA) and sectoral gross output. Each of these options for the economic activity indicator has strengths and weaknesses.

In the National Accounting System, gross output measures the total revenue of a particular sector, while GVA is defined as gross output net of intermediate costs and taxes (and so reflects the net contribution of each sector). The advantage of using GVA as an indicator of productive activity is that, unlike gross output, it does not reflect changes in the cost of other intermediate goods and services that may not impact on the energy requirements for the production process but would impact on the gross output measure of production. However, the issue with using GVA as an indicator of productive activity is that, if intermediate consumption of energy falls (e.g. due to energy efficiency improvements), then, by definition, GVA will increase, as the total cost of energy would be lower for the same level of output. This would lead to a bias in the results. To better isolate the impact of productive activity on energy demand we instead use gross output (in real terms).

We identified three data sources for industry output:

- Bundesamt für Statistik (BFS) (2018), Produktions-, Auftrags- und Umsatzstatistik im sekundären Sektor: Turnover by industry sector over the period 1991-2017 (quarterly data); GVA by industry sector over the period 2005-2017 (quarterly data)
- OECD (2018), STAN database, Value added in manufacturing over the period 1990-2016
- Eurostat: National Accounts Aggregates by Industry (*nama_10_a64)*

A combination of these sources is used to generate data over the required timeframe.

2.1.2.4 **Technological progress**

Increased deployment of energy-efficient technologies and industry structural changes are likely to be important drivers of future industry energy demand but are inherently difficult to capture in a top-down econometric equations. In previous studies (e.g. see Madelner et al, 2011), a deterministic time trend has been included in the econometric specification as a proxy for energy saving technological progress, to capture, and control for, the effects of technological improvements and gradual changes in industry structure. An alternative approach for controlling for technological progress would be to include a measure of total spending on R&D and/or investment, which could be a good proxy for total investment in technologies and would form a quality adjusted measure of investment. Due to issues with data availability for spend on R&D and investment, we instead test a specification with a time trend as a proxy for technological progress.

2.1.2.5 Summary of data source

Table 2 provides a summary of the key data sources and the time periods for which they are used.

Table 2: Summary of data sources used for estimation of energy demand equations (short time series)

Data	Time series used	Sources
Energy demand	Energy Demand Data available from BFE 1999 to 2016 Energy Demand Data available from IEA from 1970 to 1999 Data from Swiss Federal Office of Energy Sector Statistics extrapolated based on growth rates for energy demand in IEA data (1970:2016)	Swiss Federal Office of Energy Sector Statistics (BFE, 2016 Data table) International Energy Agency (IEA) – World Energy Balance and Energy prices and taxes series
Energy prices	Energy Prices and taxes: from 1978:2016 from the IEA Extended back from 1978 to 1970 using data from E3ME at a more aggregate level.	International Energy Agency (IEA) – World Energy Balance and Energy prices and taxes series
Industry output by sector	Index of industry output by sector from 1999 to 2017, 2010 = 1 The growth rates from data included in E3ME – which is based on Eurostat data and other sources – is used to extrapolate BFS data from 1970 to 1999	Swiss Federal Statistical Office, 'Production, order and turnover statistics in the secondary sector - quarterly time series, Index of Gross output, (BFS, 2017b). OECD STAN database Eurostat: National Accounts Aggregates by Industry *nama_10_a64*

2.1.3 Econometric methodology

2.1.3.1 Functional form

Our approach to estimation of energy demand is consistent with the equation specification used in the E3ME global macro-econometric model (CE, 2014). First, an aggregate energy demand equation is estimated, which captures the causal relationship between output, energy prices and energy demand. The price elasticity in this equation implicitly captures both energy-saving behavior and substitution to other factor inputs, following an increase in energy prices. Gas and electricity share equations are then estimated to capture fuel switching effects. A time trend is tested in some specifications, as a proxy for energy-saving technological progress.

$\textit{Total energy demand}_i = \beta_1 \textit{ Gross Output}_i + \beta_2 \textit{ Weighted Energy Price}_i \; (+\ \beta_3 \textit{Time Trend}) + u_i$

$\textit{Gas share in energy demand}_i = \beta_1 \textit{ Gross Output}_i + \beta_2 \textit{ Relative Fuel Price}_i \; (+\ \beta_3 \textit{Time Trend}) + u_i$

$\textit{Electricity share in energy demand}_i = \beta_1 \textit{ Gross Output}_i + \beta_2 \textit{ Relative Fuel Price}_i \; (+\ \beta_3 \textit{Time Trend}) + u_i$

Individual equations are estimated for each industry sector, 'i', (refer to Table 12 in the Appendix).

The framework allows for the distinction of price elasticities for each energy user and fuel type. Individual fuel share equations are estimated for gas and electricity. These equations are intended to capture substitution between energy carriers by users on the basis of relative prices, although overall fuel use and the activity are also allowed to affect the choice. As outlined above, regressions are tested both with and without the inclusion of a deterministic time trend. We take logarithms of each variable included in the regressions, so that the parameter estimates can be interpreted as elasticities.

2.1.3.2 **Functional form**

The existence of stochastic trends in most economic and energy data suggests that standard regression techniques will lead to spurious regression results. We therefore use a cointegrating econometric approach, with error-correction representation, to capture both the short-term dynamic, relationship between variables, as well as the longer-term relationships. The econometric equations are estimated using a two-step error-correction methodology Engle and Granger (1987)[5]. In brief, the process involves two stages. The first stage is a levels relationship, whereby an attempt is made to identify the existence of a cointegrating relationship between the chosen variables. The second stage regression, known as the error-correction representation, involves a dynamic, first-difference, regression of all the variables from the first stage, along with lags of the dependent variable, lagged differences of the exogenous variables, and the error-correction term (the lagged residual from the first stage regression). Stationarity tests on the residual from the levels equation are performed to check whether a cointegrating set is obtained.

We specify equations in Error Correction form:

$$\Delta y_t = \beta_0 + \beta_1 \Delta x_t + \beta_2 \Delta y_{t-1} + \beta_3 (y_{t-1} - \alpha_0 - \alpha_1 x_{t-1})$$

We then use the Engle-Granger 2-stage method to estimate

1. A long run equation: $y_t = \alpha_0 + \alpha_1 x_t + \varepsilon_t$
2. An error-correction term: $ECM_t = y_t - \alpha_0 - \alpha_1 x_t$
3. A dynamic equation: $\Delta y_t = \beta_0 + \beta_1 \Delta x_t + \beta_2 \Delta y_{t-1} + \beta_3 ECM_{t-1}$

Cointegration analyses focus on long-run movements between variables. Using the error correction specification, we can estimate the initial response in the year or two following a shock or deviations, as well as the adjustment to the long run relationship. The coefficient on the error correction term determines speed and type of return to trend relationships following an external shock to the system.

2.1.4 Unit root and cointegration tests

If the model contains a stochastic trend and the underlying time series for the variables in the regression are non-stationary, standard regression analysis will result in spurious results. In this case, it may be possible to run a regression using first-differences of each variable in the model, to convert the underlying time series to stationary series. However, this approach would lose important long-run relationships between variables that we are most interested in capturing. Instead, a cointegrating analysis can be performed if the series are all integrated of the same order, and if it is found that a linear combination of the series is stationary. Stationary linear combinations of time series suggest that those series share a common stochastic drift and trend together in the long run. In this case, the variables are said to be cointegrated.

[5] Granger Representation Theorem states that, if a cointegrating relationship exists, then we can represent these in an error-correction model.

To test for these properties of the underlying time series data we first perform a test for unit roots and then, if it is found that all of the underlying series do contain a unit root, we perform a cointegrating test to test whether there is a long-run cointegrating relationship between the variables.

An Augmented Dicky-Fuller (ADF) test is used to check presence of a unit root. The ADF tests the null hypothesis that the variable being tested contains a unit root (is generated from a non-stationary process).

Table 4 below shows the results from the ADF test on energy demand. If the absolute value of the reported test statistic, Z(t), is lower than the absolute value of all critical values reported, then the null hypothesis cannot be rejected, the variable being tested in the Augmented Dicky Fuller test contains a unit root and was generated by a non-stationary process. For ease of interpretation p-values are also reported in parentheses. The results of the ADF test shows that, in all cases (with the exception of energy demand and gross output in Chemicals) the p value is greater than 0.05, meaning that we fail to reject the null hypothesis (at the 5% level) - the underling series contain a unit root.

Table 3: Results from unit root test on energy demand

Sector	Energy demand	Gross output	Weighted average energy price
Iron and steel	-0.79 (0.82)	-2.47 (0.12)	-1.45 (0.55)
Non-ferrous metals	-1.63 (0.46)	-2.47 (0.12)	-2.39 (0.14)
Chemicals	-2.67(0.07)	-2.80 (0.05)	-2.02 (0.27)
Non-metallic minerals	-1.31 (0.62)	-0.16 (0.95)	-0.03 (0.95)
Food and drink	-0.37 (0.91)	-0.11 (0.94)	-1.40 (0.57)
Textiles and clothing	-0.31 (0.92)	-1.91 (0.32)	-2.11 (0.23)
Paper, Paper Products	-1.72 (0.41)	0.01 (0.96)	-1.83 (0.36)
Engineering	-1.87 (0.34)	-2.40 (0.14)	-1.95 (0.30)
Other Industry	-1.66 (0.45)	-0.93 (0.77)	-2.46 (0.12)

Note(s): The critical value for the test statistic at the 1% level is -3.63; at the 5% level is -2.95 and at the 10% level is -2.61. P-values are reported in parentheses.

After identifying the presence of unit roots in the underlying data series in the model, the next step is to test that the variables are cointegrated i.e. that they trend together in the long run. We perform a cointegrating test to test for the stationarity of the residual term in the long-run residuals in the estimated equation. The results of the test indicate that, in all cases, cointegrating relationships do exist between energy prices and energy demand.

2.1.5 Results and discussion

The econometric specification, which allows for the estimation of both a short-term dynamic equation and a long-term relationship produces interesting insights for energy use in Switzerland. Parameters capture the effect of changes in gross output and energy prices on energy demand.

We test equation specifications using a shorter time series (over 1999-2016) and a long time series (over 1970-2016). We also tested specifications both with and without a time trend as a proxy to capture technological progress and structural change[6]. We found that, in most cases, the econometric equation that was estimated using the longer time series data (over the period 1970-2016) and which included a deterministic time trend performs best, with highest explanatory power and estimated parameters that are mostly intuitive and consistent with economic theory. There are some exceptions to this finding.

2.1.6 Aggregate energy demand

Table 4 and Table 5 below present the estimated parameters (in the long run and short run) from the aggregate energy demand equation. Table 4 presents the long run relationship between energy prices (which is of most relevance for our subsequent modelling work), while Table 5 presents the immediate short-term response following a shock. In many cases, the price elasticity in the dynamic equation is not statistically significant, suggesting that, in the short term, firms do not change their level of energy use following a deviation in energy prices. In fact, in the short-term equation, we only find a statistically significant effect in the 'Paper & pulp' and 'Food, drink & tobacco' sectors, which that there is only evidence of these sectors adjusting energy use immediately following a change in energy prices. The error correction model (ECM) term in the dynamic equation indicates the speed of adjustment to long-run relationships (with a value of -1 indicating an immediate return to long-run behaviour within the year following the energy price shock). Our estimates for the ECM term suggest that long-run relationships between energy prices are typically reached within 1-5 years following a disequilibrium.

Table 4: Estimated parameters in long run energy demand equation (specification including time trend)

	Gross Output	Weighted Average Fuel Price	2009 dummy variable	Time trend	Constant/ Intercept
Iron & steel	0.20**	-0.14**	-0.19**	0.02**	4.52**
Non-ferrous metals	-0.40**	-0.37*	-0.60**	-0.03**	9.89**
Chemicals	0.45**	-0.25**	-0.15*	-0.01	6.54**
Non-metallics nes	0.70**	-0.74**	0.09	0.01**	5.76**
Food, drink & tob.	0.94	-0.26	0.20	0.05**	1.04
Tex., cloth. & footw.	-0.81**	0.03	-0.28	-0.05**	9.17**
Paper & pulp	1.27**	-0.71**	-0.15	0.03**	3.47
Other industry	-2.74**	1.10**	0.02	0.03**	10.78**

** indicates statistically significant at 5% level
* indicates statistically significant at 10% level

The parameters in the long run equation reflect the relationship between energy prices and energy use in the long run (i.e. around 5 years after any initial shock). Overall, we find larger and more significant effects in the long run equation, suggesting that most industries take time to adjust their energy-using behaviour following a change in energy prices (i.e. it takes time to change manufacturing processes and procedures or to invest in more energy-efficient equipment). The results suggest considerable heterogeneity in estimated price elasticities among industry sectors. One of the sectors that is least responsive to a change in energy prices is 'Iron & steel', where our estimates indicate a 0.14% reduction in energy demand in the long run for a 1% increase in energy prices. By contrast, in the 'Non-metallic

[6] The coefficient on the time trend is positive and significant in most sectors, suggesting that energy consumption is growing over time, due to external factors that cannot be explained by changes to growth in output or fuel prices. Exceptions to this include the 'Non-ferrous metals' sector and the 'Textiles, clothing and footware' sector, where, in both cases, there is a statistically significant and negative time trend, that could indicate exogenous energy efficiency improvements being implemented in these sectors.

minerals' and 'Paper and pulp' sectors, we find that energy demand in more elastic as firms in these sectors are more responsive to a change in energy price, with an estimated price elasticity of -0.7 implying that firms in these sectors, on average, will reduce energy demand by 0.7% for a 1% increase in relative energy prices. In 'Textiles' and 'Other industry', we find unintuitive results, with an estimated positive relationship between energy prices and energy demand. In the case of 'Textiles', our parameter estimate is insignificant and could be explained by the fact that 'Textiles' is a relatively small industry sector in Switzerland with few firms operating in it. In the case of 'Other industry', our parameter estimate is large in magnitude, statistically significant and positive. 'Other industry' is a very heterogenous sector, as a catch-all for industries that are not elsewhere classified. It is therefore highly likely that our unintuitive result for this sector is explained by factors and structural change within the sector that cannot be adequately controlled for in our estimated equation.

Table 5: Estimated parameters in short run dynamic energy demand equation

	Gross Output	Weighted Average Fuel Price	2009 dummy variable	Lagged change in total energy demand	Lagged residual (ECM term)	Constant/ Intercept
Iron & steel	0.47**	0.05	-0.14**	0.05	-0.61**	0.02**
Non-ferrous metals	-0.40	-0.10	-0.34**	0.39**	-0.36**	-0.02
Chemicals	0.43**	-0.15	-0.10**	0.54**	-1.22**	-0.03
Non-metallics nes	-0.32	-0.04	0.22**	0.16	-0.32**	0.03
Food, drink & tob.	2.47	-0.60**	0.06	-0.10	-0.24**	0.04
Tex., cloth. & footw.	0.32	0.13	-0.08	-0.24	-0.09	-0.01
Paper & pulp	0.05	-0.42**	-0.20**	0.11	-0.52**	0.02
Other industry	0.06	0.04	0.01	0.09	-0.22*	0.01

** indicates statistically significant at 5% level
* indicates statistically significant at 10% level

In Table 6, we compare our estimated price elasticities to those in other studies and find that our estimates are in a similar range to those estimated for industry sectors in other regions, but typically towards the lower-end of the range.

Table 6: Estimated energy price elasticity from our study compared to other studies

	Weighted average fuel price (Switzerland- this study)	L. Mohler (2016) - Switzerland	Polemis (2007) - Greece	Bjoerner and Jensen (2002) - Denmark
Iron and steel	-0.14	Low energy intensity firms: -1.03* Medium energy intensity firms: -0.56 High energy intensity firms: -1.03	-0.85 to -0.35	Average energy price elasticity of -0.44
Non-ferrous metals	-0.37			
Chemicals	-0.25			
Non-metallic minerals	-0.74			
Food and drink	-0.28			
Textiles and clothing	0.03			
Paper and pulp	-0.71			
Other industry	1.10			

2.1.7 Fuel shares

In addition to the aggregate energy demand equation, we have also estimated equations for the share of (i) gas and (ii) electricity in total energy demand. In these cases, our estimated elasticities reflect the effect of changes in the price of gas (or electricity) relative to the price of other fuels. They therefore capture a fuel switching effect. We find our results for the fuel share equations are often insignificant or less intuitive and are harder to explain. This is particularly the case in the gas share equations.

In the electricity share equations, we estimate price elasticities that are statistically significant when using data for Germany with a long time-series and time trend included (as shown in Table 6). However, in this case, the magnitude of the elasticity estimate is quite low- between -0.1 to -0.3. Our results for Switzerland are typically insignificant (see Table 7), even when testing alternative specifications (i.e. with/without a time trend) and using different lengths of time-series data. The low elasticities estimated in the case of Germany, and insignificant results for many industries in Switzerland, suggests that there is little evidence of fuel switching following a change in the relative price of fuels.

Table 7: Estimated electricity price elasticities in Switzerland and Germany

	Electricity price elasticity - Switzerland	**Specification**	**Electricity price elasticity - Germany**	**Specification**
Iron and steel	0.00	LS/TT	-0.08	LS/TT
Non-ferrous metals	-0.01	LS/TT	-0.22*	LS/TT
Chemicals	0.20	LS/TT	-0.14	LS/TT
Non-metallic minerals	-0.39	LS/TT	-0.29*	LS/TT
Food and drink	0.00	LS/TT	-0.23*	LS/TT
Textiles and clothing	-0.13**	LS/TT	-0.28*	LS/TT
Paper and pulp	-0.22**	LS/TT	-0.23*	LS/TT
Other industry	-0.08*	LS/TT	x	LS/TT

Note(s): SS – 'Short time series'; LS – 'long time series'; TT- 'inclusion of time trend'
* indicates statistically significant at 5% level

2.2 WP2: Investigation of future long-term developments of the Swiss industry sector

2.2.1 General overview and scope

In WP2, we conduct a forward-looking analysis (until 2050) for investigating long-term energy demand for the Swiss industrial sector, for which we improve and apply the Swiss TIMES Energy systems Model (STEM) (Kannan and Turton, 2014). STEM is a technology-rich bottom up energy systems model for Switzerland which operates under a cost-optimisation framework with a long-term perspective. For the analysis of the Swiss industrial energy technology developments, the representation of the industry sector in STEM has been improved within the scope of this project. Initially, STEM distinguishes six industrial subsectors with energy service demands (industrial energy usages) for each sub-sector.

We started with task 1 of WP2 which deals with advancements regarding the representation of the industry sector in STEM. The focus of the advancements are: model re-calibration to recent energy/statistical data, further disaggregation of industrial sub-sectors and inclusion of new/emerging technologies specific to certain industrial subsectors. A first major step in this project was the recalibration of STEM, i.e. update the model input data according to latest available statistics, as well as improvement in technology parameters.

2.2.2 STEM model recalibration

Our re-calibration and re-analysis of industry sub-sectoral is based on the annual energy data from the Swiss Federal Office of Energy (BFE, 2016a; 2016b); and supplemented by the International Energy Agency's (IEA, 2017) publication on the sub-sectoral industry related energy consumption for Switzerland. For example, we use data from the IEA (2017) on the energy consumption in 13 industrial sub-sectors by fuel type in combination with statistical data on energy end-use based on BFE (2016a). The aim of the re-calibration is to better represent the recent trends in industrial energy use pattern[7]. For the model calibration, we disaggregate annual energy balances for the different industrial subsectors to derive energy service demand at sub-sectoral level. Year 2014 was the latest data year, for which a comprehensive set of required data were available when this task of the project was conducted[8]. In the BFE (2016b) data, the industrial sector is divided into 12 different branches with a division oriented to the NOGA classification - the official general classification of economic activities of the Swiss Federal Statistical Office (BFS). Information on the total amount of different fuels consumed by the industrial sector is taken from BFE (2016b), which provides data on the type of usage of fuel and electricity for end use application such as space heating or process heat. This source also entails data on how the final energy for each service demand is allocated to the industrial sub-sectors.

Accounting of cogeneration (or combined heat and power generation (CHP)) technologies is treated differently in the energy balances of IEA and BFE. We consider in our calibration and sectoral disaggregation, that for cogeneration, only the 'on-site' energy commodities used for generation of heat and electricity consumed are accounted as industrial energy usage as in BFE (2015a). Electricity generated by thermal applications in different industry sectors as well as the corresponding fuels consumed by cogeneration applications is derived from BFE (2015a). This source also provides data on the types of cogeneration units, an indication of their location (canton) and their capacities. We use this information to allocate the heat from cogeneration to the subsectoral level according to main industrial activities identified for the respective cantons. For further detailed cogeneration data we

[7] The re-calibration is not limited to the industrial sector, but other end use sectors and supply sectors have also been updated.
[8] Swiss energy consumption is available for 2017. However, some data are not yet available at sub-sectoral level or their application by end use.

consider insights from Rossi (2013) who analyzed CHP application in the Swiss industry and disaggregated process heat demand to different temperature levels.

In 2014, the industrial sector accounted for 19% (157 PJ) of the total final energy consumption in Switzerland. Natural gas (42%) and electricity (24%) together represent two thirds of the total fuel consumption in industry (Figure 3). Almost half of the total fuel consumption is used for the generation of process heat, as shown in Figure 3.

Compared to initial version of the STEM model (Kannan and Turton, 2014), now we reorganize the representation of industrial sub-sectors differently. For example, in the initial version of STEM, food, textile and pulp and paper sectors were lumped together as IFTP sector. Now food and pulp and paper are modelled as separate subsectors, while the textile subsector is merged with the other sub-sectoral category. Figure 4 shows the energy consumption based on our new industrial sectoral clustering, i.e. seven disaggregated industrial subsectors.

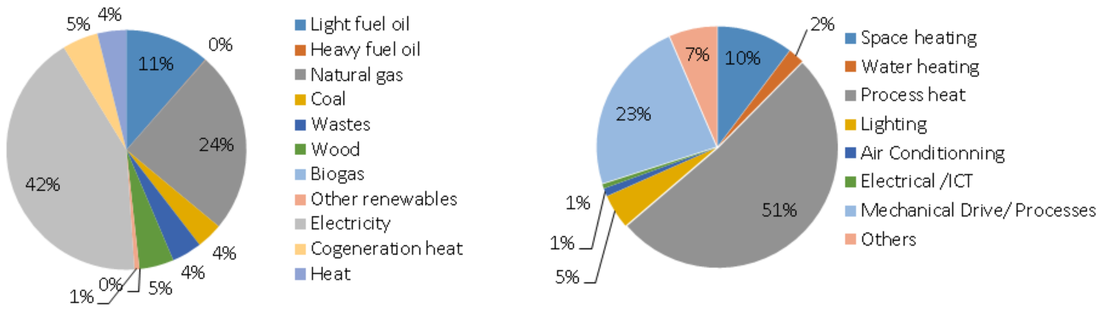


Figure 3: Final Energy consumption industry in 2014 by fuel (left) and by type of energy service demand (right)

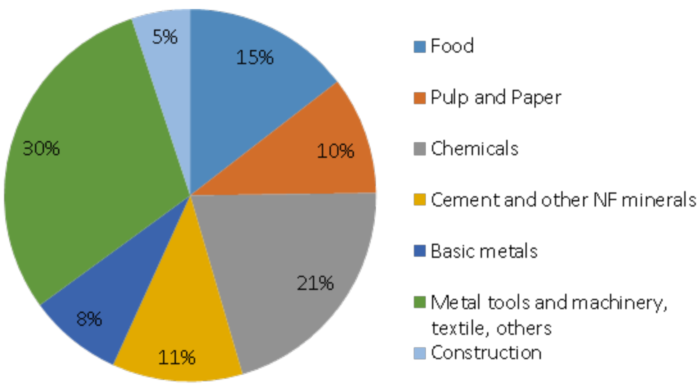
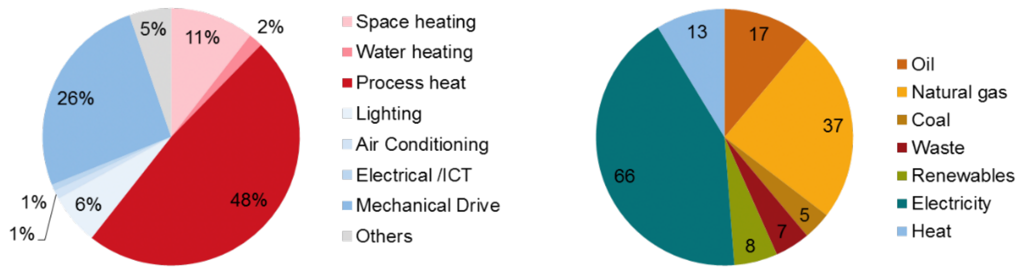


Figure 4: Final Energy consumption industry in 2014 by branches

Besides the aggregate of machinery, textile and other industries, which represents 30% of the total final consumption of the industry sector, chemical (21%) and food production (15%) are the second and third largest industry subsectors with respect to their share in final energy consumption. Each, the pulp and paper and cement & other nonferrous minerals subsectors has a share of about one-tenth of the industry sector's final energy consumption. The disaggregation of the industry sector in STEM depends on multiple factors, including available statistical indicators and figures as well as prospective data on demand developments, technology data, etc., which all will be taken into consideration for determining model further developments as envisaged in work package 2. In the following section, we describe the development of the industrial subsector in STEM within the framework of this project in 2018.



Note: ICT: Information and communication technologies

Figure 5: Energy consumption in industry in 2014 (by energy service demand (left) and by fuel in PJ (right)

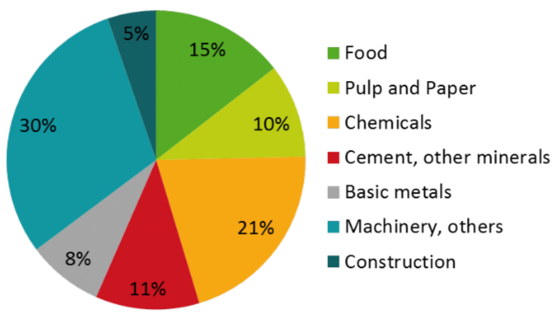


Figure 6: Share of industrial branches in end energy usage in 2014

2.2.3 Modelling the industrial subsectors

The branches of relevance are characterized in terms of their structure and relevant production properties. We refine the iteratively derived split of fuel consumption into different Energy Service Demands (ESDs) that we include in STEM for each branch. Furthermore, energy-related characteristics are incorporated in the model, e.g. temperature levels of process heat demand. We include new and emerging technologies that hold potential for being used in the respective branches. Other energy saving options such as the improvement of existing technologies and process-related measures are identified. For refining the industrial sector, we divide the industrial final energy demand into seven branches, as described in section 2.2.2. Starting from the year 2010, STEM models 5-year periods for the near-term and 10-year periods in the long-term. As such, the year 2015 is a milestone year in STEM. We use the detailed 2014 data for the industry sector to approximate the calibration for the year 2015.

2.2.3.1 Food industry

The food industry was the second largest consumer of the Swiss industrial energy in 2014 (Figure 4). Figure 7 shows the energy consumption in food industries (IEA, 2017). Process heat accounted for most final energy demand, followed by mechanical drives (Figure 9). Natural gas is the main energy carrier for process heat production, while the other energy demands were mainly satisfied using electricity. Overall, over 40% of the ESDs were satisfied by using electricity, while the usage of natural gas provided another 40% of the energy demand. Based on Hofer (1994), approximately 3% of the electricity in the food industry is used for process heat, for example in baking. Cooling in the food industry accounts for 28% of the electricity demand (Eichhammer et al., 2009), while another 30% is used for mechanical drives. The rest is split between process technology, pumps, ventilation and air compression. Based on this assumption, we estimated the ESDs in the food industry.

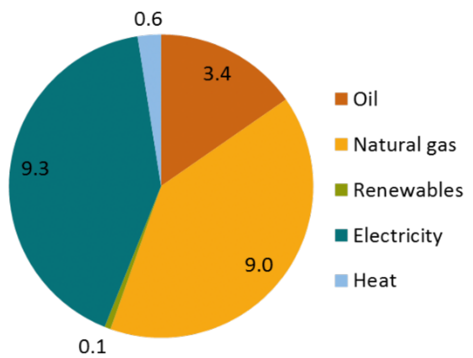


Figure 7: Final energy consumption of the food industry (PJ) (International Energy Agency, 2014), own calibration

Table 8 summarizes the key processes in the food industry and their temperature levels. We constrain our model in such a way that a realistic representation of the process heat demand is ensured, even though processes are not modeled explicitly. For example, the process heat demand over 140°C is mainly used for baking and therefore, must be provided with appropriate oven systems.

Table 8: Temperature levels of main processes in food industry

Process	Temperature (ºC)
Drying	30 – 90
Washing	40 – 80
Pasteurizing	80 – 110
Boiling	95 – 105
Sterilizing	140 – 150
Heat treatment	40 – 60
Baking	150 – 300

In terms of end use application, a quarter of the heat demand in the food industry can be attributed to space heating (SH) and hot water (WH), while another 40% of the heat demand is process heat (PH) lower than 100°C (Figure 8). The remaining 35% of the heat demand accounts for process heat between 100 °C and 300 °C, of which only a small share occurs over 140 °C.

