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Switzerland Energy Transition Scenarios – Development and Application of the Swiss TIMES Energy System Model (STEM)

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Table of contents

List of figures

List of tables

List of abbreviations

Aviation(D)	–	Domestic aviation
Aviation(I)	–	International aviation
BAU	–	Business as usual
BEV	–	Battery electric vehicle
CHF	–	Swiss Franc
CHP	–	Combined heat and power generation
CO_2	–	Carbon dioxide
CROSSTEM-E	–	Swiss cross border electricity model
ESD	–	Energy service demand
ETS	–	Emission trading scheme
EU	–	European union
FC	–	Fuel cell
GDP	–	Gross domestic product
GTCC	–	Gas turbine combine cycle plant
HGV	–	Heavy goods vehicle
HP	–	Heat pump
ICE	–	Internal combustion engine
ICT	–	Information and communication technology
KEV	–	Kostendeckenden Einspeisevergütung (Feed in tariff)
LC	–	Low carbon
LGV	–	Light good gehicle
MARKAL	–	Market Allocation—modelling framework
PHEV	–	Plug-in hybrid electric vehicle
Rail(F)	–	Rail—Freight transportation
Rail(P)	–	Rail—Passenger transportation

RES	–	Reference energy system
Rp	–	Rappen (cent)
SEC	–	Secure energy supply
SEP	–	Swiss Energy Perspectives
SMR	–	Steam methane reformer
STEM	–	Swiss TIMES energy system model
STEM-E	–	Swiss TIMES electricity model
TIMES	–	The Integrated MARKAL EFOM System—modelling framework
t-km	–	tonne kilometre
vkm	–	vehicle kilometre –

Executive summary

The energy system in Switzerland is at crossroads, with systemic structural changes in technology and fuel choice required over the long term to realise environmental, energy security, economic and social goals. To illustrate, the current energy system is highly dependent on imported heating and transport fuels, and is thus incompatible with long-term climate change mitigation and energy supply security goals. Further, the transition away from nuclear generation, in response to some social and risk related concerns, requires broader technology changes to avoid exacerbating or creating additional challenges for climate change mitigation, energy security and economic development.

Many technological options exist on the supply and demand sides to realise a future energy system that addresses the multiple challenges and goals faced by decision makers in Switzerland. However, it is not clear which combination offers the best approach given significant uncertainty about future technology performance, energy prices, demand growth and other factors (including policy decisions). Moreover, the suitability of different technological options in one part of the energy system (e.g. transport) is likely to be affected by developments in other parts of the energy system (e.g. electricity generation). Accordingly, understanding possible structural changes in the energy system requires analytical approaches that are able to account for system-wide effects and uncertainty over the medium and long term.

Energy models have emerged as a useful methodology for generating insights into future energy system options and their associated uncertainties. However, existing models have one or more limitations that render them less suitable for addressing some of the complexities and uncertainties affecting whole-energy-system development and structural change in Switzerland. Therefore a comprehensive and flexible model of the Swiss energy system—the Swiss TIMES energy system model (STEM)—has been developed for the analysis of plausible energy pathways.

The entire energy system of Switzerland is represented in STEM with a high level of technology detail, a long time horizon, and a high time resolution covering seasonal/diurnal variations in energy demand and supply. The representation of the entire energy system enables STEM to determine the lowest-cost configuration of the energy system accounting for cross-sectoral interactions and competition for the allocation of energy carriers (for instance, the implications of electricity sector technology choice for the electrification of end-use sectors; or the allocation of biomass to electricity, heat or transport). The 'whole energy system' approach is also essential for identifying cost-effective CO_2 abatement options.

The high level of technology detail ensures that the future energy pathways identified by the model account explicitly for the characteristics of the necessary technology options, and thus are feasible from an engineering perspective. The century long time horizon of STEM facilitates the analysis of long-term goals and challenges, and accounts for the long lifetimes of energy-related capital infrastructure. Finally, the high level of time resolution enables STEM to account for the temporal variations in supply and demand, which is critical for evaluating the deployment of intermittent renewables, electrification of transportation and heating, and an emerging need for storage and/or additional flexibility in imports and exports. STEM is thus a powerful tool for the analysis of exploratory transition scenarios of the energy system.

To illustrate key features, we have analysed in detail a small selection of scenarios focusing on selected uncertainties related to policy (climate change mitigation, energy security, and the acceptability of new centralized electricity generation) and international fuel price volatility. The results illustrate that even without additional policy intervention specifically targeting climate change or energy security, a number of other driving forces (energy prices, economic structural change, and improvements in technology performance/cost) are likely to reduce final energy demands 0.35–0.88 percent per annum during 2010–2050, through increasing efficiency and electrification of end uses. These developments also go some way towards climate change mitigation goals, reducing CO_2 emissions by around 30%. However, achieving more ambitious abatement targets, such as a 60% or greater reduction in line with European goals, requires substantial changes to the energy system. Key technology options on the demand side include further electrification of heating (i.e., heat pumps) and transport (e-mobility), and adoption of cost-effective building conservation measures.

On the supply side, the phase out of nuclear generation and continuous growth in electricity demands due to electrification of end-uses creates a need for additional capacity in both the short and long term (across the analysed scenarios). The large-scale exploitation of renewable resources is a key requirement to avoid increasing dependence on net imports. In addition, the acceptability of new centralized generation options, namely gas combined cycle plants, is critical for realising climate change or security of supply goals at lowest cost. Despite its reliance on natural gas, this technology supports (further) efficient electrification of end uses, substituting direct use of fossil fuels and reducing net emissions. Without centralized gas plants, decentralized natural gas CHPs are attractive in the industrial sector, but direct use of conventional fuels continues to be necessary in many end uses, with natural gas (rather than electricity) being cost-effective in car transport.

In addition to determining the lowest-cost energy pathways to realise future policy goals, the STEM framework provides insights into the economic implications of realising these goals. For instance, the technology changes needed to achieve a 60 percent reduction in CO_2 emissions by 2050 requires investment in some more expensive options, increasing annual (undiscounted) costs in 2050 by CHF_{2010} 6.8–8.3 billion (or CHF 750–920 per person), with the overall energy system cost increasing to 7.3–7.5% of GDP, compared to 5.7% in a business-as-usual scenario.

Policy support will be critical in realising many of the developments required in a transition to an energy system that addresses environmental, security, social and economic goals, despite uncertainty regarding the exact nature of future domestic climate change and energy security policies, and international developments. Based on the scenario analysis, key areas for policy support include: measures promoting building efficiency; incentives to support deployment of heat pumps for space heating and decentralized generation options like solar PV (where there may be high upfront capital costs); and promotion of combined heat and power systems, particularly in industry. In the transport sector, advanced and hybrid conventional vehicles represent a cost-effective technology choice in the medium term across the scenarios analysed, which can likely be realized with continuing price signals (along with incentives in the EU on vehicle standards). However, over the longer term the choice, particularly the role of electric vehicles, depends on policy choices related to the availability of cheap electricity (either in the form of imports or domestic generation from new centralized plants). In this context, policy certainty will ultimately be required to attract investment in new infrastructure and larger-scale technology options (like centralized gas plants).

The scenario analysis presented in this report serves to illustrate the suitability of STEM for the analysis of a wide range of scenarios exploring key policy questions and uncertainties confronting decision makers in Switzerland. STEM also provides a basis for further modelling enhancements aimed at providing additional insights into other factors affecting long-term energy transitions, such as emerging technology options for energy storage or additional behavioural factors. The development of STEM, particularly the incorporation of a high level of temporal resolution, has also pushed the state of the art among the international energy modelling community.

Zusammenfassung

Das Schweizer Energiesystem steht an einem Scheideweg: In einem Umfeld, das von technologischen Strukturveränderungen des Systems geprägt ist, müssen langfristige Entscheidungen gefällt werden, um Ziele in den Bereichen Umwelt, Versorgungssicherheit, Wirtschaftlichkeit und der Gesellschaft zu erreichen. Momentan ist das Schweizer Energiesystem stark von importierten fossilen Brenn- und Treibstoffen abhängig, was den langfristigen Zielen der Vermeidung des Klimawandels und der Versorgungssicherheit widerspricht. Ausserdem braucht es aufgrund des gesellschaftlich und ökologisch begründeten Ausstiegs aus der Kernenergie zusätzliche technologische Veränderungen um die obengenannten Ziele zu erreichen.

Es gibt sowohl auf der Angebots- wie auch auf der Nachfrageseite zahlreiche technische Möglichkeiten, welche den Entscheidungsträgern zur Entwicklung eines Energiesystems, das den obengenannten Herausforderungen und Zielen entspricht, zur Verfügung stehen. Jedoch ist aufgrund grosser Unsicherheiten sowohl in Bezug auf zukünftige Technologien, Energiepreise und Nachfrageentwicklung als auch in Bezug auf andere Faktoren (u.a. politische Entscheide) nach wie vor unklar, welche Kombination von Technologien für die Erreichung der gesteckten Ziele am besten geeignet ist. Zudem bestehen innerhalb des Energiesystems Abhängigkeiten, die den Nutzen gewisser Technologien beeinflussen; so wird zum Beispiel der Einsatz einer Technologie im Verkehrssektor von deren Einsatz in anderen Bereichen des Energiesystems (z.B. im Elektrizitätssektor) beeinflusst. Aufgrund solcher Abhängigkeiten braucht es eine analytische Herangehensweise, um die strukturellen Veränderungen des Energiesystems besser zu verstehen und um umfassend mittel- und langfristige Entwicklungen und Unsicherheiten in die Analyse miteinbeziehen zu können.

Mit Modellen des Energiesystems wurden in den letzten Jahren nützliche Werkzeuge entwickelt, die Einblicke in die Entwicklung künftiger Energiesysteme und in die dazugehörenden Unsicherheiten erlauben. Die bisher entwickelten Modelle haben eine oder mehrere Unzulänglichkeiten in der Analyse von Komplexitäten und in der Beurteilung von Unsicherheiten, die die Entwicklung des gesamten Energiesystems und seiner strukturellen Veränderungen betreffen. Deshalb wurde ein umfassendes und flexibles Model des Schweizer Energiesystems – das Swiss TIMES Energiesystem-Modell (STEM) – entwickelt, das die Analyse verschiedener möglicher Entwicklungspfade erlaubt.

In STEM ist das gesamte Energiesystem mit detailliert modellierten Technologien abgebildet; dies mit einem langen Zeithorizont und mit einer hohen zeitlichen Auflösung, die die saisonalen und täglichen Schwankungen von Energieangebot und –nachfrage abdeckt. Aufgrund des Einbezugs des gesamten Energiesystems kann mit STEM die kostenminimale Konfiguration des Energiesystems bestimmt werden und dabei sektorübergreifende Interaktionen und der Wettbewerb zwischen den Energieträgern (z.B. Auswirkungen der Wahl der Technologien im Elektrizitätssektor auf die Elektrifizierung im Verbrauchsektors, oder die Nutzung der Biomasse im Strom-, Wärme- oder Verkehrssektor) miteinbezogen werden. Dieser Gesamtsystemansatz ist zudem unerlässlich, um die kostengünstigsten Kohlendioxid (CO_2)-Vermeidungsoptionen bestimmen zu können.

Die detaillierte Abbildung der Technologien ermöglicht es, dass die mit dem Modell ermittelten Entwicklungspfade die Charakteristika der verwendeten Technologien berücksichtigen und damit auch technisch umsetzbar sind. Die Langzeitperspektive von STEM erlaubt es, langfristige Ziele zu analysieren, und sie trägt der langen Lebensdauer der Energieinfrastrukturen Rechnung. Schliesslich erlaubt die hohe zeitliche Auflösung von STEM die Schwankungen von Angebot und Nachfrage, die für die Beurteilung von erneuerbaren Energien, die Elektrifizierung von Verkehr und Heizung, und den zunehmenden Bedarf von Speichertechnologien und/oder zusätzlicher Flexibilität durch Importe und Exporte nötig sind, zu berücksichtigen. STEM ist deshalb ein mächtiges Werkzeug für die Analyse von explorativen Szenarien für das Schweizer Energiesystem.

Um die obengenannten Eigenschaften des Modells zu illustrieren, untersuchten wir im Detail eine kleine Auswahl von Szenarien, bei denen Unsicherheiten in der Politik (Vermeidung des Klimawandels, Versorgungssicherheit und Akzeptanz neuer Grosskraftwerke) und die Volatilität der internationalen Energiepreise im Zentrum stehen. Die Resultate zeigen, dass auch ohne zusätzliche spezielle politische Massnahmen gegen Klimawandel oder für Versorgungssicherheit andere Faktoren (erhöhte Energiepreise, wirtschaftlicher Strukturwandel und Verbesserungen bei Technologieentwicklung und -kosten) die Endenergienachfrage aufgrund von erhöhter Effizienz und Elektrifizierung um 0.35-0.88 Prozent pro Jahr von 2010 bis 2050 reduzieren. Diese Entwicklung trägt zu den Zielen zur Vermeidung des Klimawandels bei, in dem sie die CO_2-Emissionen um 30% reduziert. Um jedoch ambitioniertere Emissionsreduktionsziele, wie zum Beispiel eine Reduktion um 60% wie in der EU, zu erreichen, braucht es tiefergreifende Veränderungen des Energiesystems. Auf der Verbraucherseite sind Technologieoptionen wie die weitere Elektrifizierung der Heizungen (z.B. mit Wärmepumpen) und im Verkehr (Elektromobilität) sowie die Umsetzung kostengünstiger energetischer Gebäudesanierungen im Haushaltssektor dafür zentral.

Angebotsseitig führen der Kernenergieausstieg und die zunehmende Stromnachfrage aufgrund der Elektrifizierung sowohl kurzfristig wie auch langfristig zu einem Bedarf an zusätzlichen Erzeugungskapazitäten (in allen Szenarien). Der starke Ausbau erneuerbarer Energien spielt bei der Vermeidung höherer Nettoimporte eine Schlüsselrolle. Zudem ist die gesellschaftliche Akzeptanz neuer Grosskraftwerke, namentlich von Gaskombikraftwerken, zentral für die kostengünstige Erreichung von Klimazielen und Versorgungssicherheit. Trotz der Abhängigkeit von importiertem Erdgas tragen diese Kraftwerke zur (verstärkten) effizienten Elektrifizierung der Verbrauchssektoren bei, und sorgen so für die Substitution des direkten Einsatzes fossiler Brenn- und Treibstoffe und damit für eine Reduktion der Nettoemissionen. Anstelle dieser zentralen Gaskraftwerke bieten dezentrale gasbefeuerte Wärmekraftkoppelungsanlagen im Industriesektor ebenfalls eine attraktive Möglichkeit. Dann bleibt jedoch der direkte Einsatz konventioneller Brennstoffe auf der Nachfrageseite bestehen, und Erdgas (anstelle von Strom) ist die kostengünstigste Option im Transportsektor.

Neben der Ermittlung der kostenoptimalen Entwicklungspfade für die Erreichung von zukünftigen politischen Zielen erlaubt das STEM Modell auch Einblicke in die ökonomischen Implikationen der Erreichung dieser Ziele. Zum Beispiel sind für die Erreichung der obengenannten Emissionsreduktion um 60% bis 2050 Investitionen in vergleichsweise teurere Technologien notwendig, was zu einer Erhöhung der jährlichen (nicht diskontierten) Energiesystemkosten um 6.8–8.3 Mrd. CHF_{2010} (oder 750–920 CHF pro Person) im Jahr 2050 führt. Damit belaufen sich die Gesamtsystemkosten auf 7.3–7.5% des BIP, verglichen mit 5.7% in einem *business-as-usual* Szenario.

Für die Umsetzung der zahlreichen Entwicklungen, die für einen Umbau des Energiesystems mit den Zielen in den Bereichen Umwelt, Versorgungssicherheit, Gesellschaft und Wirtschaft notwendig sind, ist politische Unterstützung unerlässlich, selbst wenn weiterhin Unsicherheiten bezüglich der Auswirkungen des Klimawandels in der Schweiz, der Versorgungssicherheit und der internationalen Entwicklung bestehen. Basierend auf der Szenarienanalyse konnten die folgenden Schlüsselbereiche für Politikmassnahmen ermittelt werden: Massnahmen für Energieeffizienz im Gebäudebereich, Anreize für die Installation von Wärmepumpen für Raumwärme und dezentrale Stromerzeugungstechnologien wie Photovoltaik (was mit hohen Vorlaufkosten verbunden sein kann), und Förderung von Wärmekraftkoppelungsanlagen speziell in der Industrie. Im Transportsektor sind moderne und hybridisierte konventionelle Antriebstechnologien in allen betrachteten Szenarien mittelfristig kostengünstig, was mit Hilfe kontinuierlicher Preissignale (im Gleichschritt mit Anreizen zu Fahrzeugstandards in der EU) auch sehr wahrscheinlich realisierbar ist. Langfristig betrachtet hängt die Wahl der Technologie – insbesondere bei der Rolle der Elektrofahrzeuge – hingegen von den politischen Entscheidungen zur Frage der Verfügbarkeit von billigem Strom (entweder in Form von Importen oder in der Form von neuen Grosskraftwerken) ab. In diesem Zusammenhang ist die politisch gewährleistete Planungssicherheit absolut zentral, um Investitionen in neue Infrastruktur und Grossprojekte (wie zum Beispiel Gaskraftwerke) auszulösen.

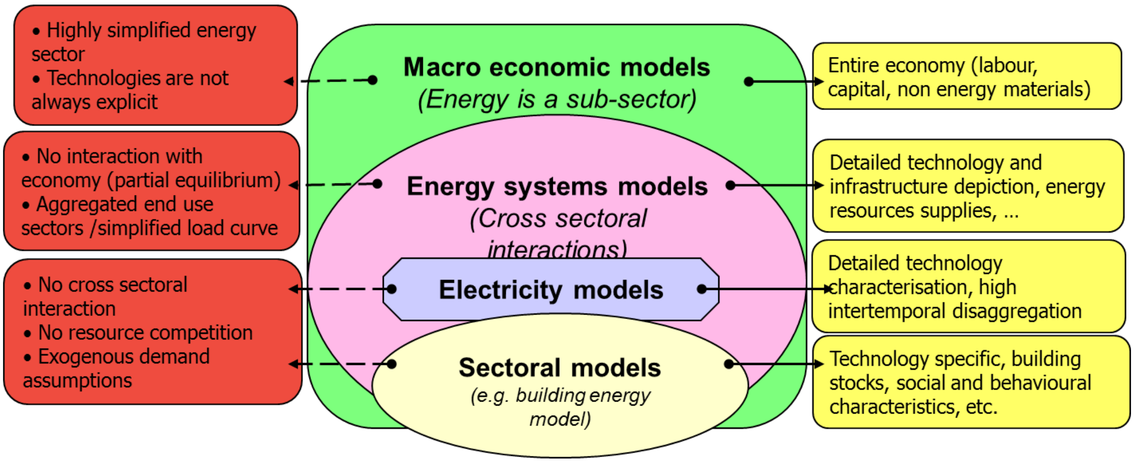
Die oben beschriebene Szenarienanalyse illustriert die Eignung des STEM für die Betrachtung einer grossen Bandbreite von Szenarien, die der Evaluation der zentralen Fragen der Schweizer Entscheidungsträger bezüglich Politikmassnahmen und Unsicherheiten dienen. STEM ist ebenso Basis für künftige Modellerweiterungen, die zusätzliche Einblicke bezüglich anderer Faktoren, die Einfluss auf den langfristigen Wandel des Energiesystems haben, wie zum Beispiel neuartige Technologien zur Stromspeicherung oder zusätzliche gesellschaftliche Aspekte, erlauben. Die Entwicklung von STEM, speziell auch der Einbezug der hohen zeitlichen Auflösung, hat den *state-of-the-art* in der Energiesystemmodellierung innerhalb der internationalen Forschergemeinde vorangetrieben.

1. Introduction

Climate change caused by carbon dioxide (CO_2) emissions from the combustion of fossil fuels, depletion of fossil reserves, and energy supply security are key challenges confronting the global energy system. While Switzerland faces the same broad set of issues, specific features of the Swiss energy system affect the nature of these challenges and give rise to additional concerns. For instance, the Swiss electricity system is dominated today by low-carbon hydroelectric and nuclear generation [4]. While this supports climate change mitigation, the high share of hydroelectricity contributes to large seasonal variations in electricity output, which do not match seasonal patterns of electricity demand. This is partly managed through integration into the European electricity grid; and Switzerland engages in both seasonal and daily electricity trading, particularly during peak hours (taking advantage of significant local pumped hydro storage capacity). Nonetheless, this dependence on neighbouring countries creates challenges for long-term electricity supply security, exacerbating Switzerland's dependence on imported fuels, with imports of oil and natural gas accounting for about two-thirds of final energy demand [5]. This dependence on fossil fuels (particularly in heating and transportation), threatens the realisation of climate change mitigation objectives. Moreover, the long-term phase out of nuclear generation threatens both climate change mitigation and supply security.

An effective response to this range of challenges will require substantial and likely systemic structural changes to the energy system in Switzerland. Many technological options exist on the supply and demand sides to address these changes, but it is not clear which combination offers the best approach given significant uncertainty about future technology performance, energy prices, demand growth and other factors (including policy decisions). To complicate the picture, the suitability of different technological structural changes in one part of the energy system is likely to be affected by developments in other parts of the energy system. To illustrate, consider the transportation sector, where there is considerable interest in alternative fuel and drivetrain options [37]. The choice of technology in transportation will have major implications for the energy supply and conversion sector (which must provide the fuels for transportation), and for other end-use sectors (which could potentially use the same fuels). In addition, any structural changes to the energy system also depend, at the most basic level, on demand for energy services and the need to ensure supply is available over seasonal and daily time periods.