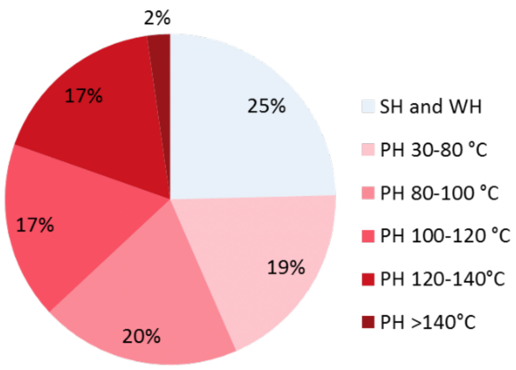


Figure 8: Temperature level of heat demands in the food industry (Rossi (2013); Rudolph and Wagner (2008)

Electric motors, compressors and refrigeration systems have potential to recover heat at temperatures between 30°C to 70°C. We consider a range of low temperature heat recovery technologies such as, heat pumps and organic Rankine cycles. Furthermore, the installation of absorption and adsorption chillers and the usage of solar energy for the generation of low temperature heat is enabled. A detailed description of technologies included in the analysis is provided in Section 2.2.4. Apart from the installation of waste heat recovery technologies and solar thermal systems, a promising measure is the usage of food processing residues as an energy resource. Based on the Federal Office of the Environment (2017a), food residuals in Switzerland accounted for 20% of the overall production, which is equivalent to 500,000 t/year. We derive a theoretically potential for waste energy based on methane yield.

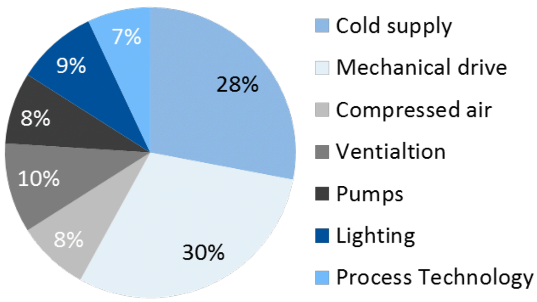


Figure 9: Share of technologies in electricity demand (Eichhammer et al., 2009)

2.2.3.2 Chemical industry

Based on final energy consumption, the chemical branch was one of the largest (21%) consumer in the industry sectors in 2014 (Figure 4). Due to the large variety of products output from chemical industries, identifying the main production processes like in the food branch is rather challenging. Furthermore, due to confidentiality, the production characteristics of the chemical branch are usually not publicly available. Over 60% of the final energy is used for process heat, and almost a quarter for mechanical drive (Figure 10). Most heat demand is provided by natural gas and heat from CHP (Figure 10). Overall, the consumed fuels are mainly natural gas, electricity and heat from CHP units.

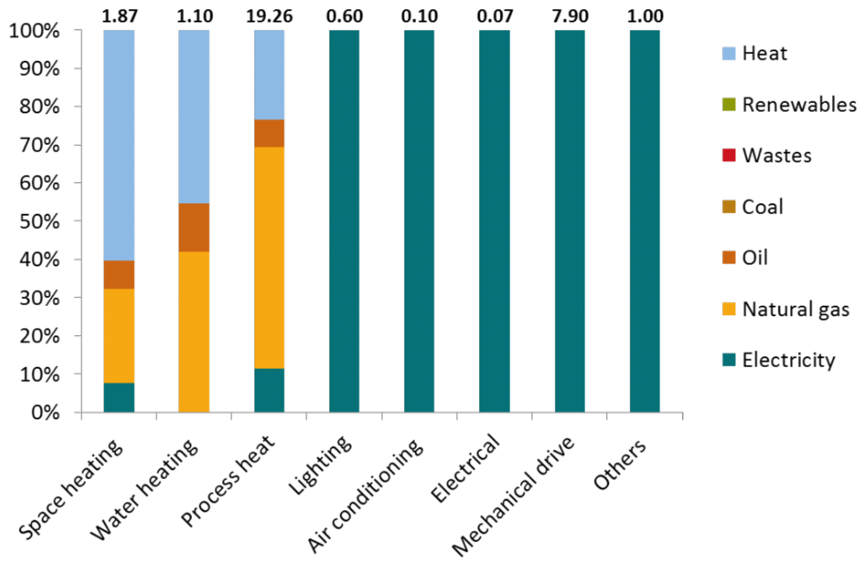


Figure 10: Final energy consumption of the chemical industry split into ESDs in 2014 (PJ) (Swiss Federal Office of Energy, 2016a,b; International Energy Agency, 2017)

We derive the temperature level of the heat demands based on Rossi (2013) and Arpagaus (2017). Due to the variety of different products, the process heat temperature is broader than in the food industry (Figure 11). Almost three quarters of the heat demand occur at temperatures over 240°C. For waste heat recovery, we assume that the maximum recoverable waste heat using heat recovery technologies is 15% of the final energy. Over 90% of this waste heat occurs at temperatures below 100°C. The description of the waste heat recovery technologies are given in Section 2.2.4.

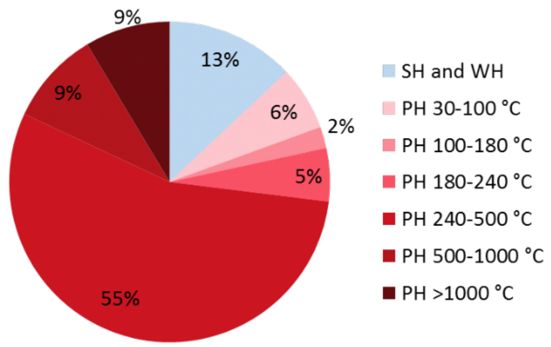


Figure 11: Temperature level of heat demand in the chemical industry (Rossi, 2013; Arpagaus, 2017)

2.2.3.3 Non-metal minerals industry

This demand sector includes cement production and other non-ferrous minerals industries. Their demand accounted for 11% of the industrial energy consumption (Figure 4). Though it has a small share of the total industrial energy, it is one of the energy intensive branches, with over 90% of the heat demand occurring at temperatures over 500°C. Thus, we investigated some of the key cement production process to assess the heat recovery and alternative technologies, which are elaborated in Granacher (2018).

In Switzerland, there are six cement plants in which 94% of the clinker is produced in rotary dry kilns, the remaining 6% are produced in semi-wet kilns. The semi-dry kilns used in Switzerland are converted wet kilns which have approximately double the production output rate and consume 15 to 20% less fuel than wet kilns (Kogel et al., 2006).

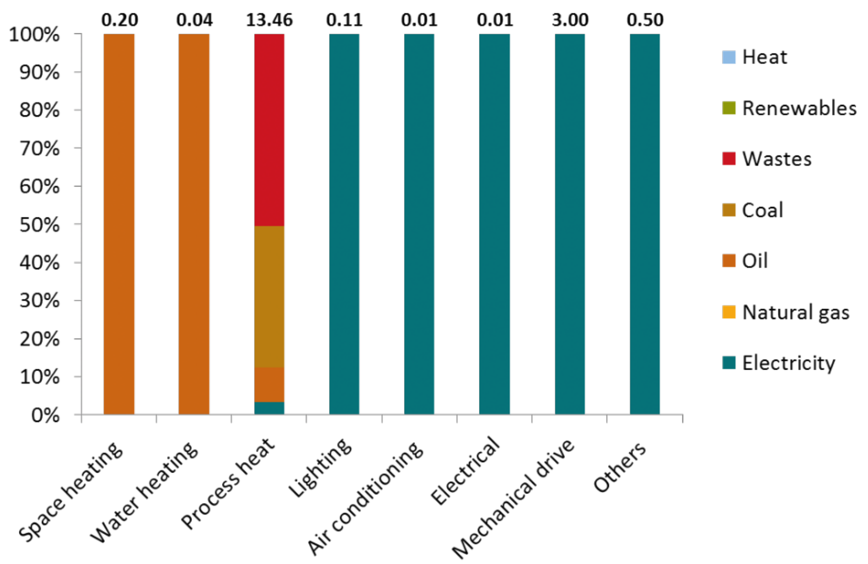


Figure 12: Final energy consumption of the non-metal minerals industry split into ESDs in 2014 (PJ) (Swiss Federal Office of Energy, 2016a,b; International Energy Agency, 2017)

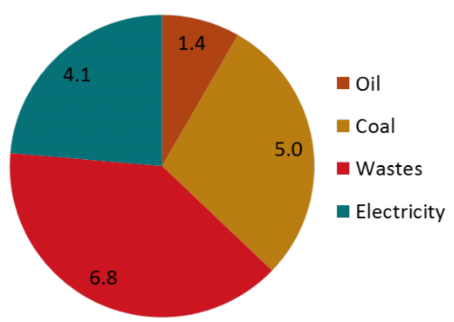


Figure 13: Final energy consumption of the non-metal minerals industry in 2014 (PJ) (International Energy Agency, 2014; VSZ, 2017)

The major share of the process heat demand, which adds up to 84% of the total energy demand, accounts for the production of cement, particularly clinker (Figure 12). The major part of the electricity demand is attributable to cement grinding, while a small share is used in other processes. For the estimation of ESDs, we use the data from BFE and the association of Swiss cement industries (VSZ, 2017) and estimate that 40% of the final energy consumption is industrial waste, 30% coal and 25% electricity (Figure 13).

In terms of energy efficiency, for a ton of clinker produced in Switzerland, 3.6 GJ of energy is used in 2015 (VSZ, 2017) while general (non-Swiss specific) literature data varies between 3.0 and 6.5 GJ (Blesl and Kessler, 2013). We consider the installation of new, more efficient clinker kilns as one measure for saving energy in addition to new milling process. Figure 14 summarizes the energy saving potential for Switzerland against its estimated costs based on Jibran et al. (2016). Besides the production of blended cement, cement plant upgrading with pre-heaters and pre-calciners provide a significant energy saving potential.

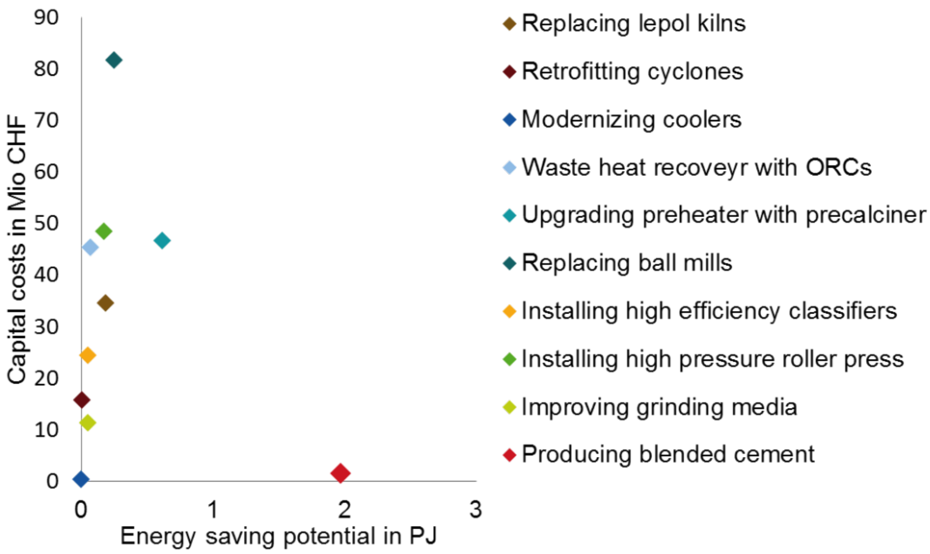


Figure 14: Measures considered for cement industry (Jibran et al., 2016)

2.2.4 New and advanced industrial energy technologies in STEM

This section gives an overview of heating and cooling technologies implemented in STEM. The main focus is on heat supply technologies for the food and the chemical branches.

2.2.4.1 Boilers, kilns and CHP

We consider a variety of boilers for the generation of process heat, space heat and hot water to be used in the industrial branches. Different fuel options such as natural gas, fuel oil, biogas, pellets, electricity, and industrial wastes are included. For the food industry, different ovens for baking are taken into account. Mostly tunnel and chamber ovens which run on electricity or fossil fuels are used today. In the cement industry, we consider new kilns for clinker production. CHP units generate heat and power simultaneously. Within the model, CHP units using natural gas, fuel oil, pellets, biogas and industrial waste are included.

Table 9: Thermal applications in the food, chemical and cement industry

Technology	Fuel	Branches
Boiler	Natural gas	Food, chemical
	Fuel oil	Food, chemical
	Pellets	Food, chemical
	Electricity	Food, chemical
	Industrial waste	Food, chemical
	Biogas	Food
Oven, Kiln	Electricity	Food
	Natural Gas*	Food, cement
	Fuel oil	Cement
	Coal	Cement
	Industrial waste	Cement
CHP unit	Industrial waste	Food chemical
	Pellets	Food, chemical
	Natural gas	Food, chemical
	Fuel oil	Food, chemical
	Biogas	Food
* Different kilns/ovens are considered for cement and food industry		

2.2.4.2 Heat pumps

Heat pumps are a promising technology when it comes to future industrial application. Their ability to transform low temperature heat to a higher temperature level is especially useful for waste heat recovery. For the future, thermo-acoustic heat pump represents one promising concept. The temperature level can be adjusted flexibly, and a high COP (Coefficient of performance) is yielded, compared to conventional heat pump technologies. However, the technology is still in a prototype-status. The first planned demo systems imply capacities of 700 kW and a maximum temperature level of 150°C (Wolf et al., 2017). We assume that the first commercially available systems will enter the market in between 2025 and 2030.

2.2.4.3 Solar thermal application

The usage of solar thermal energy in industrial production processes is limited to few applications today. Most of the solar systems currently in use in industry are deployed for drying processes in the food industry. Technologies for providing heat at up to 290°C are being developed (Weiss, 2005).

Different solar thermal collector types are available on the market. Within this work, flat plate collectors and evacuated tube collectors are considered for low temperature applications like space heating, hot water and suited shares of the process heat demand. For the application of solar devices, thermal storage units are crucial in order to make the heat accessible when it is needed. Therefore, thermal storage units are included in the model on a day-night level. In the food branch, the application of solar thermal components holds high potential, since over 60% of the heat demand occurs at temperatures below 100°C. The food industry implicates a lot of cleaning and washing processes, which occur at temperatures below 100°C and offer great potential for the usage of vacuum tube and flat plate collectors.

The alignment of industrial demands to seasonal and daily variations of solar radiation is only feasible to a restricted degree. Therefore, the installation of thermal storage units and the combination of solar systems with compensating technologies that can be used in winter is favorable when looking at solar heating systems in industry.

2.2.4.4 Organic Rankine cycle

An essential element of the detailed analysis is energy saving and waste heat recovery. Waste heat is considered all forms of heat escaping a system after provide its primary purpose. For example, sources of waste heat are furnaces, drying processes, refrigeration systems. The reduction of waste heat can generally be addressed by different approaches:

- Minimization of waste heat generation through efficiency measures such as insulation or process optimization
- Re-usage of waste heats within processes, for example in preheaters or drying processes
- Transformation of waste heat into other usable energy, for example temperature update or generation of electricity through heat pumps
- Transfer of waste heat to other consumers.

Currently, conversion of waste heat into usable forms of energy is considered and we explored the following three options:

- Transformation of heat into electricity using an organic Rankine cycle (ORC)
- Shifting of heat to higher temperature levels using heat pumps
- Direct utilization of heat.

Based on Bühler et al. (2014)technical waste heat recovery potential is about 30% of the theoretical waste heat. The reusable waste heat in the food and the chemical branch is assumed based on Hita et al. (2011) in combination with temperature levels of Bühler et al. (2017).

Organic Rankine cycles (ORC) are a promising technology for recovering waste heat. The process is based on a conventional turbine process, while an organic working fluid is used instead of water. Due to the low boiling point of the organic working fluid, low temperature heat can be transferred to electricity. Commercially available organic Rankine applications have an electric efficiency of 10-15% depending on the temperature of waste heat (Blesl and Kessler, 2013). Promising potential for ORC devices can be found in the cement industry, since waste heat occurs at high temperature levels. In the food industry, most waste heat occurs below 100°C, which limits the diffusion potential of organic Rankine cycles. The application of the technology in the chemical industry is estimated to be promising due to the higher temperature level of waste heat.

2.2.4.5 Process cooling

Most cooling applications currently used in the industry are compression chillers. They operate in the same principle as heat pumps, while using the heat sink for cooling applications. Temperatures from 30°C to −100°C can be reached (Blesl and Kessler, 2013). Absorption chillers are the most common thermal chiller systems currently used. As in absorption heat pumps, the compression process is realized thermally by using waste heat. In adsorption chillers, temperatures of −10°C can be reached (Blesl and Kessler, 2013). Compared to compression chillers, absorption chillers offer the following advantages:

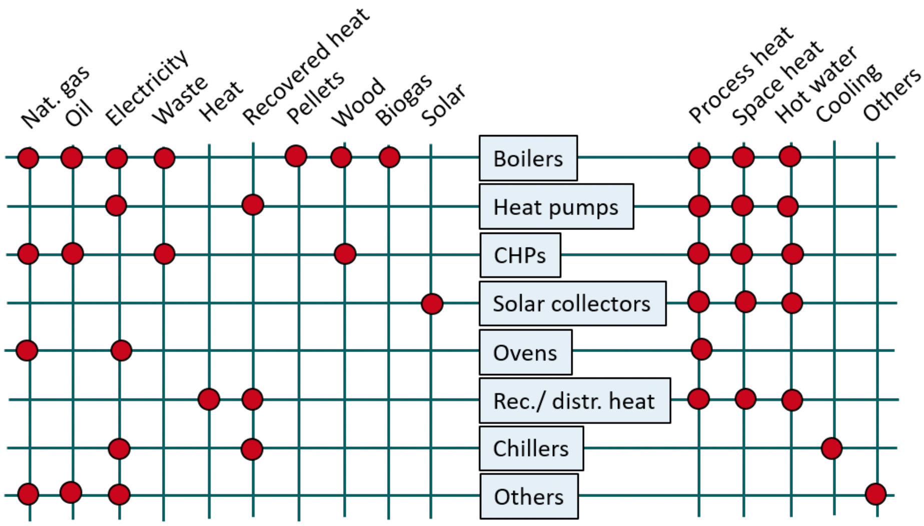
- Recovery of waste heat
- No rotating/ moving components
- Low maintenance
- High life time
- High performance in part load behavior

Table 10: Cooling technology for industrial applications

Technology	Branches
Compression chiller Absorption chillers Adsorption chillers	Food

2.2.4.6 Summary of the modelling approach of industrial sector

For the food, the cement and the chemical industry, we incorporated a range of new technologies. Furthermore, the properties of the individual industrial branches including process heat temperature levels and waste heat potential as described are included. For the food industry, we incorporate constraints that ensure the representation of the sub-sectors' characteristics with regards to their production processes and necessary temperature levels and technologies. For example, the process heat demand of the baking industry needs to be provided by ovens. Since the disaggregation of production processes in the chemical sector is very complex, no product-specific characteristics are considered. For the cement industry, we include a specific set of energy-saving measures. For the food and the chemical industry, the resulting energy system for providing the demands is presented in Figure 15.



Note: Rec: recovered, distr: district, Chillers are only modeled explicitly for food industry

Figure 15: Energy system for chemical and food industry

For both industrial branches, process heat can be provided by a set of different boilers, kilns, heat pumps and CHP units. Furthermore, recovered heat or district heat can be used for providing process heat, but only in line with feasible temperature levels of the demand. Heat recovery is directly linked to the activity of heat generating devices that produce waste heat. Using solar thermal for process heat demand, warm water and space heating is enabled. Solar radiation is modeled on an hourly resolution, so that hourly and seasonal variations in availability are considered. Cooling demand in the food branch is provided by either compression, adsorption or absorption chillers. In the chemical industry, the cooling demand is not modeled explicitly and is therefore included in the ESDs for mechanical drive and air conditioning. For the branches that are not elaborated further in this study, a generic set of demand-providing technologies is included for all ESDs.

2.2.5 Scenario definition

For the SWIDEM project, future dynamics of energy and emissions' developments in Swiss industry are investigated based on two scenarios, *E-POL* and *CLI*. The former is based on the objectives of the Swiss Energy Strategy and the latter is based on the objectives of the Swiss Climate Strategy. These scenarios are in line with other scenario modelling activities, i.e. those of SCCER JA Scenarios & Modelling.

Table 11: Underlying drivers of the scenarios

Theme	Scenarios	
	E-POL	**CLI**
Decarbonisation (& energy policy)	SES-2050 implemented and extrapolated	Climate target compatible with the Paris Agreements, implementation of the long-term emissions reductions goal according to FOEN (2018b)
Tech Innovation	Tech/Market/Cons behaviour according to current knowledge/plans	Tech/Market/Cons behaviour according to current knowledge/plans
Renewables	Current knowledge	Current knowledge
Regional integration		Participation in ETS
Infrastructure	Net Transfer Capacities according to TYNDP, CCUS excluded	Net Transfer Capacities according to TYNDP; CCUS excluded
Demand side and DSM	Current knowledge of tech development in the demand side	Current knowledge of tech development in the demand side

2.2.5.1 Definition of the E-POL scenario

The E-POL scenario implements the New Energy Act, which is in force from 2018 (the revised law on federal direct tax enters into force the 1.1.2020)[9]. It includes current policies initiatives and measures adopted in the Swiss Energy Strategy 2050. It is not a strict decarbonisation scenario, in the sense that no specific GHG emission reduction targets are set. Among the objectives of the E-POL scenarios is to evaluate the level of the GHG emissions abatement achieved with strong efficiency measures that on a trajectory of achieving a 2000-Watt society by 2050 (referring to primary energy, EnergieSchweiz, 2019). Table 12, presents the key assumptions of the scenario, organised by the main topic.

Other assumptions in this scenario include:

- Social discount rate: 2.5%[10]
- Fuel prices as in Figure 16. The cross-border electricity trade cost are derived from a European electricity system model (EUSTEM) compatible with the temporal resolution as applied in STEM. The right panel in Figure 16 illustrates the average annual prices for 2016 and 2030 and 2050 as an indication for future trends.
- Swiss Emissions trading scheme is harmonised with the EU-ETS in the way that we assume the same emissions reductions rate for Switzerland as envisaged for the entire EU-ETS.

[9] See http://www.bfe.admin.ch/energiestrategie2050/index.html?lang=en&dossier_id=07008
[10] We assume a social discount rate across the entire energy system of 2.5% based on Prognos, 2012

According to the EU-ETS directive, the emissions cap of the EU-ETS is reduced by 2.2 % per year between 2021 and 2030 (EC, 2018). We assume the emissions in Switzerland attributable to installations under the EU-ETS to decline at least at the same rate as the overall target. For the period beyond 2030 a continuation of the contraction of total allowed emissions at 2.2% p.a. is assumed towards 2050 (in line with the scenario "new energy policy" of SES).

- Climate change impacts (regarding hydroelectricity production, heating and cooling degree days) are based on a +3°C trajectory
- Net Transfer Capacities develop according to ENTSOE-TYNDP 2018 (see Figure 17) and cross-border electricity prices from an EU TRENDS-compatible scenario[11]

Table 12: Main assumptions in the E-POL scenario

Strategic objective	Implementation in E-POL
Nuclear power	No new nuclear power In this study, we assume 60 years lifetime for the existing nuclear power plants (except for Muehleberg that went out of business in Dec. 2019)
Renewable energy	2020: 4.4 TWh of renewable energy excluding hydropower 2035: 11.4 TWh of renewable energy excluding hydropower 2050: 24.2 TWh of renewable energy excluding hydropower Hydropower: 37.4 TWh in 2035, 38.6 TWh in 2050 After 2024 no new commitments in the feed-in premium scheme After 2031 no one-time remuneration Network surcharge increases to 2.3 Rp/kWh (to support feed-in tariffs, capacity remuneration and refunding schemes)
Efficiency	Average reduction in per capita final energy consumption (excl. intern. aviation): - 16% in 2020 from 2000 - 43% in 2035 from 2000 - 54% in 2050 from 2000 (at least, according to scenario "new energy policy") Building programme promoting efficiency & RES increases by 450 MCHF/yr. until 2030 (1/3 from the CO2-tax revenues) - new buildings only renewable heat supply, partial self-supply of electricity, no electric boilers Industrial technology funds promoting efficiency of 25 MCHF/yr until 2030 (financed from the CO2-tax revenues) - reduction in energy consumption for process heat at least 30% in 2050 from 2000 levels - reduction in energy consumption for drives and processes at least 20% in 2050 from 2000 levels CO2 tax for heating fuels can increase to 120 CHF/t-CO2 after 2020 Average per capita electricity consumption: - declines by 3% in 2020 from 2000 - declines by 13% in 2035 from 2000 - declines by 18% in 2050 from 2000 (at least, according to scenario "new energy policy") Emission standards in mobility: - Reduction to 95 g-CO2/km by the end of 2024 for new passenger cars fleets - Reduction to 147 g-CO2/km by the end of 2024 for light-duty vehicles - After 2025, harmonisation with the EU standards: emissions standards for both cars and light duty vehicles, -30% in 2030 from 2021 - In 2050, targets are set to 25 g-CO2/km for cars and 60 g-CO2/km for light-duty vehicles (as in EUCO scenarios) Efficiency standards in trucks: harmonisation with the European policy, 1.5% increase per year (as in EUCO scenarios)
Electricity grid	Implementation of the Swissgrid 2025 network

[11] See https://ec.europa.eu/energy/en/data-analysis/energy-modelling

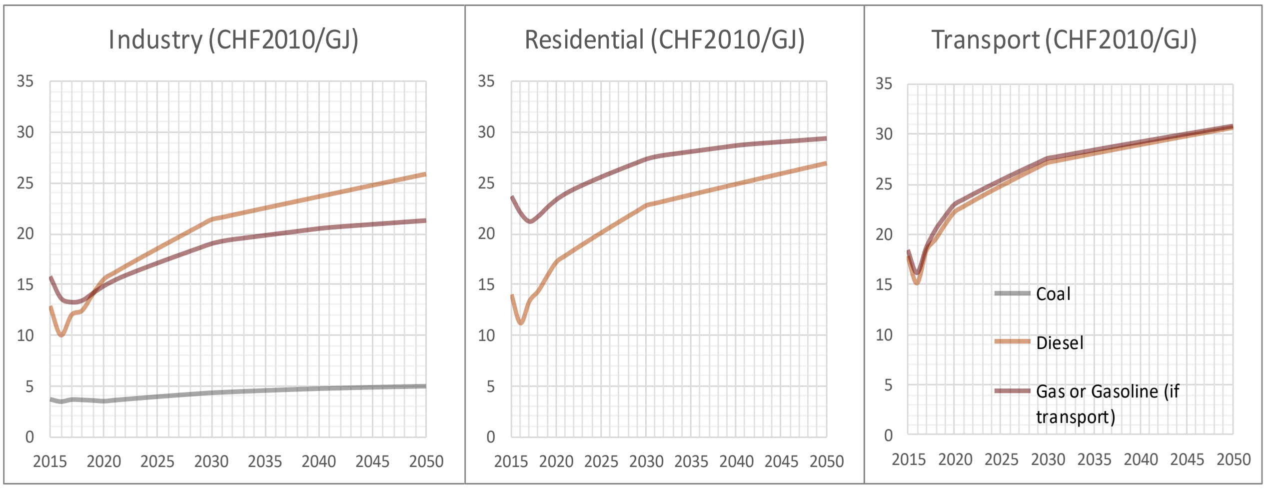


Figure 16: Assumptions on Swiss consumer prices (excluding taxes, including distribution costs)[12]

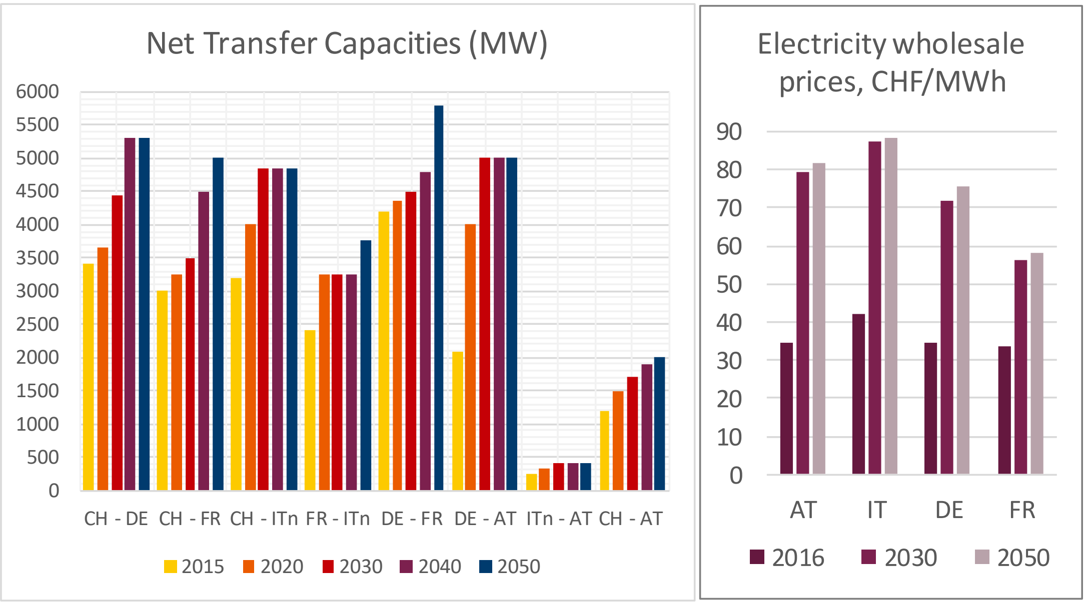


Figure 17: Average annual Net Transfer Capacities and indicative assumed electricity prices in the neighbouring countries

2.2.5.2 Definition of the CLI Scenario

The CLI scenario is driven by a political commitment of meeting the aspirations of the Paris Agreements to keep temperature increase below 1.5°C by the end of the century. While the E-POL scenario is driven by high energy savings, this scenario is mainly driven by carbon prices (equal for ETS and non-ETS sectors). In the CLI scenario, we determine a CO_2 emissions trajectory in the energy systems model rather than pre-defining a price for a tonne of CO_2. As such, the value per unit of CO_2 is an endogenous

[12] Based on *IEA Energy Technology Perspectives 2017 – Reference Technology Scenario* https://www.iea.org/etp/
These fuel price pathways do not include costs attributable to achieve the climate targets or other policy objectives. These costs are calculated by STEM endogenously.

value of the systems model reflecting the marginal value of the energy system to achieve the imposed emissions target. Carbon values do not represent a cost to economic actors outside ETS (where they coincide with the ETS price) but are economic drivers that change decision making of the modelled agents and influence technology uptake and demand behaviour. In this sense, efficiency remains a key ingredient in the decarbonization pathway, but the efficiency targets of the E-POL scenario are not strictly implemented in the CLI and serve as indicative targets upon which the efficiency gains of CLI are benchmarked. The emissions trajectory assumed in the CLI scenario is on track to achieve carbon neutrality by 2060.

Table 13: Main assumptions in the CLI scenario

Strategic objective	Implementation in CLI
Nuclear power	No new nuclear power In this study, we assume 60 years lifetime for the existing nuclear power plants (except for Muehleberg that went out of business in Dec. 2019)
Renewable energy	2020: at least 4.4 TWh of renewable energy excluding hydropower 2035: at least 11.4 TWh of renewable energy excluding hydropower 2050: at least 24.2 TWh of renewable energy excluding hydropower Hydropower: 37.4 TWh in 2035, 38.6 TWh in 2050 After 2024 no new commitments in the feed-in premium scheme After 2031 no one-time remuneration Network surcharge increases to 2.3 Rp/kWh (to support feed-in tariffs, capacity remuneration and refunding schemes)
GHG emission reduction targets	-20% in 2020 from 1990 levels (all domestic) -50% in 2030 from 1990 levels (at least 30% domestic, max 20% abroad) - 85% in 2050 from 1990 levels (domestic and abroad) - Carbon neutrality by 2055/60 For direct energy- related CO2 emissions (excluding international aviation) the assumed targets are (see also Figure 19): 2020: 31.7 Mt-CO2/yr 2030: 27.7 Mt CO2/yr (reflecting that 8.5 Mt CO2/yr are mitigated outside Switzerland) 2050: 2.4 Mt CO2/yr
Efficiency and emission standards	Building programme promoting efficiency & RES increases by 450 MCHF/yr. until 2025 (1/3 from CO2-tax revenues) - new buildings only renewable heat supply and be autonomous, partial self-supply of electricity, no electric boilers Emissions standards for buildings (direct emissions): - Residential and services buildings 6kg CO2/m2 from 2029 - Commercial buildings 4 kg CO2/m2 - New buildings 0 kg CO2/m2 Municipal solid waste incineration plants extrapolate the current commitment to reduce net emissions by 1 Mt over the period 2010 – 2020. Industrial technology funds promoting efficiency of 25 MCHF/yr. until 2025 (financed from the CO2-tax revenues): at least 20% of the refunded amount to be used for energy efficiency measures Emission standards in mobility: - Reduction to 95 g-CO2/km by the end of 2024 for passenger cars - Reduction to 147 g-CO2/km by the end of 2024 for light-duty vehicles - After 2025, harmonisation with the EU standards: emissions standards for both cars and light duty vehicles, -30% in 2030 from 2021 - In 2050, are set to 25g-CO2/km for cars and 60g-CO2/km for light-duty vehicles (as in EUCO scenarios) Efficiency standards in trucks: harmonisation with the European policy, 1.5% increase per year (as in EUCO scenarios) Partial compensation of CO2 emissions from motor fuel use in the framework of the revised CO2 law
Electricity grid	Implementation of the Swissgrid 2025 network

Other assumptions in this scenario include:

- Social discount rate: 2.5%
- Fuel prices as in Figure 18
- Climate change impacts (regarding hydroelectricity, heating and cooling degree days) are based on a +1.75°C trajectory

- Net Transfer Capacities as in the E-POL scenario, but higher cross border electricity prices (see for example Figure 20). The electricity prices reflect the price development under EU climate policy and include corresponding emissions mitigation action and its feedback on the electricity prices.
- Participation of Switzerland in the EU-ETS. The linear factor is at least 2.2% p.a. from 2020 to 2030 and at least 2.6% p.a. beyond 2030[13]. Aviation (in our case domestic) is included in CORSIA[14] from 2020 onwards and eventually into EU-ETS. If new gas power plants are built, then they have to participate in the EU-ETS.

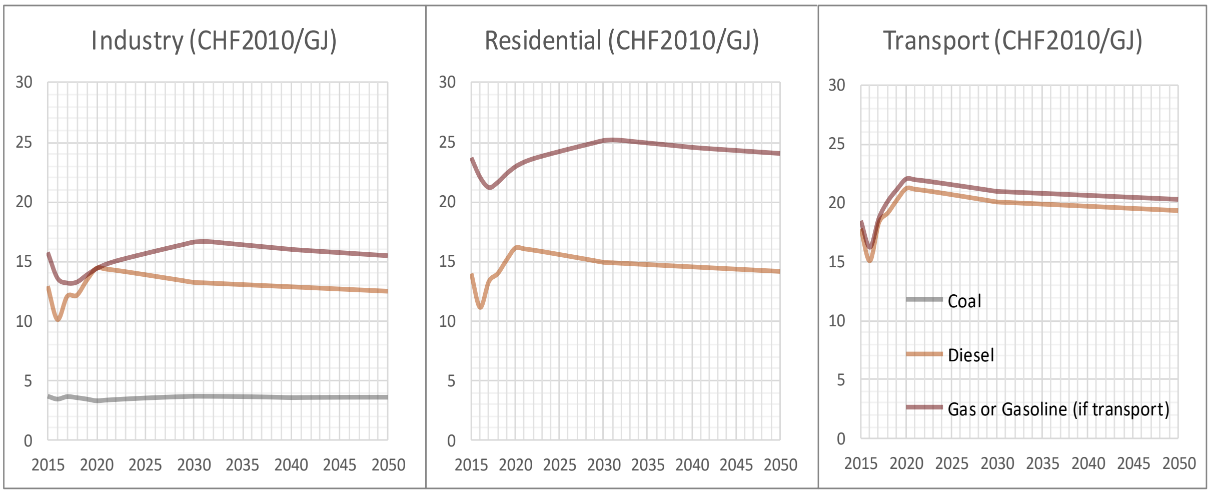


Figure 18: Assumptions regarding Swiss consumer prices (excluding taxes, including distribution costs)[15]

[13] See *Panos and Kannan, 2018. Challenges and opportunities for the Swiss energy system in meeting stringent climate change mitigation targets. In: Limiting Global Warming to Well Below 2°C, Springer*

[14] https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

[15] Based on *IEA Energy Technology Perspectives 2017 – Reference Technology Scenario.* These fuel price pathways do not include costs attributable to achieve the climate targets or other policy objectives. Such costs are calculated by STEM endogenously.

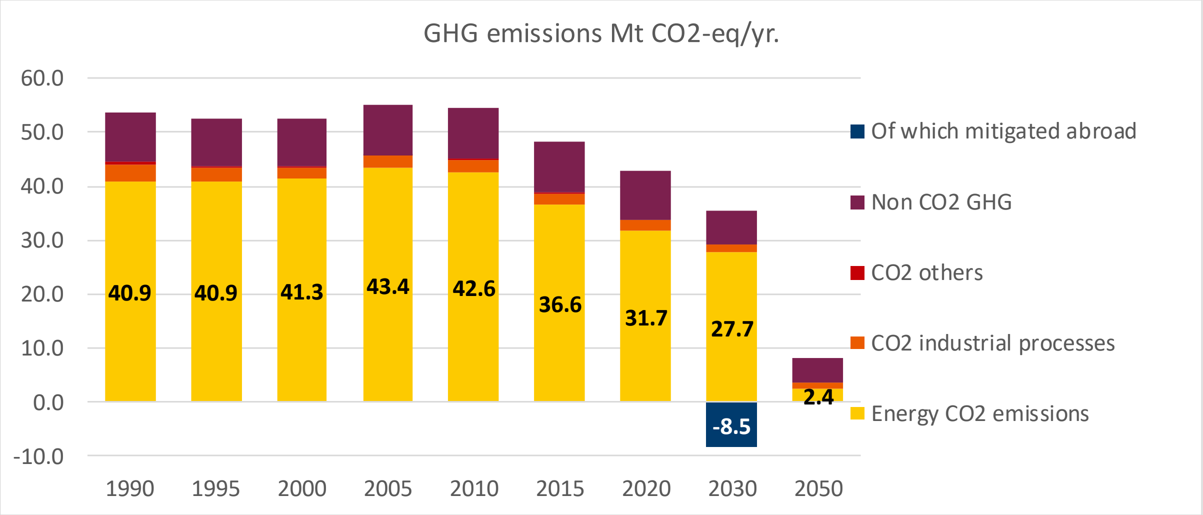


Figure 19: GHG trajectory assumed in the CLI scenario, including GHG emissions mitigated abroad[16]

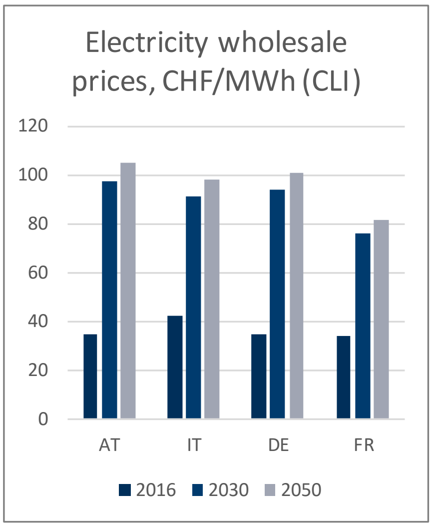


Figure 20: Indicative wholesale electricity prices in CLI scenario[17]

[16] For the year 2030, 8.5MtCO_2e are assumed to be mitigated abroad, which allows domestic GHG emissions of 35.4 MtCO_2e. To derive at the -50% emissions target in 2030, which corresponds to 26.9 MtCO_2e, one needs to substract 8.5MtCO_2e from 35.4 MtCO_2e.

[17] Based on *Panos & Densing, 2018. The future developments of the electricity prices in view of the implementation of the Paris Agreements: will the current trends prevail, or a reversal is ahead?, IEW, 2018* and on https://ec.europa.eu/energy/en/data-analysis/energy-modelling

2.2.6 Mapping the macro-economic model and the energy system model

2.2.6.1 **About E3ME**

The structure of E3ME includes a dynamic input-output table for Switzerland and a series of behavioural equations that are estimated using historical economic data. The input-output structure is used to estimate indirect supply-chain effects (which, in this case, includes the effects of changes in energy prices and investment in the energy system). The model also includes a series of econometric equations, to estimate the net economy-wide effects of investment and associated energy market impacts on key macroeconomic indicators (including GDP and its components, employment, prices, real incomes and trade flows).

E3ME includes explicit representation of 61 global regions (including explicit representation of the Swiss economy), with a historical database covering the period since 1970 annually. Energy balances are sourced from the IEA. To ensure that the analysis is carried out on a consistent basis, E3ME was calibrated to the same baseline forecast as STEM.

Figure 4 shows the key economic flows and feedbacks that are represented in E3ME's modelling framework. Of particular relevance for this study, the diagram shows how E3ME iteratively estimates the effect of:

- an output-investment loop (where increases in investment drive increases in GDP, which boosts business confidence, leading to further increases in investment)
- an income-expenditure loop (as increases in employment lead to increases in real income and consumption, thereby leading to further increases in output and employment).

At the same time, E3ME captures the dynamic effects of trade between Switzerland and external trading partners.

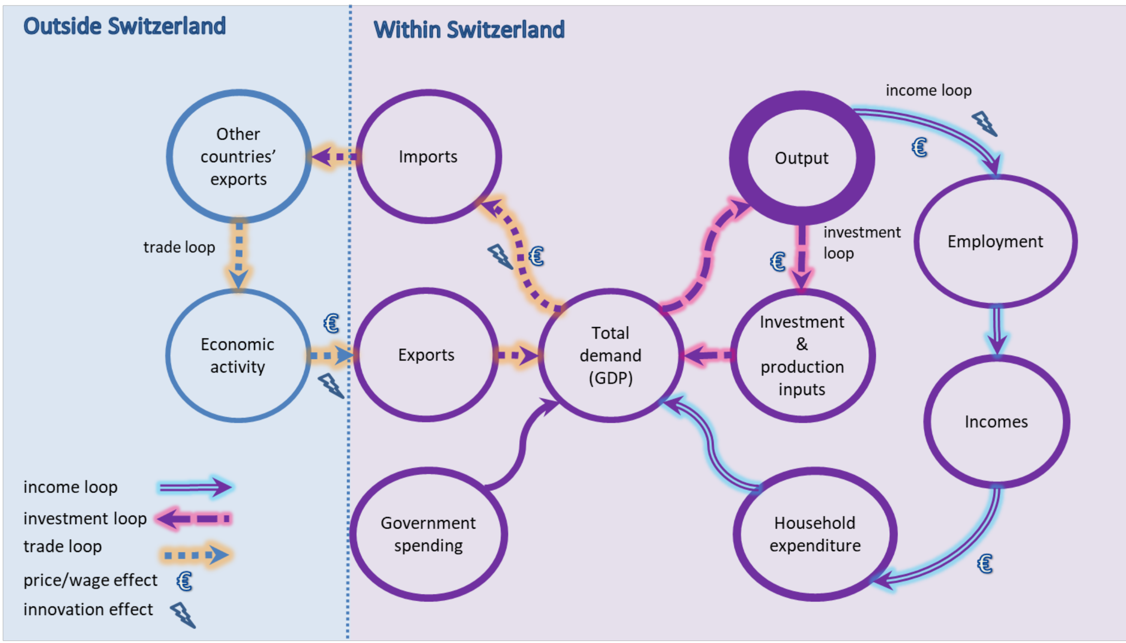


Figure 21: Key feedbacks captured in E3ME

2.2.6.2 Linking E3ME and STEM

For the joint scenario analysis, we soft-link the STEM energy system model with the macro-economic model, E3ME. Figure 22 illustrates how the STEM and E3ME models interact, in particular the energy sector results that are taken from STEM and used as inputs to the E3ME macroeconomic model.

In summary, energy prices, final energy consumption, capital outlays (investment) and the power sector capacity mix are taken from the STEM model, as inputs to E3ME, to capture the wider macroeconomic impact of the two scenarios.

In further iterations of scenarios, the STEM model takes E3ME results for impact on gross output by sector, and uses these as inputs, to re-estimate the change in energy service demands[18]. The re-estimated demand explicitly capture demand response and price effects associated with the lower levels of industry output (and hence, lower demand for fuel). For example, higher energy prices (from STEM) reduce competitiveness of industrial sector and thereby output (E3ME), which then leads to lower energy demand requirements and therefore a lower energy and policy costs (STEM). This process is explained in more detail in the section 2.2.6.5.

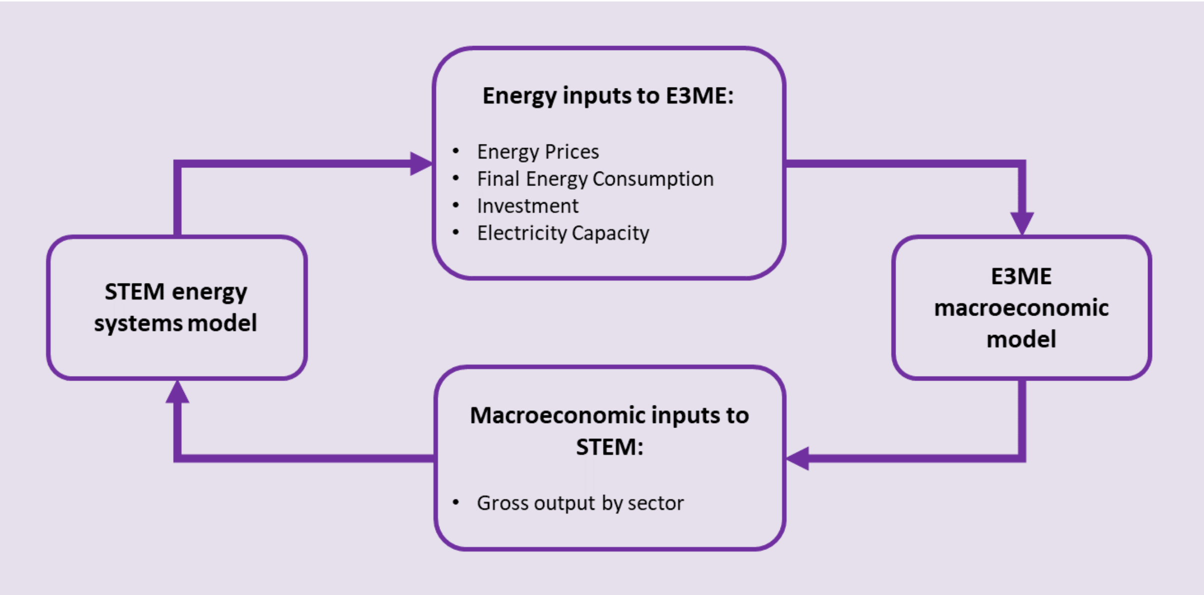


Figure 22: STEM and E3ME interactions

The table below shows the key results from STEM that were taken as inputs to E3ME. It describes how these inputs were transformed before being input to E3ME and how the two models were aligned.

[18] The gross output (in monitory term) from E3ME is used as basis for estimation of sub-sectoral production index. Using these production index, energy service demands for STEM are re-estimated.

Table 14: STEM model results linked to E3ME

Variables	How used or input to E3ME
Final Energy Consumption	Final energy consumption in the E3ME baseline is set to grow in line with the STEM baseline. Final energy consumption across the scenarios are integrated into E3ME by applying the relative difference from baseline in STEM to the E3ME baseline.
Capital Outlays – investment	Investment in each scenario is added as an absolute difference from baseline in STEM. Capital Outlays are shared between E3ME sectors by taking the share in baseline investment in E3ME. Residential capital outlays are allocated to consumer spending on household maintenance. It is assumed that the increased investment requirements are financed by higher prices across industry and service sectors. In the case of capital outlays for road transport, this almost entirely relates to higher vehicle sales prices. Therefore, to model this in E3ME we assume higher vehicle manufacturing costs and prices.
Energy Prices	STEM energy prices are integrated into E3ME by applying the relative difference from baseline in STEM to the E3ME baseline.
Power sector assumptions	Power sector capacity and the generation mix in E3ME are aligned to STEM.
GDP	GDP and the components of GDP are scaled to be consistent with the GDP assumptions in the STEM baseline.

In order to incorporate the macro-economic feedback from E3ME into STEM, a sub-model has been developed that allows to translate changes in macro-economic model results (i.e. sectoral Gross Value added) into energy service demands as used in STEM. This procedure is necessary as STEM does not use macro-economic drivers directly as model input. The method is described in the following sections. We re-estimate energy service demands for the residential, services and industrial sub-sectors, while we keep the transportation demands (in vehicle kilometre and ton kilometre) unchanged. Changes of mobility demand incorporates behavioural aspects (e.g. related to technology/fuel choice and choice of the transport mode), which we do not explicitly captured by the sub-model to translate macro-economic impacts into changes of energy service demands. Influences of behavioural aspects in long-term transport sector developments is subject of the SCCER Joint Activity CREST-Mobility, for instance.

2.2.6.3 **Energy Service Demands in STEM and their drivers**

STEM supplies end-use energy service demands (e.g. industrial process heating, space heating, lighting, or travelling needs) at minimum cost or more accurately at minimum loss of total surplus. The calculation of the energy service demands is based on socioeconomic drivers such as the Gross Domestic Product (GDP), Population, sectoral Gross Value Added (GVA), sectoral Production Index (PI), floor area for heating and lighting in the different sectors (FA), and vehicle-kilometers (vkm). The link between the energy service demands and the socioeconomic drivers is presented in Table 15. A scenario with STEM consists of a coherent set of assumptions regarding the future trajectories of the drivers for energy service demands.

Table 15: Overview of the energy service demands and their drivers in STEM (based on (Kannan and Turton, 2014)

Energy service demand	Main driver	Climate correction
Industrial sectors – space heating	FA per sector	Yes
Industrial sectors – process heating	PI per sector	No
Industrial sectors – lighting	FA per sector	No
Industrial sectors – cooling	FA per sector	Yes
Industrial sectors – other uses, e.g. equipment and motor drives	PI per sector	No
Services sector – space heating	FA	Yes
Services sector – lighting	FA	No
Services sector – other uses, e.g. equipment, motor drives	GVA	No
Residential sector – space heating	FA per building typology	Yes
Residential sector – water heating	Population	Yes
Residential sector – cooling	FA	Yes
Residential sector – lighting	FA	No
Residential sector – other uses, e.g. appliances, cooking	Income and number of households combined	No
Transport sectors	vkm per transport mode	No

2.2.6.4 Price elastic energy service demands

Additionally to the elasticity of the energy service demand to its driver , the STEM modelling framework also allows the definition of the elasticity of the energy service demand to its own price. When such an elasticity of the energy service demand to its own price is provided, then the demand component of STEM allows for an endogenous adjustment of the energy service demands. It is assumed that each energy service demand has a constant own price elasticity, via which a demand function is defined:

$$\frac{D}{D_0} = \left(\frac{P}{P_0}\right)^E \qquad \text{(eq. 1)}$$

where (D_0, P_0) is the pair of demand and price values for that energy service demand over the forecasted horizon in the reference (or baseline) scenario, and (D, P) is the pair of the resulted demand and price in the policy scenario calculated via the negative elasticity E.

However, there are no studies on the price elasticities of energy service demands and usually, within the TIMES modelling community these elasticities are based on the price elasticities of the final energy consumption. The passage from the fuel consumption price elasticity to energy service demand price elasticities is based on the following relation:

$$F = D * U \qquad \text{(eq. 2)}$$

where F is the final energy consumption, D is the energy service demand and U is the final energy consumption per unit of energy service demand. It follows that U is a function of capital and energy.

The modification of the energy service demand via the price elasticity can be based on the estimated price elasticities of fuel consumption in WP1. However, a translation layer is needed according to equation (eq. 2) which is described in detail in the next section.

2.2.6.5 **Two options for modifying the STEM energy service demands**

In the SWIDEM project, the E3ME model provides the change in the drivers, such as GDP and GVA, while WP1 estimates price elasticities of industrial fuel consumption. Therefore, the energy service demands in STEM can be modified via two options: the first is the coupling with the E3ME model on the basis of the major macro-economic drivers; the second option involves the use of the estimated price elasticities in WP1 to allow also a modification of the energy service demands with respect to their cost.

The two options are not necessarily mutually exclusive. The modification of the energy service demand via the driver reflects macroeconomic and demographic structural changes. In contrast, the modification of the energy service demands via the price elasticity reflects behavioural changes. The above can be clarified with a simple example, as follows, regarding the residential space heating demands. A low GDP economic growth, e.g. due to an international financial crisis, can lead to lower incomes and, hence, to lower demand for single family houses. As a result, the floor area in single family houses that needs to be heated is reduced. Hence, this is the response of the energy service demand to the macroeconomic conditions. At the same time, due to lower incomes, consumers see high cost of energy and this can lead to behavioural changes, i.e. heating the houses by one degree less. The latter is the response of the energy service demand to its own price.

Below, we provide more details how the energy service demand in STEM is modified via the change in the drivers and via the change in the price. The first option is implemented via the coupling of STEM and E3ME, while the second option is implemented via the estimated price elasticities in WP1.

2.2.6.6 **Option 1: Modification of energy service demands by coupling E3ME and STEM**

The first option to adjust the energy service demands in STEM is to use to the output from the E3ME model to modify the underlying drivers. While the E3ME model provides GDP, average income and sectoral GVA, STEM uses these additional drivers for the calculation of energy service demands. These include, for example, production indices, floor areas, or ownership of appliances. To this end, a translation is needed to calculate the required drivers from the GDP, average income and sectoral GVA from E3ME.

The modification of the energy service demands via the coupling of STEM with E3ME requires sub-models that translate the economic output from E3ME to STEM drivers. In the next sections, we present the sub-models for the industrial demands, the demands in services sector and the demands in the residential sector. In the coupling of STEM with E3ME models we do not alter the transport demands, because there is not enough evidence from the E3ME output regarding the direction of the modification, i.e. modal shifting or mere reduction.

Translating sectoral gross value added to industrial production index and floor area

A reduced-form econometric model has been estimated to translate the gross value added of each industrial sector to production index and floor area. The model is based on available statistics (e.g. from Bundesamt für Statistik – BFS) and projections (Prognos, 2012).

The general structure of the estimated econometric equation linking the production index of an industrial subsector with its gross value added:

$$\log\left(\frac{p_{s,t}^{i}}{p_{s,t-1}^{i}}\right) = c_{s,0} + c_{s,1}\sum_{k}\gamma_{s,t-k}\cdot\log\left(\frac{g_{s,t-k}}{g_{s,t-k-1}}\right) + \varepsilon_{s,t} \qquad \text{(eq. 3)}$$

where $p_{s,t}^{i}$ is the production index of sector s in time t , $g_{s,t}$ is the gross value added of sector s in time t , and $\varepsilon_{s,t}$ is the error term of the regression. The estimated coefficients $c_{s,1}$ correspond to the elasticity of the production index to the sectoral value added. To account for both long term and short term elasticities, as well as to remove collinearity, we apply a polynomial distributed lag (PDL) of depth k on the growth of the gross value added. The estimated coefficients $\gamma_{s,t-k}$ are coefficients of a linear polynomial of depth k, using the Almon's method. Where necessary, an autocorrelation regression coefficient is applied to remedy for autocorrelation in the error terms. From the definition of the PDL, it follows that the coefficient $c_{s,1}$ corresponds to the total elasticity of the production index to sectoral gross value added. The resulting estimated parameters are presented in Table 16.

Table 16: Estimated coefficients of the equation linking production index and gross value added in industrial subsectors

Industrial sector s (NOGA 2008 code)	**Constant $c_{s,0}$**	**PDL coefficient $c_{s,1}$**	**PDL Depth, Constraint**	**Autocorrelation coefficient**
Chemicals (20-21)		0.163 (***)	5 , far	0.961 (***)
Construction (41-43)	0.006 (***)	0.008 (**)	5, near	0.767 (***)
Electrical & electronic equipment (26-27)		0.057 (*)	3 , far	
Energy (05-06, 19, 35-39)		0.305 (***)	3, far	0.425 (*)
Food (10-12)		0.218 (***)	3, far	0.848 (***)
Other (07-09, 16, 18, 22, 31-34, 40)		0.742 (***)	2, far	0.991 (***)
Machinery (28-30)		1.562 (***)	1, far	0.990 (***)
Basic metals (24)		0.033 (***)	6, near	0.748 (***)
Metal products (25)		0.635 (***)	0	0.965 (***)
Non-metallic minerals (23)		0.146 (***)	7, far	0.792 (***)
Paper and pulp (17)		0.035 (***)	6, near	0.751 (***)
Textiles (13-15)	-0.003 (***)	0.224 (***)	4, far	0.486 (***)

Thus, the GVA projections from E3ME for the different industrial subsectors enter into equation (eq. 3) to obtain the production indices used to calculate the demand for industrial process heat in STEM.

A similar reduced-form econometric model is estimated to translate the production index into floor area for offices, production facilities and buildings in the different industrial subsectors. The general formulation of the model is:

$$\log\left(\frac{f_{s,t}^{i}}{f_{s,t-1}^{i}}\right) = c_{s,0} + c_{s,1} \sum_{k} \gamma_{s,t-k} \cdot \log\left(\frac{p_{s,t-k}^{i}}{p_{s,t-k-1}^{i}}\right) + \varepsilon_{s,t} \qquad \text{(eq. 4)}$$

where $f_{s,t}^{i}$ is the floor area required in offices, production facilities and buildings and $p_{s,t}^{i}$ is the production index in sector s and time t. Thus, the production index calculated from equation (eq. 3) by using the GVA output from E3ME is given as an input in equation (eq. 4) to estimate the floor area required for production facilities. The estimated coefficients of equation (eq. 4) are presented in Table 17.