Structural change in the energy system is generally a long-term, uncertain and systemic process, affected by patterns of demand and technology choices across the entire energy system. Thus, understanding how structural changes in energy supply may occur requires analytical approaches that are able to account for system-wide effects and uncertainty over the medium and long term. Energy models have emerged as a useful methodology for energy research aimed at evaluating future energy supply options and generating insights into some of the associated uncertainties. There are many types of energy model covering a wide range of analytical approaches, with tools often developed for specific objectives, with a predefined methodological scope and limited application. In Switzerland, a range of energy models, like energy-economy equilibrium models, technology-rich MARKAL energy system models and sector-specific energy models have been implemented for analysing energy and climate change mitigation policies (see [31]). Some of the models are rich in the level of technological detail, while others have a greater focus on the representation of energy-economic linkages. The objectives and scope of these models (Figure 1) are diverse, with different strengths and weakness, providing complementary insights on a range of aspects of the energy system. However, existing models have one or more limitations that render them less suitable for addressing some of the complexities and uncertainties affecting whole energy system development and structural change in Switzerland. Specifically, none of the existing models includes a system-wide technology-rich methodology, the combines a long time horizon with a sufficient level of detail to account for the impact of important seasonal and diurnal variations of energy demand and supply. Therefore a comprehensive and flexible model (the Swiss TIMES Energy system Model—STEM) has been developed for the analysis of plausible energy pathways.



Source: Kannan and Turton [31]

Figure 1: Strengths and weakness of modelling approaches

STEM is a bottom-up, technology-rich model built in the TIMES framework. TIMES (The Integrated MARKAL EFOM System) [35] is the successor to the MARKAL energy system framework [34], which has been used for many policy application in Switzerland [39][16]. TIMES includes several unique features that make it particularly suitable for Switzerland, including its ability to depict certain technologies in more detail (e.g. electricity storage), represent more dynamic electricity load curves, and account for real-world factors in technology deployment (e.g., construction times), economic risk (technical lifetime vs. economic lifetime), and a number of others.

This report documents the development of STEM. A selection of scenarios have been analysed using STEM and the results from the analysis are also described. The report is presented in two parts. In Part I, the model is described in terms of structure, key input data and assumptions. Part II describes the scenarios with key macroeconomic input drivers and presents the results from STEM. Additional and detail data and results are also included in Annexes.

PART I: MODEL STRUCTURE AND DATA

2. Swiss TIMES energy system model (STEM)

The analytical framework used for the model development is The Integrated MARKAL/EFOM System (TIMES) [35]. TIMES is a widely applied, dynamic, technology-rich linear programming energy systems optimisation framework. In its partial equilibrium formulation, TIMES is used with linear optimization software to determine the energy system configuration with the lowest total discounted system costs (capital, fuel and operating costs for resource, process, infrastructure, conversion and end-use technologies) over the entire modelling horizon [35].

In the Swiss TIMES energy system model (STEM), the full energy system is depicted from resource supply to end-use energy service demands (ESDs), such as space heating, mechanical processes, and personal/freight transport (in vehicle- or tonne-kilometre). The model represents a broad suite of energy and emission commodities, technologies and infrastructure as illustrated in the reference energy system below. The model also combines a long time horizon (2010-2100) with an hourly[1] representation of weekdays and weekends in three seasons.

The model is used to identify the least-cost combination of technologies and fuels to meet future ESDs (which are given exogenously based on a set of scenario drivers), while fulfilling other technical, environmental and policy constraints (e.g. CO_2 mitigation policy). The model outputs include technology investment and energy commodity use across all sectors, which can be aggregated to report primary energy supply and final energy consumption, seasonal/daily/hourly electricity demand and supply by technology type, carbon dioxide (CO_2) emissions, cost of energy supplies, and the marginal cost of energy and emission commodities, among others.

2.1. Reference energy system

The reference energy system (RES) describes the structure and energy flows of the Swiss energy system covering primary energy resources, conversion technologies (e.g. electricity and heat production technologies, hydrogen production facilities), transmission and distribution infrastructure (e.g. electricity grid or gas pipeline), end-use technologies (e.g. boilers, heat pumps, motors, cars) and energy service demands. Figure 2 presents a simplified version of the RES of STEM. Primary energy resources in the model comprise domestic renewables and imported fuels, which are used as inputs to conversion and processes technologies. Energy commodity outputs from the conversion and process technologies are distributed to five end-use sectors and subsectors (residential, services, industry, transport and agriculture, with the industrial sector further disaggregated into six subsectors (see §3.3)). At the end-use sectors, the energy commodities are converted to energy services by end-use technologies. Carbon dioxide (CO_2) emissions from fossil fuels are tracked at the resource-supply and sectoral-consumption levels.

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[1] The 8760 hours of the year are represented in 144 hourly time steps with three seasonal (winter, intermediate and summer) and two daily (weekdays and weekends) levels of disaggregation.

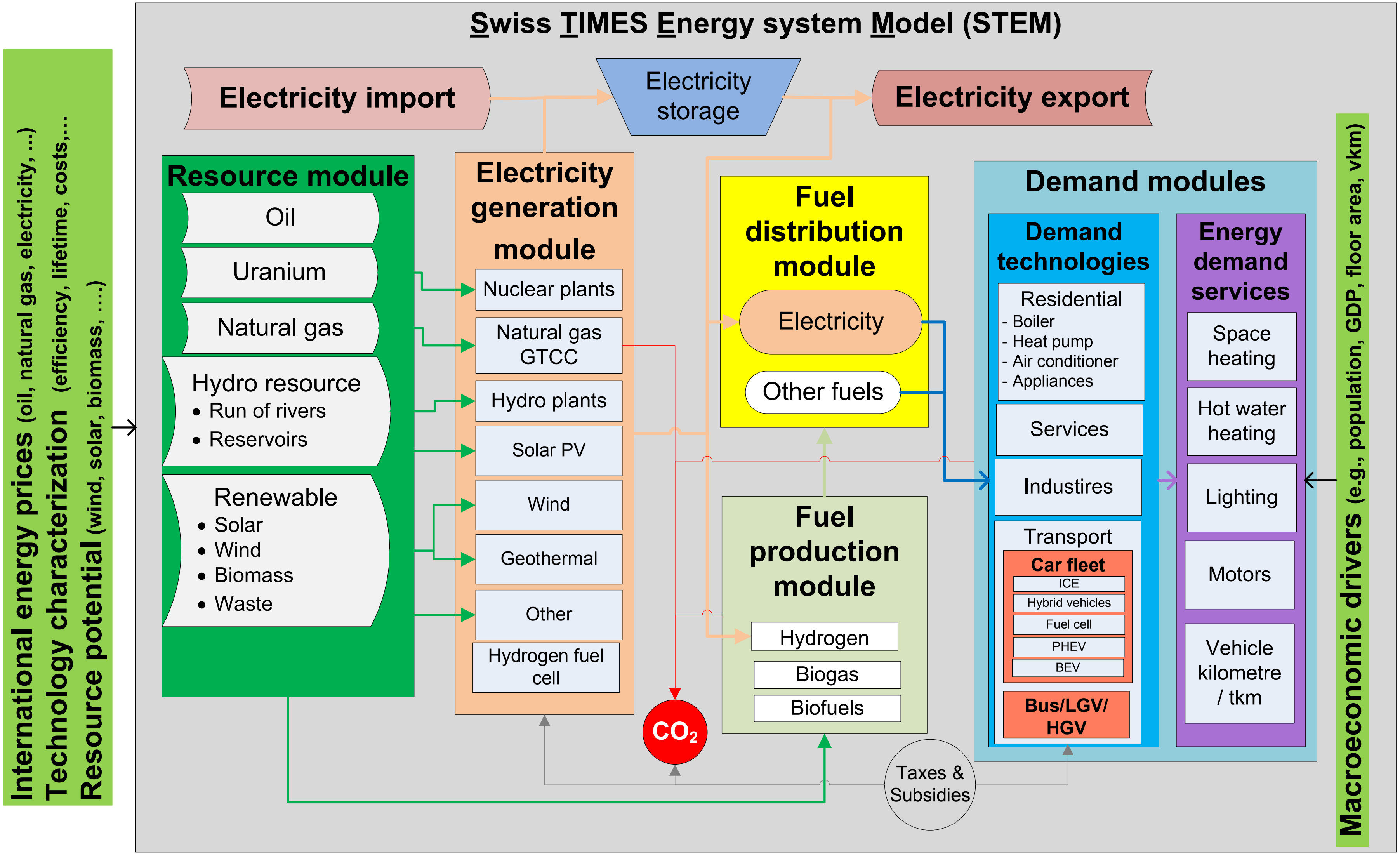


Figure 2: Simplified reference energy system of STEM

Since a large share of final energy is used for heating (31%) and transport (26%) [3][5], a higher level of detail has been included in STEM for these applications. Some of the other end-use applications (e.g. appliances) are implemented with a more aggregate level of detail and represent areas for further model development (see § 14). In the following subsections, the model structure, input data and underlying assumptions are described from resource supply to end uses. It is worth noting that the electricity sector in STEM has a similar structure to the Swiss TIMES electricity model (STEM-E), which is described in detail elsewhere [28][31][30][29][27].

2.2. **Model structure**

STEM has a modular structure for each of the five end-use sectors, primary energy resource supply, electricity generation, new and emerging fuel production options (e.g. hydrogen and biofuels) and infrastructure (fuel distribution) (see Figure 2). The model has a time horizon of 2010-2100 in 12 unequal periods (Table 1). This long time horizon enables long-term energy issues to be considered (such as climate change mitigation or fossil fuel depletion), and accounts for the long lifetime of much energy infrastructure. However, uncertainties also increase over such a long horizon across a whole range of parameters (like socio-economic development, technology breakthroughs, costs), and thus a longer period length is used to minimize computational requirements. At the intra-annual level, an hourly representation of weekdays and weekends in three seasons (summer, winter, and an intermediate season) are modelled. Thus, the model has 144 hourly[1] timeslices (Figure 3).

Table 1: Model time horizon

Period number	Number of years in the period	Start year of the period	Middle (milestone) year of the period	End year of the period
1	1	2010	2010	2010
2	3	2011	2012	2013
3	3	2014	2015	2016
4	7	2017	2020	2023
5	4	2024	2025	2027
6	5	2028	2030	2032
7	5	2033	2035	2037
8	6	2038	2040	2043
9	13	2044	2050	2056
10	17	2057	2065	2073
11	14	2074	2080	2087
12	25	2088	2100	2112

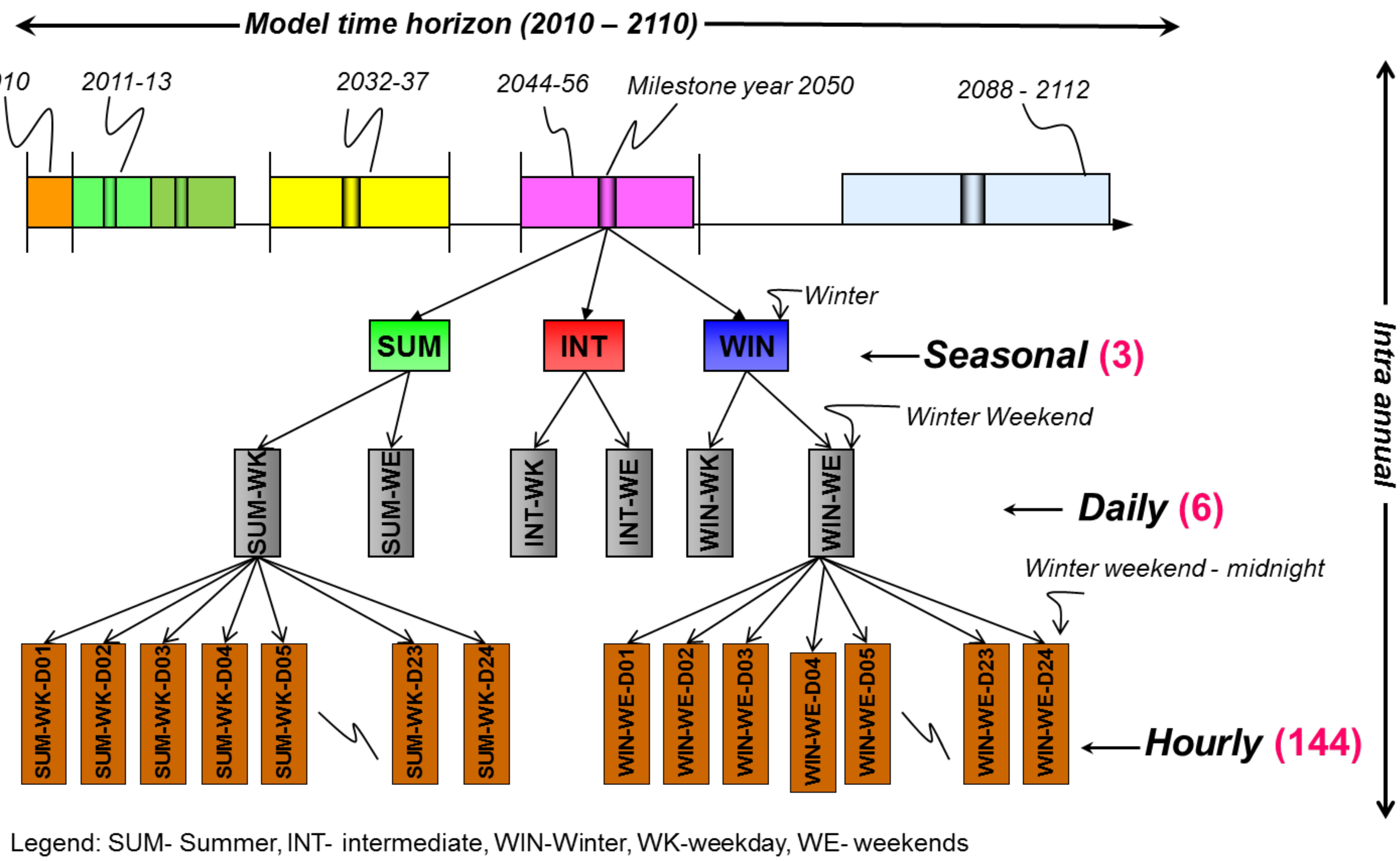
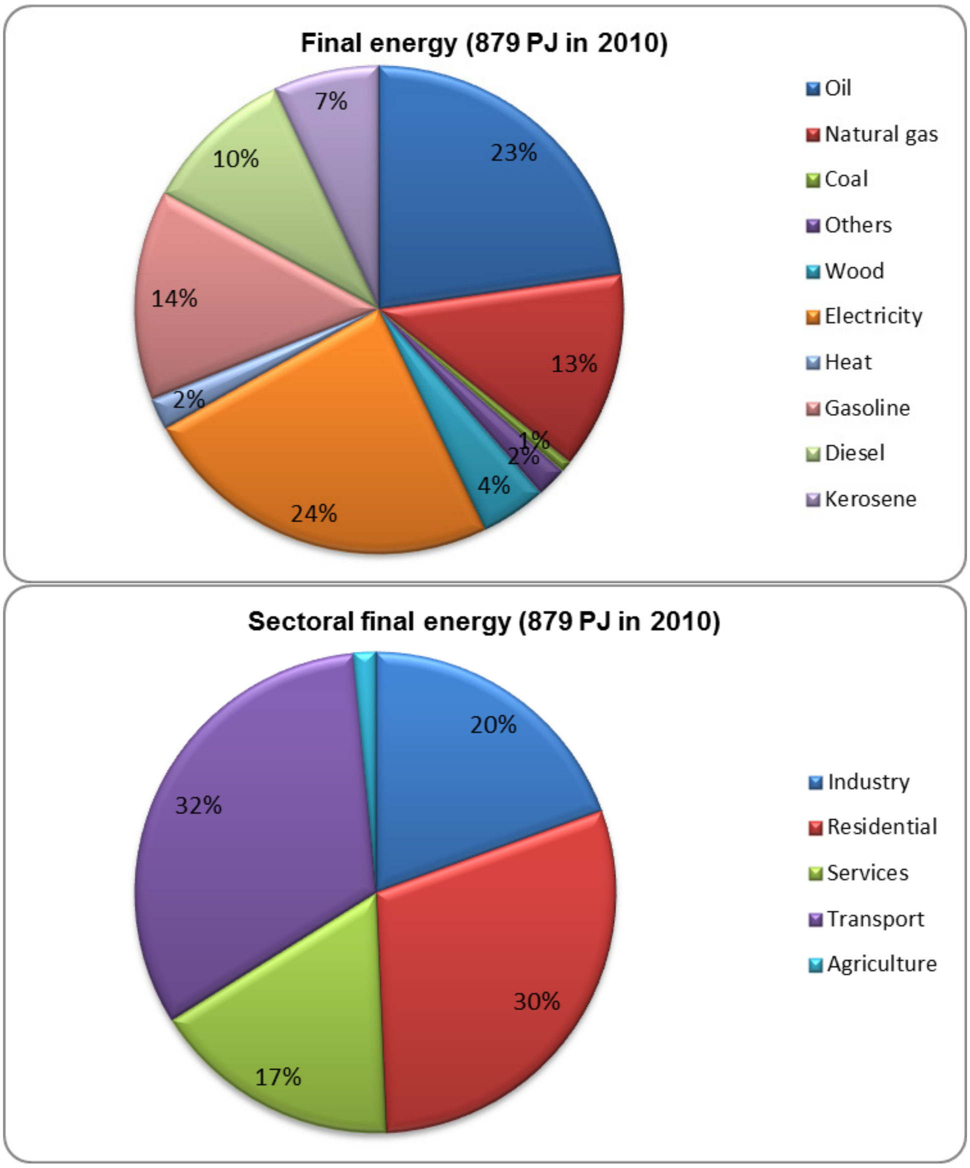


Figure 3: Temporal depiction in STEM

3. End-use sectors

End-use demands are represented for five aggregate end-use sectors. The end-use sector module of STEM includes drivers for future ESDs and end-use technology parameters (including costs, and technical and operational characteristics). It is worth noting that the ESDs are given exogenously, and are thus considered fixed and inelastic to price changes for a given scenario. In the following subsections the end-use sector modules are described. The methodology is presented in detail for the residential sector only, with the same approach applied to the other end-use sectors (and industrial subsectors).



(Source file: VT_CH_R_V17.xls)

Source: BFE [5][3][2]

Figure 4: Final energy consumption by fuel and end-use sector in 2010

3.1. **Residential sector**

The residential sector accounts for 28% of final energy consumption (Figure 4). Figure 5 shows that nearly half of the final energy is heating oil, followed by electricity (26%) and natural gas (17%). In terms of end-use applications, over two-thirds of the residential energy is used for the space heating and 13% for hot water applicaitons [3]. The depiction of the residential sector and the underlying assumptions applied in the model are described in the following subsections.

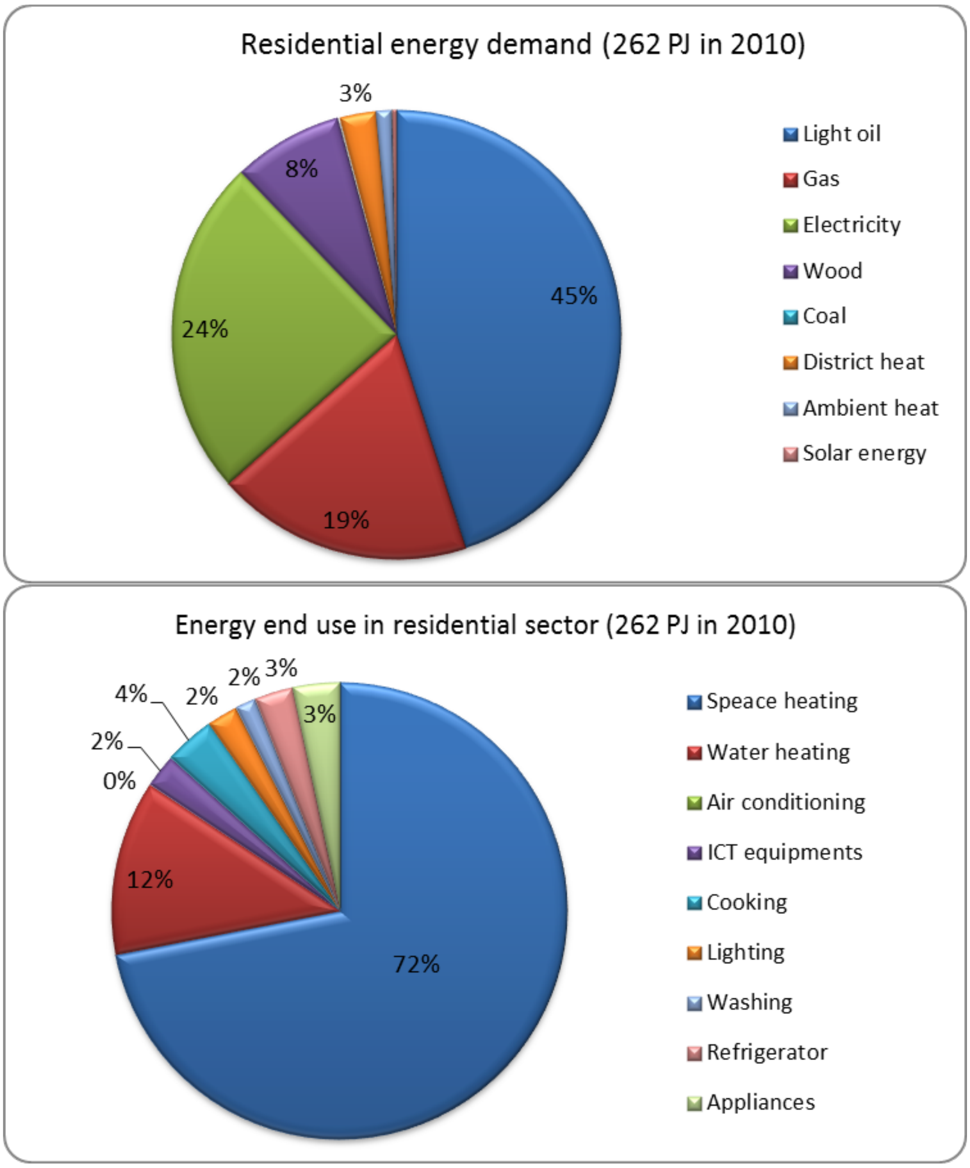


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Figure 5: Residential final energy by fuel and end use in 2010

3.1.1. Calibration

For the residential sector, energy use according to end-use application [3] was used to calibrate nine categories of ESD (see Table 2) depicted in STEM. In the base year 2010, ESD are estimated from the final energy use for each application [5][3] using a set of assumptions on end-use technologies. For space and water heating, efficiencies of end-use technologies are adopted from the Swiss Energy Perspectives (SEP) [37]. Table 2 shows the estimated ESDs for the base year 2010.