Table 17: Estimated coefficients of the equation linking floor area with production index in industrial subsectors

Industrial sector s (NOGA 2008 code)	Constant $c_{s,0}$	PDL coefficient $c_{s,1}$	PDL Depth, Constraint	Autocorrelation coefficient
Chemicals (20-21)	0.004 (*)	0.022 (***)	5, far	0.981 (***)
Construction (41-43)	0.011 (***)	0.056 (**)	2, far	0.874 (***)
Electrical & electronic equipment (26-27)	0.011 (*)	0.078 (***)	2, far	0.972 (***)
Energy (05-06, 19, 35-39)		0.006 (***)	15, near	0.751 (***)
Food (10-12)		0.0425 (***)	7, far	0.800 (***)
Other (07-09, 16, 18, 22, 31-34, 40)	0.007 (***)	0.074 (***)	2, far	0.823 (***)
Machinery (28-30)		0.430 (***)	1, far	0.775 (***)
Basic metals (24)		0.012 (***)	3, far	0.991 (***)
Metal products (25)		0.095 (***)	1, far	0.973 (***)
Nonmetallic minerals (23)		0.449 (***)	1, far	0.983 (***)
Paper and pulp (17)		0.074 (***)	1, far	0.991 (***)
Textiles (13-15)		0.412 (***)	1, far	0.978 (***)

Translating sectoral gross value added to floor area in services

Given that the E3ME model also provides sectoral value added for the services sector, we apply the same methodology as above to translate the gross value added into floor area. We then use the floor area to estimate the space heating and lighting demands in the services sector. The econometric estimation is based on available statistics from BFS and projections (Prognos, 2012).

Because the services sectors are aggregated into a single sector in STEM, the general form of the econometric estimation linking the gross value added in services is:

$$\log\left(\frac{f_t}{f_{t-1}}\right) = c_0 + c_1 \cdot \log\left(\frac{g_t}{g_{t-1}}\right) + \varepsilon_t \quad \text{(eq. 5)}$$

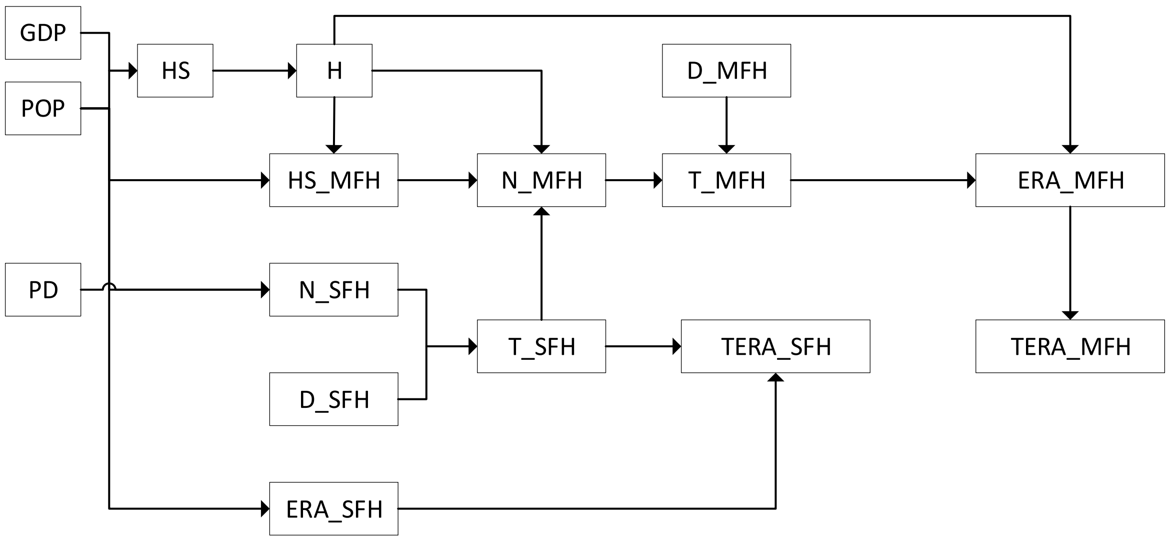
where f_t is the floor area in services sector (aggregated across all subsectors) and g_t is the gross value added. The estimated parameters are $c_0 = 0.006\ (***)$ and $c_1 = 0.075\ (***)$, while the autocorrelation coefficient is $\rho = 0.985\ (***)$.

Thus, using the GVA output from E3ME for services we translate it to floor area used to calculate the heating demands (the rest of the energy service demands in the services sector, and which are presented in Table 15, are linked to the GVA).

Translating consumption into residential floor area for space heating and lighting

Finally, the average per capita income (or household income, if combined with the household size) can be used to modify the floor are in the residential buildings (which is the main driver of the heating and lighting demands) and the ownership of the appliances.

The floor area in buildings is based on a building stock model that considers buildings of different vintages and types (single or multi-family houses). The general structure of the model is given in Figure 23.



GDP: Gross Domestic Product
POP: Population
PD: Population density
HS: Average household size
H: Number of households
MFH: Multi family houses
SFH: Single family houses
HS_MFH: Households in a multi family house
N_SFH: new single family houses
D_SFH: Existing single family houses after applying the demolition function (weibull)
D_MFH: Existing multi family houses after applying the demolition function
T_SFH: Total single family houses (existing plus new)
T_MFH: Total multi family houses (existing plus new)
ERA_SFH: Energy reference area in single family houses per vintage
ERA_MFH: Energy reference area in multi family houses per vintage
TERA_SFH: Total energy reference area in single family houses
TERA_MFH: Total energy reference area in multi family houses

Figure 23: Overview of the structure of the building stock model used to calculate the floor area per building type in STEM

The main drivers of the building stock model are the population and the incomes. Both drivers are exogenously given to the model and constitute its main inputs. Based on the projection of the population and incomes, the average household size is estimated together with the number of households. Incomes also define the demand for new single-family houses, which is however constrained by building area limitations approximated by the population density in settlement areas. The construction of new single-family houses together with the remaining stock of existing single-family houses constitute the total building stock of single-family houses.

Based on the total number of households the number of apartments hosted in a new multifamily house can be calculated. By also accounting for the number of households in single family houses and the demolition of existing multifamily houses, the new constructions of multifamily houses can be calculated to cover the gap in the housing needs. The existing multi-family houses, after demolitions, and new constructions results in the total building stock of multi-family houses.

The energy reference area (or floor area for space heating and lighting) in single family houses is driven by incomes and it is calculated per vintage. The energy reference area of multi-family houses is driven by the number of households and it is also calculated per vintage. It follows that the application of the energy reference area per vintage and building typology to the stock of buildings belonging to this vintage and typology results into the total floor area required for space heating and lighting. The demand for space heating is then calculated by applying the heating demand per square meter to the calculated floor area. The hating demand per square meter is a scenario assumption, and it is currently based on (Prognos, 2012).

Hence, the projection of E3ME regarding average incomes modifies the need for new single-family houses. However, the total floor area in the residential sector is rather inelastic to incomes (i.e. elasticity less than 1) as a modification in the floor area in single family houses due to the response in incomes is partly offset by a modification towards opposite direction in the multifamily houses to meet the total housing needs, if population and number of households remain unchanged.

Translating consumption into residential floor area and electrical appliances

The projection of incomes from E3ME can be also used to modify the ownership rate of electrical appliances. However, not all of electrical appliances are elastic to incomes as they can also depend on the number of households. Cookers, washing machines and refrigerators belong the type of appliances mainly driven by the demographic developments, and consequently, the number of households. In this context, these ownership rates of these appliances are not modified by the projections of E3ME, since population remains unchanged

At the same time, most of the appliances that are elastic to incomes also display saturation effects. In this category belong for example the information and communication devices (e.g. laptops, desktops and smartphones) as well as audio-visual devices such as TV sets and video/DVD players. Due to the already high incomes in Switzerland, the ownership rates of these devices is close to their (theoretical) saturation levels.

In general, the ownership rate of electrical appliances of type a is given from the following equation:

$$r_{a,t} = \frac{SAT_a}{1+\exp\left(c_{0,a} \cdot I_t + c_{1,a} \cdot H_t\right)} \qquad \text{(eq. 6)}$$

where $r_{a,t}$ is the ownership rate of appliance a in year t, SAT_a is the saturation level of ownership (e.g. 100%), $c_{0,a}$ is the estimated coefficient (or weight) of income I_t and $c_{1,a}$ is the estimated coefficient (or weight) of the number of households H_t.

2.2.6.7 Option 2: Modification of the energy service demands via the price elasticity

The energy service demands can be also modified on the basis of the price elasticities of WP1, after applying the adjustment factor U of equation (eq. 2). In this section, we provide more details regarding the adjustment of the price elasticities of the fuel consumption derived in WP1 in order these to reflect price elasticities of the energy service demands.

The adjustment factor U implies that there is a fix relation between capital and energy in the production function of energy services (Leontieff structure). Then the price elasticity of the energy service demand is a function of the price elasticity of fuel consumption and the share of the energy cost in the end use sector:

$$E = \varepsilon * s \qquad \text{(eq. 7)}$$

where E is the elasticity of energy service demand on its own price, ε is the price elasticity of the final energy consumption and s is the share of the energy cost in the marginal cost of the energy service demand, as it is calculated by STEM.

Assuming substitution possibilities between capital and energy in the production function, then the price elasticity of energy service demand will also depend on the substitution elasticity , resulting in the following relationship:

$E = (\varepsilon + \sigma \cdot (1 - s))/s$ (eq. 8)

The distance between the two elasticities depends on the share of the energy cost to the total cost as well as on the substitution possibilities. The elasticities are closer to each other when the share of energy cost to the total cost is large, while they differ when the substitution elasticity is large.

The above relationship can be applied to the price elasticities of WP1, by using the shares of energy costs to marginal costs calculated by STEM and assuming a substitution elasticity between capital and energy in the production function of the industrial sector (e.g. from the E3ME model).

2.2.6.8 Combining the driver and price elasticities to modify the energy service demands in STEM

The modification of energy service demands as a result of changes in the driver reflects macro-economic and demographic changes. In contrast, the modification of the energy service demands based on the changes in the cost of energy service could reflects consumer behavioural changes or efficiency measures not explicitly captured in the bottom-up techno-economic framework of STEM.

Therefore, a two-stage modification mechanism can be established. In the first stage, the underlying drivers of the energy service demands are modified based on the coupling with the E3ME model. In the second stage, the modified energy service demand can respond to their price elasticity (adjusted from the elasticities of WP1) to additionally reflect the deployment of efficiency measures.

However, in the context of the SWIDEM project we modify the energy service demands based on the modification of the drivers and the output from the E3ME model. We do not apply the modification of the energy service demand based on its price elasticity due to the heterogeneity of the industrial sectors represented in STEM. As discussed in WP1, the heterogeneity of the industrial sectors could result in unintuitive results: in some aggregated industrial sectors the elasticities are positive (e.g. in “Other Industry”) and in other sectors extremely large (e.g. in the “Cement Industry”). Extremely large price elasticities are usually the result of extensive efficiency measures or structural changes in the production of the sector occurred in the past. It follows that these large price elasticities cannot be maintained in the future as well, as the efficiency potentials are reached or the structural changes mature.

Another issue regarding the application of the price-elastic energy service demands lies on the reliance of the marginal costs for the translation of the price elasticities. The obtained marginal costs of the energy service demands from the STEM model should follow a “smooth” trajectory over time, avoiding “bang-bang” solutions or abrupt changes. However, in stringent scenarios (such as the EPOL and CLI scenarios), obtaining smooth marginal costs for the long-term horizon is challenging as the model is stretched to its limits and the duals of different constraints can be very large. The application of price-elastic demands in this context would have resulted in “shocks” in the model solution, infeasible solutions and numerical instabilities.

Therefore, we followed a conservative approach in coupling the two models to ensure that we do not violate their equilibrium properties and we do not overestimate the savings potentials. At the same time, by coupling the STEM and E3ME beyond the industrial sectors we ensure that we account for the broader induced changes in the energy system due to the macro-economic developments.

2.2.7 Results of the joint scenario analysis

In this section we describe the results of the joint scenario analysis where in the first part the long-term energy system developments are presented with a focus on the industry sector. The second part highlights the corresponding macro-economic impacts.

2.2.7.1 Long-term energy system developments with focus on industry

In the *BAU* scenario, the CO_2 emission decline in the near term due to efficiency improvements in the transport sector and in the building sector (see final energy consumption in Figure 24). However, when the last (and the biggest) unit of the Swiss nuclear power plant goes off-grid, CO_2 emissions bounce back because new gas fired power plants substitute some of the nuclear electricity supply (see Figure 29).

The *EPOL* scenario leads to a reduction in total CO_2 emission of about 50% in 2050 compared to the 2010 level (vs. 22% in BAU), which is insufficient to meet stringent climate mitigation goals. The industrial sector emissions also declines by 50% and most of these emission reductions result from energy efficiency and fuel substitution from high carbon intense fuels to low carbon fuels (see Figure 24). Some of the fuel substitution is driven by the energy efficiency standards. At the same time, price-induced reduction in energy service demands (about 9% across all industry sectors) also contributes to overall industrial emission reduction.

Though the industrial CO_2 emissions reduce in the *CLI* scenario, this sector remains one of the challenging sectors for mitigation and accounts for 30% of the remaining emissions in the energy system in 2050. It is important to keep in mind, that in this scenario analysis only the energy-related CO_2 emission are accounted, and process related emission are not considered.

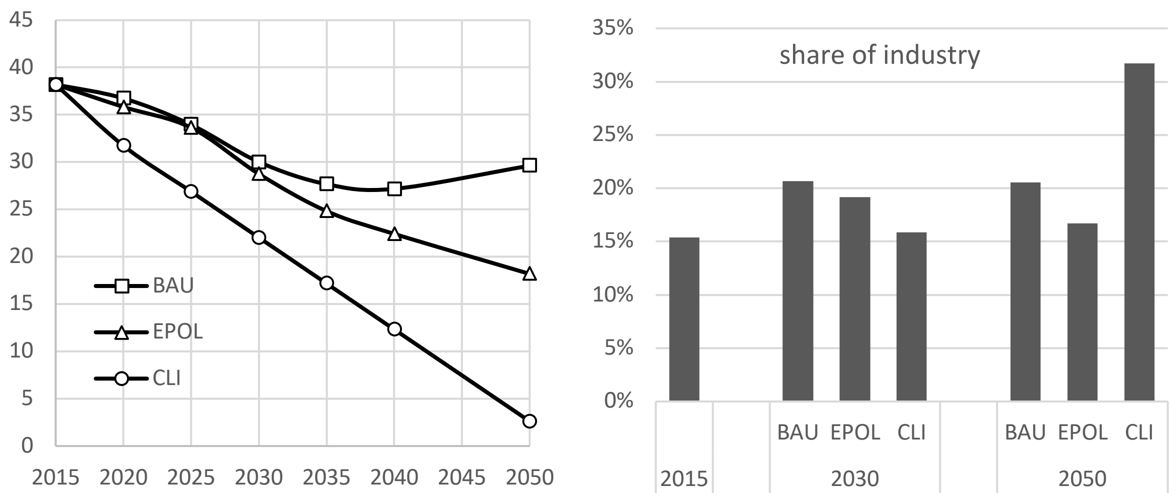


Figure 24: left panel: Energy-related CO_2 emissions, excluding emissions from international aviation (in Mt CO_2); right panel: share of industrial energy-related emissions of total energy-related CO_2 emissions (excl. intl. aviation)

The final energy consumption follows the trajectory set-out by the energy and electricity targets (see Table 12 and Figure 25). Most of the reduction in final energy consumption is achieved through energy efficiency improvements, which is partly also related to fuel switching (e.g. if fossil fuel combustion is replaced by electric appliances). Particularly, the transport and residential sectors contribute to a significant reduction of the final energy consumption in the long run (2050). However, in *EPOL* scenario, some level of substitution from fossil fuel to electricity does not materialize due to the existence of the policy goal that limits the overall per capita electricity consumption, and hence prevents increased levels of the electrification. In the industrial sectors, the less energy efficiency are deployed compared to the residential, transport and partly services sectors, which results in a remaining or even increasing share of the industry of the total final energy consumption.

Despite a significant reduction in final energy consumptions in the EPOL scenario in the mid-term (2030/2035) but also in the long run until 2050, there is no significant reduction in CO_2 emissions because emissions are shifted from the demand sectors to the energy supply sector by demanding higher shares of synthetic low-carbon fuels.

Compared to the *CLI* scenario, the change in total final energy consumption in the *EPOL* scenario is only about 15% higher in 2050. However, *EPOL* scenario's performance with respect to CO_2 reduction is less pronounced because the electricity target prevents increased deployment of cost-effective electrification, particularly in the building and transport sectors. Conversely, in the *CLI* scenario, electricity is very prominent in the final mix with positive implications for the CO_2 emissions in the demand sectors.

A general trend across all scenarios is the reduction in oil produces, which is driven by increasing energy prices and an improved competitiveness of gas technologies and electricity-based heating and mobility technology. The consumption of waste in the demand sectors reduces in the *EPOL* and *CLI* scenarios due to the comparably low efficiencies of waste combustion technologies versus other heating technologies in the *EPOL* scenario and due to the CO_2 emissions associated with waste combustion which represents a limiting factor in the case of the *CLI* scenario.

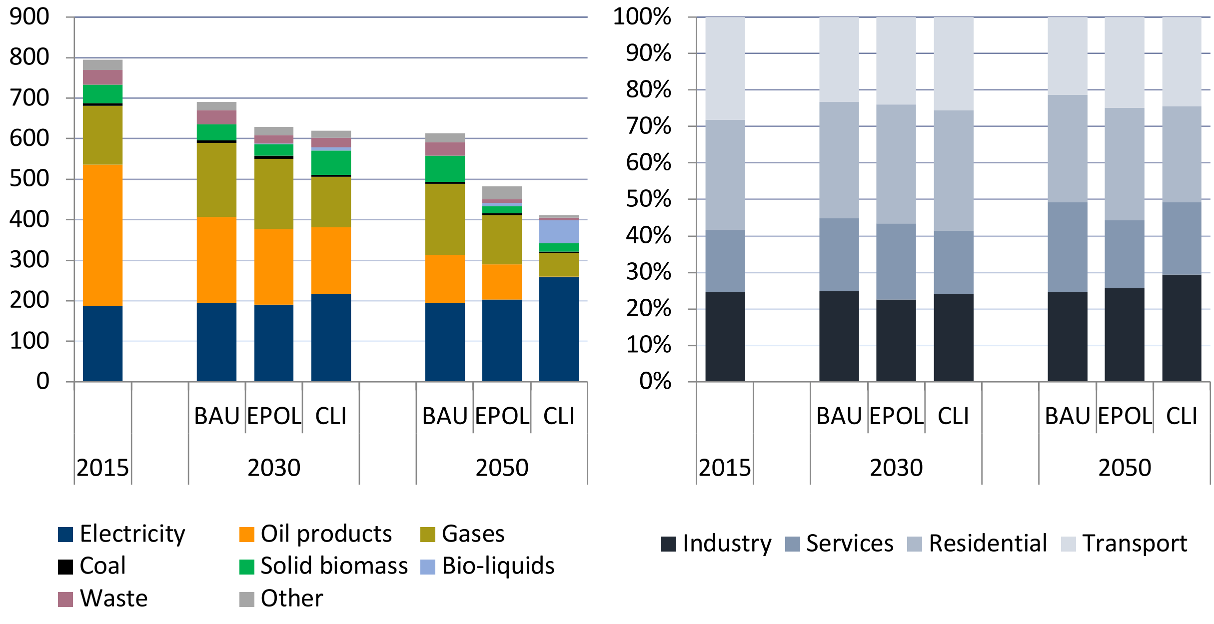


Figure 25: left panel: final energy consumption by energy carrier (in PJ); right panel: sector shares of final energy consumption

Due to the decline of the overall final energy consumption and the stable or increasing electricity consumption, the share of electricity of total final consumption increases across all three scenarios from about 24% in 2015 to 28-35% in 2030 and 32-62% in 2050. In absolute terms, the electricity demand roughly remains at the 2015 level in EPOL and BAU, while it grows by almost 40% in the CLI scenario between 2015 and 2050. The total electricity supply grows from 62 TWh in 2015 to 65-71 TWh in 2030 and further to 71-82 TWh in 2050 (Figure 26). The generation in nuclear plants diminishes after 2030. In response to the nuclear phase-out and the growing electricity demand new generation capacities are commissioned, specifically solar PV, wind and in the BAU scenario also gas power plants. In addition, imports from the neighbouring countries increase towards 2030 and 2050. At the same time, some of the biomass (and wastes) from the end use sector is diverted to the electricity sector either because of the energy efficiency target in the end use sectors or CO2 targets, i.e. wood cannot be used energy efficiently to meet the final energy efficiency targets. Comparing the EPOL scenario and BAU and CLI shows, that the comparably lower demand for electricity also reduces the need for imported electricity. The combination of energy efficiency and the electricity target decelerates the uptake of CHP plants in industrial sector. Unlike the EPOL scenario, electrification in the CLI scenario is high and thereby higher demand for electricity (see Figure 25). Most of these additional demands are met with imported electricity. In the CLI scenario, net imports reach a peak of 16 TWh in 2050 which corresponds to about 70% of today's electricity generation from nuclear power.

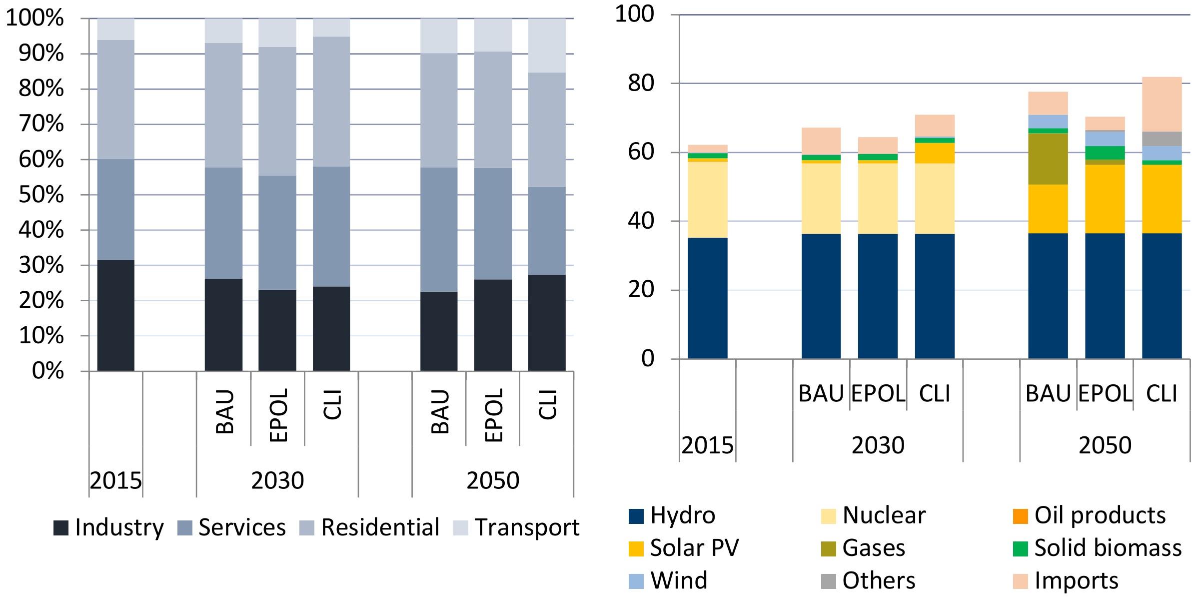


Figure 26: left panel: Electricity consumption by sector; right panel: Electricity generation (in TWh)

In industry, the share of electricity of the total industrial final energy consumption increases from 33% in 2015 to 34-38% in 2030 and 39-62% in 2050, which results from the overall decline of energy consumption in industry (Figure 27). The absolute electricity consumption of the industry sector declines slightly from 2015 to 2030 in all three scenarios, and in BAU and EPOL also beyond 2030. Only in CLI scenario in 2050, electricity consumed in industry is higher than in 2015. While there energy savings for electrical appliances are realised, new electrification is driven by deployment of low temperature heat pumps in selected subsectors (e.g. food, and paper and pulp sectors).

Across all industry sectors, the use of gases remains a dominant combustible fuel until 2050. In all scenarios the share of gaseous fuels is in a range between 20 and 33% the total final energy consumption of the entire industry. Under increased climate change mitigation ambition, bio-methane is widely used in the industrial sector where the deployment of alternative fuels/technologies is limited. Some of the energy efficiency improvements in the industrial sector are associated with fuel substitution effects. For example, coal in the cement sector is partly substituted with natural gas resulting in gains in energy efficiency and thereby a reduction in final energy.

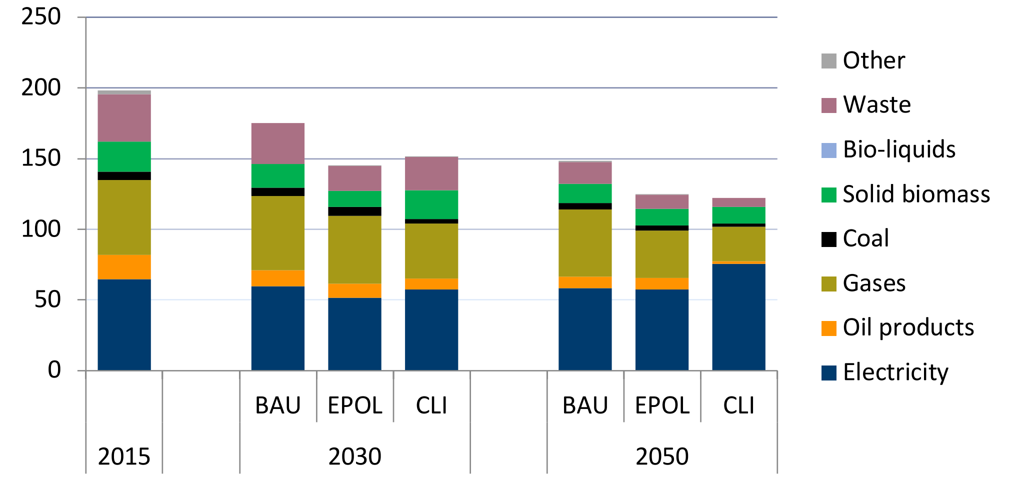


Figure 27: Final energy consumption industry (in PJ)

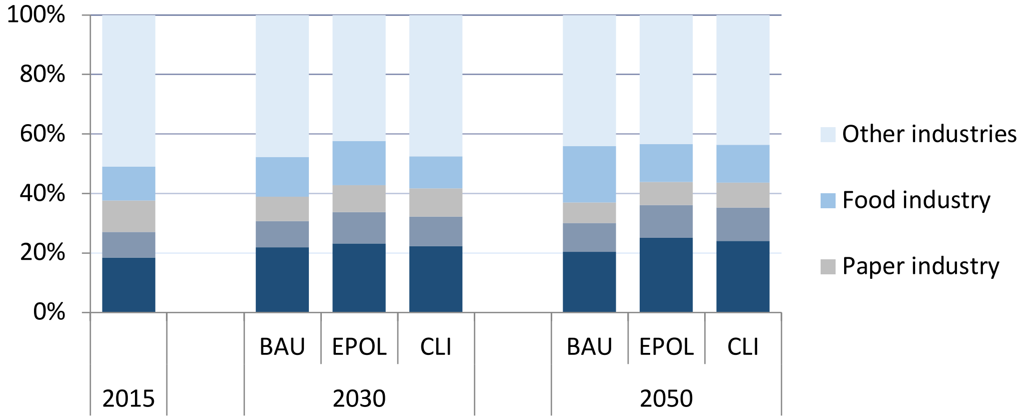


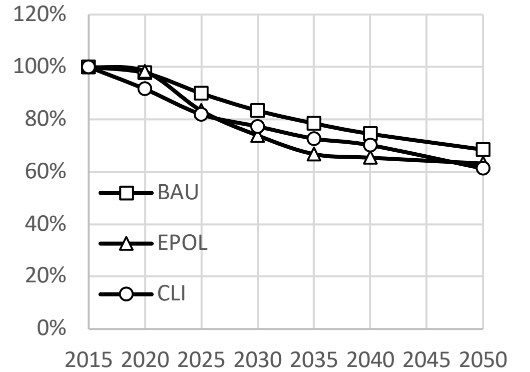
Figure 28: Industry sub-sectors' shares of final energy consumption industry

The share of the energy intensive branches of total industrial energy consumption increases over time in all scenarios (Figure 28), indicating better opportunities to unlock energy efficiency improvements in non-energy-intensive sectors. This observation is supported by Table 18 which depicts the energy intensity of industrial energy service demands relative to the year 2015 for the entire industry sector in the left panel and for selected industries in the right panel. Across all scenarios, the development over all industrial sectors shows a reduction of the energy intensity compared to 2015 by 17-23% in 2030 and 32-39% in 2050. In order to achieve the overall policy goal to reduce the per-capita final energy consumption, as well as the per-capita electricity consumption pushes energy efficiency measures in the EPOL scenario in the period 2030 to 2040 below the level deployed in the CLI scenario. The reason for this development is that in industry, it is more cost-effective to pursue decarbonization through increased electrification around 2035 rather than deploying energy efficiency measures to a very large extend, which is the case to achieve the goals of the EPOL scenario. Another interpretation of this dynamic is that, although it makes sense to promote efficient use of electricity, a target imposed on the overall consumption of electricity (even though relative to the population growth) might have disadvantages for a broad roll-out of modern electric end-use technologies. Instead of overall electricity consumption goals, specific electricity consumption standards per technology class (or end-use purpose) could help to use electricity efficiently while allowing consumers to decarbonize through electricity in a broader range of applications. Among the different industry branches, the sector of non-metallic minerals shows a comparably lower energy intensity improvement over time indicating limited technology substitution options due to the high temperature levels in this sector.

Towards 2050, the stringent emission targets assumed in the CLI scenario accelerate energy efficiency (besides fuel switch) resulting in 2020 in an overall energy intensity slightly below the level of EPOL. The results for the industrial sub-sectors show, that the sectors Non-metallic minerals and Chemical, and to some extend the paper industry, reduce their energy intensity at a slower pace than other industry sectors, which is driven by the limited fuel substitution possibilities to produce high temperature heat.

Table 18: Energy intensity relative to 2015 for the overall industry (left) and selected industry sectors (right); N.B.: energy intensity refers to energy consumption per unit of energy service (e.g. process heat) provided

Total industry



Selected sectors

	2030			2050		
	BAU	EPOL	CLI	BAU	EPOL	CLI
Non-metallic minerals	91%	91%	89%	94%	90%	90%
Chemical	94%	83%	83%	70%	75%	69%
Food	95%	88%	66%	106%	62%	59%
Paper	86%	74%	82%	67%	64%	68%

Insights on sub-sectoral developments are provided in Figure 29 and Figure 30 which illustrate the final energy consumption of selected branches, namely Chemicals, Non-metallic minerals, Paper and Food, as well as the aggregate of the remaining industry sectors. In chemical sector, the current energy mix largely remain in all three scenarios until 2030, and in BAU and EPOL also until 2050. In the CLI scenario, an increased level of electrification is needed to meet the climate goal. For the supply of process heat, this requires to shift from combustion technologies towards the application of high-temperature heat pumps.

In the EPOL scenario, the non-metallic mineral industry sector (of which cement industry is a main contributor) reduces the energy intensity and the sector's CO_2 emissions in 2050 through the switch from coal to natural gas. Compared to EPOL, the share of coal in 2050 decreases further while bio-fuels are used as liquid combustible fuels in the sector. It is worth remembering that process related CO_2 emissions are not accounted in the current modelling framework of STEM. Further insights on the cement sector in particular are provided in section 2.2.7.2 where we present complementary results derived from a sector-focused modelling approach.

In the food and paper sub-subsectors the model results indicate new end use technologies to enable higher levels of electrification. Heating applications based on oil products are phased out because alternative heating systems are available and allow to generate heat at comparably lower costs. For example, the energy efficiency targets imposed in the EPOL scenario support the deployment of low temperature heat pumps in combination with waste heat recovery leading to about 40% more efficient use of energy in this sector. Particularly in the CLI scenario in 2050, such electrification is a substantial CO_2 mitigation measure and cost-effective over other measures to provide process heat in these sectors.

In the food industry, the use of bioenergy is beneficial to reduce the consumption of natural gas, which not only has a positive climate impact (CLI scenario) but also helps to reduce fuel expenditures (in the case of the BAU scenario). Usage of increased amounts of bioenergy in food industry requires to build the corresponding supply infrastructure to deliver biogenic resources to the industry sites. This may also require to establish storage systems for biogenic resources to ensure continuous fuel supply.

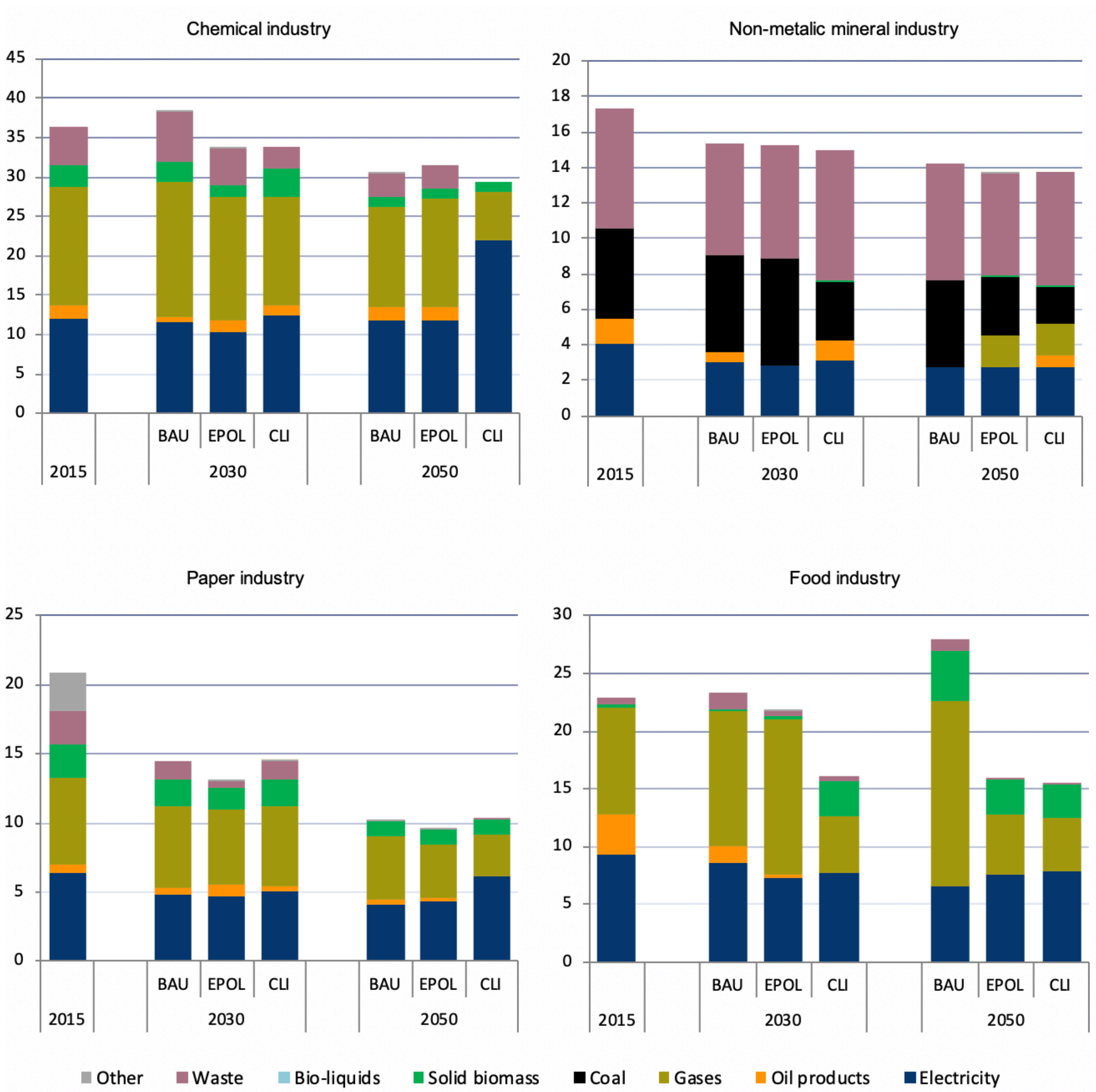


Figure 29: Final energy consumption of selected industry sectors (in PJ)

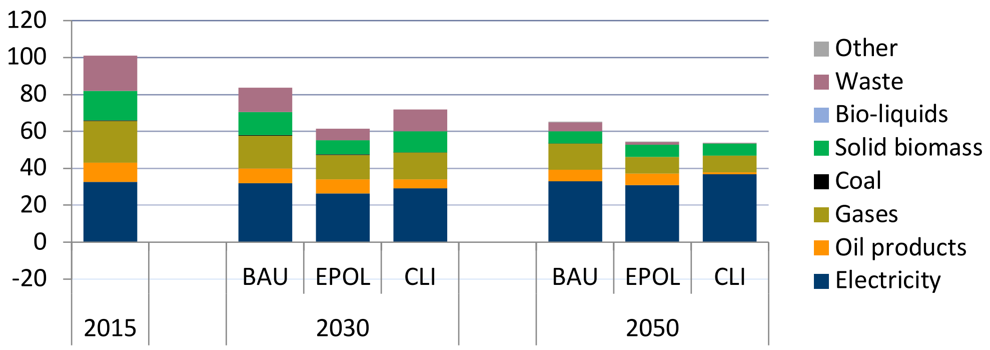


Figure 30: Final energy consumption of other industry sectors (in PJ)

2.2.7.2 Excursus: Cement sector analysis

In STEM, the cement sector, which is one of the most energy-intensive industries in Switzerland, is part of the non-metallic minerals sector. As such, an explicit model representation of cement production process and material flows is not supported. Nevertheless, all major fuels and technology characteristics are implemented in STEM. Current research concerns the development of a dedicated cement sector model which features a highly detailed and complex technological approach of cement production process. We depict different combinations of advanced energy and process technologies as well as material flows. Most importantly, the cement sector model include process-related CO_2 emissions in addition to energy-related emission (covered in STEM). This new modelling tool exceeds the original scope of the advancements of the model representation of the Swiss industry as envisaged in this project, and provides additional insights in the interdependencies of efficiency improvements measures and CO_2 mitigation options for the cement industry.

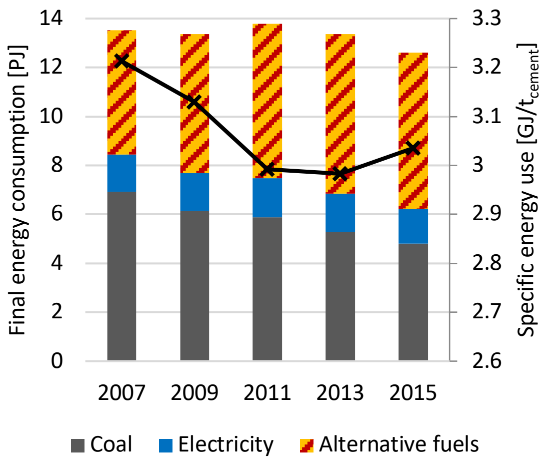


Figure 31: Final energy consumption and specific energy use in the Swiss cement industry

The Swiss cement sector is analyzed in a detailed sector specific model including the process steps with the major material and energy flows. With this advanced representation, efficiency improvement options can be applied to each process step of the cement production chain. The model includes details with regard to waste heat recovery, carbon capture, recycling of waste concrete and carbon utilization for on-site methanation. Also, the carbonation of waste concrete is included in the model.

In Switzerland, six cement plants with a total capacity of almost 5 Mt of cement per year are in operation (Cemsuisse, 2016). The total final energy consumption for the cement production in 2015 was 12.8 PJ and the total (both process and energy related) CO_2 emissions were 2.5 Mt (Federal Office for the Environment FOEN, 2019). This corresponds to 8% of the total final energy consumption of the Swiss industrial sector (Bundesamt für Energie BFE, 2016) and 36% of the CO_2 emissions of the Swiss industrial sector respectively (Federal Office for the Environment FOEN, 2018). Around two-thirds the CO_2 emissions are related to the process of converting limestone into clinker (clinker making process), while the remaining emissions are related to fuel combustion. This results in a specific final energy use of 2.65 GJ/t_{cement} or 3.6 $GJ/t_{clinker}$. Compared to the global cement industry with a specific final energy use between 3.4 and 4.7 $GJ/t_{clinker}$, the Swiss cement industry is one of the most energy efficient in the world and has only a slightly higher specific energy use per tonne of cement than the current best available techniques (BAT) with 3.3 $GJ/t_{clinker}$ (European Commission, 2013). The specific energy use per ton of cement has decreased over the past years as it can be observed in Figure 31. The reason for the improvement in energy intensity is mainly due to the declining clinker content in cement. Furthermore, the fuel switch from coal to alternative fuels (mainly waste and biomass) in order to reduce the CO_2 emissions from cement production can also be identified in Figure 31.

The analysis of energy efficiency and CO_2 emissions mitigation for the cement sector, is performed outside of the scenario framework applied to the whole systems model STEM, which focuses on the two scenarios EPOL and CLI. For the cement sector specifically, we employ a number of additional target scenarios that aim at illustrating the technology options available in the cement industry to achieve these targets. The cement sector scenario framework is characterised as follows:

- **BAU - Business as usual**
  This scenario assumes frozen policy and an unchanged market environment for the cement industry. We assume the demand for cement to remain stable, with the average clinker content decreasing to 60% until 2050 and the CO_2 tax is held constant at a level of 20 EUR/t_{CO2} which approximates a continuation of today's EU-ETS certificate price level.
- **CC - CO_2 Cap scenario group**
  The CO_2 cap scenarios assume a reduction of the CO_2 emissions by 2050 compared to 2015. The reduction is assumed to be linear from 2015 until 2050. We investigate four emissions reduction trajectories, namely ICNM-CC 40, ICNM-CC 60, ICNM-CC 80 and ICNM-CC 100, which aim at an emissions reduction in 2050 of 40%, 60%, 80% and 100%, respectively, compared to the BAU scenario emission level.
- **EE - Energy efficiency scenario group**
  These scenarios represent energy efficiency targets aiming at an energy reduction per ton of cement until 2050 from 2015 levels of 30% (ICMN-EE30) and 35% (ICMN-EE35).
- **TAX – CO2 tax scenario group**
  The CO_2 tax scenarios are used to investigate different CO_2 tax policies. The CO_2 tax is increased linearly from 20 EUR/t_{CO2} (in 2015) to 70 to 100 CHF/t_{CO2} in 2050 (ICMN-TAX70, ICMN-TAX80, ICMN-TAX90, ICMN-TAX100).

The BAU scenario shows that the final energy consumption decreases because of declining clinker content and deployment of more efficient production processes in the future (Figure 32). Since coal is the cheapest fuel, coal decreases only by 12% compared to the other fuels (electricity -24% and Alternative fuels, such as waste and biomass -33%), indicating substitution effects from alternative fuels to coal for those process steps that require high temperature levels. In the 80% CO_2 cap scenario, a fuel switch towards less CO_2 intensive fuels can be observed already until 2030. After 2030 carbon capture is assumed to be available as an option for the cement industry. This allows to use coal while reducing emissions substantially. Compared to the combustion process without CCUS, energy intensities are higher if CO_2 is captured due to the additional energy requirements for the capture process. This effect is visible in the scenario results for the CC-80 scenario where the total final energy consumption in 2050 exceeds the consumption level of the BAU scenario. In 2050, 65% of the electricity is used for the carbon capture process. Specifically, this analysis reveals that the oxyfuel technology to be the most cost-effective CCUS technology in 2050. Conversely to other CCUS technologies, such as monoethanol-amine processes, for which additional energy is needed for thermal purposes to recover the amine solution, oxyfuel-based CCUS need additional electricity to operate the air separation unit for providing oxygen for the combustion process.

The analysis of the energy efficiency (EE) scenarios shows that an efficiency improvement up to 35% is possible with the best available technologies compared to an efficiency improvement of 20% in the BAU scenario. The additional energy efficiency is achieved by fuel switch (from coal/waste to natural gas), which eventually increases the production costs of cement significantly.

The TAX scenarios indicates that up to a tax of 60 EUR/t_{CO2} there is no major change in energy consumption or CO_2 emissions. In other words, these carbon price does not enable fuel switching as seen in the EE scenario. With a CO_2 tax of 80 EUR/t_{CO2} and above, CO_2 abatement with carbon capture becomes cost effective. However, the energy consumption in the TAX scenario TAX-80 increases compared to the BAU scenario due to the deployment of CCUS technologies, which is similar to the observations under the CO_2 CAP scenario.

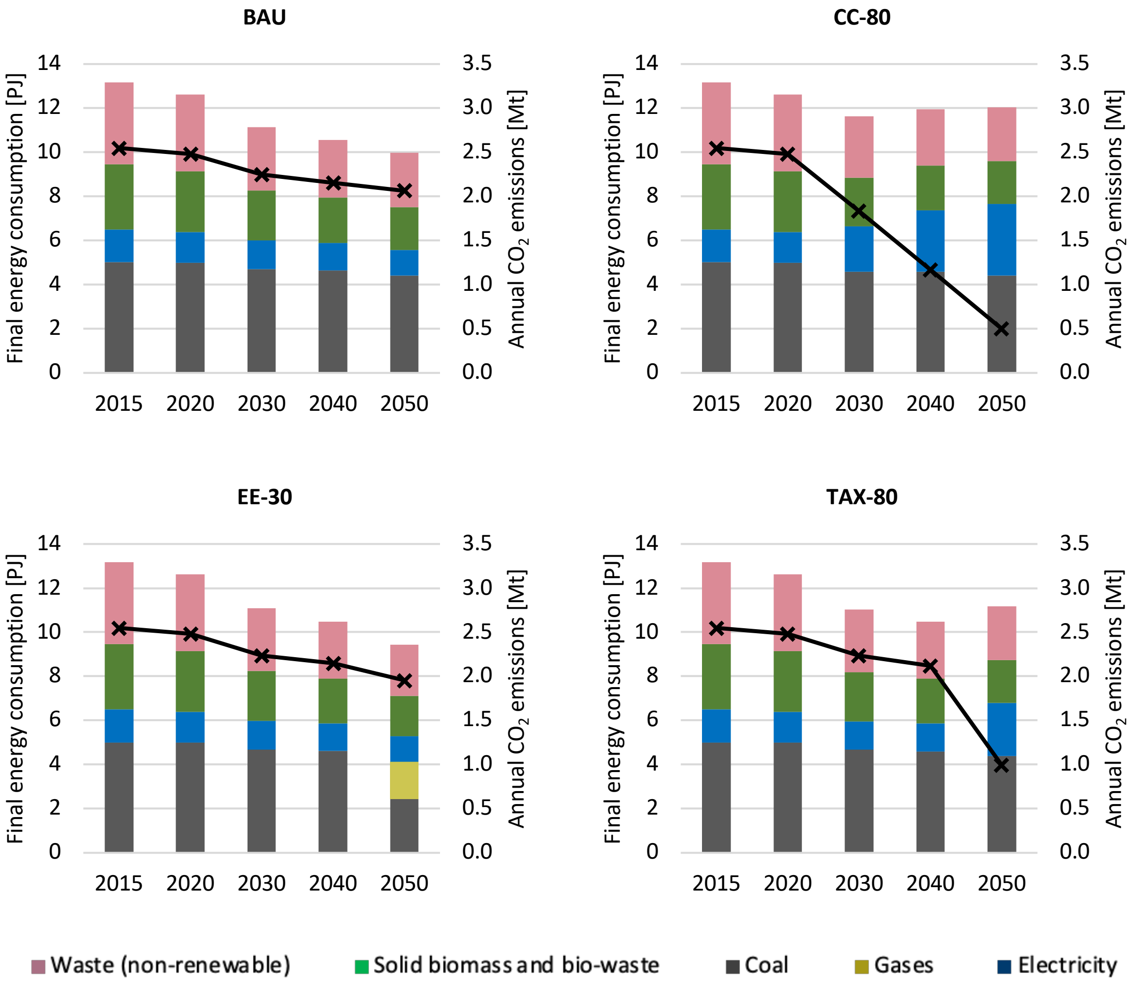


Figure 32: Final energy consumption in the Swiss cement industry (the line in plots depicts the annual CO_2 emissions from energy combustion and process-related CO_2)

Because of the decreases in energy consumption in the BAU scenario, the total CO_2 emissions (energy and process-related) decrease correspondingly. With a CO_2 tax up to 60 EUR/t_{CO2} there is no change in CO_2 emissions compared to BAU (Figure 33). At a CO_2 tax of 80 EUR/t_{CO2}, the CO_2 emissions in 2050 reduce by 60% in 2050 while a CO_2 tax of 100 EUR/t_{CO2} is sufficient to cover the costs of CO_2 capture technology for cement production (costs for transport and storage or utilization of CO_2 would need to be considered additionally) assuming CCUS technology is an available option. Furthermore, because of the lower energy consumption in the EE scenarios compared to the BAU scenario, the CO_2 emissions also decrease slightly faster in the EE scenarios compared to BAU.

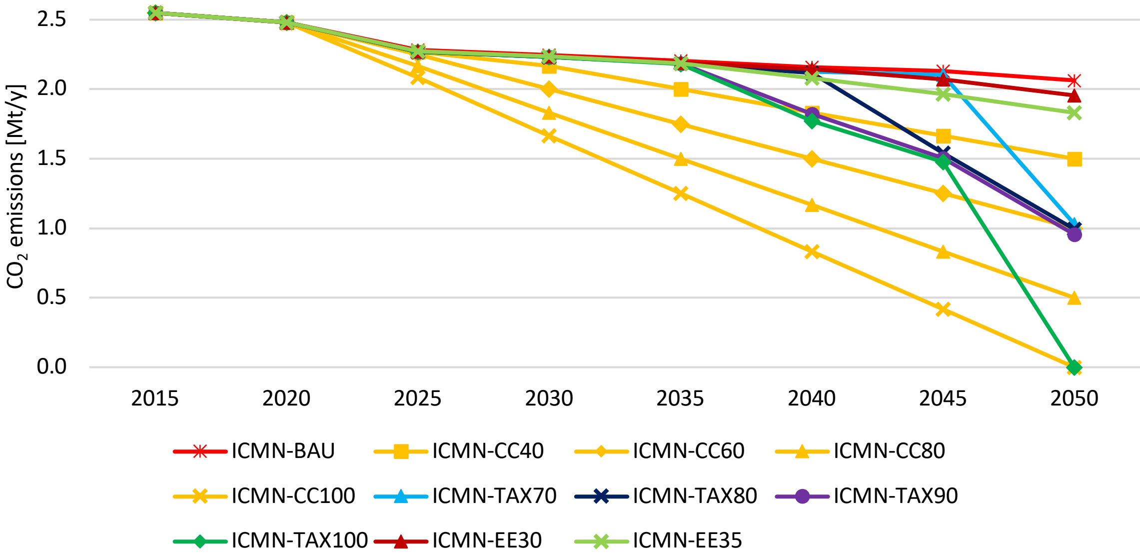


Figure 33: Annual CO_2 emissions of the Swiss cement industry under specific policy constraints imposed to the cements sector only

From our dedicated analysis of the cement sector we can draw a number of key messages which go beyond the analysis shown in section 2.2.7.1.

- Future cement production improves its energy efficiency and decrease its CO_2 emissions even without policy action mainly due to the decreasing clinker content in cement and deployment more efficient technologies (to replace existing technologies).
- No significant reduction of the CO_2 emissions is possible in the cement sector without carbon capture and the corresponding infrastructure to transport and sequestrate CO_2.
- Although a CO_2 tax up to 60 EUR/t_{CO2} results in a more expensive cement production, the total CO_2 emissions will not be reduced significantly.
- A CO_2 tax above 60 EUR/t_{CO2} makes is economically attractive to avoid CO_2 emissions with carbon capture technologies with the benefit of avoiding both, energy and process-related CO_2 emissions.
- Carbon capture will increase the specific electricity consumption of the cement industry if oxyfuel technology is employed.
- From an economic point of view, fuel switching is only a limited option to decrease the CO_2 emissions of the cement industry because of the high share of process related emissions and limitations with regards to switching of burner technologies in the complex process setting of a cement plant.

2.2.7.3 Macro-economic impacts

Figure 34 shows the main feedbacks from the energy system to the economy that are captured in E3ME. Energy prices and energy consumption determine the energy costs that are faced by final users (i.e. industry and households). In the case of industry, higher energy prices increase costs of production and prices, driving reductions in competitiveness and demand for their products. This drives a reduction in industry output and GDP. In the case of households, higher product prices and higher energy bills reduce real incomes and consumption, leading to further reductions in industry output and GDP. The indirect multiplier effect exaggerates this impact (i.e. as industry output falls, employment demand falls, driving further reductions in disposable income and consumption).

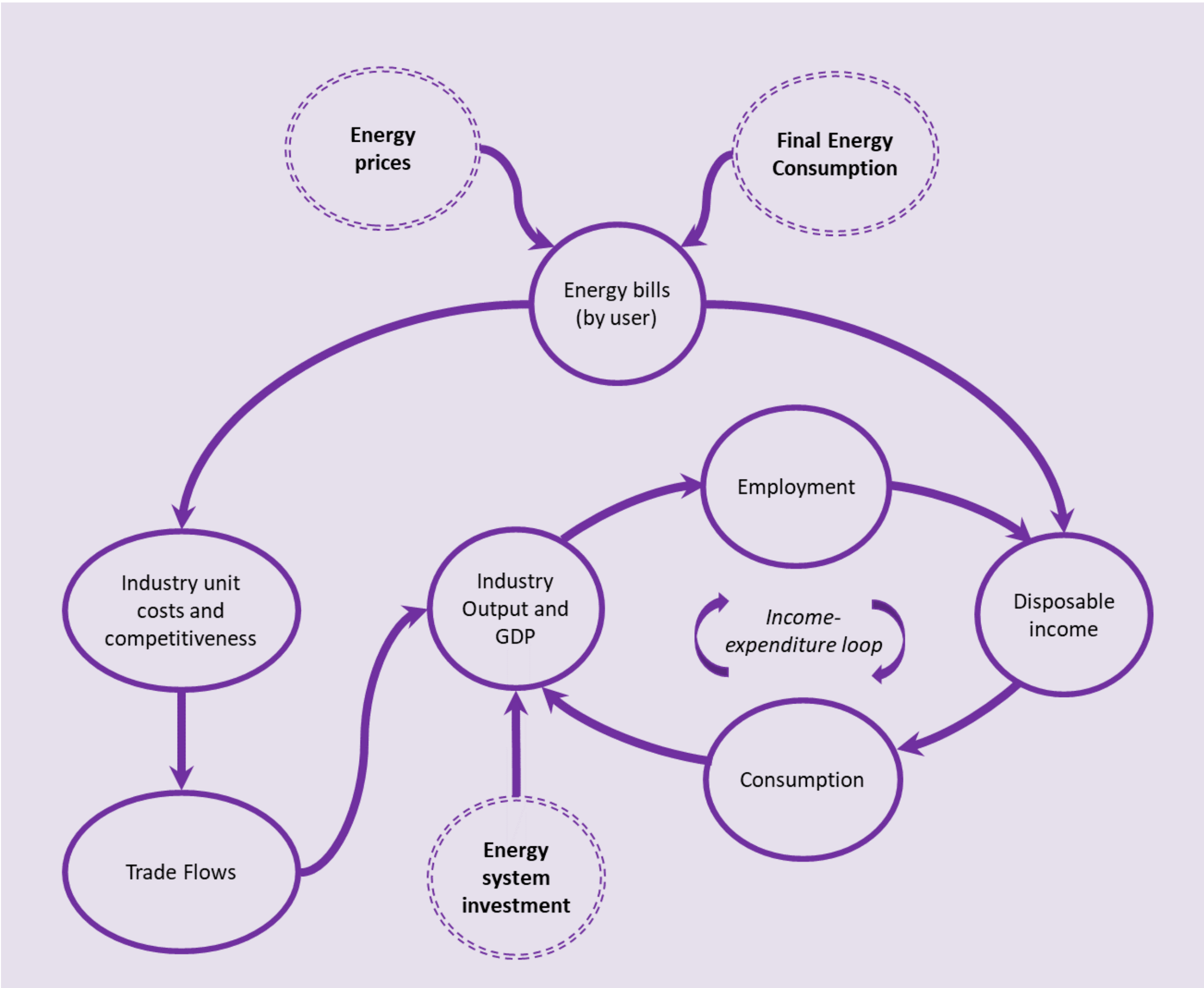


Figure 34: The economic impacts of energy system scenarios (as modelled in E3ME)

Energy Prices

In our approach for the joint modelling, we use the long run marginal costs provided by STEM for each fuel as an indicator of the long-term energy price development that is input to E3ME. Relevant for the macro-economic impacts are the relative price changes compared to the baseline development. In our analysis, the baseline is represented by a scenario assuming a continuation of current existing policies in Switzerland but neglecting future goals of the Swiss Energy Strategy 2050 and the long-term Swiss climate goals. We use long-run marginal costs which not only reflect changes in the energy supply mix but also capture the effect of changes in energy consumption on marginal costs of an energy commodity. As such, the marginal costs used cover the cost of financing of new infrastructure investments in energy security and taxing of CO_2, for instance. As we use marginal costs to indicate future energy price developments, the costs and availability of energy technologies has an impact on the price levels.