For space heating, we have assumed that the hourly and seasonal demand pattern of the residential sector is homogenous, with the magnitude varying between different building vintages and types (e.g. single vs. multi-family houses[2]). In STEM, the space heating demand is disaggregated into four sub categories, *viz.* existing single-family houses, existing multi-family houses, new single-family houses and new multi-family houses. This disaggregation of space heating by building type enables analysis of the potential role of energy conservation measures (see §3.1.3) and differences in economies of scale in heating technologies.

Table 2: Residential final energy consumption and ESD in 2010

ESD category	**Final energy**	**Estimated ESD**	**Average Efficiency**
	PJ	*PJ*	
Space heating	188.80	166.50	88% (see Table 3)
Water heating	32.60	23.76	73% (see Table 3)
Air conditioning	0.10	0.30	300%
ICT Equipment	6.17	6.17	
Cooking	9.46	7.40	78%
Lighting	5.67	*	22.8 *lm/W**
Washing	3.78	3.78	
Refrigerator	7.17	7.17	
Appliances	8.76	8.76	
Total	**262.51**		

* Specified lumens (lm)—estimated based on weighted average efficacy (*lm/W*) of lighting based on EU market share of lighting fixtures (conventional lamp (6 *lm/W*)—52%, halogen lamps (20 *lm/W*)—20%, CFLs (56 *lm/W*)—28%, LED (15-1000 *lm/W*) ~ 0%) [11].

[2] For clarity, note that "single family house" refers to a single dwelling and "multi-family house" indicates a multi-dwelling building (irrespective of the number of 'families' occupying a given dwelling or building).

Table 3: Assumptions on heating system efficiency in 2010

Fuel	Space Heating	Water Heating
Heating oil	83%	64%
Natural gas	87%	71%
Coal	72%	60%
Wood	72%	46%
Heat pump	305%	260%
Electrical heating	90%	78%
District heat	95%	76%
Solar energy	80%	80%

Unlike residential space heating, hot water demand depends highly on the number of occupants per dwelling and their behaviour, rather than on the building type. Accordingly, hot water demands are not disaggregated to minimise computational resource requirements. It is worth noting that in STEM, hot water and heating are supplied by different technologies, although many households have one heating system supplying both applications. This difference is reconciled by incorporating additional constraints in STEM to minimise potential distortions.

Other than heating demands, air conditioning, cooking and lighting demands are modelled in detail, whereas other end-use applications (ICT, appliances, etc.) are depicted as final electricity demands—that is, without an additional efficiency factor (see also scenario assumptions in § 8.2.1) .

The future ESDs are estimated from the base year ESD based on a set of scenario-specific macroeconomic drivers (see Table 16) like population, number of households, floor area, appliance ownership, etc. For example, for the scenarios presented later in this report, future space heating demands of new houses are based on the assumed growth in heated floor area (in Table 15) and the specific energy use defined in new building standards (Table 4). Table 16 shows the underlying drivers of each of the residential ESD. The macroeconomic drivers used in the scenarios in this report are given in Table 15 in Section 8.1.

Table 4: Specific energy demand for new-build houses

House type	2010	2015	2020	2025	2030	2035	2040	2045	2050
	(MJ/m^2)								
New single family	258	248	237	227	216	206	195	184	174
New multifamily	231	220	209	198	187	176	165	154	144

Source: Estimated based on Prognos, 2012 [37]

To account for potential reductions in heating demands due to warmer weather conditions as a result of climate change, a 15% reduction in space heating demand and 4% reduction in hot water demand are assumed between 2010 and 2050 [37]. Similarly for air conditioning, an increase in the number of cooling degree days is assumed, e.g. 120 degree-days in 2010 vs. 280 degree-days in 2050, to reflect higher temperatures from climate change [37].

For the existing buildings, energy conservation measures (§ 3.1.3) are also included. The potential of these measures depends on renovation rates, and for the scenarios presented later in this report, we have applied a rate from Prognos, 2012 [37].

3.1.2. End-use technologies

To meet the ESDs, a range of end-use technologies are included in the model. The existing stock of heating technologies is assumed to be retired linearly over the next 35 years. A range of new technologies are available to replace current heating systems, or for installation in new buildings (Figure 6). These options cover different fuels and technologies based on oil, natural gas, woody biomass, pellets, resistance heating, heat pumps, or solar thermal systems for the all four categories of buildings. However, wood-fired boilers are assumed to be available only in single family houses. Technical and cost data of heating technologies have been adopted from various studies [37][1][11][23]. Table 5 shows costs and efficiency of new heating technologies in the residential sector. The data sources are chosen to ensure consistency among competing technologies within each building category.

Table 5: Characteristics of residential heating systems (new)

Heating and cooling system	**Capital cost (*CHF/kW*)**			**Efficiency/COP***		
	Space heating		**Hot-water**	**Space heating**		**Hot-water**
	Single	**Multi**		**Single**	**Multi**	
Natural Gas boiler	1460	756	1607	95%	87%	76%
Oil boiler	1587	822	1746	86%	78%	68%
Pellet biomass boiler	2363	1764	2599	90%	87%	54%
Woody biomass boiler	2045			56%		
Electric boilers	730	378	584	95%	95%	95%
Heat pump	2848–3435	2180	4465	260–340%	351%	130–170%
Solar thermal system	8110	5661	8110	75%	75%	75%
Electricity (air conditioning)	660–1320			335–469%		

* Coefficient of performance (with respect to heat pumps)

Source: Prognos [37], PSI [1], ETSAP [11], Jakob et al [23] and estimations

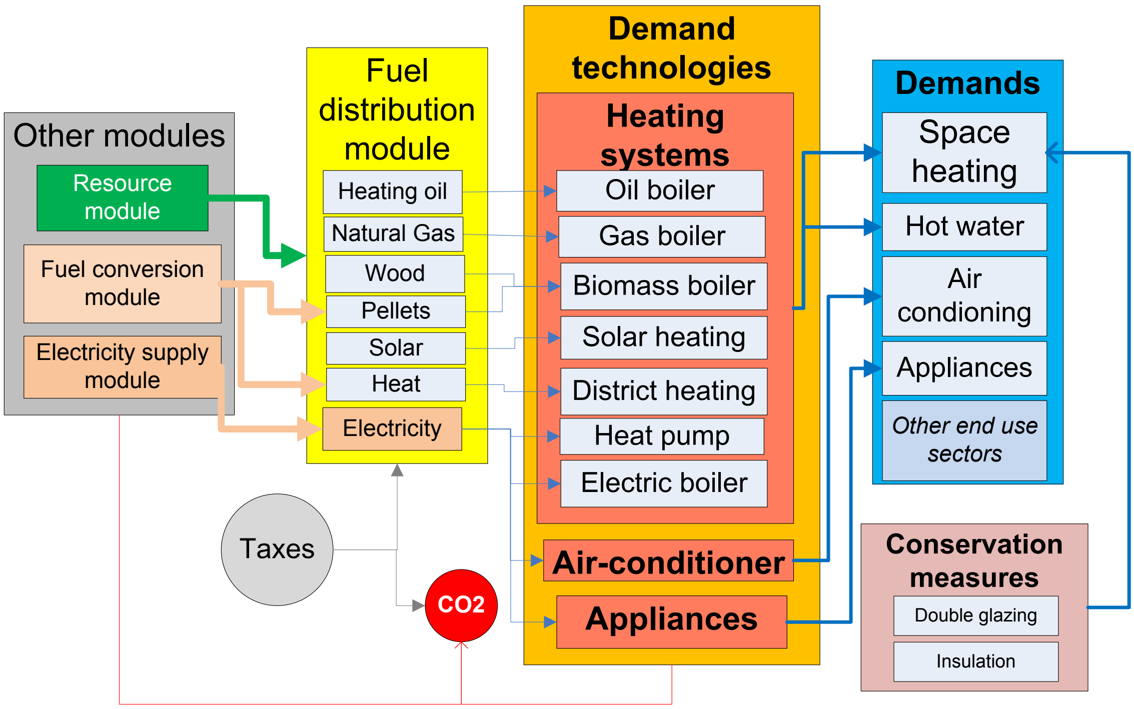


Figure 6: Technology options for residential space and water heating

For heat supply, the model also represents district heating systems, for which heat is produced from a range of technologies (see § 4.1). Moreover, the model has option to invest in small-scale (distributed) CHP in the residential sector. For such technologies, the electricity and heat is assumed to be used within the residential sector, i.e. excess heat or electricity from the micro CHP cannot be exported/used elsewhere in the energy system.

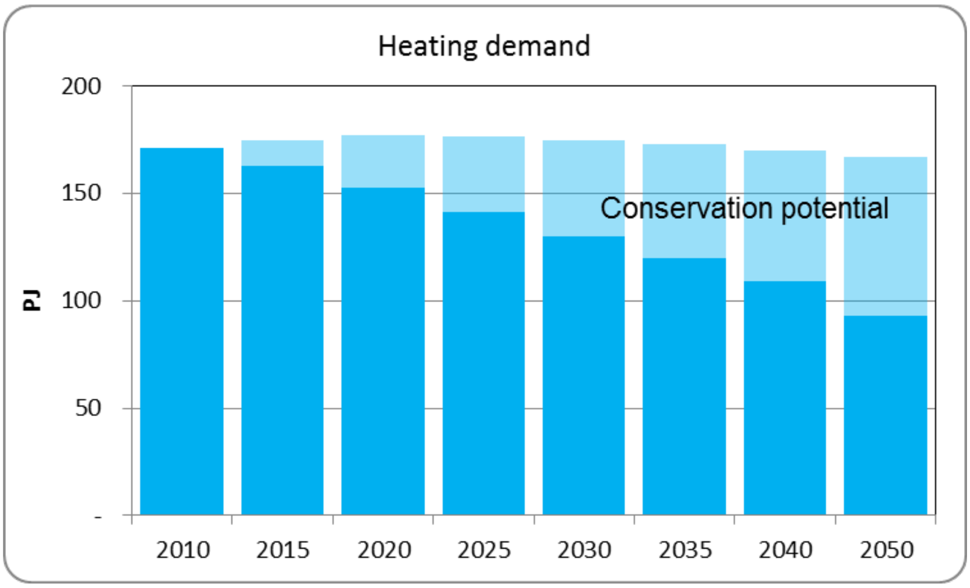
Similar to the representation of heating systems, the model includes a range of alternative air conditioning (AC) and lighting technology options (although in contrast to heating, these are predominantly electricity based). Cooking technologies fuelled by either gas or electricity are represented, although the availability of natural gas for cooking is assumed to be limited according to the use of gas for heating– i.e. we assume gas grid is not expanded solely to supply cooking (or, hot water applications alone).

Although all nine ESDs shown in Table 2 are modelled in STEM, space and water heating and air conditioning have been developed extensively in terms of alternative technology and fuel options. Alternative technologies for other appliances are not yet fully represented in detail.

3.1.3. Building energy conservation measures

The model accounts for a range of energy efficiency measures like wall and loft insulation, and window double glazing, for residential buildings. These conservation options are represented in the form of a supply curve describing the available conservation potential at a given cost during each cycle of renovation or new construction (Figure 8 presents the cumulative supply curves to 2050 for the four types of the residential buildings). Importantly, conservation measures not implemented during construction or renovation cannot be deployed at a later time. These costs and potentials are estimated from the earlier studies

[39] but using the building renovation rates similar to the WWB scenario [37]. Figure 7 illustrates the potential of the set of conservation options in the model relative to the heating demand in the business-as-usual (*BAU*) scenario presented later in this report (see §8.2.1).



(Source file: SubRES_CSV-Residentialv6.xls)

Figure 7: Residential heating demands in *BAU* and energy conservation potential

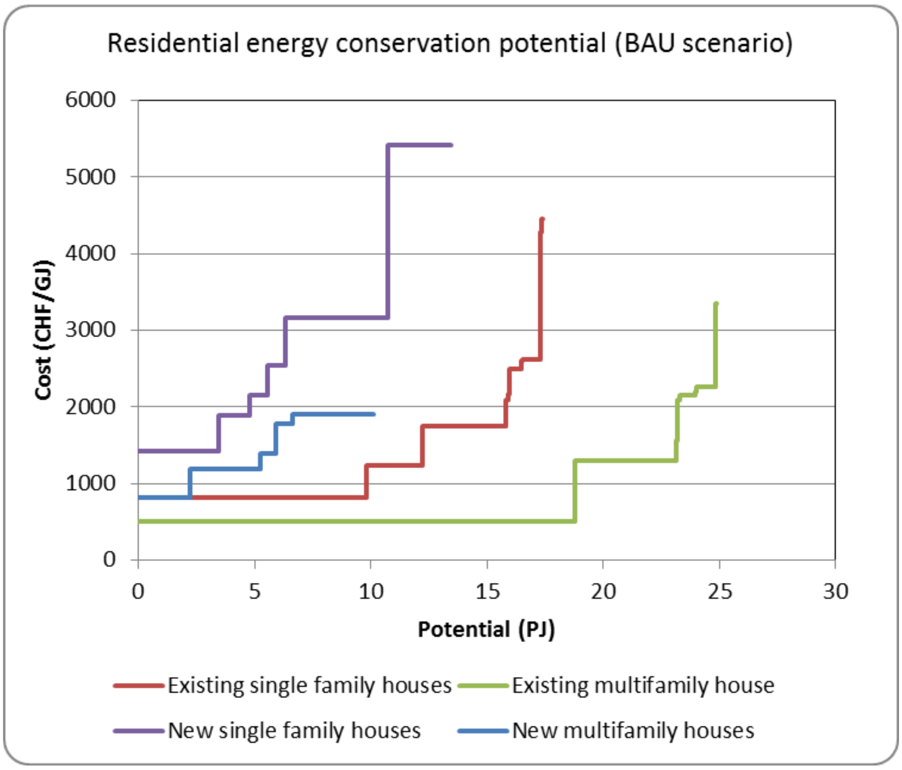


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Figure 8: Investment cost curve of residential conservation measures in 2050

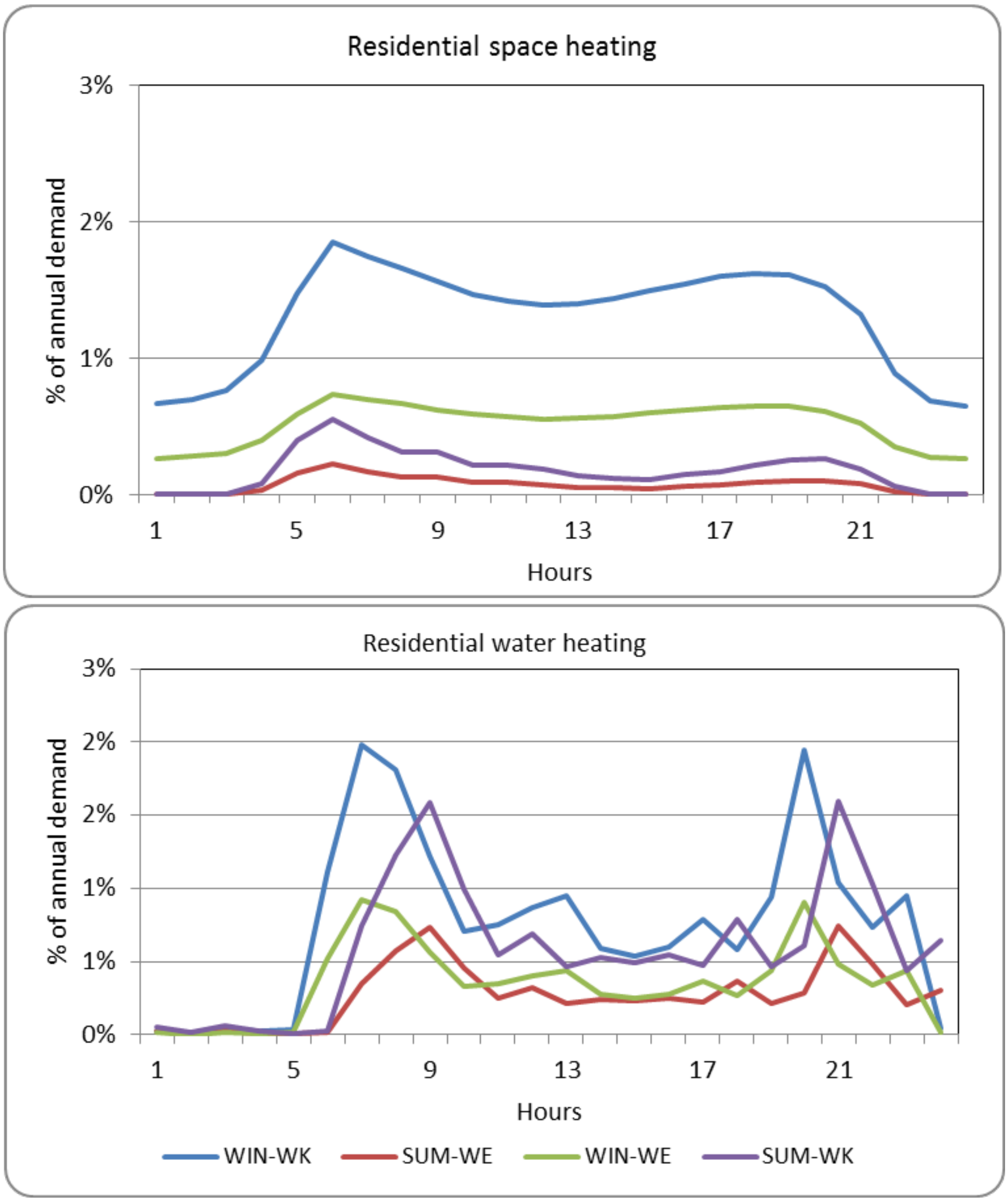
3.1.4. Demand curve

One of the key features of STEM is its hourly time resolution. To take advantage of this high time resolution, STEM requires as input typical demand curve (i.e. user profiles) for each of the ESDs for different seasons, days and hours (for the entire model horizon). However, demand profile data for many ESDs are not readily available for Switzerland (or many other countries). For STEM, various data sources from Switzerland and other counties are adopted to estimate the hourly demand profile of each ESD. For example, hourly space heating demand profiles are estimated based on daily heat demand patterns from Germany [17] and adjusted for heating degree days in Switzerland [36]. The residential hot water demand profiles are based on surveys conducted in Switzerland and Germany [24]. Again, the hot water demand profiles are adjusted for differences in heating degree days. Figure 9 shows the space heating and hot water demand pattern of existing single family houses on winter and summer weekdays and weekends.

The space heating demand exhibits a morning peak followed by a long day-time plateau and a smaller evening peak.[3] In winter, the variation in daytime demand is less pronounced (i.e., the ratio between peak daytime demand and the lowest day-time demand is closer to unity).

The water heating demand profile is characterised by two peaks, one in the morning and one in the evening [24]. Between the two peaks the load varies marginally reflecting cooking and other moderate uses of hot water. The hot water profile is characterised by more sharp variations compared to the space heating profile, as the use of hot water varies considerably over the day.

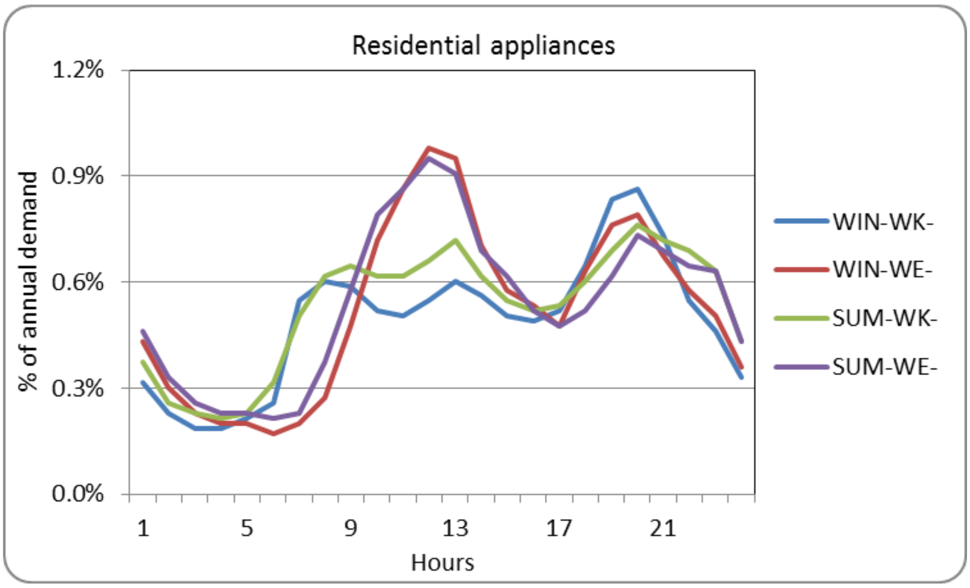
[3] The latter is presumably due to the night set back operation of thermostats which adjust the heat temperature at lower levels at night times, both in single family and multifamily houses. In multi-family houses the night set back comes later compared to the single-family houses because the design of the facilities in multi-family houses is different from those of single-family houses.