In both the E-POL and CLI scenarios, energy prices initially increase relative to baseline (2015-2020), and then remain higher than in the baseline over the period to 2035. In the period post-2035, energy prices in the E-POL and CLI scenarios grow at a much faster rate than in the baseline. This fast growth is particularly evident in the CLI scenario, where the STEM results for electricity supplied to household indicate marginal supply costs 350-500% higher than baseline by 2050 (as shown in the Figure 35). The high marginal cost in the long run is mainly due to stringency in climate target in the CLI scenario. One has to interpret this price level against the assumptions made in the CLI scenario, where we assume a solar PV potential of 20 TWh at most and 4.3 TWh of electricity from wind (Table 37) while all nuclear power plants are phased out by 2045 and no CO_2 capture technology is assumed to be available in the energy sector. These assumptions are very restrictive with significant impacts on the marginal costs to provide electricity in the long run. A sensitivity analysis of the availability of low-carbon electricity technologies was therefore run to test the impact under assumptions of (i) greater solar PV resource availability and (ii) greater CCUS technology availability. The results from the sensitivity analysis show that, if solar PV technologies can be deployed up to 36 GW (equivalent to about 36 TWh of production), long-run marginal electricity supply costs under CLI-policy conditions are only 30% higher than in the baseline scenario in 2040 and twice as high in 2050. Such a dampening effect on marginal supply costs (compared to the central CLI scenario) can also be observed for technologies using capture, transport and storage of CO_2 (CCUS). Ultimately, based on the approach used in this study, a higher availability of low-carbon technologies translates into less-severe macro-economic costs.

In the E-POL scenario, the implemented energy policy goals and available supply and demand technologies to achieve these goals determine the marginal costs of electricity and fuels. Specifically, limiting the per capita electricity consumption triggers high costs as expensive fuel supply and demand options need to be deployed. For example, at constraint electricity consumption, more building insulation is required to further reduce heat consumption as electricity applications for heating purposes are more difficult to deploy, because they compete with electric vehicles in the transport sector needed to meet the vehicle emission targets. These interdependencies in the energy system make electricity a scarce product of very high value.

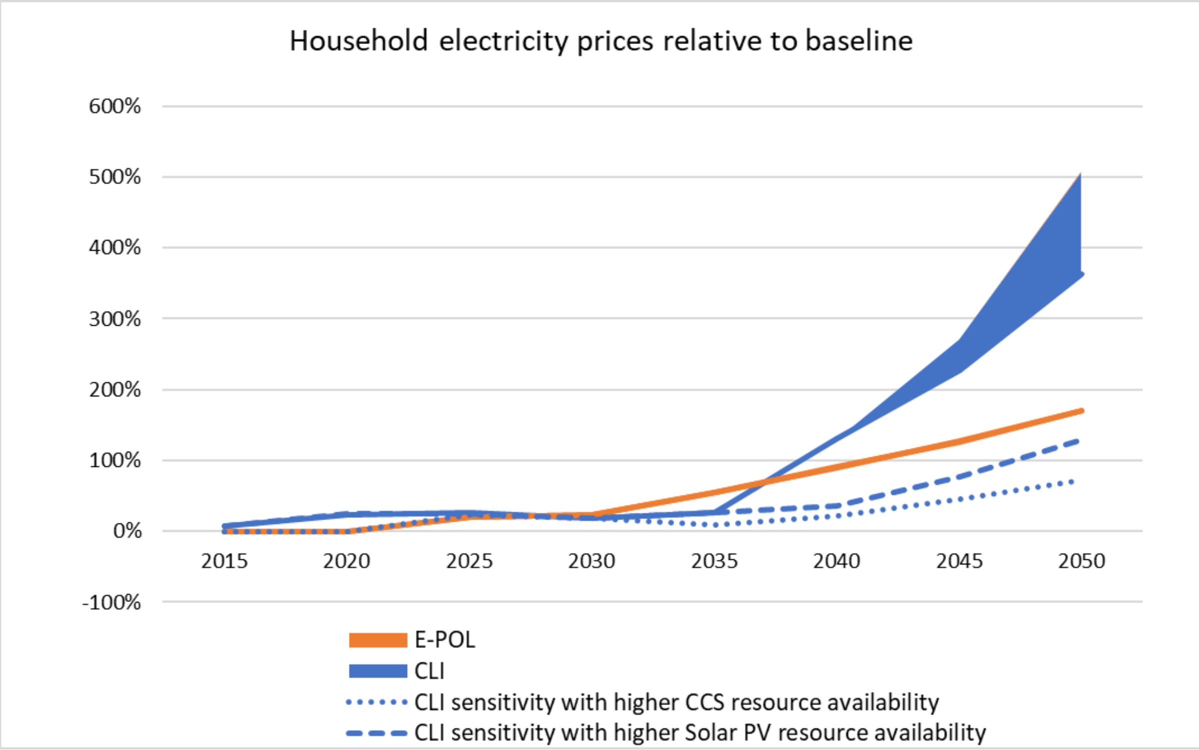


Figure 35 Household electricity prices relative to baseline

Consumer prices, real income and consumption

The consumer price index reflects the pattern seen in energy prices. There are direct effects of higher energy costs for consumers and indirect impacts, as higher energy costs faced by firms drive up prices of other goods and services. In addition, there are considerably higher vehicles prices in the CLI scenario (and the E-POL scenario, to a lesser extent). Over the period to 2030, the scale of increase in energy prices is less extreme and so consumer prices remain less than 2% above baseline in the E-POL and CLI scenarios. However, over the period 2035-2050 energy prices grow more rapidly and, by 2050, the considerably higher energy prices drive up the consumer price index to 12% above baseline in the E-POL scenario and 27-40% above baseline in the central CLI scenario. By means of comparison, this reflects annual growth in average consumer prices in the central CLI scenario of around 1ppts above baseline over the period to 2050.

In the sensitivities that assume greater availability of renewable resources, the impacts on consumer prices are more muted, reflecting the slower growth in electricity prices, compared to the central CLI scenario.

The higher consumer prices in the CLI and E-POL scenarios (compared to baseline) reduces real disposable income and consumption in both scenarios.

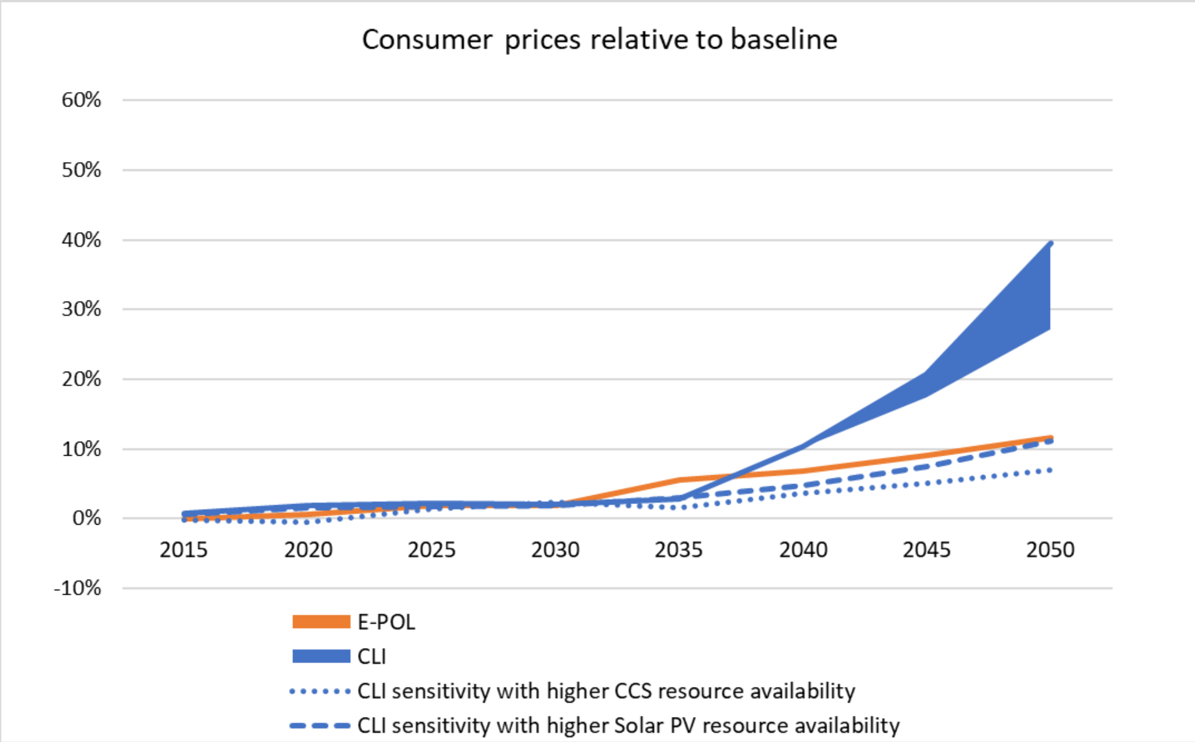


Figure 36 Consumer prices relative to baseline

Investment

Energy system investments in the CLI and E-POL scenarios are higher than baseline, for the majority of the time period. Investments in the power sector are particularly volatile, reflecting the lumpy nature of these large infrastructure projects. Despite higher investments in the energy system, the net investment effect is reduced somewhat by lower levels of investment across most other sectors of the economy, due to lower industry output expectations, as a result of lower levels of GDP and demand. After taking into account these (negative) indirect investment effects due to higher energy prices and lower GDP growth, final investment is negative in each scenario for most of the modelling period. Exceptions occur in years where energy system investments are at their highest, (i.e. in 2030 and 2050 in the CLI scenario and over the period 2035-2050 in E-POL).

The charts below show the scale of net annual investment in the CLI and E-POL scenario in 2050, decomposed into a direct energy systems investment effect and an indirect investment effect.

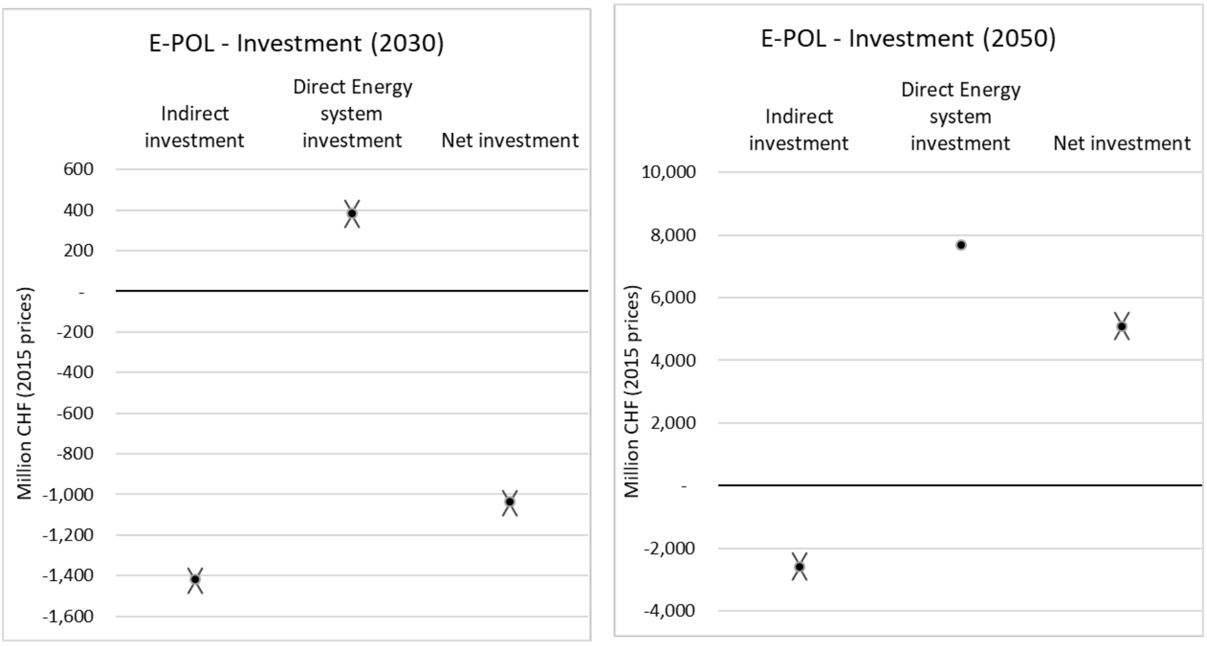


Figure 37 Annual investment in E-POL

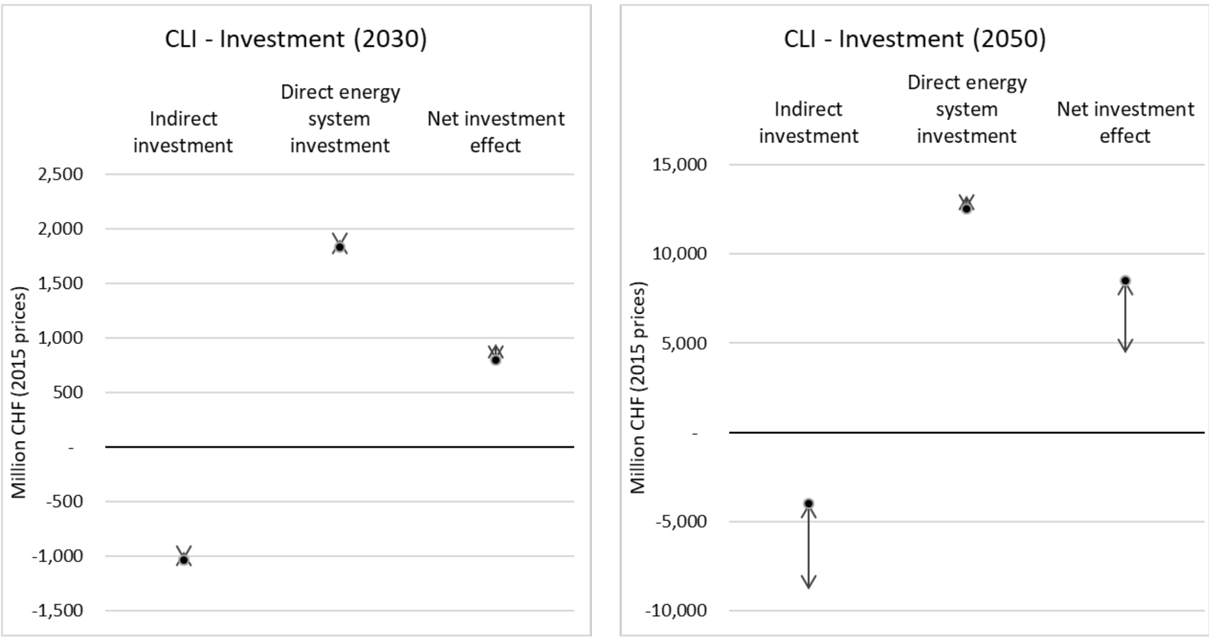


Figure 38 Annual investment in CLI

Trade

There is a small increase in net exports (in absolute terms). The demand for imports falls due to reduced domestic output and consumption. Demand for exports also falls, but to a lesser extent.

The trade results are driven by two key effects:

1. price effects: higher energy costs in Switzerland reduce the competitiveness of industry
2. demand effects: domestic demand is reduced and global demand is also affected by the global low-carbon policies that are assumed to be simultaneously implemented.

Sectoral results (Gross output and Employment)

Gross output falls relative to baseline across most sectors in both the E-POL and CLI scenarios. Sectors that see a particularly large negative impact include the agriculture sector, where margins are already thin, and the transport and distribution sector, due to higher transportation costs and reductions in trade. Industry and service sectors are also affected by reduced competitiveness internationally and reduced domestic demand (as production costs increase and consumers' discretionary spending falls). For CLI, an increase in electricity demand and an increase in investment in electricity (towards 2050) drives an increase in output in this sector, but this is negated by reductions in demand and output in other utilities sectors (including gas supply).

The impact on employment is largely driven by the impact on output. The overall impact on employment is slightly lower than the impact on output, partly because of substitution between energy and labour (i.e. as energy costs increase, there is some movement away from energy towards labour inputs to production). This effect is small, however, as it is typically difficult (and, in some cases, impossible) to substitute between these inputs to production.

Gross output

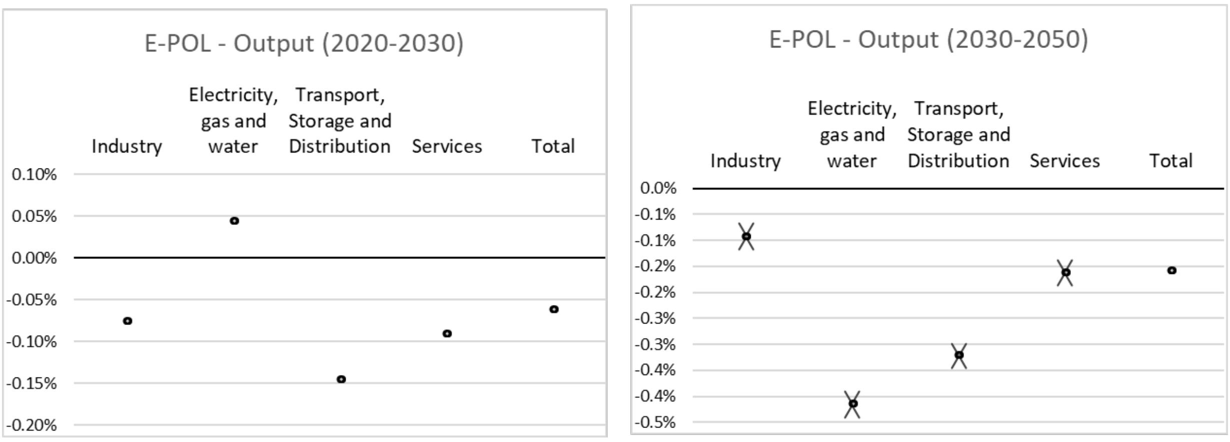


Figure 39 Impact on annual growth in gross output compared to baseline (E-POL)

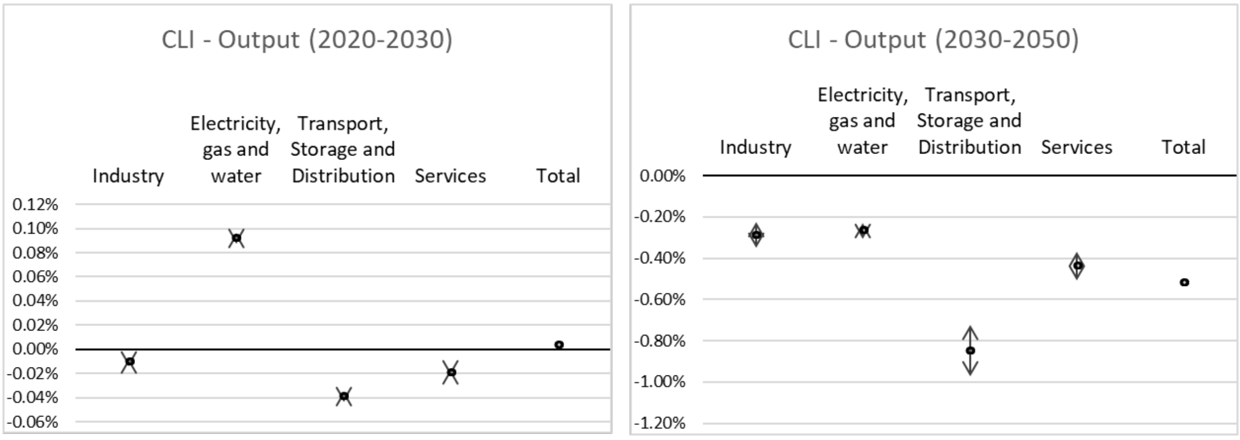


Figure 40 Impact on annual growth in gross output compared to baseline (CLI)

Employment

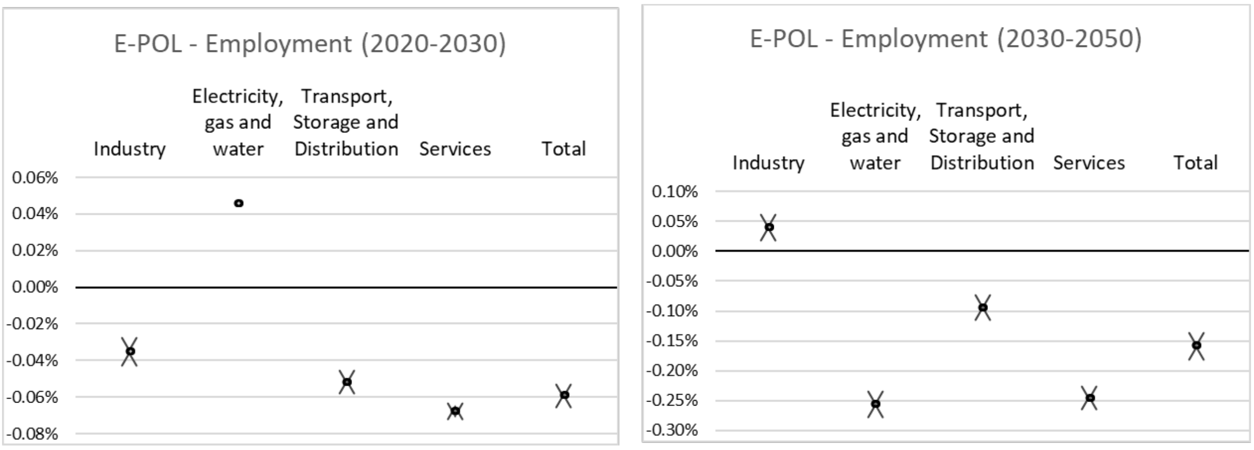


Figure 41 Impact on annual growth in employment compared to baseline (E-POL)

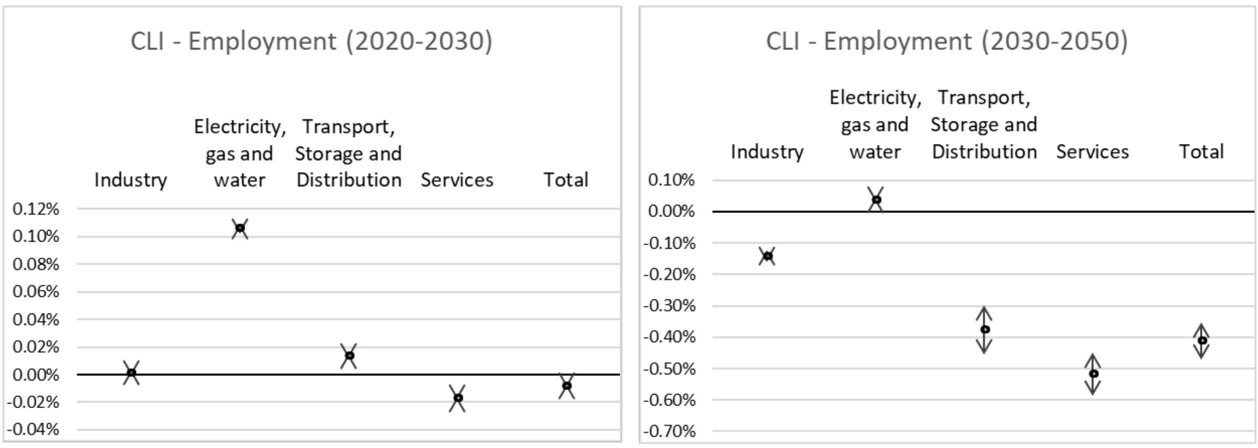


Figure 42 Impact on annual growth in employment compared to baseline (CLI)

GDP

The impact on GDP is negative in both scenarios, as a result of the substantially higher energy prices faced by final consumers as a consequence of the more ambitious energy and climate policies, and the higher CO2 price. The (negative) GDP impact observed in each scenario follows a similar pattern to the relative increase in energy prices, with relatively small differences compared to baseline over the period to 2040, and a larger GDP impact coming through in the period 2040 to 2050, when energy price growth is fastest. By 2050, the level of GDP is 4.1%-4.9% lower than baseline in the E-POL scenario (which translates to an annual GDP growth 0.1ppt lower than baseline over the period 2020 to 2050). In the central CLI scenario, the level of GDP is 0%-0.2% lower than baseline in 2030 and 7.8%-11.7% lower than baseline in 2050 (equivalent to annual GDP growth 0.3ppt lower than baseline over the period to 2050). Interestingly, in 2030, the impact on GDP is lower in the CLI scenario (0%-0.2% lower than baseline) compared to the E-POL scenario (0.7%-1% lower than baseline). The main reason for this is that, in the CLI scenario, there are larger energy investments that take place in the earlier years. This investment stimulus is sufficient to offset the negative effects associated with the higher energy prices in this scenario in the early years.

Table 19 Impact on GDP, consumption and investment(percentage difference from baseline)

		2030 (high)	2030 (low)	2050 (high)	2050 (low)
GDP	E-POL	-0.7%	-1.0%	-4.1%	-4.9%
	CLI	0.0%	-0.2%	-7.8%	-11.7%
Consumption	E-POL	-1.7%	-2.4%	-10.3%	-13.1%
	CLI	-1.3%	-2.1%	-20.3%	-30.8%
Investment	E-POL	-0.3%	-0.5%	0.7%	1.7%
	CLI	1.1%	1.2%	0.8%	2.1%

Table 20 Impact on other macroeconomic variables (percentage difference from baseline)

		2030 (high)	2030 (low)	2050 (high)	2050 (low)
Consumer Prices	E-POL	1.8%	1.8%	11.7%	11.6%
	CLI	2.1%	2.0%	26.6%	39.5%
Real incomes	E-POL	-1.7%	-2.4%	-10.3%	-13.1%
	CLI	-1.3%	-2.1%	-20.3%	-30.8%
Employment	E-POL	-0.3%	-0.7%	-1.8%	-3.7%
	CLI	-0.3%	-0.8%	-3.8%	-9.6%

Results from sensitivity analyses

Revenues from carbon tax and energy tax policies, when re-invested back into the economy, can create a positive economic stimulus. In previous modelling analyses using E3ME, we have found that if this revenue used in effectively, it is possible that the net economic impact of a carbon tax policy can be positive, creating an 'environmental double dividend'.[19]

In the model results presented for the central scenarios, there is no mechanism in place to recycle revenues from energy and carbon taxes back into the economy: it is implicitly assumed that these revenues are used to pay off government debt. In both the E-POL and CLI scenarios, the high energy and carbon taxes create sizeable revenues for government (reaching around 16bn CHF annually by 2050, in the CLI scenario). If these revenues are spent by the government, re-invested, or used to cut taxes elsewhere, this will generate macroeconomic benefits which will at least partially negate the negative GDP impacts that are observed in these scenarios. In a sensitivity analysis, we find that the impact of carbon tax revenue recycling would reduce the scale of the negative GDP impacts observed in the CLI scenario by a quarter.

In the central scenarios, it is assumed that there is limited possibility for increasing electricity imports, and limited availability of solar PV and CCUS resources, which therefore limits the options for cheaper low-carbon electricity generation or electricity imports in the more ambitious climate scenarios. To test the impact of the resource availability assumptions on the GDP result, we tested two further sensitivities: one where we assumed increased potential for solar PV electricity generation, and one where we assumed increased potential for CCUS generation. In these sensitivities, we find that the increased availability of lower-cost low-carbon resources has a substantial effect on the electricity price, so that, by 2050, the household electricity price is only around double that in the baseline (compared to four times as high as the baseline, in the central CLI scenario). The slower growth in electricity prices (compared to the central CLI scenario) substantially reduces the scale of the negative economic results observed in the results for the two sensitivities. In 2030, the GDP result is not substantially different to baseline (the negative economic impact related to slightly higher energy prices is negated by the positive effect of the low-carbon investment stimulus). By 2050, GDP is around 3%-4% lower than baseline in these results, due to improved availability of low-carbon generation options, as shown in Table 22.

Table 21 Impact on GDP and employment in the CLI scenario sensitivities

		2030	2050
GDP	CLI (revenue recycling + improved CCUS technology availability)	-0.47%	-3.16%
	CLI (revenue recycling + improved solar PV resource availability)	0.30%	-4.12%
Employment	CLI (revenue recycling + improved CCUS technology availability)	-0.24%	-2.31%
	CLI (revenue recycling + improved solar PV resource availability)	-0.28%	-3.85%

[19] For example, see Ekins et al. (2012), Ekins et al. (2011) and Lee et al. (2012).

3 National cooperation

The energy system modelling work of this project links to several modelling activities performed under the Swiss Competence Centres for Energy Research (SCCER), in particular to the SCCER Joint Activity *Scenarios and Modelling* in which STEM model is applied to perform an integrated system analysis. This SCCER Joint Activity joins forces of all eight SCCERs with allows for synergies of industry sector focused model development as envisaged in SWIDEM with the research undertaken in SCCER Efficiency of Industrial Processes (EIP). Contact has been made with the team of University of Geneva and EPFL and further exchange on potential collaboration is planned for 2019. Moreover, there is cooperation with the project team of the SCCER Joint Activity *White Paper Power-to-X*, where electricity-based hydrogen and related products are also investigated for the industry sector. Spill overs from this project were gained for the SWIDEM project as well.

4 International cooperation

The project team itself, with PSI and Cambridge Econometrics as partners, represents an international cooperation. In addition, both research teams are involved in different international cooperation's based on other on-going research projects related to analysis of energy-economy interactions (CE) or related to energy systems modelling (PSI as member organisation of IEA-ETSAP).

Cooperation directly related to this project, in particular concerning the exchange of common data sources, is envisaged with the research group of the Centre for European Economic Research (ZEW) in Mannheim (Germany) that works on the SFOE funded research project on "Empirical Estimation of Electricity Demand Elasticities for Different Customer Groups in Switzerland and Implications for Energy Policies". The first year project progress review was held jointly in October 2018 in Zürich.

5 Outlook

The SWIDEM project is a first and very important step in advancing the representation of industry in the Swiss energy systems model. It has proven valuable to expand the system model with details on new technology concepts and measures that promote energy efficiency and CO_2 emissions mitigation. Compared to other energy end-use sectors, the industry sector is extremely heterogenous with respect to the type of energy applications and the opportunities for technology shifts and process improvements. This requires detailed analytical tools that incorporate the opportunities and limitations of the applications of energy technology for the various industry branches. The model advancements performed in the SWIDEM project will contribute to multiple other research activities in future, specifically under the framework of the SCCERs, where future scenarios for the Swiss energy systems are investigated with its inter and intra-sectoral trade-offs. This allows evaluation of industrial options versus other options of the energy system in a more detailed and elaborated manner. Particularly for deep decarbonization scenarios, the model development focusing on the cement sector represents an important step since it expanded the scope from energy-related CO_2 emissions to process-related CO_2 emission which ultimately play a significant role if substantial emissions reduction are to be achieved. The work on a more detailed analysis of the industry sector in a holistic systems context is expected to be continued by incorporating further technology details in industrial sub-sectors.

Building on the knowledge gained through the collaboration with Cambridge Econometrics and the improved understanding of the opportunities and challenges in linking an energy systems model with a macro-econometric model we seek further opportunities to amplify such research in order to achieve a more comprehensive assessment of the implications of energy policy and long-term energy sector development pathways. In SWIDEM, the focus on the joint model application was on industry, however, the established approach can be applied for other economic sectors as well.

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Appendices

I Industry sectors in STEM and E3ME

Table 22: Overview of the new composition of the industrial sub-sectors in STEM

Industry sectors	Industrial energy usage
IFOO -- Food	SH - Space heating
IPUP -- Pulp and Paper	WH - Water heating
ICHM -- Chemicals	PH - High temperature process heat
ICMN -- Cement and non-ferrous minerals	LT - Lighting
IBMT -- Basic metals (Iron and steel and non-ferrous metals)	AC - Air conditioning
IMMO -- Metal tools, machinery, textile, other industries	EQ - Electrical and ICT equipment
ICNS -- Construction	MD - Mechanical drive
	OT – Others

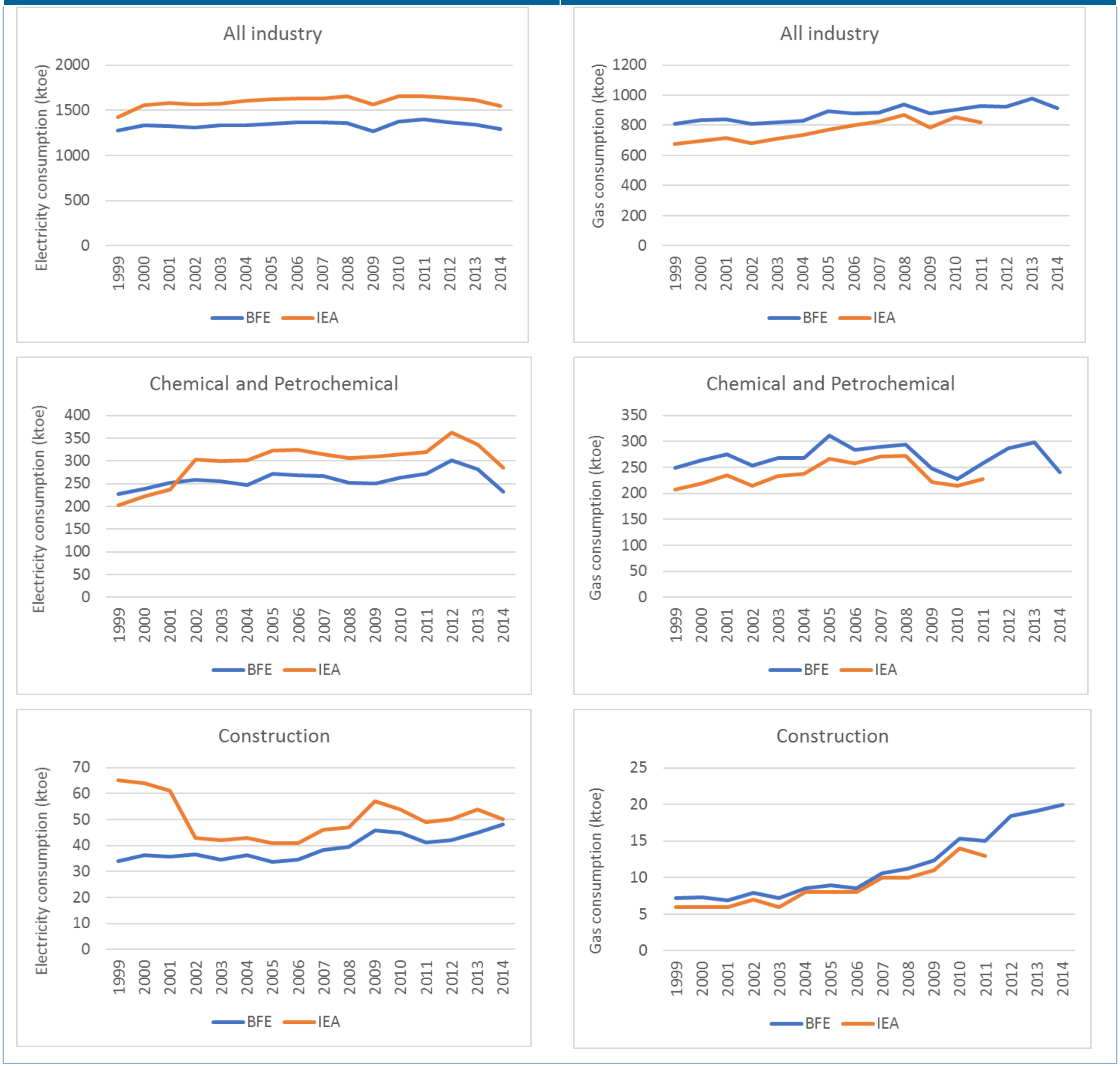
Table 23 Energy sectors (Fuel Users) covered in E3ME (industry sectors are highlighted in red)

1 Power own use & transformation	12 Other industry
2 Other energy own use & transformation	13 Construction
3 Iron and steel	14 Rail transport
4 Non-ferrous metals	15 Road transport
5 Chemicals	16 Air transport
6 Non-metallic minerals	17 Other transport services
7 Ore-extraction (non-energy)	18 Households
8 Food, drink and tobacco	19 Agriculture, forestry, etc
9 Textiles, clothing & footwear	20 Fishing
10 Paper and pulp	21 Other final use
11 Engineering etc	22 Non-energy use

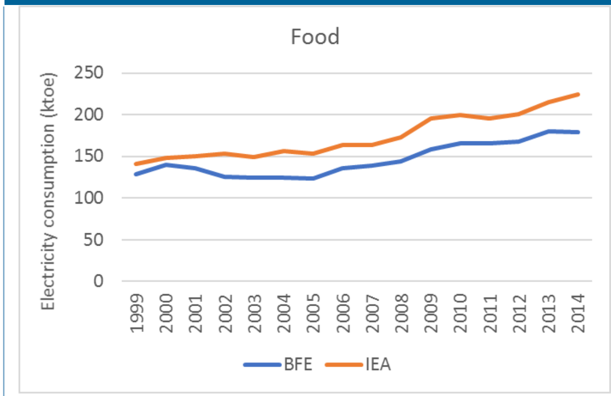
II Comaprison of data on industry energy consumption

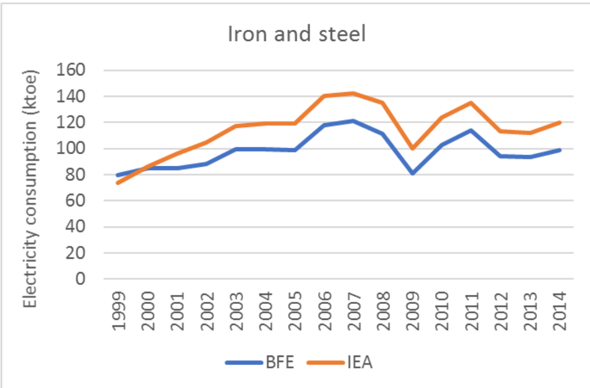
Figure 43: Gas and electricity consumption by industry sector: comparison between IEA and BFE data

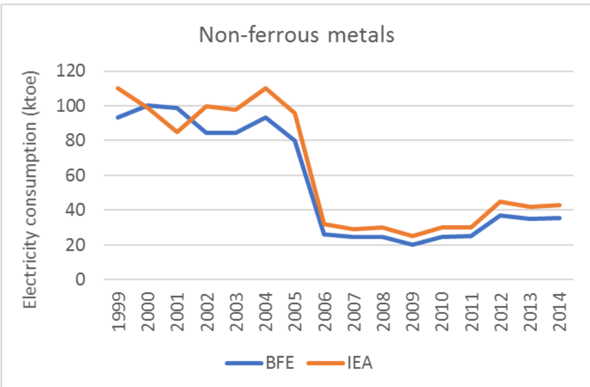
Electricity consumption data by industry sector	Gas consumption data by industry sector

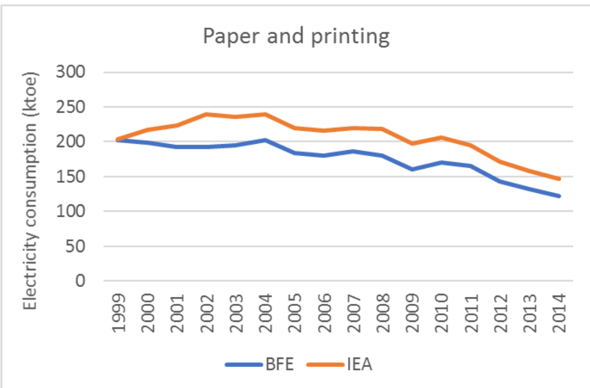


Electricity consumption data by industry sector

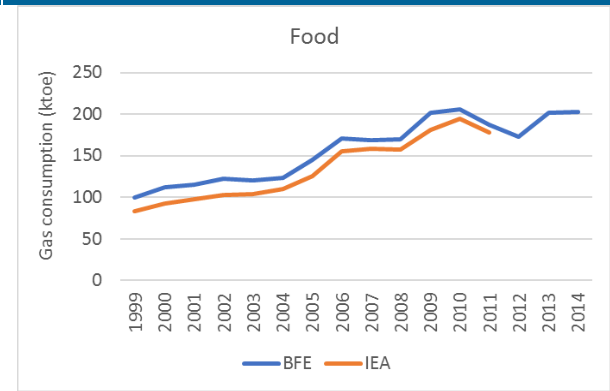


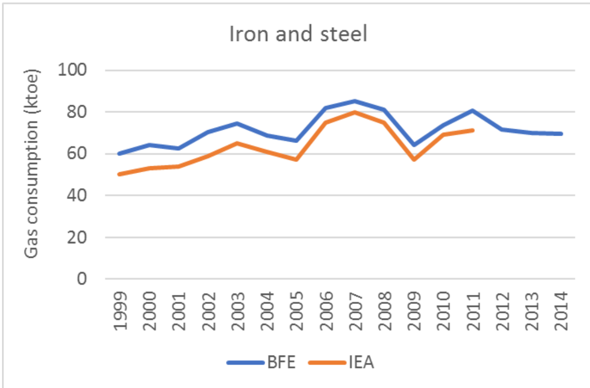


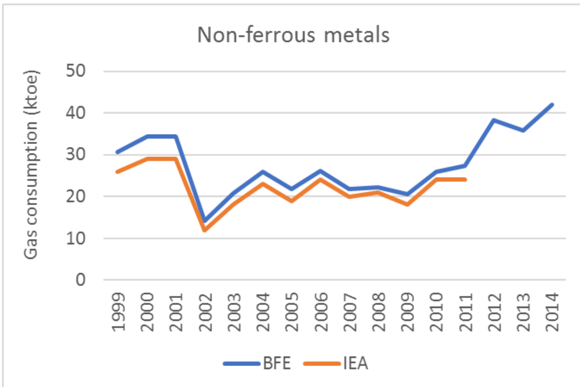


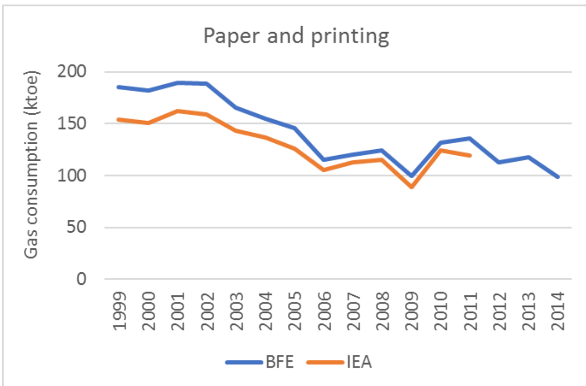


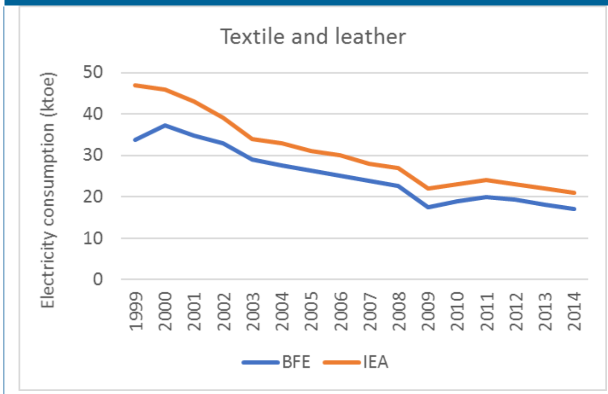
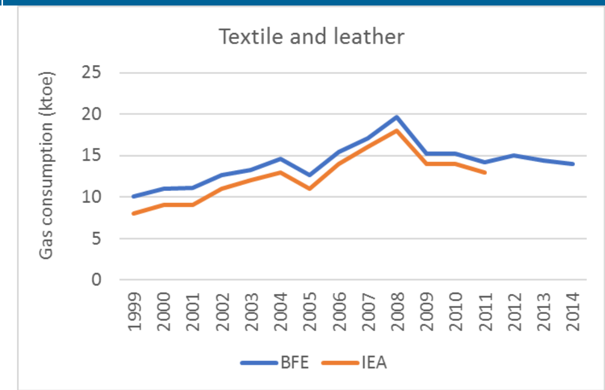
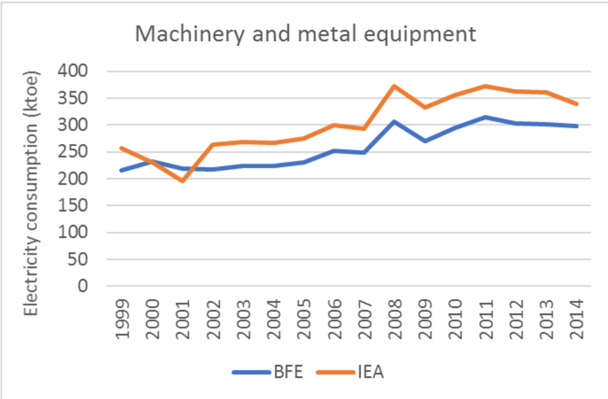
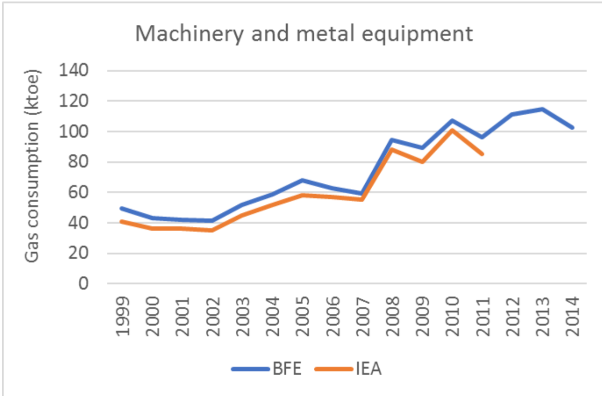
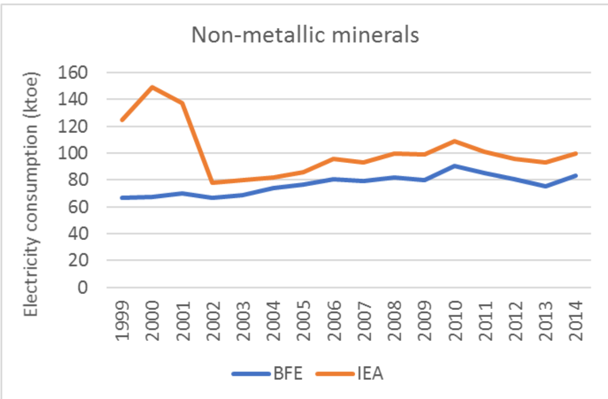
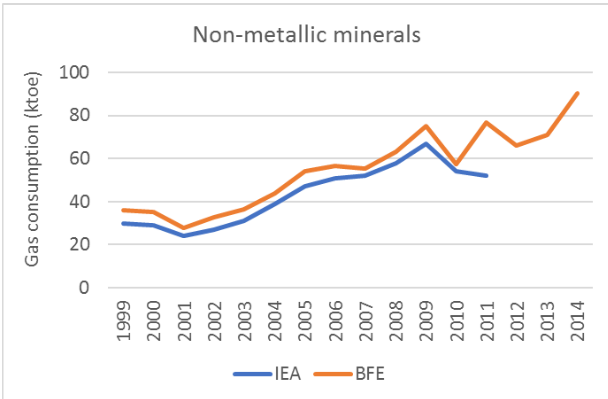
Gas consumption data by industry sector



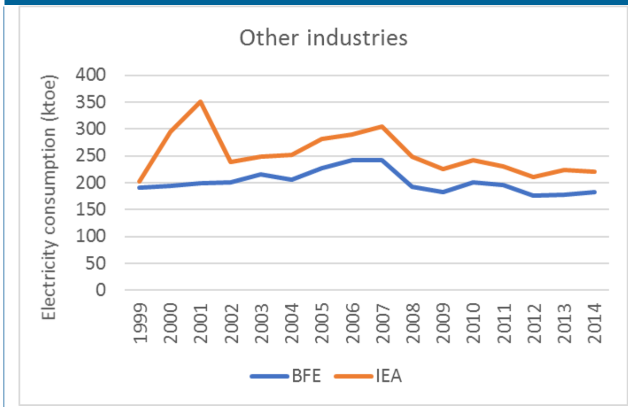


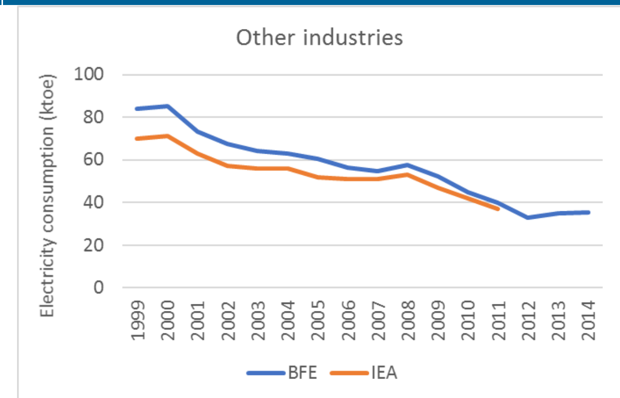




Electricity consumption data by industry sector	Gas consumption data by industry sector
	
	
	

Electricity consumption data by industry sector	Gas consumption data by industry sector





III Sector-specific elasticity estimates in energy demand studies

Table 24 Results from 'Econometric Estimation of Energy Demand Elasticities' (Madlener et al. 2011) - uses sector-level electricity data for Germany from 1970-2007 and cointegrating econometric approach

Sector	Economic activity	Price elasticity (electricity)	Significant time trend?
1: Food & Tobacco	SR: 0.17 LR: 0.7	SR: 0 LR: 0	yes (positive)
4: Pulp & Paper	SR: 1.02 LR: 1.9	SR: 0 LR: -0.52	no
5: Chemicals	SR: 0.74 LR: 1.11	SR: 0 LR: 0	yes (negative)
6: Non-metallic Minerals	SR: 0.51 LR: 1.01	SR: -0.57 LR: -0.3	yes (positive)
8: Transport Equipment	SR: 0.48 LR: 1	SR: -0.31 LR: -0.3	no

Table 25 Results from 'Variation in price and substitution elasticities between sectors – A microdata analysis' (Tamminen and Tuomaala, 2012) - Uses firm-level data for Finland from 2000-2009 and cointegrating econometric approach

	Price elasticity (electricity)	Price elasticity (other energy)	Shadow elasticity of substitution (all energy inputs)
24: Manufacture of chemicals	-0.98*	-0.98*	1.57*
25: Manufacture of rubber and plastic products	-1.00*		
26: Manufacture of glass and ceramic products	-1.30*	-0.95	6.01
28: Manufacture of metal products	-1.00*		
156: Manufacture of food products, beverages and tobacco	-0.2		
271: Manufacture of iron and steel	-0.98*	-1.00*	0.23*
2725: Manufacture of processed iron and steel products	-1.29*	-1.00*	0.96*
21121: Manufacture of pulp, paper and paperboard	-0.97	0.83*	1.0*

Note: * indicates estimates are significant at the 5% level

IV Detailed technical and economic assumptions (baseline learning rates)

The assumptions for the electricity generation technologies relevant to Switzerland are presented in Table 26. Table 27 presents the technology characterisation for heat supply in end-use sectors: the cost ranges reported in the residential sector correspond to single houses (small-scales) and multi-family houses (medium-scales). Table 28 presents the typical costs and efficiencies for medium-sized private cars, while Table 29 presents the typical costs and efficiencies for medium-sized buses. Table 30 presents the costs and efficiencies for medium-to-large sized two-wheelers. Table 33 presents the techno-economic assumptions of stationary non-hydro electricity storage, while Table 34 the assumptions for stationary thermal storage. Table 35 presents the hydrogen-related technologies for production, methanation and storage.

Table 26: Technical-economic characterisation of key electricity generation technologies[20]

	Size	Specific Inv. Cost (CHF/kW)			Fixed O&M (CHF/kW)			Efficiency electric			Efficiency thermal		
	MW	2015	2030/5	2050	2015	2030/5	2050	2015	2030/5	2050	2015	2030/5	2050
Large hydropower	-	6000	6000	6000	30	30	30	-	-	-	-	-	-
Small hydropower	-	11500	11500	11500	250	250	250	-	-	-	-	-	-
Pumped hydro	100	1250	1250	1250	30	30	30	78%	78%	78%			
Wind power onshore	3	2500	2200	2100	100	125	130	-	-	-	-	-	-
Solar PV rooftop	0.006	2600	1400	1200	97	64	59	-	-	-	-	-	-
Wood combustion CHP	11	6400	6400	6400	740	740	740	24%	24%	24%	42%	42%	42%
Biogas CHP	0.27	9500	9500	9500	540	540	540	41%	41%	41%	34%	34%	34%
Wood ORC CHP	0.6	18300	18300	18300	500	500	500	14%	14%	14%	52%	52%	52%
Wood gasification CHP	0.18	6700	6700	6700	350	350	350	30%	30%	30%	45%	45%	45%
Waste Incinerator	13	6000	6000	6000	910	910	910	20%	20%	20%	45%	45%	45%
Deep geothermal	8	14500	14500	14500	44	44	44	-	-	-	-	-	-
Gas CHP (micro scale)	0.001	16800	14900	14000	-	-	-	26%	28%	29%	66%	64%	63%
Gas CHP (small scale)	0.01	4500	4000	3800	-	-	-	28%	30%	31%	64%	62%	61%
Gas CHP (medium scale)	0.1	3000	3000	3000	-	-	-	37%	39%	40%	50%	48%	47%
Gas CHP (large scale)	1	4000	4000	4000	-	-	-	40%	43%	44%	46%	43%	42%
Gas turbine CC	500	990	940	940	25	23	23	58%	62%	63%	-	-	-
Gas turbine CC with CO2 cap	390	1600	1300	1200	43	43	43	50%	54%	55%	-	-	-
Nuclear	1000	6000	6000	6000	110	110	110	-	-	-	-	-	-
Gas Fuel Cell	0.3	7500	4000	3000	100	45	45	42%	55%	60%	38%	33%	30%

[20] Based on *Bauer et al, 2017. Potentials, costs and environmental assessment of electricity generation technologies, BFE Report*

Table 27: Technologies for heat supply in end-use sectors[21]

	Investment cost CHF/kWth		Fixed O&M cost CHF/kWth		Efficiency for heat	
Industrial heat supply technologies	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Oil boilers	33	33	0.3	0.3	77%	80%
Gas/biogas/bio-methane boilers	44	44	0.4	0.4	80%	82%
Heat pumps (reference values)	363	363	3.1	3.1	296%	345%
Electric boilers	30	30	0.3	0.3	84%	85%
Solar thermal	2750	2750	0.2	0.2	-	-
Pellet boilers	75	75	0.6	0.6	74%	75%
Wood boilers	73	73	0.6	0.6	59%	60%
Coal boilers	58	58	0.5	0.5	66%	68%
Wastes boilers	58	58	0.5	0.5	66%	68%
Heavy fuel oil	30	30	0.3	0.3	66%	72%
Services heat supply technologies						
Oil boilers	109	109	0.6	0.6	83%	86%
Gas/biogas/bio-methane boilers	140	140	0.8	0.8	87%	95%
Heat pumps (reference values)	630	630	0.7	0.7	305%	420%
Electric boilers	60	60	0.4	0.4	90%	95%
Solar thermal	3800	1500	0.2	0.2	-	-
Pellet boilers	230	230	1.4	1.4	90%	90%
Wood boilers	170	170	0.9	0.9	72%	72%
Residential heat supply technologies (ranges refer to single – the most expensive – and multi – the cheapest – family houses)						
Oil boilers	410 - 1350	410 - 1350	0.5 - 1.6	0.5 - 1.6	83%	86%
Gas/biogas/bio-methane boilers	430 - 1460	430 - 1460	1.5 - 1.7	1.5 - 1.7	87%	95%
Heat pumps (reference values)	1360 - 3140	950 - 2200	1.4 - 1.5	1.4 - 1.5	305%	420%
Electric boilers	190 - 640	190 - 640	0.6 - 0.7	0.6 - 0.7	90%	95%
Solar thermal	3760 - 4370	1500 - 1700	0.3 - 0.4	0.3 - 0.4	-	-
Pellet boilers	630 - 2360	630 - 2360	1.9 - 7.1	1.9 - 7.1	90%	90%
Wood boilers	500 - 1610	500 - 1610	0.6 - 1.9	0.6 - 1.9	72%	72%

Table 28: Private car costs and efficiencies (engine size 60 – 100 kW, 80 – 140 hp , 12000 km/yr.)[22]

Car Technology and Fuel	Cost per car (CHF)			Efficiency (vkm/MJ)		
	2015	2030	2050	2015	2030	2050
ICE - Gasoline	16100	16300	16500	0.41	0.53	0.64
ICE - Diesel	16300	16600	16800	0.47	0.59	0.70
ICE - Natural Gas	18100	18300	18000	0.42	0.54	0.65
Hybrid - Gasoline	20500	18600	17900	0.53	0.71	0.87
Hybrid - Diesel	20700	18900	18200	0.59	0.76	0.91
Hybrid - Natural Gas	22300	20400	19200	0.54	0.70	0.86
BEV - Electricity	43800	27400	25300	1.28	1.53	1.80
Fuel Cell - Hydrogen	74500	33900	22500	0.72	0.88	1.06
Plug-in Hybrid - Electricity & Gasoline	32800	23200	21600	0.75	1.00	1.27

[21] Based on *Panos and Kannan, 2016. The role of domestic biomass in electricity, heat and grid balancing markets in Switzerland*
[22] Based on assessment from the SCCER Mobility Capacity Area B2

Car Technology and Fuel	Cost per car (CHF)			Efficiency (vkm/MJ)		
	2015	2030	2050	2015	2030	2050
Plug-in Hybrid - Electricity & Diesel	33000	23500	21900	0.80	1.05	1.31
Plug-in Hybrid - Electricity & Natural Gas	34900	24900	22800	0.74	1.00	1.26

Table 29: Buses costs and efficiencies (engine size 230 kW, 31280 km/yr.)[23]

Bus Technology and Fuel	Cost per car (CHF)			Efficiency (vkm/MJ)		
	2015	2030	2050	2015	2030	2050
ICE- Diesel	298800	299300	300100	0.06	0.07	0.08
ICE- Natural gas	320400	309000	306700	0.05	0.06	0.08
Hybrid- Diesel	444800	338300	333900	0.08	0.09	0.11
BEV long range- Electricity	888300	385900	314400	0.18	0.22	0.26
BEV short range- Electricity	698800	335400	294100	0.19	0.23	0.27
Fuel cell- Hydrogen	951900	416800	331300	0.09	0.11	0.15

Table 30: Two-wheelers costs and efficiencies (engine size 25 kW, 3400 km/yr.)