(Source file: Scen_B_DemandCurve-RESV6.xls)

Figure 9: Demand profile of residential space and water heating

The demand profile for residential appliances has been adopted from [33], with the demand profile for winter and summer days shown in Figure 10. The lighting demand profile is based on [41].



(Source file: Scen_B_DemandCurve-RESV6.xls)

Source: Knight and Ribberink, *2007* [33],

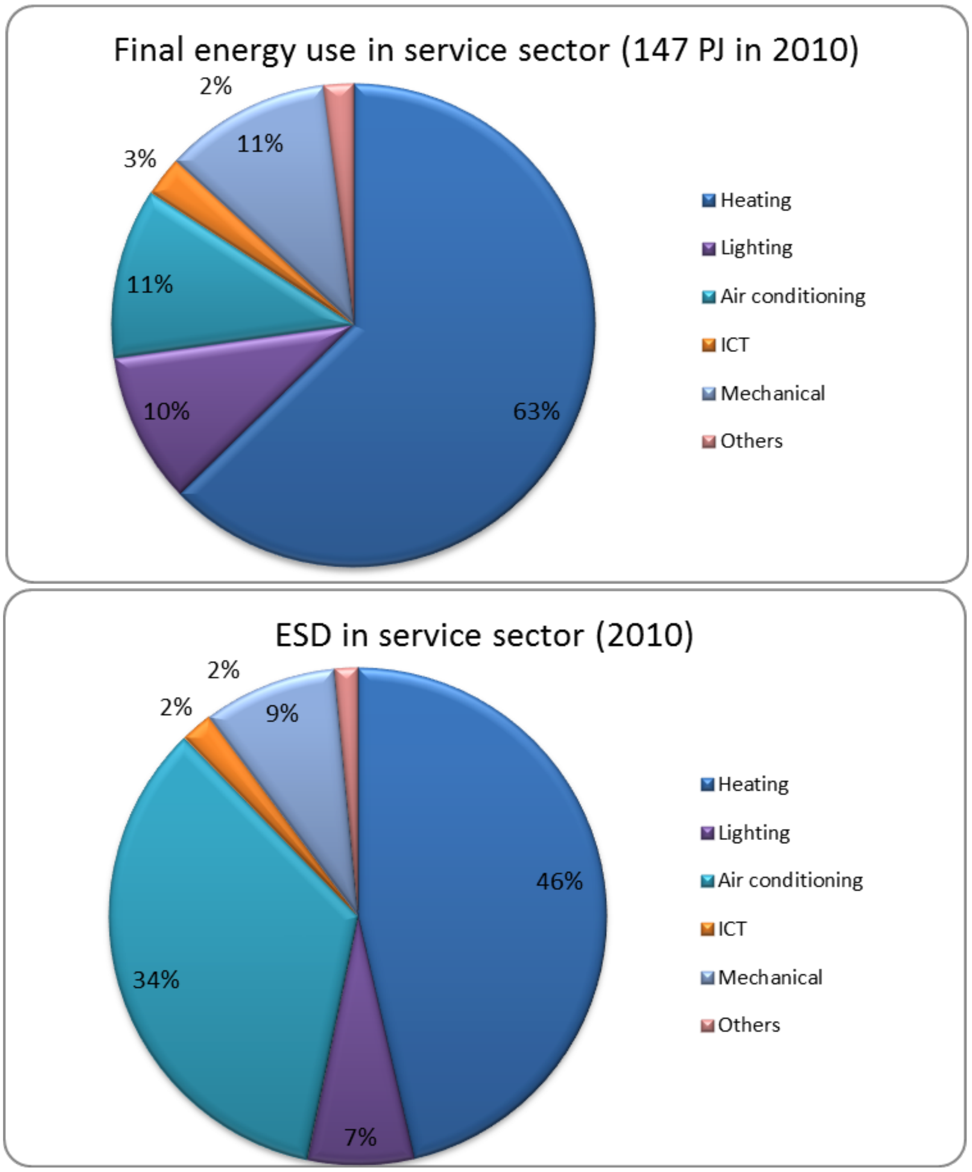
Figure 10: Demand profile of residential appliances

For all of these ESD patterns, it is worth remembering that the model selects the least-cost end-use technologies to deliver the required demand. Accordingly, depending on the choice of technology (and efficiency of that technology), the aggregate electricity demand profile is determined endogenously by the model (see [25] for details).

3.2. **Services sector**

The services sector accounts for 17% of total final energy consumption (Figure 4) and two thirds of this is used for heating (space heating and hot water) [3]. Although the services sector includes a heterogeneous mix of activities and building types (office buildings, hotels/restaurants, hospitals/schools, etc.), the space heating and hot water demand is aggregated in STEM, mainly due to inadequate demand profile data for subsectors and the relatively smaller share of this sector compared to the other aggregate sectors (which are disaggregated in more detail).

Similar to the residential sector, ESDs are estimated from the final energy statistics for 2010. Figure 11 shows final energy demand by end-use application and the estimated ESDs.



Note: air conditioning also includes ventilation

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Figure 11: Services sector energy consumption and end-use applications in 2010

For scenario development, future ESDs are estimated by linking the base year (2010) ESD to appropriate macroeconomic drivers of the services sector. Table 17 shows the links between the demand drivers and the individual ESDs in the services sector (although other drivers can be adopted depending on the scenario of interest). For the scenario analysis presented later in this report, the macroeconomic demand drivers (floor heating area and economic value addition) are given in Part II (see Table 18).

STEM represents a range of heating systems in the services sector covering similar fuel and technology options as in residential multifamily houses. The model also includes an explicit representation of alternative technologies for air conditioning and lighting. Table 6 shows the technical characteristics of heating (and air-conditioning) systems. For the remaining

ESDs (e.g., office equipment) the technology choice is specified exogenously according to scenario drivers.

Table 6: Characteristics of service and industrial heating systems

Heating and cooling system	**Capital cost* (*CHF/kW*)**	**Efficiency/COP+**
Natural Gas boiler	686	82%
Oil boiler	746	74%
Biomass boiler	1602	82%
Electric boilers	343–429	95%
Heat pump	2633–3511	351–389%
Solar thermal collectors	7360	82%
Air conditioner	594–1188	335–469%
*Costs are based on a combination of single and multifamily houses in Table 5. + coefficient of performance (with respect to heat pumps)		

Figure 12 shows heating (space and hot water) demand profiles for 2010 in the services sector for a typical working day and weekends. On working days, the demand peaks early in the morning, mainly for space heating. On weekends the level of demand for space and water heating is lower than on working days, since most offices and commercial activities are not operating.[4] The overall heat demand profile is quite smooth as a result of the aggregation of the different sub-sectoral profiles reported in the literature [17].

For air conditioning, due to a lack of data we assume that the summer cooling demand profile matches the winter heating demand profile (in Figure 12).[5] For the remaining ESDs in the services sector (which are all supplied by electricity, e.g., lighting, office equipment), a demand profile is adopted representing the "residual demand"—this is calculated by subtracting from the national electricity demand curve the electricity demands from heating, air conditioning (from all sectors), and residential lighting and appliances. This methodology enables us to calibrate the model to the total electricity profile in 2010. However, this method likely introduces inconsistencies for some ESDs and should be revised if better data become available for ESD demand profiles.

[4] However, in specific subsectors of the services sector, such as restaurants or entertainment, heat demands are likely to be higher on weekends.

[5] That is, if heating demand in winter peaks at 8:00, we assume cooling demand peaks at 8:00 in summer. This deserves to be revisited since the coldest time of the day in winter (early morning) does not coincide with the hottest time of the day in summer (mid afternoon).

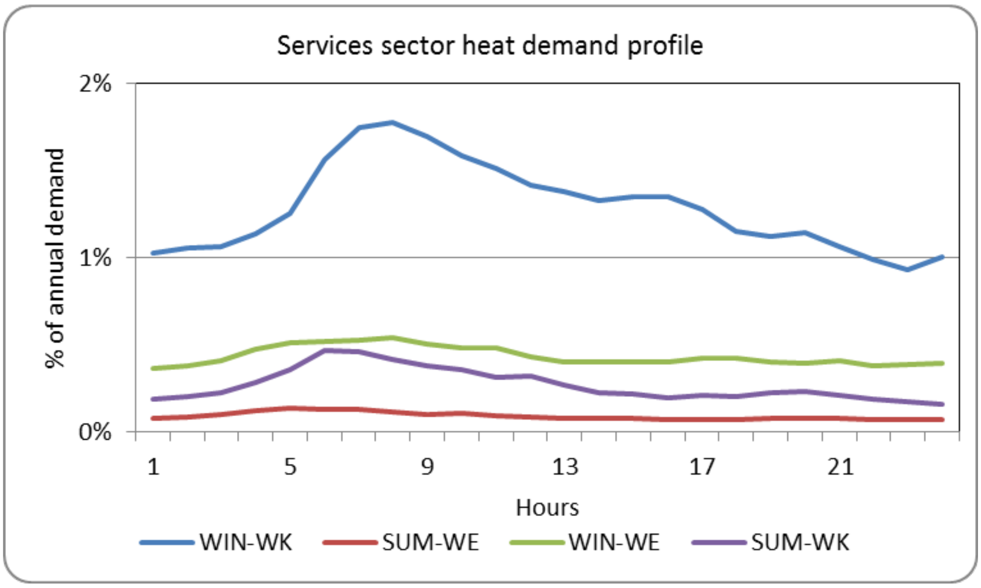
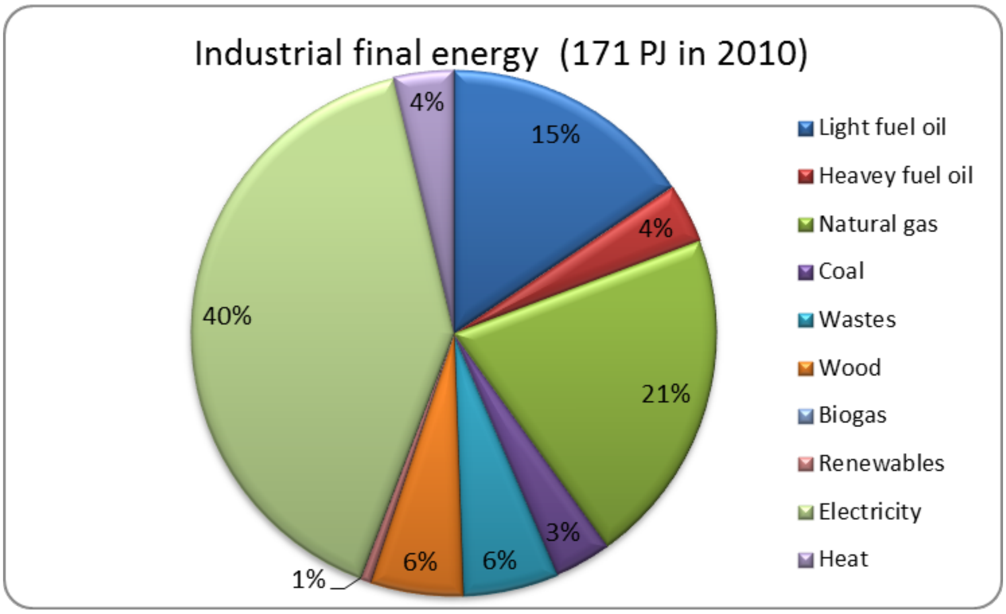


Figure 12: Heating (space and hot water) demand profile of services sector

3.3. **Industrial sector**

The industrial sector accounts for 14% of total final energy consumption (Figure 4). The fuel mix is dominated by electricity (40%), natural gas (21%) and light fuel oil (15%) (Figure 13). A majority (55%) of this energy is used for the production of process heat, while mechanical drives (motors) account for 23%. In addition to process heat, there is also a significant demand for space heating (14%). Given the differences in industrial subsectors in terms of several factors (e.g., energy intensity; process heat requirements[6]; fuel options; temporal energy demand patterns; future economic growth) the industrial sector in the model is further disaggregated to six industrial subsectors, as shown in Figure 14. For the future ESDs, the space heating, water heating and air conditioning are linked to floor area and the rest of the demand is linked to the subsectoral GDP. Table 19 shows the macroeconomic drivers for the set of scenario analysis presented later in this report.

[6] e.g. low-medium temperature heat for food and processing industry versus high temperature heat for basic metals, cement, and chemicals.



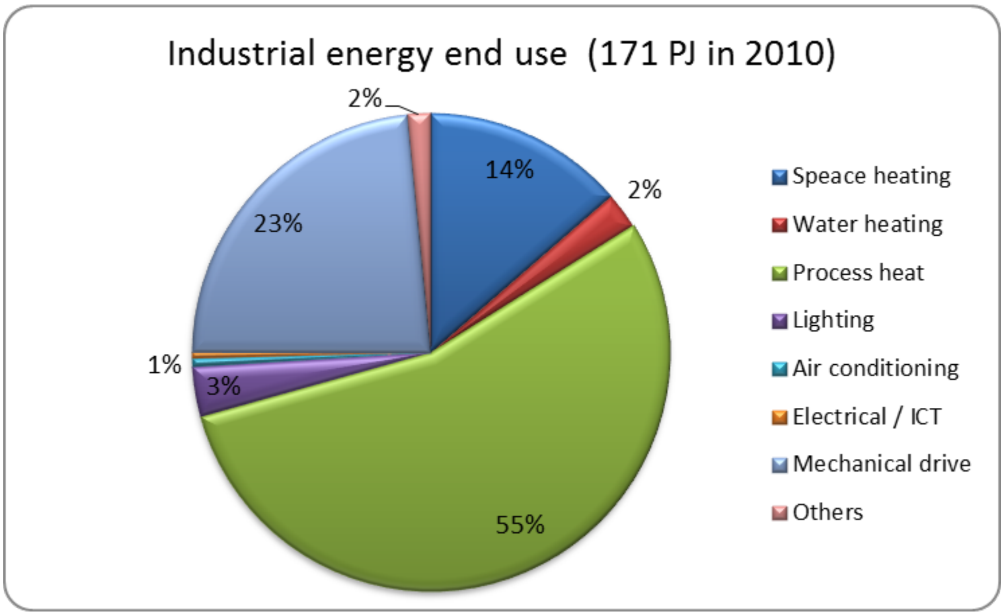


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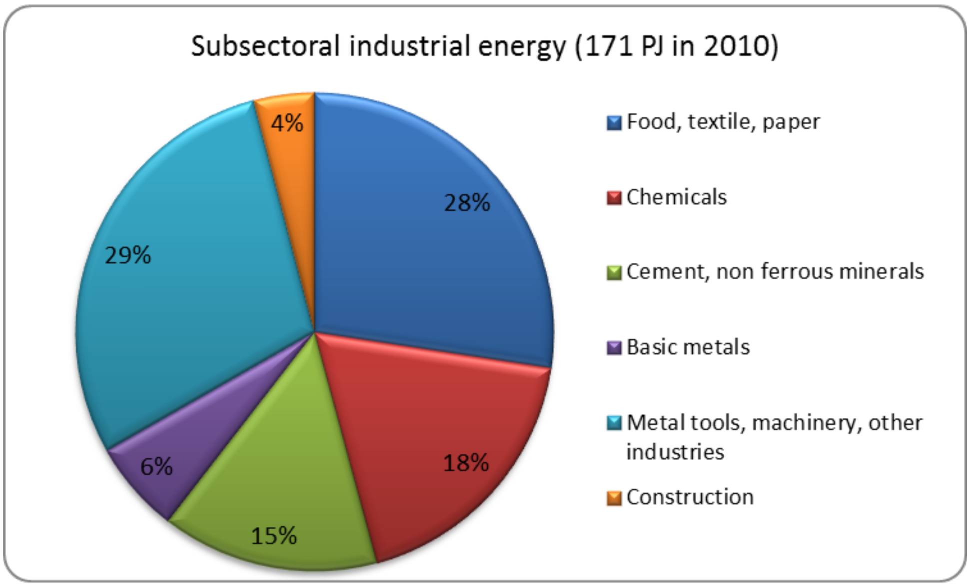
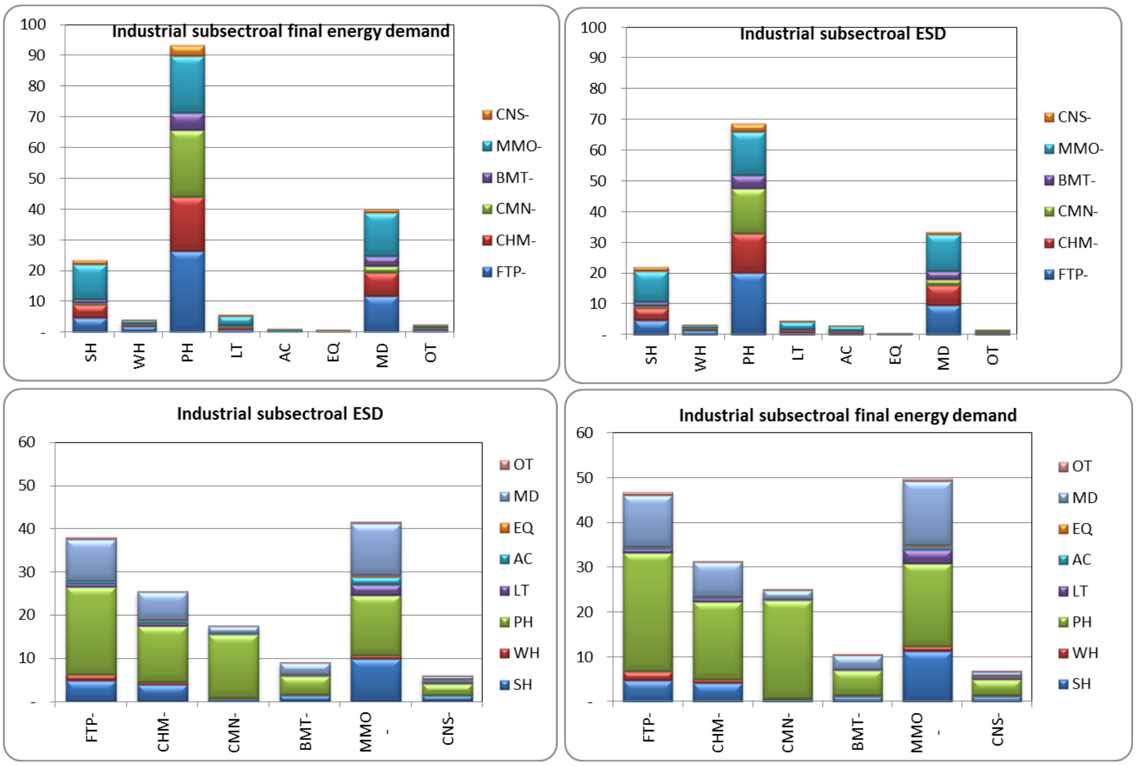
Figure 13: Industrial energy consumption by fuel and end use in 2010



Source file: VT_CH_I_V20

Figure 14: Energy use in industrial subsectors in 2010



IFTP - Food, Textile, Pulp and Paper
ICHM - Chemicals
ICMN - Cement and non-ferrous minerals
IBMT - Basic metals (Iron and steel and non-ferrous metals)
IMMO - Metal tools, machinery, other industries
ICNS - Construction

SH - Space heating
WH - Water heating
PH - High temperature process heat
LT - Lighting
AC - Air conditioning
EQ - Electrical and ICT equipment
MD - Mechanical drive
OT - Others

Figure 15: Detailed energy use in industrial subsectors in 2010

For the production of industrial process heat (and space/water heating), the model has a range options. They include technology and fuel combinations such as:

– Boilers: coal, natural gas, oil, biomass, waste, electric resistance heaters etc.
– Heat pumps: electric and natural gas
– Centralised and decentralised CHPs fuelled by natural gas, biogas, and biomass for low temperature process heat (<500 °C), and space/water heating applications.

Table 7 shows the characteristics of process heat technologies in the model. For AC and space heating, the technology characteristics from the services sector are used (Table 6). For other ESDs (of which mechanical drives is the only one of significance), no alternative future technology or fuel substitution options are included.

Table 7: Efficiency of industrial heating systems in 2010

Fuel type	Space heating	Water heating	Process heating
Light fuel oil (diesel)	83%	64%	74%
Heavy fuel oil	75%	58%	66%
Natural gas	87%	71%	79%
Coal	72%	60%	66%
Wastes	-	-	53%
Wood	72%	46%	59%
Biogas	78%	64%	71%
Heat pump	305%	260%	-
Electricity	90%	78%	95%

Figure 16 shows the aggregated industrial process heat demand pattern [17]. Due to lack of heat demand profile data for individual subsectors, the heat demand profile of the entire sector is adopted for all subsectors. For space heating and water heating, the demand profile of the services sector (Figure 12) is adopted. For the demand profile of other industrial demand categories, the ‘residual’ profile described in section 3.2 (in relation to other demands in the services) is used.

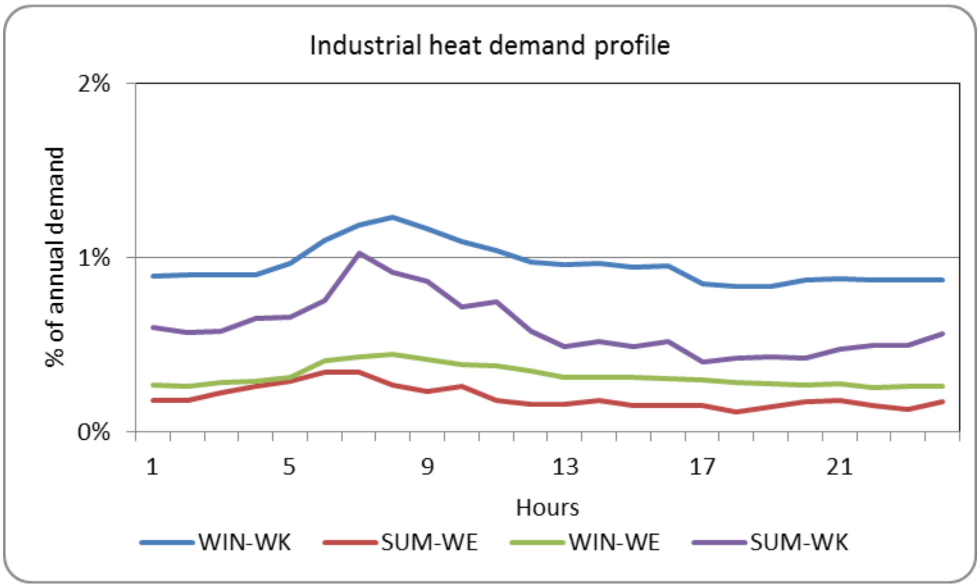
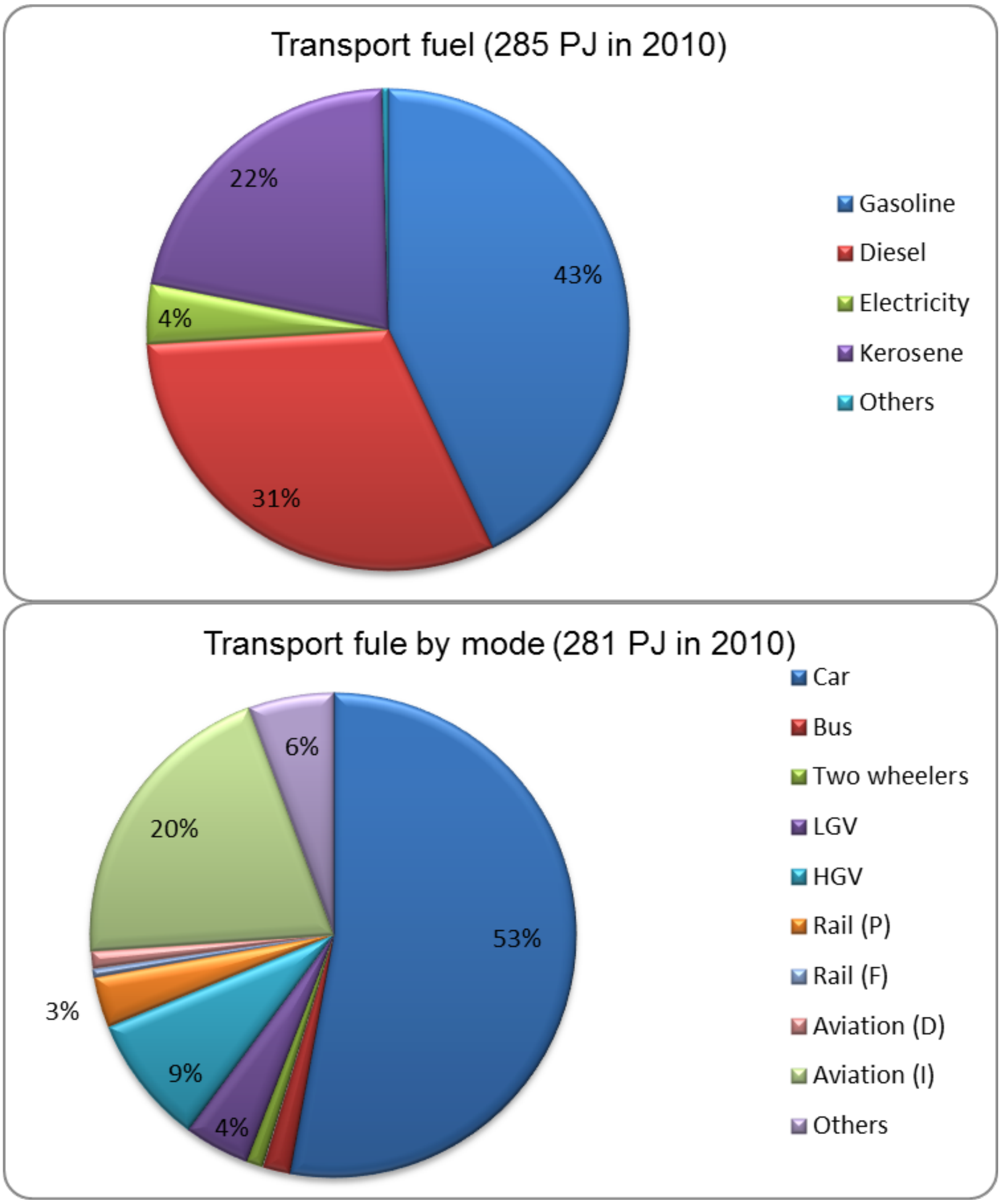


Figure 16: Aggregated industrial heating demand profile

3.4. Transport sector

The transport sector accounts for one third of final energy demand (Figure 4), and over half of this is used in the car fleet (Figure 17). The transport sector in the model covers the two broad transport service demand categories, viz. personal and freight transport, which are quantified in terms of vehicle kilometre (vkm) and tonne kilometre (t-km). The model includes ten modes of transport as elucidated in Figure 17. International aviation and military transport (others) are not modelled in any detail, but are included for calibration to the Swiss final energy balance [5]. To meet the transport ESD, a wide range of existing and future vehicle technologies (e.g. cars, buses, and trucks) and fuel supply options are depicted. A high level of detail is included particularly for the car fleet, with a wide range of alternative drivetrains and fuels (see Table 9). The other transport modes (buses, trucks or rail) are depicted with a more limited number of alternative technology and fuel options. Figure 18 shows a simplified RES of the transport sector and the link to other modules (Figure 2).



Source file: VT_CH_T_V27.xls

Figure 17: Transport sector energy consumption by fuel and fleets in 2010

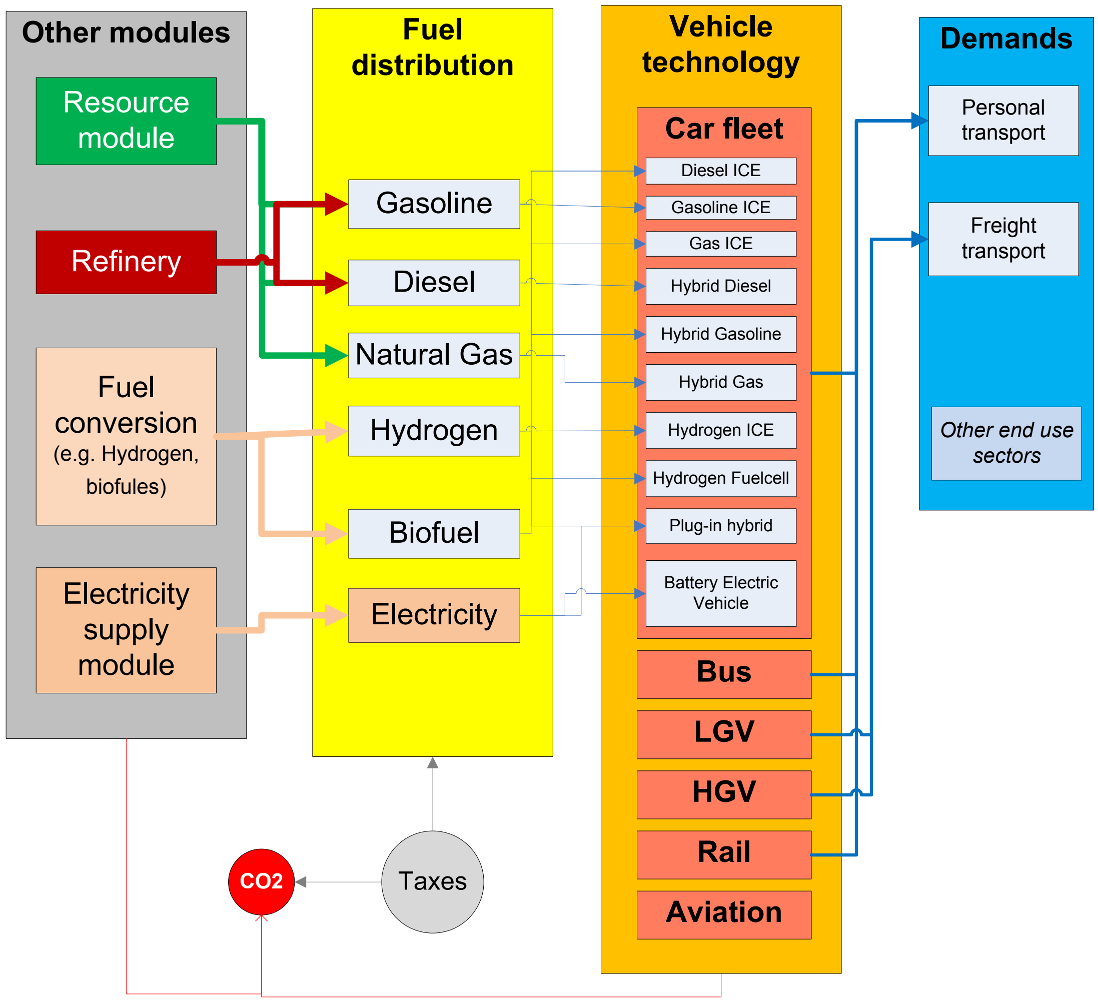


Figure 18: Simplified RES of the transport module

The model is calibrated for 2010 for each mode of transport based on final energy use[7] [5], annual vehicle kilometres travelled [37], and fuel efficiency [14]. The existing car fleet is aggregated in three fuel categories viz. gasoline, diesel and natural gas[8]. The aggregated[9] fuel efficiencies for the existing car fleet are adopted from the Swiss national greenhouse gas inventory [14]. All the existing cars are assumed to be retired linearly over the next 12 years.

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[7] It should be noted that the transport fuel consumption in the Swiss energy statistics includes fuel tourism [3][5], i.e. cross-border tanking to benefit from fuel price/tax differences. This fuel tourism is excluded for the estimation of ESDs based on greenhouse gas emissions inventory data [14].

[8] The number of existing battery and electric plug-in cars is insignificant (< 1%) [7] and therefore not modeled explicitly.

[9] The fuel efficiency is the Swiss national average that could also include efficient hybrid- and inefficient old cars.

Car ESD is modelled as a single demand, without distinguishing between different usage patterns. In addition, each car technology is modelled as a representative car with similar performance characteristics (i.e., such that each type of drivetrain/fuel combination represents an equivalent substitute in terms of performance). This means that STEM does not seek to model the choice between a large and small car (since a cost optimisation framework is less suited for this purpose)[10], but rather the choice of drivetrain or fuel. Changes to the size distribution of the car fleet over the model horizon can be specified in the scenario data inputs.

Table 8: Characteristics of existing car fleet in 2010

Total vehicle kilometres	(million *vkm*)	57,419
Total number of vehicles	(million)	4.075
Maximum remaining lifetime	(*years*)	12
Cars by fuel type	Fuel efficiency (*km/GJ*)	No. of cars (million)
Gasoline	364	3.31
Diesel	442	0.73
Natural gas (and others)	398	0.03

Source: [14][6][3]

Similarly, for other transport modes the model is calibrated based on vkm and tkm from [37] and fuel efficiency from [14]. For the national and international aviation and other transport demand, kerosene, gasoline and diesel demands are directly adopted.

For the scenarios presented later in this report, future transport service demands are adopted from the SEP [37], and are given in Figure 22.

3.4.1. Vehicle technologies

In addition to the existing vehicle technologies, a range of new and future vehicle technologies are represented with alternative fuel and drivetrain options (see Table 9). New vehicle technologies are depicted in five-year vintages reflecting improvements in fuel efficiency and/or cost reductions. The technical characterization and capital cost of cars are based on [10] and shown in Table 9. An annual driving distance of 14,000 km per year and lifetime of 12 years is assumed for all car technologies. In the Thelma project [42] Swiss specific car technology has been characterised and this car technology data will be implemented in the future update of STEM.

[10] In a cost optimization framework, small cars will be attractive due to their lower fuel consumption and lower purchase price. That is, the choice of a larger car is driven by behaviour factors and preferences unrelated to cost.

Table 9: Characteristics of new car technologies

Car technology type		Fuel efficiency (*km/GJ*)				Capital cost (*'000 CHF_{2010} per car*)			
Fuel type	**Drive train**	**2010**	**2020***	**2030***	**2050***	**2010**	**2020***	**2030***	**2050***
Gasoline	ICE	332	2%	4%	4%	24	0%	1%	1%
	ICE (Advanced)	440	6%	13%	13%	24	2%	4%	4%
	Hybrid	545	25%	67%	67%	29	-3%	-6%	-8%
Diesel	ICE	368	2%	4%	4%	26	0%	1%	1%
	ICE (Advanced)	474	8%	23%	23%	27	0%	0%	0%
	Hybrid	575	26%	72%	72%	31	-3%	-6%	-7%
Gas	ICE	447	5%	11%	11%	25	1%	1%	1%
	Hybrid	600	21%	54%	54%	30	-3%	-6%	-8%
Electricity	Battery Vehicle	1'409	5%	10%	10%	43	-18%	-28%	-32%
Electricity /Gasoline	Plug-in hybrid**	983	13%	30%	30%	35	-8%	-14%	-17%
Hydrogen	Fuel Cell	1'000	6%	13%	13%	42	-8%	-19%	-29%
	ICE	564	24%	63%	63%	32	-3%	-6%	-7%

* Relative change from the vintage year 2010

** Combined efficiency based on gasoline (50%) and electric (50%) drive mode. STEM has the flexibility to use different share between these two modes, but with a maximum of 85% of the annual distance covered by electric mode.

(Source file: SubRES_TRN-v7.xls)

Source: Densing et al, 2012 [10]

3.4.2. Electric mobility

For the car fleet, two types of electric vehicle—viz. pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—are represented in STEM. For the PHEV, separate electric- and gasoline/diesel-mode efficiencies are implemented. It is assumed that driving patterns enable the PHEV battery to store energy for up to 85% of the annual drive distance. It has flexibility to choose pure gasoline/diesel, if the electricity cost is prohibitively expensive in a season or period. For the both types of electric car (i.e. BEV, PHEV), the time of charging is unconstrained, but constraints are included to control the rate of charging based on the existing infrastructure of 220 volt and 16 ampere household fuses.

Table 10: Characteristics of new vehicle technologies

Vehicle type	Change in fuel efficiency (km/GJ)					Change in vechicle capital costs (CHF/vkm)				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
HGV Diesel ICE	96	105%	110%	116%	121%	1'721	96%	96%	96%	96%
HGV Hydrogen ICE	99	112%	125%	139%	155%	2'621	82%	75%	71%	68%
HGV Hybrid diesel ICE	110	111%	120%	126%	133%	1'838	95%	94%	93%	93%
LGV BEV	872	108%	113%	118%	123%	1'913	96%	94%	89%	81%
LGV Diesel ICE	320	105%	110%	116%	121%	1'140	100%	100%	100%	100%
LGV Hydrogen ICE	267	120%	143%	171%	205%	1'698	81%	76%	73%	70%
LGV Gasoline ICE	236	105%	110%	116%	121%	1'046	100%	100%	100%	100%
LGV Hydrogen FC	514	120%	139%	148%	164%	3'701	44%	39%	37%	34%
LGV Hybrid diesel ICE	426	120%	137%	144%	151%	1'252	98%	99%	98%	97%
LGV Hybrid gasoline ICE	315	120%	137%	144%	151%	1'368	93%	92%	89%	88%
LGV PHEV diesel	830	109%	113%	118%	123%	1'478	94%	93%	90%	89%
LGV PHEV gasoline	793	114%	118%	123%	129%	1'296	92%	91%	88%	86%
Bus BEV	301	109%	113%	118%	123%	5'105	91%	88%	85%	83%
Bus Diesel ICE	102	105%	110%	116%	121%	3'676	98%	98%	98%	98%
Bus Hydrogen ICE	121	124%	154%	191%	238%	4'204	90%	88%	87%	87%
Bus Hydrogen FC	168	124%	148%	158%	175%	6'151	68%	66%	64%	63%
Bus Hybrid diesel ICE	169	124%	147%	154%	161%	4'161	95%	90%	90%	89%
2-wheeler Battery EV	7'504	108%	113%	118%	123%	1'400	95%	94%	93%	91%
2-wheeler Gasoline ICE	765	121%	125%	125%	125%	1'133	100%	100%	100%	100%
2-wheeler Hydrogen FC	4'420	114%	129%	148%	164%	3'221	47%	44%	41%	39%
Rail Diesel (passenger)	8	105%	117%	132%	151%	33'443	100%	96%	94%	94%
Rail Electric (passenger)	21	104%	109%	114%	120%	31'592	100%	100%	100%	100%
Rail Hydrogen FC (passenger)	13	106%	113%	121%	130%	41'759	82%	81%	80%	79%
Rail Diesel (freight)	7	103%	110%	118%	128%	17'176	98%	98%	98%	98%
Rail Electric (freight)	18	101%	102%	103%	105%	15'758	100%	100%	100%	100%
Rail Hydrogen FC (freight)	11	104%	107%	111%	115%	28'882	72%	65%	64%	62%

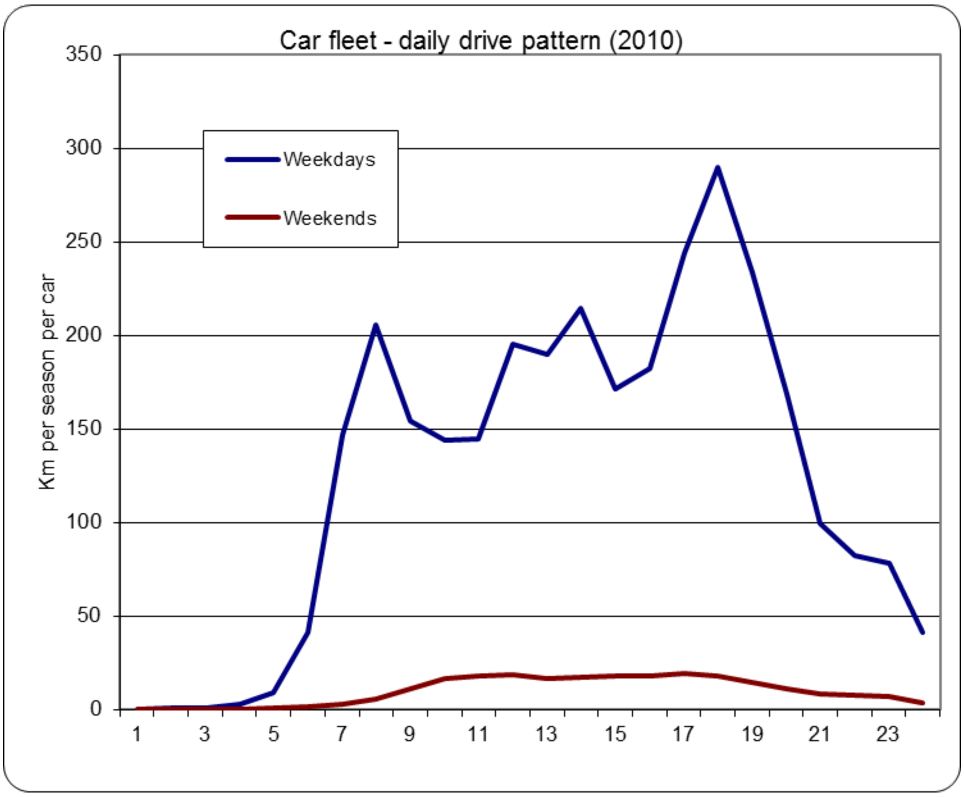
Source: [26][11][16]

Similar to the car technologies, new and alternative vehicles are represented for other transport demands. Table 10 shows the relative change in fuel efficiency and the capital cost. Most of the technical and cost data are adopted from PSI's analysis on global transport [16][10] and other data sources [26][11].

3.4.3. Demand curve

For cars, the demand curve is estimated based on micro-census data on individual car travel [6]. Figure 19 shows demand pattern on weekdays and weekends. We have normalized total annual car demand to follow this pattern and do not differentiate across the three seasons. It is worth noting that for the BEV and PHEV, recharging is only possible when the car is not being used.

For the other transport modes only an annual demand is specified without a detailed demand curve at this stage.



(Source file: Swiss Transport-demand curvev2.xls).

Source: BFS, 2005 [6]

Figure 19: Aggregated average car user profile

3.5. **Agriculture sector**

The agriculture sector accounts for a relatively insignificant share of energy demand, but is included in the model so as to cover the complete energy balance. The final energy from the agriculture sector is assumed to be used for three broad end-use applications as shown in Figure 20. The future ESDs are linearly extrapolated based on economic value added in the sector [5]. All demand in the agriculture sector is assumed to be annual and no load curve is included.