Two Technology and Fuel	Cost per car (CHF)			Efficiency (vkm/MJ)		
	2015	2030	2050	2015	2030	2050
ICE - Gasoline	7200	7400	7600	0.72	0.77	0.83
BEV - Electricity	12800	8700	6700	3.98	4.3	4.65
Fuel cell - Hydrogen	15900	9500	6900	1.97	2.33	2.88

Table 31: Heavy duty trucks costs and efficiencies (ranges refer to the period of 2015 – 2050)

Truck technology and fuel	Investment cost per vehicle	FOM/v-km	Efficiency [lde/100 v-km]
Diesel ICEV	120000	0.16	34-45
Diesel HEV	160000	0.16	32-42
CNG	145000	0.16	37
LNG	165000	0.16	29-38
FCEV	200000 - 500000	0.1	25-27
BEV	200000 - 370000	0.16	18.2

Table 32: Technical, economic characterisation of light-duty vehicles[24]

LDV Technology and Fuel	Cost per car (CHF)			Efficiency (vkm/MJ)		
	2015	2030	2050	2015	2030	2050
Light goods vehicle Battery EV	150000	140000	120000	0.91	0.99	1.07
Light goods vehicle Diesel ICE	90000	90000	90000	0.33	0.35	0.39
Light goods vehicle E85 Flex-Ethanol ICE	100000	100000	80000	0.24	0.26	0.29
Light goods vehicle Hydrogen ICE	110000	100000	100000	0.29	0.38	0.55
Light goods vehicle Methanol ICE	100000	90000	90000	0.27	0.29	0.32
Light goods vehicle Gasoline ICE	80000	80000	80000	0.24	0.26	0.29

[23] Based on assessments from SCCER Mobility Capacity Area B2 (https://www.psi.ch/eem/ProjectDetailSCCERMobEN/CarTechnlogiesForSTEM_2016.pdf)
[24] Based on the UK MARKAL Energy systems model documentation https://www.ucl.ac.uk/energy-models/models/uk-markal

Light goods vehicle Hydrogen FC	140000	120000	100000	0.56	0.71	0.84
Light goods vehicle Methanol FC	160000	160000	170000	0.33	0.42	0.50
Light goods vehicle Hybrid diesel ICE	100000	100000	100000	0.47	0.59	0.65
Light goods vehicle Hybrid gasoline ICE	100000	100000	100000	0.34	0.43	0.48
Light goods vehicle Plug-in hybrid diesel ICE	110000	110000	100000	0.87	0.94	1.02
Light goods vehicle Plug-in hybrid gasoline ICE	100000	90000	90000	0.826	0.939	1.021

Table 33: Stationary non-hydro based electricity storage

Electricity stationary storage	Energy cost (CHF/kWh)			Power cost (CHF/kW)			Efficiency		
	2015	2030	2050	2015	2030	2050	2015	2030	2050
Li-Ion battery consumer (5 - 250 kWh)	335	150	80	2200	1300	1100	85%	90%	95%
Li-Ion battery utility (50 - 60 MWh)	335	150	80	316	190	158	87%	89%	92%
Adiabatic CAES (450 MWh)	130	130	130	600	600	600	68%	69%	70%

Table 34: Thermal storage[25] technologies

Thermal storage	Density kWh/m3	Thermal Capacity m3	Efficiency % (2015 -2050)	Specific Costs CHF/m3	Yearly losses
Sensible storage (water)	25	0.4 - 2	50% - 90%	3 - 300	
Large seasonal sensible storage (water)					30%
- Tank	70	40000	50% - 90%	310	
- Underground	70	50000	50% - 90%	230	
- Borehole	25	70000	50% - 90%	80	
- Aquifer	35	77000	50% - 90%	60	
Latent storage (ice)	100	1	50% - 90%	4000	
Thermochemical storage	300	0.65	75% -100%	20000	

Table 35: Hydrogen production, storage, distribution and methanation technologies

	2015	2030	2050
Large-scale PEM electrolyser			
Investment cost (CHF/kW_{H2})	2400	1700	950
O&M cost (CHF/kW_{H2}/yr)	50	36	20
Efficiency (%)	63	70	75
Medium scale PEM electrolyser			
Investment cost (CHF/kW_{H2})	4200	3000	1650
O&M cost (CHF/kW_{H2}/yr)	100	70	40
Efficiency (%)	63	70	75
Hydrogen storage			
Investment cost (CHF/kgr_{H2})	900	680	450
O&M cost (CHF/kW_{H2}/yr)	9	6	5
Efficiency (%)	99	99	99
Large-scale hydrogen methanation			
Investment cost (CHF/kW_{CH4})	1500	1050	800

[25] Based on *BFE, 2013. Energiespeicher der Schweiz: Bedarf, Wirtschaftlichkeit und Rahmenbedingungen im Kontext der Energiestrategie 2050*

	2015	2030	2050
O&M cost (CHF/kW$_{CH4}$/yr)	100	70	50
Efficiency (%)	70	75	85
Medium scale hydrogen methanation			
Investment cost (CHF/kW$_{CH4}$)	2100	1300	1000
O&M cost (CHF/kW$_{CH4}$/yr)	130	80	60
Efficiency (%)	70	75	85
Compression H2			
Investment cost (CHF/kW)	200	180	160
O&M cost (CHF/kW/yr)	12	11	10
Efficiency (%)	76%	76%	76%
Compression SNG			
Investment cost (CHF/kW)	570	570	570
O&M cost (CHF/kW/yr)	34	34	34
Efficiency (%)	60%	60%	60%
Pipeline H2 & SNG 10 bar			
variable Investment cost (kCHF/km)	130	130	130
fixed Investment cost (kCHF)	50	50	50
O&M cost (% CAPEX / yr)	2%	2%	2%
Pipeline H2 & SNG 60 bar			
variable Investment cost (kCHF/km)	300	300	300
fixed Investment cost (kCHF)	200	200	200
O&M cost (% CAPEX / yr)	2%	2%	2%
Refuelling station H2			
Investment cost (CHF/kW)	3000	1800	1600
O&M cost (% CAPEX / yr)	8%	8%	8%
Methanol synthesis			
Investment cost (CHF/kW)	1500	1000	700
O&M cost (% CAPEX / yr)	8%	8%	8%
Efficiency (%)	76%	76%	76%
H2 from Gas Steam Reforming			
Investment cost (CHF/PJ-a)	70	70	70
O&M cost (% CAPEX / yr)	3%	3%	3%
Efficiency (%)	76%	76%	76%
H2 from Gas Steam Reforming with CO2 capture			
Investment cost (CHF/PJ-a)	115	115	115
O&M cost (% CAPEX / yr)	3%	3%	3%
Efficiency (%)	69%	69%	69%
H2 from biomass			
Investment cost (CHF/PJ-a)	300	300	300
O&M cost (% CAPEX / yr)	10%	10%	10%
Efficiency (%)	64%	64%	64%

V Detailed socio-economic drivers

The table below presents the quantification of the key socio-economic drivers influencing the energy service demands. The drivers are common to all scenarios and variants.

Table 36: Key socio-economic drivers influencing energy service demands

	2010	2015	2020	2030	2040	2050
Population (million)	7.870	8.320	8.758	9.541	10.044	10.280
Average household size (persons per household)	2.26	2.25	2.23	2.20	2.18	2.14
Number of households (millions)	3.408	3.631	3.849	4.231	4.497	4.730
Residential buildings (number of buildings)						
Single family houses	945240	983210	1012919	1069225	1103267	1146570
Before 1919	133198	127357	127838	125317	117362	98445
1919 - 1945	103080	109211	105535	90684	60491	31389
1946 - 1960	110652	109242	105576	89471	57184	32185
1961 - 1970	95325	94336	90785	75794	46144	28421
1971 - 1980	124704	123326	121963	115722	100202	68188
1981 - 1990	136487	135333	135126	135126	131025	114902
1991 - 2000	121077	120504	120389	120389	119460	114349
2001 - 2005	61788	61681	61468	61468	61468	60536
2006 - 2010	58929	58805	58675	58675	58675	58398
2011 - 2015	0	43415	43415	43415	43410	43276
2016	0	0	6921	6921	6921	6912
Post 2016	0	0	35228	146243	300925	489569
Multi family houses	422645	450457	479646	526368	557977	558821
Before 1919	89463	88184	88801	87977	84724	75989
1919 - 1945	49360	52586	51641	46906	36484	16627
1946 - 1960	55157	55041	53931	48523	36826	14796
1961 - 1970	55138	55952	54946	48934	36141	15342
1971 - 1980	49837	51033	51098	49614	45388	35918
1981 - 1990	44880	44880	44796	44236	42251	37188
1991 - 2000	40157	40157	40154	40072	39533	37656
2001 - 2005	16017	16017	16017	16015	15970	15699
2006 - 2010	22636	22575	22606	22606	22606	22438
2011 - 2015	0	24032	24032	24032	24029	23959
2016	0	0	5115	5115	5115	5108
Post 2016	0	0	26509	92338	168910	258101
Heating floor area (Million sqm)						
Food	8	8	9	9	8	8
Textile	2	2	2	1	1	1
Pulp and Paper	2	2	2	2	2	2
Chemicals	6	6	6	6	6	7
Non metalic minerals	3	3	3	2	2	2
Basic metals	1	1	1	1	1	1
Metal tools & products	6	6	7	6	5	4
Machinery	10	11	11	12	12	13
Electrical equipment	15	16	17	18	19	19
Construction	6	6	6	7	8	9
Energy industries	2	2	2	2	2	2
Other industries	11	11	12	12	13	14
Services & Agriculture	152	157	162	172	182	192
Existing single family houses	220	230	228	215	187	153
New single family houses	0	0	16	65	115	164
Existing multi family houses	247	269	264	253	227	176
New multi family houses	0	0	38	127	180	252
Other heating area with partial residential use	20	20	21	23	24	24
Residential lighting floor area (Million sqm)	475	512	554	670	718	752
Electrical appliances in the residential sector (thousands)						
Geschirrspüler	2183	2499	2672	3313	3796	4246

	2010	2015	2020	2030	2040	2050
Kühlschrank	3332	3483	3598	3949	4165	4343
Kühl-Gefrier-Kombi	1193	1360	1992	2193	2323	2421
Tiefkühltruhe	596	472	212	147	104	79
Tiefkühlschrank	1818	2061	2238	2623	2856	2995
Waschmaschine	3434	3628	3730	4018	4211	4362
Waschtrockner	78	109	28	42	52	64
Wäschetrockner	2498	2861	3025	3623	4181	4667
Farb-TV	4185	4479	4603	5190	5606	5978
Video	3071	3427	3636	4377	5046	5604
Computer	5267	6049	7032	8684	9619	9981
Mobil-, Schnurlostelefone	9022	9739	10761	13811	15268	15618
Passenger transport (pkm)	**122.0**	**129.9**	**135.0**	**145.9**	**153.0**	**156.1**
Private road transport	90.9	96.8	96.7	103.3	107.3	109.0
Personal cars	85.9	91.9	91.5	97.7	101.5	103.1
Motorcycles, motorbikes	2.4	2.1	2.2	2.3	2.3	2.4
Other private transport	2.5	2.8	3.1	3.3	3.5	3.5
Public road transport	23.6	25.2	29.8	33.3	35.7	36.8
Trams	1.0	1.2	1.3	1.5	1.6	1.7
Trolleybuses	0.5	0.5	0.6	0.7	0.8	0.9
Buses	2.5	2.7	3.6	4.7	5.2	5.5
Rail	19.6	20.8	24.3	26.3	28.1	28.6
Bikes	2.1	2.5	2.3	2.6	2.8	2.9
On foot	5.5	5.4	6.1	6.8	7.2	7.4
Freight transport (tkm)	**26.7**	**29.6**	**30.0**	**33.4**	**36.6**	**39.1**
Road transport	16.9	17.2	18.8	20.6	22.4	23.8
Light duty vehicles	0.9	0.9	1.1	1.2	1.3	1.4
Heavy trucks	16.0	16.3	17.8	19.4	21.1	22.3
Rail transport	9.8	12.4	11.2	12.8	14.2	15.3
Passenger motorised transport (bkm)	**54.5**	**59.2**	**58.3**	**62.3**	**64.6**	**65.6**
Private road transport	54.0	58.7	57.6	61.5	63.8	64.8
Personal cars	52.1	56.6	55.4	59.2	61.5	62.4
Motorcycles, motorbikes	1.9	1.9	2.0	2.1	2.1	2.2
Other private transport	0.1	0.1	0.1	0.2	0.2	0.2
Public road transport	0.3	0.3	0.4	0.5	0.6	0.6
Trams	0.028	0.033	0.033	0.034	0.035	0.036
Trolleybuses	0.027	0.027	0.028	0.030	0.034	0.037
Buses	0.2	0.3	0.4	0.5	0.5	0.5
Rail	0.2	0.2	0.2	0.2	0.3	0.3
Freight transport (bkm)	**5.8**	**6.4**	**6.9**	**7.2**	**7.9**	**8.5**
Road transport	5.7	6.4	6.9	7.1	7.9	8.4
Light duty vehicles	3.5	4.1	4.4	4.4	5.0	5.3
Heavy trucks	2.2	2.2	2.5	2.7	2.9	3.1
Rail transport	0.027	0.029	0.041	0.047	0.049	0.1

VI Renewable potentials in E-POL and CLI scenarios

The sustainable renewable potentials for heat and electricity generation used in the core scenarios are given in Table 37.

Table 38 presents the detailed breakup of the bioenergy according to the primary source.

Table 37: Sustainable potential by renewable source in PJ[26]

PV rooftop	72.0
Wind	15.5
Geothermal	15.5
Large hydropower	122.4
Small hydropower	19.8
Woody biomass	49.6
Biogas	12.5
Solar thermal	31.4

Table 38: Detailed decomposition of the bioenergy potential, in terms of primary energy[27]

Forest wood	24.0
Industrial wood	8.8
Waste wood	12.0
Wood from landscape maintenance	4.8
Biogas from manure	24.0
Biogas from agricultural crop by-products	2.6
Biogas from industrial and commercial biowaste	0.7
Organic part of household garbage	-2.1
Biogas from green waste collection	3.3
Biogas from sewage sludge	1.4

VII Mapping of exchange variables for joint model application

E3ME variable	E3ME	STEM
FRCT	Coal	Coal
FRET	Electricity	Electricity
FRGT	Gas	Natural Gas
FROT	Heavy Oil	Heavy Fuel Oil
FR05	Middle distillates	Gasoline, Diesel, Jet Fuel

[26] Based on *Bauer, C., et al, 2017. Potentials, costs and environmental assessment of electricity generation technologies. Report to BFE.*
[27] Based on *Bauer, C., et al, 2017. Potentials, costs and environmental assessment of electricity generation technologies. Report to BFE.*

FRBT	Biofuel	Wood, Biogas
FR09	Heat	Heat
FR10	Combustible Waste	Waste

STEM	**E3ME**
basic metal	4 Iron and steel 5 Non-ferrous metals
chemical	6 Chemicals
cement	7 Non-metallic minerals
construction	14 Construction
paper	11 Paper and pulp
food	9 Food, drink and tobacco
Other industry	8 Ore-extraction (non-energy) 10 Textiles 12 Engineering etc 13 Other industry, clothing & footwear
Transport	15 Rail transport 16 Road transport 17 Air transport 18 Other transport services
Households	19 Households

STEM	**E3ME**
Electricity	26 Electricity
Infrastructure	4 Coal 5 Oil and Gas 27 Gas, steam & air conditioning 26 Electricity
Residential	Consumption of Household Maintenance
Industrial	6 Other mining 7 Food, drink & tobacco 8 Textiles & leather 9 Wood & wood prods 10 Paper & paper prods 11 Printing & reproduction 12 Coke & ref petroleum 13 Other chemicals

	14 Pharmaceuticals 15 Rubber & plastic products 16 Non-metallic mineral prods 17 Basic metals 18 Fabricated metal prods 19 Computer, optical & electronic 20 Electrical equipment 21 Other machinery & equipment 22 Motor vehicles 23 Other transport equipment 24 Furniture; other manufacturing 25 Repair & installation machinery 28 Water, treatment &supply 29 Sewerage & waste management 30 Construction 31 Wholesale/retail motor vehicles 32 Wholesale excl. motor vehicles 33 Retail excluding motor vehicles 37 Warehousing
Transport	34 Land transport, pipelines 35 Water transport 36 Air transport
Service	38 Postal & courier activities 39 Accommodation & food services 40 Publishing activities 41 Motion picture, video, television 42 Telecommunications 43 Computer programming, info services 44 Financial services 45 Insurance 46 Aux to financial services 47 Real estate 48 Imputed rents 49 Legal, account, & consulting services 50 Architectural & engineering 51 R&D 52 Advertising & market research 53 Other professional 54 Rental & leasing 55 Employment activities

	56 Travel agency 57 Security & investigation, etc 58 Public administration & defence 59 Education 60 Human health activities 61 Residential care 62 Creative, arts, recreational 63 Sports activities 64 Membership organisations 65 Repair computers & personal goods 66 Other personal services. 67 Households as employers Extraterritorial organisations
Agri	1 Crops, animals, etc 2 Forestry & logging 3 Fishing

STEM	**E3ME**
Hydro	16 Large Hydro
Nuclear	1 Nuclear
Pump storage	
Oil	2 Oil
Gas (CC, OC)	7 CCGT
Gas (CHP	24 CHP
Biogas (CHP)	24 CHP, 13 Biogas
Wastes	13 Biogas
Wood	9 Solid Biomass, 10 S Biomass CCUS
Solar	19 Solar PV, 20 CSP
Wind	17 Onshore, 18 Offshore
Geothermal	21 Geothermal
Hydrogen	23 Fuel Cells
CAES/Batteries	

VIII Description of the E3ME model

1.1 Overview

E3ME is a computer-based model of the world's economic and energy systems and the environment. It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessment, for forecasting and for research purposes. The model is global in scope with explicit coverage of 61 different global regions/countries, including Switzerland. It has a detailed sectoral coverage, with explicit representation of 70 industry sectors (in Europe) and 44 industry sectors in regions outside of Europe.

This model description provides a short summary of the E3ME model. For further details, please read the full model manual available online from www.e3me.com.

1.2 Applications of E3ME

Scenario-based analysis

Although E3ME can be used for forecasting, the model is more commonly used for evaluating the impacts of an input shock through a scenario-based analysis. The shock may be either a change in policy, a change in economic assumptions or another change to a model variable. The analysis can be either forward looking (ex-ante) or evaluating previous developments in an ex-post manner. Scenarios may be used either to assess policy, or to assess sensitivities to key inputs (e.g. international energy prices).

For ex-ante analysis a baseline forecast up to 2050 is required; E3ME is usually calibrated to match a set of projections that are published by the European Commission and the International Energy Agency but alternative projections may be used. The scenarios represent alternative versions of the future based on a different set of inputs. By comparing the outcomes to the baseline (usually in percentage terms), the effects of the change in inputs can be determined.

Price or tax scenarios

Model-based scenario analyses often focus on changes in price because this is easy to quantify and represent in the model structure. Examples include:

- changes in tax rates including direct, indirect, border, energy and environment taxes
- changes in international energy prices

Regulatory impacts

Price changes above can be represented in E3ME's framework reasonably well, given the level of disaggregation available. However, it is also possible to assess the effects of regulation, albeit with an assumption about effectiveness and cost. For example, an increase in vehicle fuel-efficiency standards could be assessed in the model with an assumption about how efficient vehicles become, and the cost of these measures. This would be entered into the model as a higher price for cars and a reduction in fuel consumption (all other things being equal). E3ME could then be used to determine:

- secondary effects, for example on fuel suppliers

- rebound effects[28]
- overall macroeconomic impacts

1.3 Comparison with CGE models and econometric specification

E3ME is often compared to Computable General Equilibrium (CGE) models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this there are important theoretical differences between the modelling approaches.

In a typical CGE framework, optimal behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. By contrast, in E3ME the determination of output comes from a post-Keynesian framework and it is possible to have spare capacity. The model is more demand-driven and it is not assumed that prices always adjust to market clearing levels.

The differences have important practical implications as they mean that, in E3ME, regulation and other policy may lead to increases in output if they are able to draw upon spare economic capacity. This is described in more detail in the model manual.

The econometric specification of E3ME gives the model a strong empirical grounding. E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend. The dynamic specification is important when considering short and medium-term analysis (e.g. up to 2020) and rebound effects[29], which are included as standard in the model's results.

Key strengths of E3ME

In summary the key strengths of E3ME are:

- the close integration of the economy, energy systems and the environment, with two-way linkages between each component
- the detailed sectoral disaggregation in the model's classifications, allowing for the analysis of similarly detailed scenarios
- its global coverage, while still allowing for analysis at the national level for large economies
- the econometric approach, which provides a strong empirical basis for the model and means it is not reliant on some of the restrictive assumptions common to CGE models
- the econometric specification of the model, making it suitable for short and medium-term assessment, as well as longer-term trends

1.4 Limitations of the approach

As with all modelling approaches, E3ME is a simplification of reality and is based on a series of assumptions. Compared to other macroeconomic modelling approaches, the assumptions are relatively non-restrictive as most relationships are determined by the historical data in the model database. This does, however, present its own limitations, for which the model user must be aware:

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[28] In the example, the higher fuel efficiency effectively reduces the cost of motoring. In the long-run this is likely to lead to an increase in demand, meaning some of the initial savings are lost.
[29] Where an initial increase in efficiency reduces demand, but this is negated in the long run as greater efficiency lowers the relative cost and increases consumption.

The quality of the data used in the modelling is very important. Substantial resources are put into maintaining the E3ME database and filling out gaps in the data. However, particularly in developing countries, there is some uncertainty in results due to the data used.

Econometric approaches are also sometimes criticised for using the past to explain future trends. In cases where there is large-scale policy change, the 'Lucas Critique' that suggests behaviour might change is also applicable. There is no solution to this argument using any modelling approach (as no one can predict the future) but we must always be aware of the uncertainty in the model results.

The other main limitation to the E3ME approach relates to the dimensions of the model. In general, it is very difficult to go into a level of detail beyond that offered by the model classifications. This means that sub-national analysis is difficult[30] and sub-sectoral analysis is also difficult. Similarly, although usually less relevant, attempting to assess impacts on a monthly or quarterly basis would not be possible.

1.5 E3ME basic structure and data

The structure of E3ME is based on the system of national accounts, with further linkages to energy demand and environmental emissions. The labour market is also covered in detail, including both voluntary and involuntary unemployment. In total there are 33 sets of econometrically estimated equations, also including the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. Each equation set is disaggregated by country and by sector.

E3ME's historical database covers the period 1970-2014 and the model projects forward annually to 2050. The main data sources for European countries are Eurostat and the IEA, supplemented by the OECD's STAN database and other sources where appropriate. For regions outside Europe, additional sources for data include the UN, OECD, World Bank, IMF, ILO and national statistics. Gaps in the data are estimated using customised software algorithms.

The main dimensions of the model

The main dimensions of E3ME are:

- 61 countries – all major world economies, the EU28 and candidate countries plus other countries' economies grouped
- 44 or 70 (Europe) industry sectors, based on standard international classifications
- 28 or 43 (Europe) categories of household expenditure
- 22 different users of 12 different fuel types
- 14 types of air-borne emission (where data are available) including the 6 GHG's monitored under the Kyoto Protocol

1.6 E3ME as an E3 model

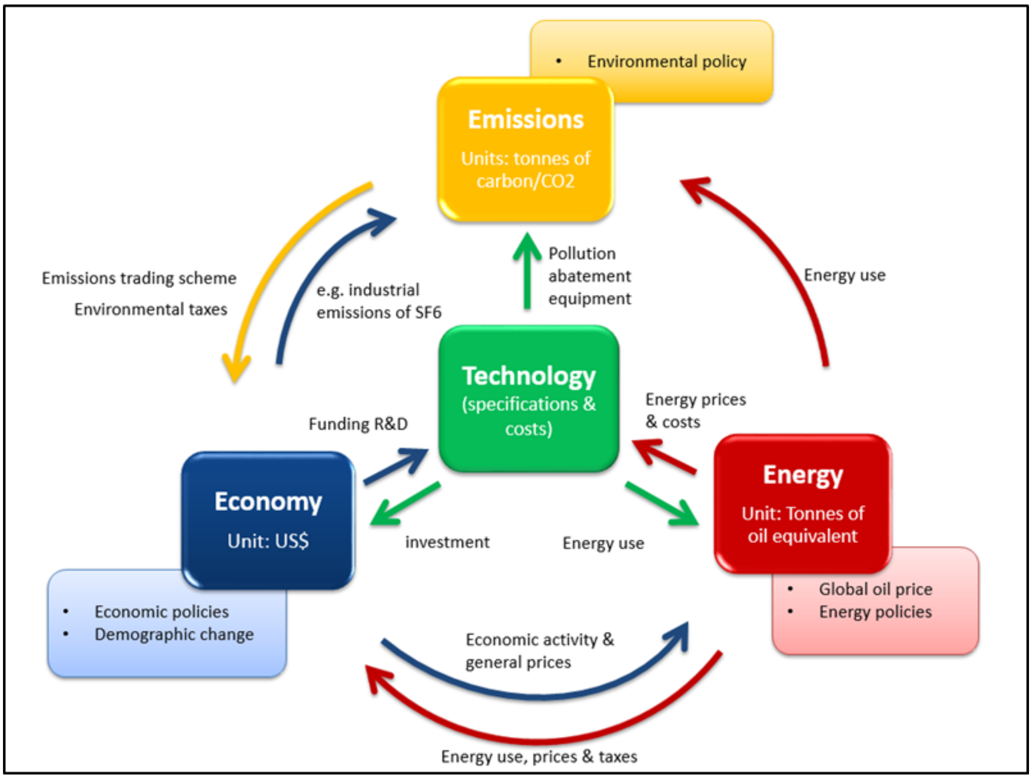
The E3 interactions

[30] If relevant, it may be possible to apply our E3-India or E3-US (currently under development) models to give state-level analysis.

Figure 44 shows how the three components (modules) of the model - energy, environment and economy - fit together. Each component is shown in its own box. Each data set has been constructed by statistical offices to conform with accounting conventions. Exogenous factors coming from outside the modelling framework are shown on the outside edge of the chart as inputs into each component. For each region's economy the exogenous factors are economic policies (including tax rates, growth in government expenditures, interest rates and exchange rates). For the energy system, the outside factors are the world oil prices and energy policy (including regulation of the energy industries). For the environment component, exogenous factors include policies such as reduction in SO2 emissions by means of end-of-pipe filters from large combustion plants. The linkages between the components of the model are shown explicitly by the arrows that indicate which values are transmitted between components.

The economy module provides measures of economic activity and general price levels to the energy module; the energy module provides measures of emissions of the main air pollutants to the environment module, which in turn can give measures of damage to health and buildings. The energy module provides detailed price levels for energy carriers distinguished in the economy module and the overall price of energy as well as energy use in the economy.

Figure 44 E3 linkages in the E3ME model



Treatment of international trade

An important part of the modelling concerns international trade. E3ME solves for detailed bilateral trade between regions (similar to a two-tier Armington model). Trade is modelled in three stages:

- econometric estimation of regions' sectoral import demand

- econometric estimation of regions' bilateral imports from each partner
- forming exports from other regions' import demands

Trade volumes are determined by a combination of economic activity indicators, relative prices and technology.

The labour market

Treatment of the labour market is an area that distinguishes E3ME from other macroeconomic models. E3ME includes econometric equation sets for employment, average working hours, wage rates and participation rates. The first three of these are disaggregated by economic sector while participation rates are disaggregated by gender and five-year age band.

The labour force is determined by multiplying labour market participation rates by population. Unemployment (including both voluntary and involuntary unemployment) is determined by taking the difference between the labour force and employment. This is typically a key variable of interest for policy makers.

The role of technology

Technological progress plays an important role in the E3ME model, affecting the economy, energy and environment. The model's endogenous technical progress indicators (TPIs), a function of R&D and gross investment, appear in nine of E3ME's econometric equation sets including trade, the labour market and prices. Investment and R&D in new technologies also appears in the E3ME's energy and material demand equations to capture energy/resource savings technologies as well as pollution abatement equipment. In addition, E3ME also captures low carbon technologies in the power sector through the FTT power sector model,[31] although it is noted that the FTT Power module in E3ME is not used for this exercise, since energy system results are instead taken from STEM.

[31] See Mercure (2012).