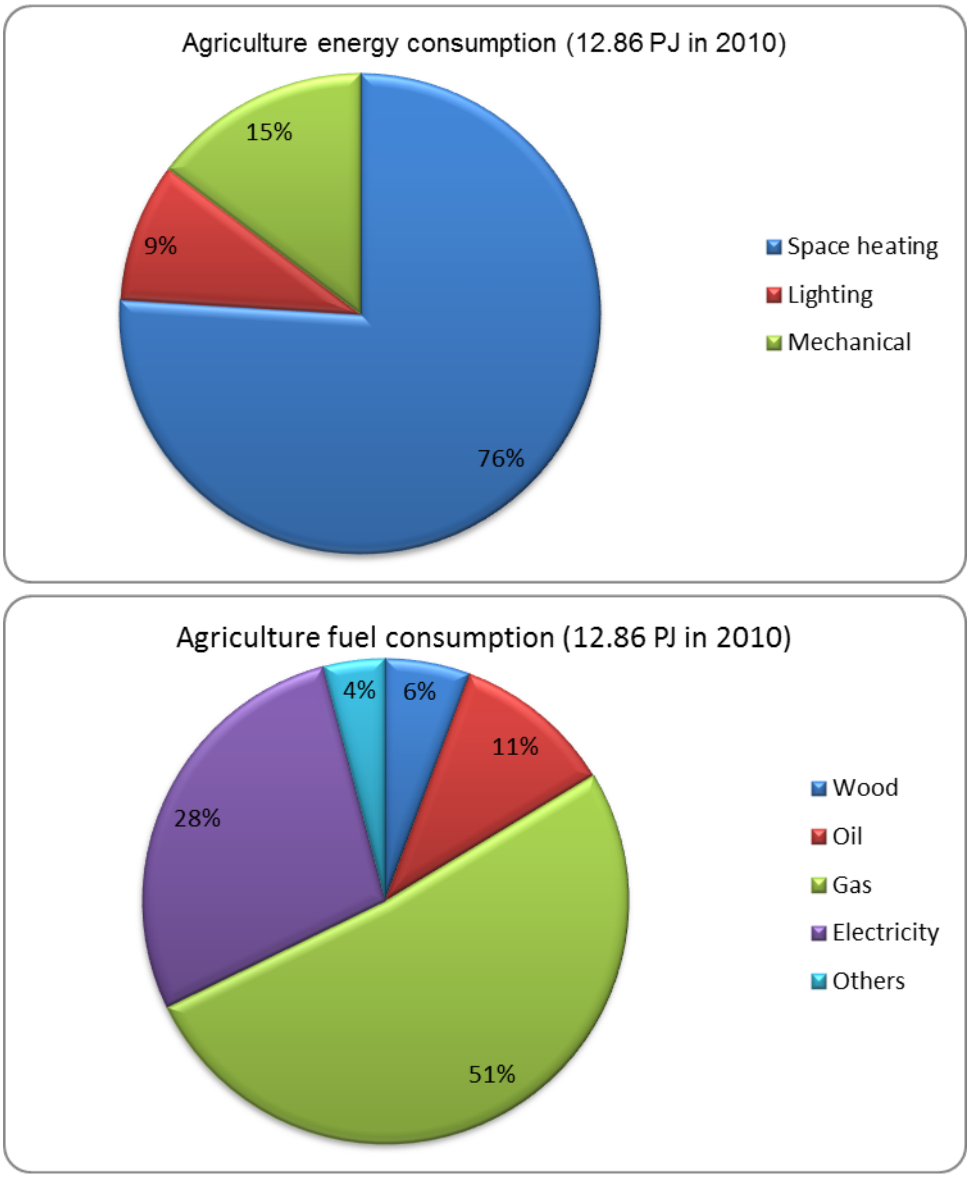


Figure 20: Agriculture sector fuel consumption in 2010

3.6. Fuel distribution network

Energy carriers are supplied to end-use technologies (Section 3) via corresponding fuel distribution networks (e.g. see Figure 18). Inputs to the distribution network comprise either primary resources (§ 5) or outputs from conversion (§ 4) technologies. Since STEM is a single-region model without any spatial details, energy distribution infrastructure is represented at an aggregated level. We estimate distribution costs as the difference between historical international fuel prices [9] and end-use prices (excluding taxes) [21]. We also split this distribution costs into estimated variable and fixed or capital cost components, based on assumptions depending on type of distribution infrastructure. For example, the distribution cost for natural gas price (via pipeline infrastructure) is assumed to be split into 80% capital and 20% variable costs. Table 11 shows illustrative costs of distribution infrastructure. The distribution cost for the service sector is assumed as the average of residential and industrial sectors.

Table 11: Aggregated fuel distribution infrastructure costs

Fuel distribution infrastructure	Capital	Variable cost	Life time
	CHF/GJ	*CHF/GJ*	*year*
Industrial coal	35.61	0.54	75
Industrial light fuel oil	2.91	0.71	75
Industrial natural gas	120.73	1.87	60
Residential heating oil	7.12	1.73	75
Residential natural gas	221.93	3.43	60
Transport gasoline	65.66	2.78	50
Transport diesel	59.79	2.53	50
Transport natural gas	288.40	4.45	60

Source: Estimated based on [9][21]

An estimate of the existing stock of infrastructure is included in the model based on the quantity of fuel delivered in 2010. This stock is assumed to be retired linearly over the next 50-80 years.

Carbon dioxide (CO_2) emissions from end-use sectors are tracked through the fuel distribution network (see Figure 18). This infrastructure module also enables the implementation of sector-specific CO_2 emission and fuel taxes (see Table 23 and Table 22).

4. **Energy conversion sectors**

STEM incorporates extensive details for electricity generation and a range of other secondary fuel production pathways for energy carriers such as hydrogen, biofuels, wood pellets, and others. The following subsections describe the conversion sectors.

4.1. **Electricity supply**

The electricity module in STEM incorporates the same structure as the STEM-E[11] model described in detail elsewhere [28][29]. One major difference, however, is that electricity demand is an exogenous input to the STEM-E model but endogenous in STEM based on the technology choice in end-use sectors (as described in Section 3). STEM represents all existing generation capacity in the Swiss electricity system at an individual plant level (e.g. nuclear plants) or aggregated by fuel and technology (e.g. river hydro, dam hydro).

[11] The STEM-E has 288 annual timeslices. For STEM, some technology characteristics (e.g. seasonal availability) are adjusted to reflect the 144 timeslices.

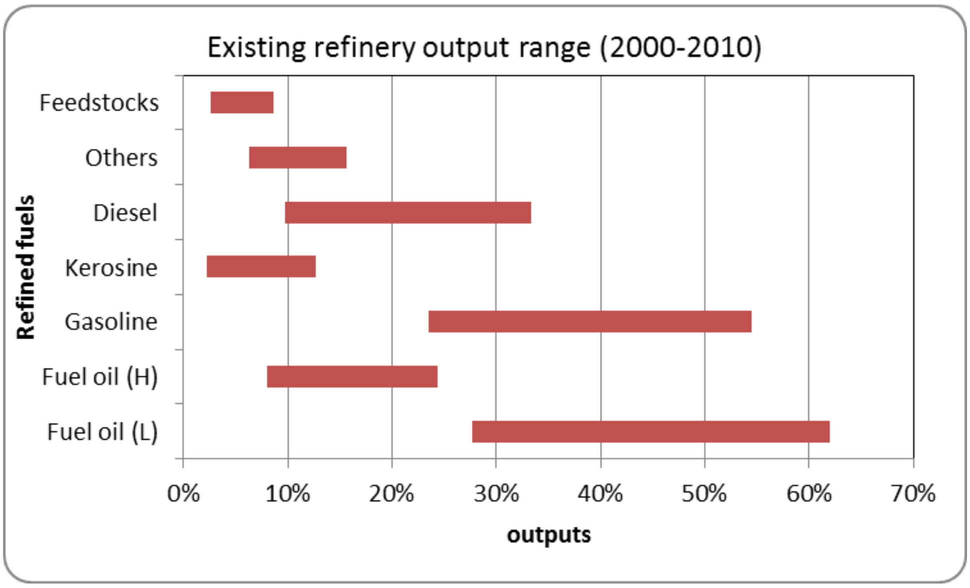
Retirement of the existing technology stock is represented for each technology category, with nuclear capacity scheduled to retire 50 years after installation (Beznau I: 2019; Beznau II and Mühleberg: 2022; Gösgen: 2029; Leibstadt: 2034) [37]. The historical average capacity factor for the last 10 years is applied as the availability factor (of the existing capacity) for future years. A range of new electricity generation technologies (centralised gas power plants, solar PV, geothermal, etc.) are available in STEM, with characteristics depending on the year of installation. The technical and cost data of the new technologies are documented in [28][30][29].

4.1.1. Electricity trade

Like in STEM-E, links between the Swiss electricity network and the European electricity network are represented in STEM. Four country-specific electric import and export interconnectors are defined to represent the links to the four bordering countries. These interconnectors are modelled as flexible technologies with options for capacity expansion (i.e. new investments) so that electricity can be imported and exported at any time. This approach enables the possibility to import cheap electricity, store the electricity via pumped storage or batteries in electric vehicles, and export electricity during periods with higher international prices. However the assumption on the flexible exchange of electricity is highly uncertain and heavily dependent on energy and electricity system development in the four neighbouring markets. Therefore, assumptions on hourly import and export price of electricity are critical inputs. For the scenario analysis reported later in this report, we have adopted international electricity price from the Swiss cross border electricity model (CROSSTEM) developed at PSI [38] given in the scenario assumptions (e.g. see Table 20).

4.2. **Refineries**

STEM represents existing refineries at the aggregated level. In 2010, Swiss refineries produced about 180 PJ of refined oil products, of which 175 PJ were supplied to the domestic market and the rest (mainly heavy heating oil and chemical feedstock) exported [5][12]. Light heating oil, diesel and gasoline make up the majority of the refined fuels (Figure 21). The refineries supply one third of the domestic fuel demands and two-thirds of the demand is imported as refined petroleum fuels [12].



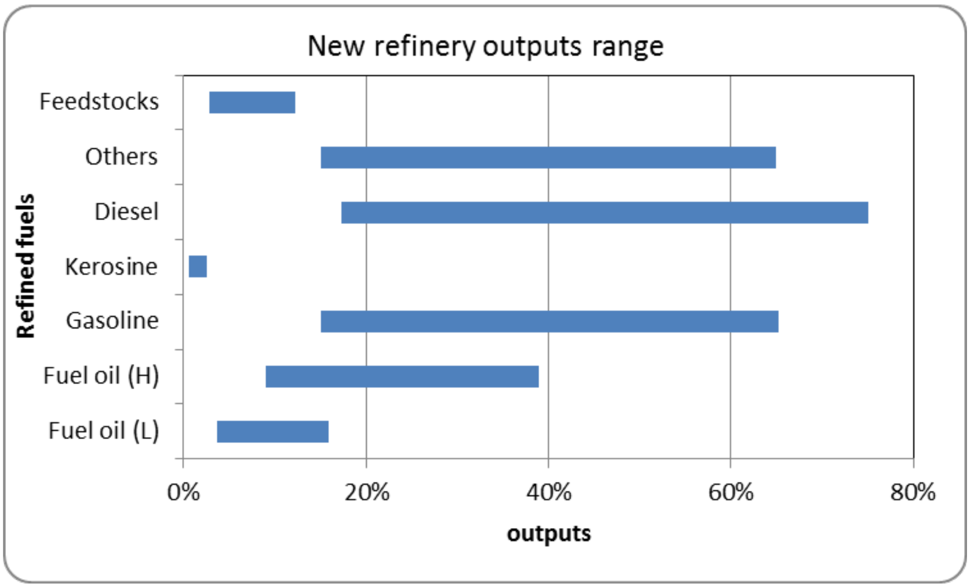


Figure 21: Swiss refinery outputs (2000–2010)

Existing refineries are assumed in the model to have some flexibility to vary the share of different outputs (fuel mix) within the range seen over the past ten years. In addition, a new refinery technology is available with more flexibility to produce a higher share of gasoline and diesel. It is important to note that the representation of refineries in STEM does not account for synergies between domestic refining and the needs of the chemical industry. That is, the investment and operation of refineries is based entirely on energy-sector costs and performance, meaning that in some scenarios STEM may find it cost effective to import refined petroleum fuels rather than invest in new domestic refining capacity, which may potentially be inconsistent with the development of the petrochemical industry.

4.3. **Biofuel synthesis**

In 2010, biofuels accounted for less than 0.1% of the transport fuel, with three types of biofuels, namely biodiesel, ethanol and vegetable oil[12] used. A major share of biodiesel (91%) and vegetable oil (64%) are produced domestically while the rest of the biofuels, including ethanol are imported [5]. Given the potential future expansion of the use of biofuels, a range of biofuel production options are depicted in STEM. The technical characteristics of biofuel production technologies are given in Table 12. Currently, ethanol is mainly mixed with gasoline up to 10% and biodiesel is mixed with diesel up to 5% [15]. However, we do not restrict the use of biofuels in conventional diesel and gasoline vehicles. We restrict import of zero-carbon biofuels in the future years because of uncertainties on cost and availability.

4.4. **Hydrogen production**

The model additionally incorporates a range of technology options to produce hydrogen from different feedstocks via several pathways, e.g., from natural gas via steam methane reforming (SMR), electricity via electrolysis, biomass/waste via gasification, among others. Technical and economic characteristics of hydrogen production technologies (see Table 12)

[12] It is unclear where and how vegetable oil was used in the energy sector.

are taken from various data sources. End-use technologies for hydrogen are included for the transport sector and electricity generation. In addition, hydrogen storage is represented.

Table 12: Characteristics of conversion technologies

Conversion technology	Fuel input	Fuel output	Capital cost *(CHF/GJ)*	Efficiency	Life
Hydrogen from biogas	Biogas	Hydrogen	57	50%	30
Hydrogen from natural gas (SMR-small)	Natural gas	Hydrogen	56–81	80%	20
Hydrogen from natural gas (SMR-large)	Natural gas	Hydrogen	18–28	76%	25
Electrolyser	Electricity	Hydrogen	28–125	75–85%	15
Hydrogen from waste gasification	Waste	Hydrogen	80	30%	30
Biogas from animal manure	Manure	Biogas	32–46	16–18%	20
Wood gasification	Wood	Biogas	62–122	56–65%	15
Wood pellet production	Wood	Pellets	40	80%	15
Biomass gasification for hydrogen	Wood	Hydrogen	79–156	51–60%	25
Biodiesel from wood pyrolysis	Wood	Biodiesel	73	56%	25
Biodiesel from wood gasification	Wood	Biodiesel	89	48%	25
Ethanol from wood pyrolysis	Wood	Ethanol	81	45%	25

Source: [39][16][26][11]

5. **Energy resources**

A range of domestic and imported primary energy resources are represented in STEM. Imported fossil fuels include crude oil and refined fuels, natural gas and coal. In addition to fossil fuels, other import options include renewable resources such as wood and biofuels, but as mentioned above these imports are restricted to ensure the energy system is not able to circumvent any carbon targets by importing zero-carbon fuels.

Table 13: Renewable resource potential

Energy resources	Resource Potentials *
Woody biomass	83 PJ_t (2025) (23 TWh_t) 98 PJ_t (2040) (27.2 TWh_t) 122 PJ_t (2100) (33.8 TWh_t) [18][30][28]
Wastes (incl. non-renewable) and Biogas^	56 PJ_t (2010) / 62 PJ_t (2050) [5] [40]
Manure	23 PJ_t [40] [18]
Geothermal	16 PJ_e (2050) (4.39 TWh_e) [29]
Wind	9.36 PJ_e (2.6 TWh_e) (2050)
Solar	35 PJ_e (9.8 TWh_e) (or 10.2 GW_e) or 254 PJ_t (2050)
Hydro existing /refurbished	35.9 TWh_e (34.4+1.55) [30]
Hydro (new)	2.4 TWh_e (2035) [29]
Pumped hydro	7.56 TWhe [37]
* Resource potential are linearly interpolated between the periods or from 2010 levels. The potential from 2050 is maintained for the rest of the model horizon	

Domestic renewable resource potentials applied in STEM are shown in Table 13, based on various sources and expert judgement.[13] In the model, wind, hydro and geothermal resource potentials are assumed to be availably solely for electricity generation. That is, geothermal resources for electricity production (deep) are not expected to compete with (shallow) geothermal sources for space and water heating (nor with sites for carbon storage). For solar, the potential is assumed to reflect available roof space which could be used for either electricity generation through solar PV or heat production through solar thermal systems, with the choice determined endogenously within the model. The renewable resource potentials are subject to a high level of uncertainty, and are thus a potential parameter for uncertainty analysis.

Since almost all fossil fuels are imported in Switzerland, the international energy price is one of the key assumptions for any scenario analysis. For the scenarios presented in Part II, the

[13] See review summary on estimates of domestic renewable energy resource potentials in Table 10 in [27].

international energy prices from IEA's Energy Technology Perspective [22] have been used. For refined petroleum fuels like diesel and gasoline, the price is estimated based on the historical correlation (1970-2010) between international oil and refined fuel prices [9][21] (e.g. see Table 21).

6. Other parameters (and features)

6.1. Discount rates

The model uses a system-wide discount rate for the entire energy system and an optional technology specific discount rate. Generally, the discount rate is applied to calculate the annuity associated with capital investments and for discounting future costs. If a technology-specific discount rate is specified, the annuity is calculated based on that rate. The discount rate in scenario specific assumptions and the assumption is given in the scenario assumptions (§ 8.2).

6.2. Taxes and subsidies

For all energy and emission commodities, taxes can be applied within the current model structure. For example, a range of taxes (e.g. CO_2 tax, transport fuel tax (e.g. Mineralölsteuer, Mineralöl-Zuschlag); electricity tax (e.g. KEV—Kostendeckenden Einspeisevergütung Zuschlag); etc.) are implemented in STEM and the assumptions are listed in the scenario assumptions § 8.2.

The model has many other features that can be further expanded. For example, the revenue from KEV can also be used to subsidise energy conservation measures or renewable electricity feed in. However, no such constraints are included in the scenario analysis presented later in this report.

6.3. Constraints

As a cost optimization model, some non-cost factors can be represented with additional constraints. We have implemented some constraints on technology choices (e.g. restriction of use of coal in residential heating, use of wastes in food processing industrial subsectors, etc.). They are also listed in technology options in the scenario assumptions § 8.2.

7. Model limitations

Like in any other modelling framework, there are limitations with TIMES in general and with STEM in particular to address some of the research questions. They are broadly classified in the following subsections.

7.1. Framework

- The cost-optimisation approach in the bottom-up models like TIMES can elucidate insights regarding the cost-optimal configuration of the energy system under different conditions. However, the choice and operation of any technology (e.g. heating system, lighting, cars) is based on total system costs, while consumer preferences often incorporate non-cost drivers like comfort or flexibility (and consumers may apply a higher discount rate than society in selecting the 'optimal' technology), although some of these factors have been implemented through user constraints in STEM. Similarly, strategic behaviour by energy producers or non-competitive market outcomes are beyond the scope of the model. Complementary consumer and market modelling approaches may be suitable for addressing specific policy questions related to such ‘real-world’ behaviours.

- Similarly, the TIMES framework does not seek to represent structural changes that might be induced under different policy scenarios, such as a switch from cars to public transport, a shift to smaller houses, behavioural changes to heating patterns, or economic structural changes partly induced by energy costs (e.g., a shift away from basic metal production to services). The impact of some of these changes can potentially be explored through elastic demand variants of the TIMES framework, but in many cases the implications of such changes are better addressed through alternative scenario analyses, or with complementary top-down modelling approaches.

7.2. Data and structure

- As a single region model, STEM cannot account for spatial patterns of demand and supply, and potential bottlenecks in distribution to ensure supply and demand are balanced across all geographical scales. Complementary localized case studies, grid modelling and, ultimately, multiregional or GIS-coupled approaches may help to explore specific spatial energy challenges.
- Similarly, the aggregated depiction of each sector groups together different sub-markets and sub-demands into each ESD. This aggregation tends to average different submarkets (such as long-distance car drivers—e.g. taxis) where different technologies may be cost-effective. Accordingly, further disaggregation may help to provide additional insights into specific submarkets, along with complementary sectoral modelling.
- Though the model represents 24 hours for the average day in each season, it is still unable to capture fully demand or supply variations across different weekdays. This temporal aggregation is particularly a limit to addressing intermittent renewables and ‘short’ term storage. This can be partly complemented with dispatch-type models.
- The current and future load curve of ESDs is an important input, particularly for determining electricity and heat demand profiles. There remains a high level of uncertainty in some of the sectoral ESDs due to data limitations. This represents a potential area for further data collection and collaboration with experts on sub-sectoral demand.
- Last but not least, the model optimization is driven by technology from various sources. These data, particularly for future technology performance and cost, is uncertainty (and thus represents a candidate for parametric uncertainty analysis).

PART II: POLICY SCENARIOS

8. Policy scenario analysis with STEM

The Swiss TIMES Energy systems model (STEM) is a flexible tool for the analysis of the medium- and long-term evolution of the *energy system*, via exploratory transition scenario analyses. Of particular note is that the TIMES backbone of STEM provides a much richer framework than previous approaches and is able to represent additional features of the energy system that are becoming more critical to decision-making—for example, issues related to load balancing, infrastructure needs, energy storage, alternative mobility, and linking long-term objectives to short-term actions. In this context, a range of scenario analyses with STEM are possible to explore structural change in the energy system, tailored to specific research and policy questions. However, it is worth remembering that such scenario analysis is not intended to predict the future, but rather explore different parametric uncertainties under a 'what-if' framework. The what-if scenario analysis provides insights into the impact of different policy options and potential energy technology/infrastructure targets for policy support.

8.1. Scenario definitions

We have analysed a small selection of scenarios in detail. These scenarios have been selected with two main aims in mind: i) to explore plausible future pathways of energy system development in Switzerland based on current policy discussions and priorities, and ii) illustrate the features and behaviour of STEM and establish its robustness. On the former, we focus on a set of scenarios based around the set of socioeconomic drivers in the Energy Perspectives 2050 [37], and dealing with key policy issues related to climate change mitigation and security of supply. On the latter, in the results we examine system-wide developments and interactions, electricity load balancing (and storage) under different technology configurations, the potential development of alternative mobility, and long-term vs. short-term developments.

Specifically, we present three core scenarios with two electricity supply variants for each. For selected cases we also report on additional sensitivity analysis on international fuel prices. The core scenarios comprise:

- A business-as-usual scenario (*BAU*)
- A low-carbon scenario that achieves a 60 percent reduction in total CO_2 emissions by 2050 (*LC60*) and
- A secure energy supply scenario in which dependence on imported oil and gas is reduced (*SEC*)

All of the scenarios share a number of common assumptions on underlying drivers, which are described in the following subsections (§ 8.2).

The three core scenarios include the option to invest in centralised natural gas combined cycle power plants (GTCC) and CHPs. However, there remains some policy uncertainty over the potential future role of natural gas in electricity generation [37], so we also explore cases without centralised gas plants and CHPs; this is denoted in the scenario name with the suffix '*NoCent*', (i.e. *BAU-NoCent*, *LC60-NoCent*, *SEC-NoCent*).

Finally, another key uncertainty likely to affect energy system transitions in Switzerland is future international energy prices. To explore this issue, we also present two further scenarios. Table 14 summaries the scenario definitions and names.

Table 14: List of scenarios and sensitivities

Core scenarios → **Sensitivities ↓**	Business as usual (*BAU*)	Low carbon (*LC60*)	Secure energy supply (*SEC*)
No centralized natural gas power plants *	*BAU-NoCent*	*LC60-NoCent*	*SEC-NoCent*
High fuel price	*BAU-FP-H*	*LC60-FP-H*	-
Low fuel price	*BAU-FP-L*	*LC60-FP-L*	
* Electricity supply variants without options to build new centralized gas power plants			

8.2. **Scenario assumptions**

STEM is a data-intensive model. For the core scenarios, we have used the following broad set of assumptions on macroeconomic drivers, international fuel price, CO_2 tax, technology availability, and other factors.

8.2.1. Common scenario assumptions

All scenarios share the set of assumptions outlined below:

Energy service demands are based on socioeconomic drivers (*GDP, population, floor area, vkm,* etc) from the SEP [37]. For each sector we present the main assumptions.

– The **residential sector** demand drivers are shown in Table 15. The population increases from 7.88 million to 9 million by 2050. Similarly, the number of households and heating floor area increase. The links between the driver and ESD is given in Table 16. Since electricity demand for appliances is assumed to be driven by appliance ownership, we have included an autonomous energy efficiency improvement of 1% per year for appliances and 1.5% for refrigerators to reflect the technology progress as in the WWB scenario [37].

Table 15: Residential sector ESD drivers

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population *(million)*	7.88	8.16	8.44	8.61	8.78	8.89	8.96	9.00	9.04
Heated floor area *(million m^2)*	487	523	561	592	614	631	645	656	666
Number of households *(million)*	3.55	3.75	3.96	4.08	4.21	4.27	4.32	4.35	4.38
Air conditioned floor area *(million m^2)*	6.2	12.6	19	35.95	52.9	84.6	123	174.5	226
Lighting floor area *(million m^2)*	475	511.5	548	574.5	601	618	631	641	651
Dishwashers *(million units)*	2.18	2.49	2.81	3.04	3.279	3.4	3.5	3.6	3.7
Refrigerators and freezers* *(million unit)*	6.34	6.90	7.46	7.79	8.12	8.31	8.47	8.55	8.64
ICT^ *(relative change)*	0%	11%	23%	30%	38%	43%	47%	49%	52%
Washing machines/ dryers* (million units)	5.93	6.49	7.05	7.31	7.58	7.75	7.91	8.03	8.16
^ ICT—information and communication technologies (e.g. TV, computers, etc.) in PJ * an exogenous autonomous energy efficiency improvement has been implemented									

Source: Prognos 2012 [37]

Table 16: Links between residential ESD and macroeconomic drivers

Drivers → ESD ↓	Population	Floor area	Ownership	Climate correction
Space heating		x		x
Hot water	x			x
Air conditioning		x		x
Lighting		x		
Cooking			x	
Dishwasher			x	
Refrigerator and freezers			x	
ICT			x	
Washing machine/dryers			x	

– The demand drivers for the **services sector** are given in Table 18. In the services sector, the total floor area increases about 25% by 2050 from the 2010 level while gross value added by the sector increase by around 50%. Unlike the residential buildings, we did not assume any improvements in buildings standards in the estimation of future (new build) heating demands in the services sector. Nor do we assume the availability of additional energy conservation measures that can be adopted during renovation or construction.

Table 17: Drivers for estimation of ESD in services and industrial sectors

Drivers → **ESD ↓**	**Floor area**	**Value added**	**Heating/cooling degree days**
Heating	x		x
Process heating		x	
Air conditioning	x		x
Lighting	x		
ICT, mechanical drive, others		x	
ESD in agriculture		x	

Table 18: Services sector macroeconomic drivers

Drivers	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Value added *(billion CHF_{2010})*	373	400	426	445	464	485	509	532	555
Floor area *(million m^2)*	152	157	162	167	172	177	181	186	191
Air conditioning (and ventilation) demand* (*relative change*)	0%	19%	38%	58%	77%	96%	108%	121%	133%
* Based on floor area and cooling degree days. Fifty percent of the total air conditioning and ventilation demand is assumed to be air conditioning, for which the cooling degree-days are applied.									

Source: Prognos 2012 [37]

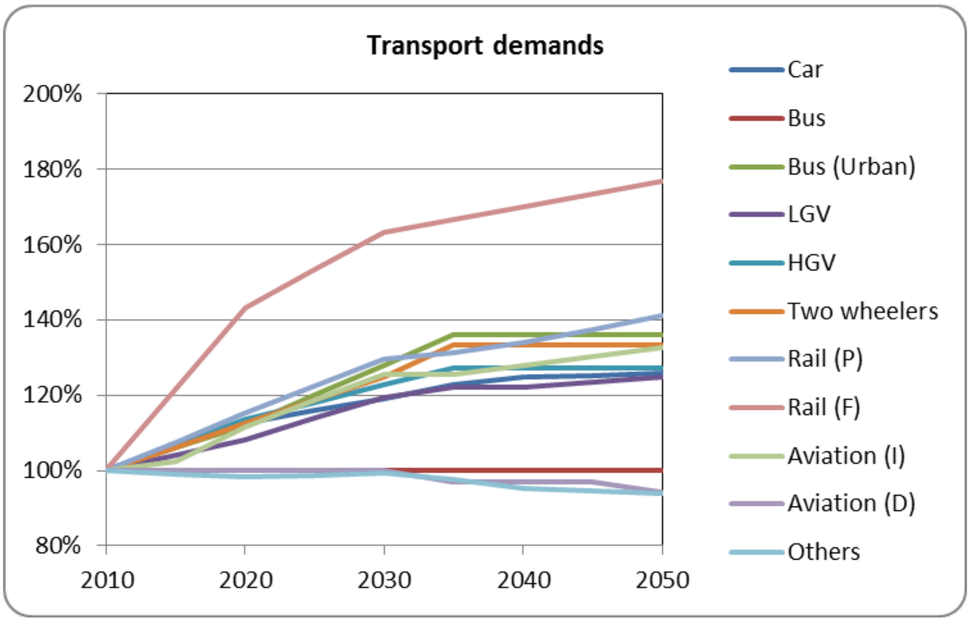
– Table 19 shows the demand drivers for the **industrial subsectors**. The space heating, water heating and air conditioning are linked to floor area and the rest of the demand is linked to the subsectoral GDP Table 17.

Table 19: Macroeconomic assumptions in industrial subsectors

	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Floor area (million m^2)								
Food, textile, paper	12	12	12	12	12	12	12	11	11
Chemicals	6	6	6	6	6	6	6	6	6
Cement, non-ferrous minerals	3	3	3	2	2	2	2	2	2
Basic metals	1	1	1	1	1	1	1	1	1
Machinery, other industries	42	44	47	47	47	48	49	49	50
Construction	6	6	6	7	7	7	8	8	9
Total	**69**	**72**	**75**	**75**	**75**	**76**	**77**	**78**	**78**
	Value added (Billion CHF)								
Food, textile, paper	14	14	15	14	14	13	13	12	12
Chemicals	22	23	25	29	33	38	43	49	55
Cement, non-ferrous minerals	2	2	2	2	1	1	1	1	1
Basic metals	1	1	1	1	1	1	1	1	1
Machinery, other industries	59	61	63	64	65	67	68	70	71
Construction	30	31	33	34	35	36	38	39	40
Total	**127**	**133**	**139**	**144**	**149**	**156**	**163**	**171**	**179**

Source: Prognos [37]

– Figure 22 shows the assumptions on **transport sector** ESD, which are again adopted from [37]. For national and international aviation and 'other' (e.g. military applications) transport demand, kerosene and diesel demands are directly adopted.



Source: Prognos [37]

Figure 22: Relative change in transport service demand

In addition to these sector-specific drivers, a number of other common scenario assumptions are applied:

– Heating and cooling demands are adjusted for the impact of climate change on heating degree days for space (-15%) and water heating (-4%) and air conditioning (+233%) across all end-use sectors (§ 3.1)
– A discount rate of 2.5% for all technologies and future costs (see § 6) to reflect the rate assumed in the SEP [37].
– Cross border electricity import (and export) prices are adopted from CROSSTEM model [38] (§ 4.1.1). Table 20 shows the international electricity price assumptions. For the all scenarios, we assume a set of electricity prices consistent with neighbouring countries adopting a stringent climate policy, i.e. electricity is produced from low-carbon and renewable sources.[14]

Table 20: International electricity price assumptions

Country	2020	2025	2030	2035	2040	2050
	Hourly electricity price variations (*Rp/kWh*)					
Austria	4 - 26	8 - 32	7 - 16	5 - 16	7 - 17	4 - 38
Germany	4 - 30	8 - 34	7 - 16	5 - 55	6 - 35	3 - 23
France	2 - 30	3 - 33	6 - 16	4 - 15	6 - 17	3 - 22
Italy	4 - 29	6 - 33	7 - 17	5 - 16	5 - 19	3 - 30

Source: CROSSTEM model [38]

– We assume there is no 'net' annual import of electricity, i.e. reflecting the recent historical balance between annual exports and imports of electricity. This, however, does not restrict the timing of electricity exchange within each projection year.
– In the all the scenarios except for the fuel price sensitivity scenarios (see Section 8.2.5), international prices of primary energy commodities and refined fuels are equivalent to those in the IEA's 4D scenario of ETP [22]—see Table 21. For refined petroleum fuels, the price is estimated based on the historical correlation (1970-2010) between international oil and refined fuel prices [9][21].

[14] It could be argued that such an assumption may be inconsistent with the BAU scenario. However, for comparability across the scenarios it was decided to adopt a single set of international electricity prices.

Table 21: Fuel price assumptions

Fuel type	2010	2015	2020	2025	2030	2035	2040	2050
	CHF_{2010}/GJ							
Natural gas	7.9	10.3	11.8	11.9	12.2	12.6	13.2	13.8
Crude oil	14.6	18.0	18.4	18.9	19.7	20.9	21.7	22.8
Coal	3.3	2.9	3.1	3.2	3.2	3.2	3.2	3.2
Gasoline	16.0	20.3	20.7	21.3	22.1	23.4	24.3	25.3
Diesel	16.4	20.6	21.1	21.6	22.5	23.9	24.8	25.9
Light fuel oil	14.8	18.6	18.9	19.5	20.3	21.5	22.3	23.3
Heavy fuel oil	13.2	17.7	18.2	18.6	19.2	20.1	20.7	21.5
Kerosene	18.1	22.7	23.2	23.8	24.8	26.2	27.3	28.5
Woody biomass	2.8 - 23	2.9 - 25	2.9 - 25	2.9 - 25	2.9 - 26	2.9 - 27	3 - 27	3 - 28
Manure	2.8	3.0	3.0	3.0	3.1	3.1	3.2	3.2
Waste	1.4 - 2.8	1.5 - 3.1	1.5 - 3.1	1.5 - 3.2	1.5 - 3.2	1.6 - 3.3	1.6 - 3.4	1.6 - 3.5
Uranium	0.80	0.81	0.81	0.81	0.81	0.81	0.82	0.82

Source: [20][22][9][21] and own estimates

- Vehicle emission standards for new cars are applied: 130 g-CO_2/km by 2015 and 95 g-CO_2/km by 2030 on test cycle [32] (§ 3.4)
- A range of energy conservation (e.g. facade /roof insulation, window replacement) measures are assumed to be available for residential buildings (as described in § 3.1.3)
- Electricity levy (KEV—Kostendeckenden Einspeisevergütung Zuschlag) of 0.9 Rp/kWh is applied to all end-use sectors. It is worth noting that the KEV Zuschlag is not assumed to be recycled to subsidise programmes for energy conservation or renewable feed-in tariffs.
- Existing energy taxes on fossil fuels (e.g. Mineralölsteuer, Mineralöl-Zuschlag) [8][13][32] are applied to all end-use sectors (transport fuel, heating oil/gas). For new and emerging energy commodities like natural gas, hydrogen, electricity, etc. in the transport sector, an energy tax similar to that applied to gasoline or diesel is implemented from 2020. Table 22 lists the fuel taxes.

Table 22: Fuel taxes

Fuels and end-use application	Fuel tax (unit)	
Electricity for industry	0.45	Rp/kWh
Electricity for households and services sector	1.85	Rp/kWh
Gas for industry	0.678	Rp/kWh
Gas for household	1.42	Rp/kWh
Light fuel oil for household	171	CHF/1000 litres
Industry low sulphur fuel oil	118	CHF/ton
Light fuel oil for industry	99	CHF/ 1000 litres
Gasoline for transport	0.87	CHF/litre
Diesel for transport	0.913	CHF/litre

Sources: IEA [19]; BFZ [8]

- Some additional assumptions are applied to specific technology options, as follows:
    - Existing policies are assumed on the phase out of nuclear generation
    - Coal is assumed to be excluded from the power sector, and from end-use sectors where coal is not used today
    - Large-scale centralised gas power plants are available from 2020 (note, does not apply in the *NoCent* scenarios)
    - Carbon capture and storage is excluded
    - Natural gas and biomass based centralised and distributed CHP generation available (note, does not apply in the *NoCent* scenarios for centralized natural gas plants, as described below)
    - Renewable energy resource (e.g. biomass, waste) potential as per Table 13
    - Geothermal energy available for electricity generation and space heating via heat pumps. However, use of geothermal heat via district heating is not enabled.
    - Options for electricity storage via pumped hydro, electric vehicles, power to gas (hydrogen for transport or electricity sectors) are assumed to be available
    - Heat storage is possible via night storage heaters in residential and service sectors
    - Solar thermal heating systems are available, but combined solar thermal and PV generation potential (roof tops) is assumed to be limited to ~10TWh$_e$ equivalent (Table 13)

- The European Union (EU) Emissions Trading System (ETS) permit price for industrial and power sectors is assumed to follow the estimates in the Energy Perspectives [37].[15] For the non-ETS sectors, existing CO_2 taxes on heating fuel in residential and service sectors are introduced [8] and assumed to increase slowly over time. The climate levy

[15] Note, however, we have not applied the ETS permit price for the aviation sector because STEM does not currently represent mitigation technologies or alternative fuel options in aviation (which is primarily international in any case).

(Klimarappen) of 1.5 Rp/l is applied for transport fossil fuel [37]. Table 23 shows the CO_2 taxes in the *BAU* scenario.

Table 23: CO_2 taxes

Taxes	2010	2020	2030	2035	2040	2050
EU ETS price (CHF/t)	14	35	42	46	48	51
CO_2 tax on heating fuels (CHF/t)	36	linearly increased				63
Transport fuels (Klima rappen)	1.5 Rp/l (or 6.5 CHF/t)					

Sources: [37][8]

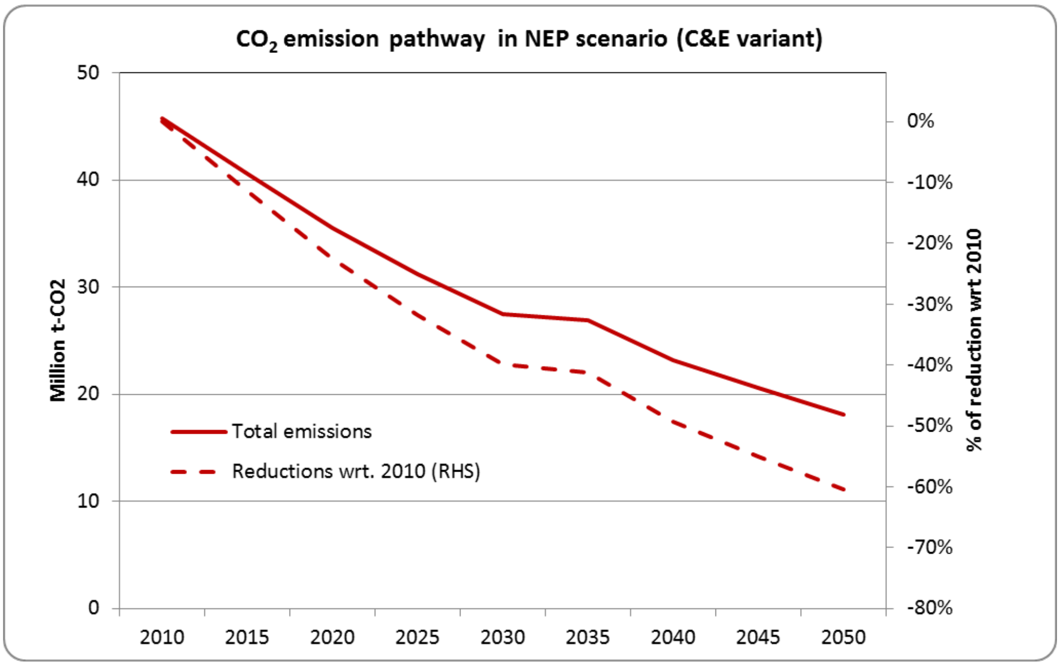
8.2.2. Business as usual (*BAU*)

The business-as-usual (*BAU*) scenario incorporates all of the common assumptions outlined in Section 8.2.1.

8.2.3. Low carbon scenario (*LC60*)

The low-carbon scenario (*LC60*) scenario incorporates all of the common assumptions described in Section 8.2.1. In addition, the low-carbon (*LC60*) scenario realises the emissions pathway of the *NEP scenario* of the SEP [37]. Figure 23 shows the CO_2 emissions trajectory from the NEP scenario [37] and reduction relative to 2010 (dotted lines, RHS axis) for the gas and renewables (“C&E”) variant from [37]. It should be noted that the Energy Perspectives [37] estimates abatement in end-use sectors in the *NEP scenario* independently of the supply options available for the electricity system (although different supply options imply different electricity generation costs and different issues in load balancing, among others). STEM, on the other hand, considers the entire energy system and can determine the optimal allocation of abatement across all sectors.

The emissions target in the *LC60* scenario equates to a 22% reduction in total CO_2 emissions by 2020 (relative to 2010, and including emissions from international aviation) and 60% by 2050.



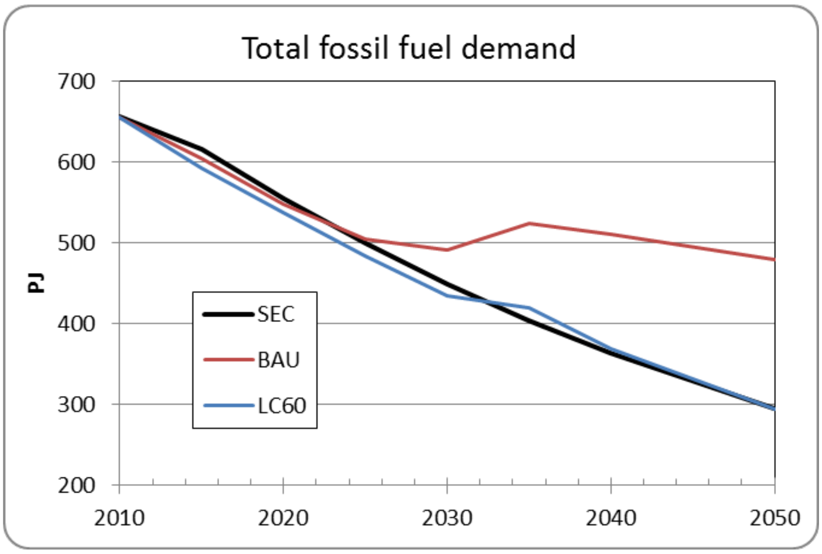
(Source file: Scen_CO2_Cap-60pc.xls)

Source: Prognos, 2012 [37]

Figure 23: CO_2 emission pathways in NEP scenario of Swiss energy strategy

8.2.4. Energy security scenario (*SEC*)

There are many possible definitions of energy security, and thus options for defining and modelling a scenario that realises improved security. As an illustrative and relevant example, the energy security (*SEC*) scenario seeks to achieve reduced dependence on imported fossil fuel resources. Based on the analytical results from the *BAU* and *LC60* scenarios (presented in the next sections), we have applied a goal in the *SEC* scenario to reduce fossil energy imports by around 55% linearly between 2010 and 2050 (see Figure 24). The *SEC* scenario also applies the common scenario assumptions outlined in Section 8.2.1.

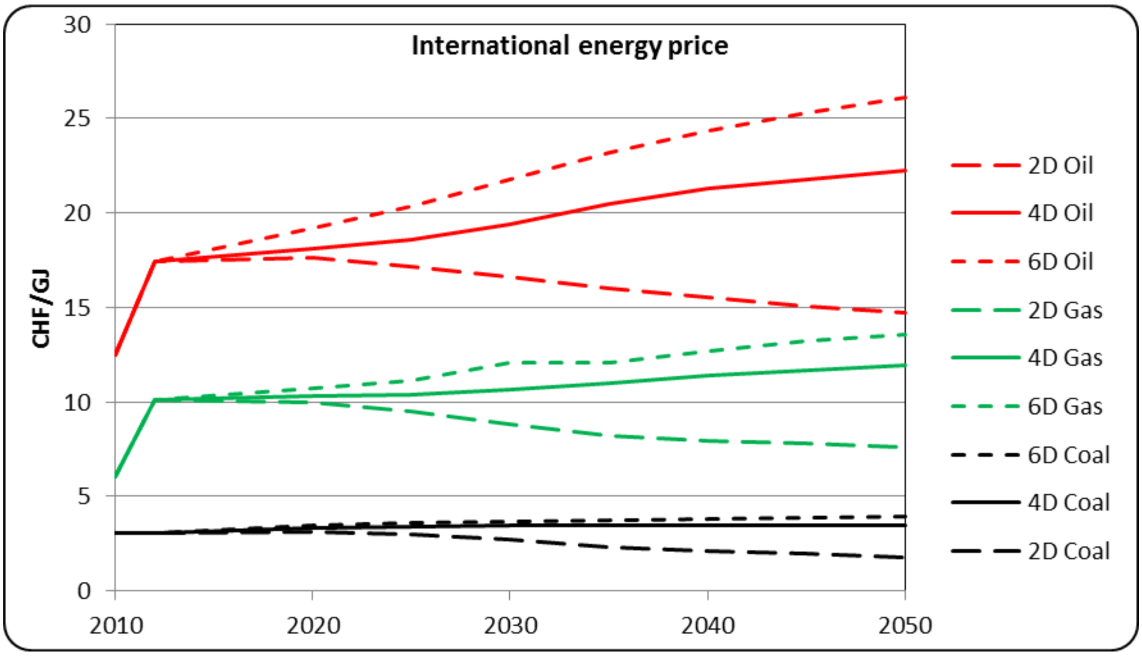


(Source file: Scen_Security.xls)

Figure 24: Fossil energy supply constraint in *SEC* scenario

8.2.5. Parametric sensitivity analysis

In addition to the main set of scenarios, sensitivities on international fuel price assumptions have been tested using high and low energy price scenarios corresponding to the IEA's ETP 2D or 6D scenarios [22] (see Figure 25). The core scenario analyses are based on middle price, i.e. 4D scenarios.



(Source file: Energy Price for STEM-v3.xlsx)

Source: IEA, 2014 [22]

Figure 25: International energy price assumptions

8.3. **Analytical results**

The following model output metrics are presented in this report for the period 2010-2050 (and some additional metrics are included in the appendix)

- Final energy demand, for each sector
- Car fleet breakdown by technology
- Electricity demand
- Electricity supply mix and installed capacity
- Output of CHP (decentralised and centralised)
- Hourly electricity generation schedule for different days and seasons
- Sectoral CO_2 emissions
- Undiscounted energy system costs
- Selected indicators, e.g. per capita energy, electricity energy intensity

For the business as usual (BAU) and low carbon (LC60) scenarios, time series results are presented for 2010 to 2050. Though the scenarios are optimized for the entire model horizon (i.e., to 2100), the focus of the results presentation is until 2050, given increasing uncertainties beyond this time horizon. For the other scenarios (security (*SEC*) and the

NoCent electricity supply variants) results for year 2050 are presented. The result descriptions should be seen as exemplary rather than exhaustive, and they are not analysed for all specific policy implications.

8.3.1. Explanatory notes to result parameters

Final energy

- The commodity "heat" in the final energy figures represents heat from centralised and distributed CHPs, along with district heating plants and waste incineration
- The conservation reported in the final energy figures reflects reductions in final energy demand
- Fuel consumption by distributed CHPs is not reported as final energy; instead the electricity and heat output is shown.
- In the case of heat pumps, only the electricity consumption is accounted in the final energy and heat extracted from the environment (ground or air sources) is not shown in final energy consumption.
- Solar energy in the final energy (if any) refers to direct use of solar energy for thermal applications, e.g. space or water heating in residential and service sectors
- Kerosene in the final energy figures includes domestic and international aviation.

Electricity supply

- Demand is also shown in the supply mix plot, representing the end-user demand excluding T&D losses and electricity used in pumped hydro plants
- Gas (Base) and Gas (Flex) refer to base-load and flexible gas combined cycle plants respectively.
- Electricity consumption of pumped storage is reported separately as "Pumps". Output from pumped storage hydro is 80% of its input, i.e. 'Pumps'.
- In electricity schedule, electricity demand (blue line) and supply mix are shown in upper plot and the lower plots shows electricity export (grey shade), charging of BEVs (brown shade) and consumption by pumped hydro (zigzag light blue shade). The red line in the upper plots is the marginal cost of electricity supply. Unlike dispatch-type models, the marginal cost from STEM is not the short-run marginal cost of generation, but the long-run marginal cost of electricity accounting for both supply and demand-side options. For example, the cost of providing one additional unit of electricity may require new generation capacity investment, or alternatively may be supplied by reducing electricity demand (e.g. by installing a gas boiler (and possibly gas infrastructure) to replace electricity). Thus, for this reason and others mentioned in Section 7.1, this marginal cost should not be interpreted as a market price for electricity.

CO_2 emissions

- CO_2 emissions are reported as direct and net-sectoral emissions. In the latter, CO_2 emissions from electricity and other conversion sectors are allocated according to sectoral electricity and fuel consumption.
- CO_2 emissions in the transport sector include emissions from international aviation, which remain the same across all scenarios.
- CO_2 emissions from decentralized electricity generation (i.e., CHPs) are included in the estimates for the end-use sectors.

Cost

- *Capital* costs cover the annuities on investment costs from all technologies in the system. However, capital costs of existing technologies (e.g. cars, heating system) are not included in the model.

- *Fixed O&M* costs are the total fixed operation and maintenance (O&M) costs from all technologies in the system.
- *Variable O&M* costs are the total variable O&M costs of all technologies. However, the *variable O&M* cost does not include fuel costs, which is reported separately
- *Sectoral* costs include capital and O&M of all technologies associated with the sector, *i.e.* transport sector includes cost of vehicles[16]. But sectoral costs exclude fuel costs and taxes, which are reported separately.
- *Fuel* costs comprise the total cost of all energy resources, including fuel use in conversion sectors. However, the fuel cost does not include the cost of imported electricity, which is reported in the "trade balance" category.
- *Trade balance* refers to the net cost from electricity trade. It is the total cost of imported electricity minus revenue from exported electricity. Even though the annual volume of net import/export is balanced (though the self-sufficiency constraint), the variations in import and export prices may lead to a positive or negative electricity trade financial balance. Capital and O&M costs of interconnectors are not included in the *trade balance* category. They are reported under the above costs categories (i.e. in capital and O&M costs).
- *Taxes* include fuel and CO_2 taxes, the nuclear waste disposal and decommissioning levy, and the electricity surcharge imposed on end-users (KEV). Revenue from taxes is not recycled.

General

- The scenario name is shown in the chart title
- Energy supply/demand does not include non-energy demand, e.g. refinery feedstock, lubricants
- For primary energy calculations, electricity from wind, solar PV and geothermal plants is reported without any fossil equivalent conversions (i.e., 100% nominal efficiency).

[16] The capital cost of existing vehicles is not included in STEM.

9. **Business as usual (*BAU*) scenario**

This section presents the quantitative results of STEM for the business-as-usual (*BAU*) scenario outlined in Section 8. The presentation of results starts with final energy demand (in aggregate and on a sectoral level), before turning to the energy conversion sector (including electricity load balancing), CO_2 emissions and primary energy. In addition, selected results for the *NoCent* electricity variant and sensitivities of international energy prices are shown.

9.1. **Final energy demand**

Figure 26 and Figure 27 show final energy demand for the *BAU* scenario by fuel and end-use sector. Total final energy demand declines about 30% by 2050 from the 2010 level, equivalent to a 0.9% average annual reduction. This reduction in final energy consumption is driven by a combination of end-use energy efficiency, fuel substitution/switching and uptake of building energy conservation measures (§ 3.1.3). Though total final energy consumption declines, end-use electricity demand increases to 288 PJ (~80 TWh) by 2050 (from 215 PJ in 2010—an average annual growth of 0.73%). At the sectoral level (see Figure 27), by 2050 fuel demands are nearly halved in the residential sector, and reduced by around 40% in transport and 15% in the services sector. Industrial energy demands remain roughly unchanged, partly due to limited technology representation and the implicit assumption that the sector is already relatively energy efficient.

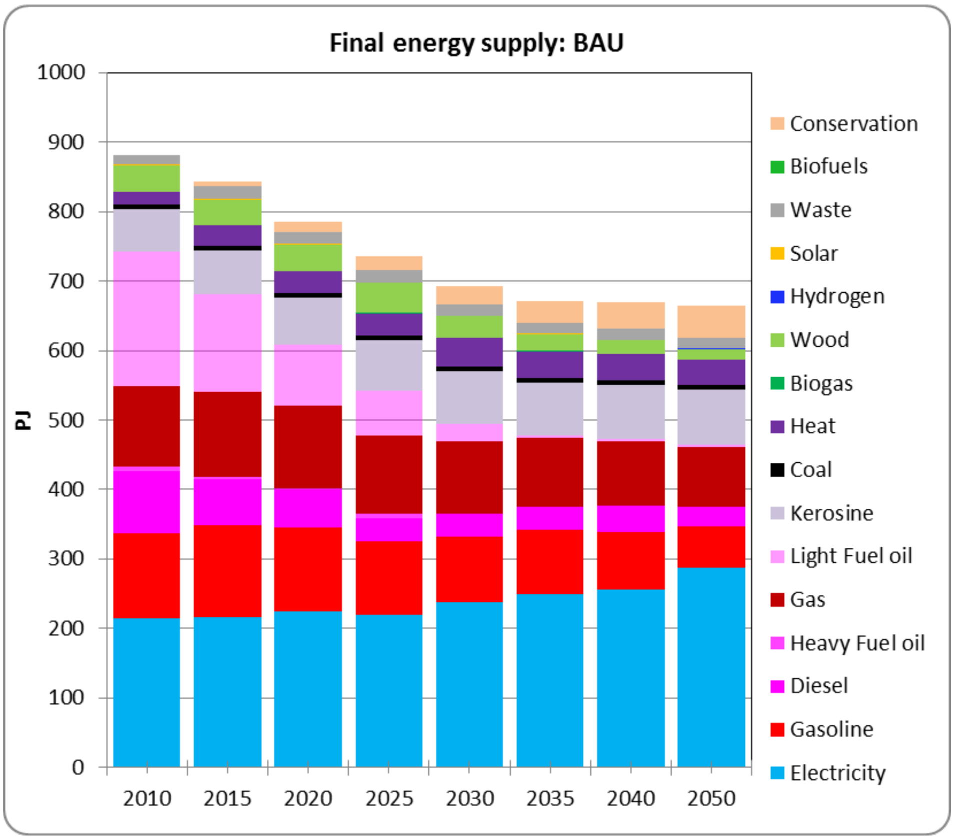


Figure 26: Final fuel consumption in the *BAU* scenario

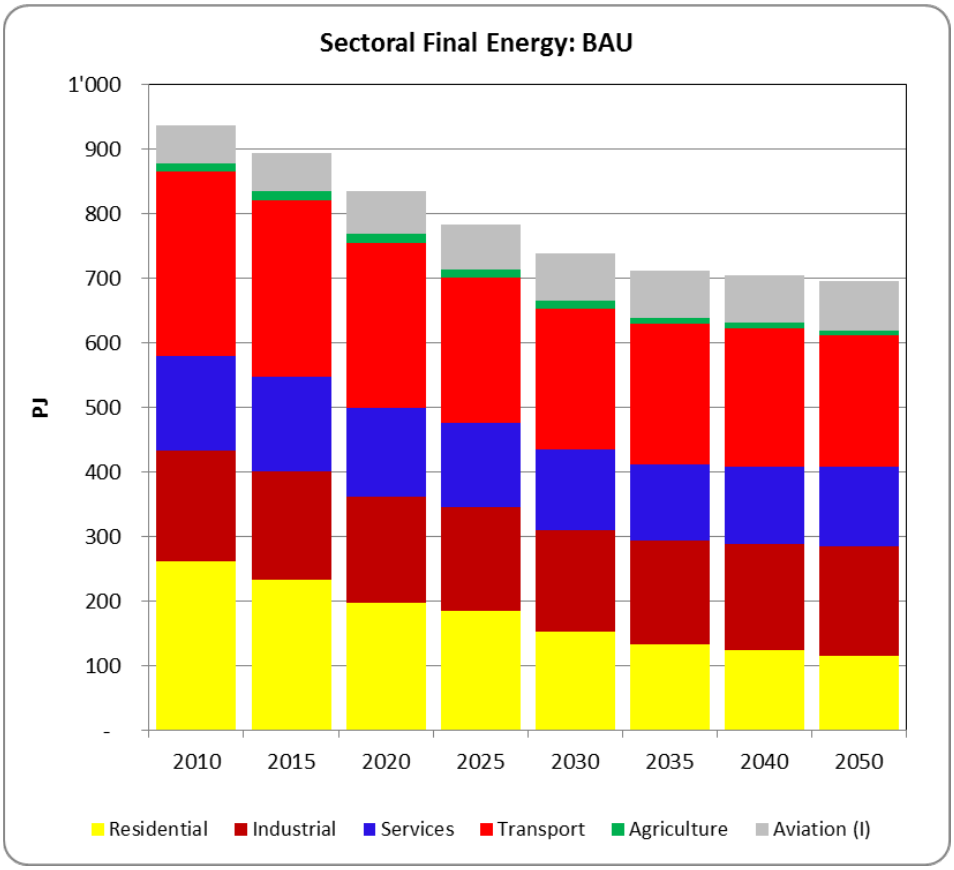


Figure 27: Final energy consumption by end-use sector in the *BAU* scenario

Figure 28 shows final energy consumption by end-use application. Fuel demand for heating (space heating and hot water) declines about two-thirds by 2050 (due to building conservation, and improved efficiency of heating technologies). Transport fuel demand declines about 40% with most of the reductions in car transportation. Electricity demand for air conditioning almost doubles, although from a very low base in 2010. Energy demands for some other ESDs (e.g. ICT or mechanical drive) increase directly in line with the assumptions described earlier in this report, given the limited fuel or technology substitutions possible. The trends and underlying drivers in sectoral energy consumption are elaborated in the following subsections.

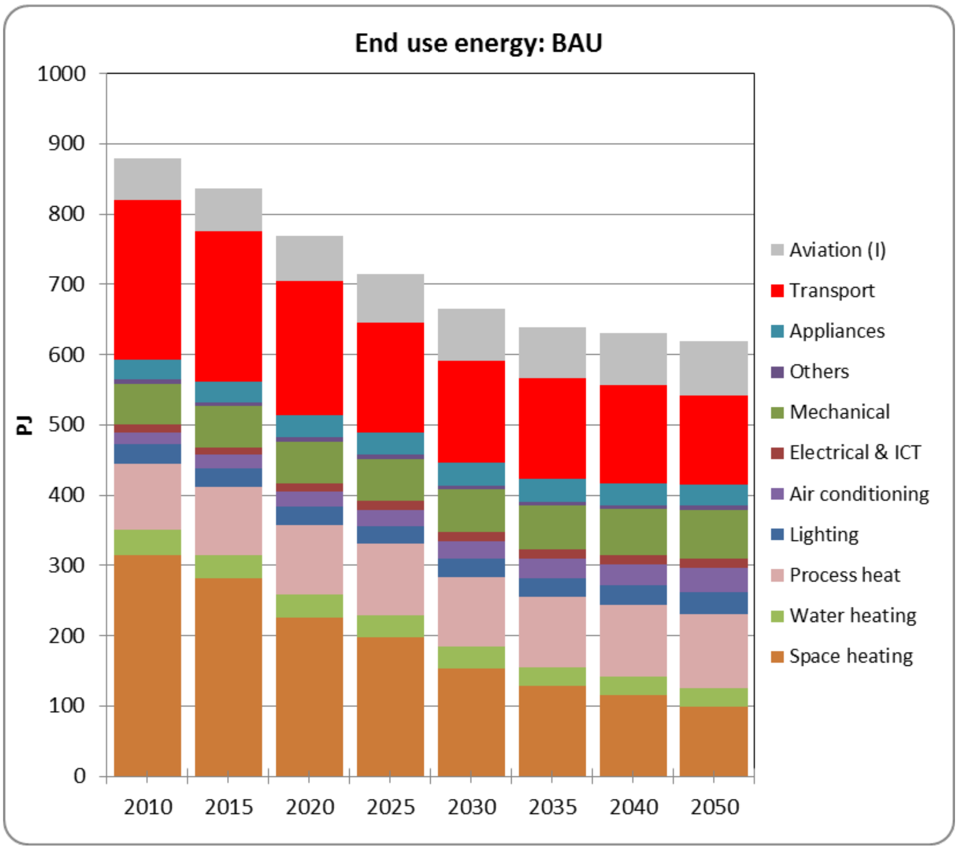


Figure 28: Final energy demand by end-use application in the *BAU* scenario

9.1.1. Residential sector

Figure 29 shows energy consumption in the residential sector, which is reduced from 262 PJ in 2010 to 114 PJ by 2050 in the *BAU* scenario—a reduction of about 2% per annum during 2010-2050. Most of this reduction occurs in space heating due to fuel and technology switching (from oil to gas in the medium term and to electric heat pumps in the longer term). Existing oil-based heating systems are phased out since the oil price is assumed to increase (Table 21). The higher efficiency of gas-based heating systems (Table 5) and a relatively lower gas price (compared to heating oil, Table 21) drives the fuel switch from oil to gas in the medium term. In the long run, there is a further switch to heat pumps, particularly in multifamily houses due to high efficiency and economies of scale. The deployment of heat pumps is also attractive compared to further deployment of gas, since it avoids the need to expand gas distribution infrastructure, which is assumed to be expensive (Table 11). Even though electricity in the *BAU* scenario is generated from natural gas-fired power plants (see § 9.2), the cost of expanding the gas network to supply centralized electricity plants is assumed to be lower than expanding the end use sector distribution network. In addition, the high efficiency (COP)[17] of heat pumps means that the electricity consumption for heating is lower (than the equivalent fuel demand for gas-based heating) and therefore the cost (if any) of expanding the electric grid is low. However, it is worth recalling that STEM is a single-region model without any spatial representation and T&D infrastructures are highly aggregated.

[17] Coefficient of performance.

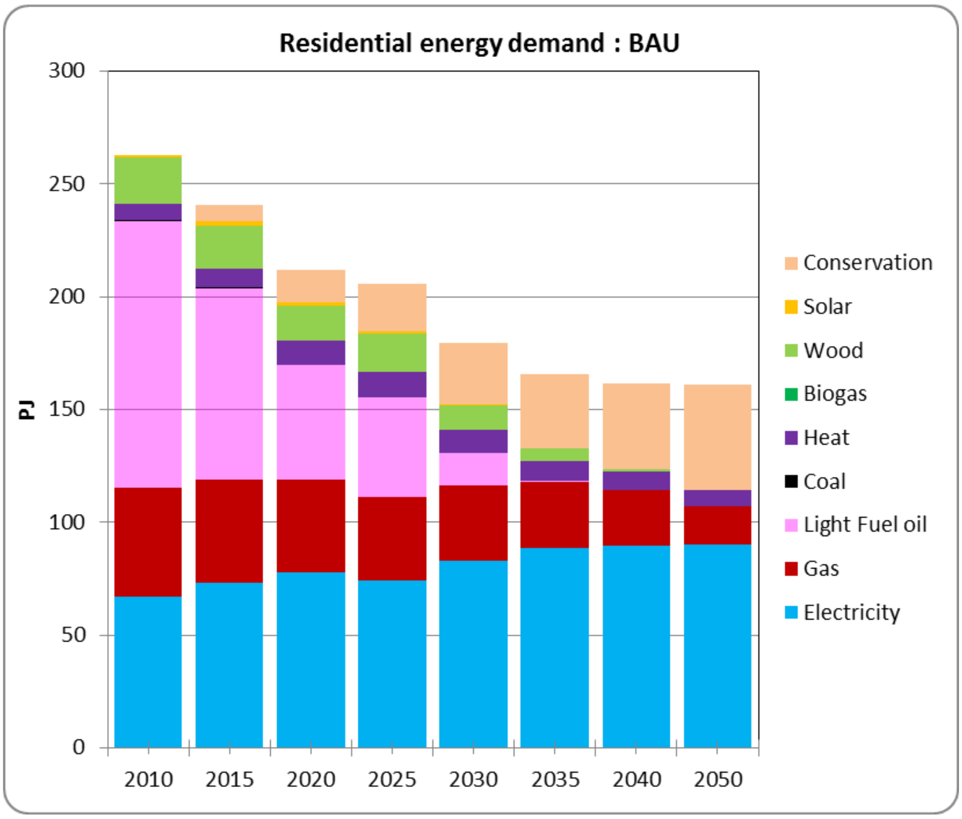


Figure 29: Residential energy demand in the *BAU* scenario

Electricity demands for other residential end-use applications (e.g. air conditioning, ICT) increase. In sum, total residential electricity demand increases 34% by 2050 (see Figure 29).

In addition to fuel and technology switching in space heating, energy demand in the residential sector is also reduced by building conservation measures (§ 3.1.3), shown in Figure 29 as 'Conservation'. Since the energy price is assumed to increase in the *BAU* scenario, a number of building energy conservation measures (see § 3.1.3) become cost effective and make a significant contribution to lowering heating demands (~47 PJ). STEM identifies conservation to be particularly cost-effective in single family houses due to the relatively higher capital cost of smaller-scale heating systems (Table 5), compared to multifamily houses. Thus, most of the building conservation in the *BAU* scenario occurs in existing single family houses, which are assumed to have a higher potential (see Figure 8). Other developments in residential heating include a moderate increase in district heating (from 7 PJ in 2010 to 11 PJ by 2030), with heat produced mainly from gas-fired CHPs (see § 9.2). Wood-based heating systems disappear from the residential sector since wood can be used more cost-effectively and efficiently in industrial subsectors via CHP (see § 9.1.3), under the assumptions in the scenario.

Figure 30 presents residential energy use by end-use application. Energy use for space heating is reduced 70% by 2050 (due to conservation and the fuel/technology switch to use natural gas and heat pumps described above). As a result, space heating accounts for only 40% of residential energy consumption in 2050 compared to 72% in 2010. Energy demand for air conditioning increases seven-fold from a very low base (so still accounts for less than 5% of residential energy demand in 2050). Energy demands for other applications increase moderately, partly because of the assumptions on the autonomous energy efficiency for some appliances (§ 8.2.1).

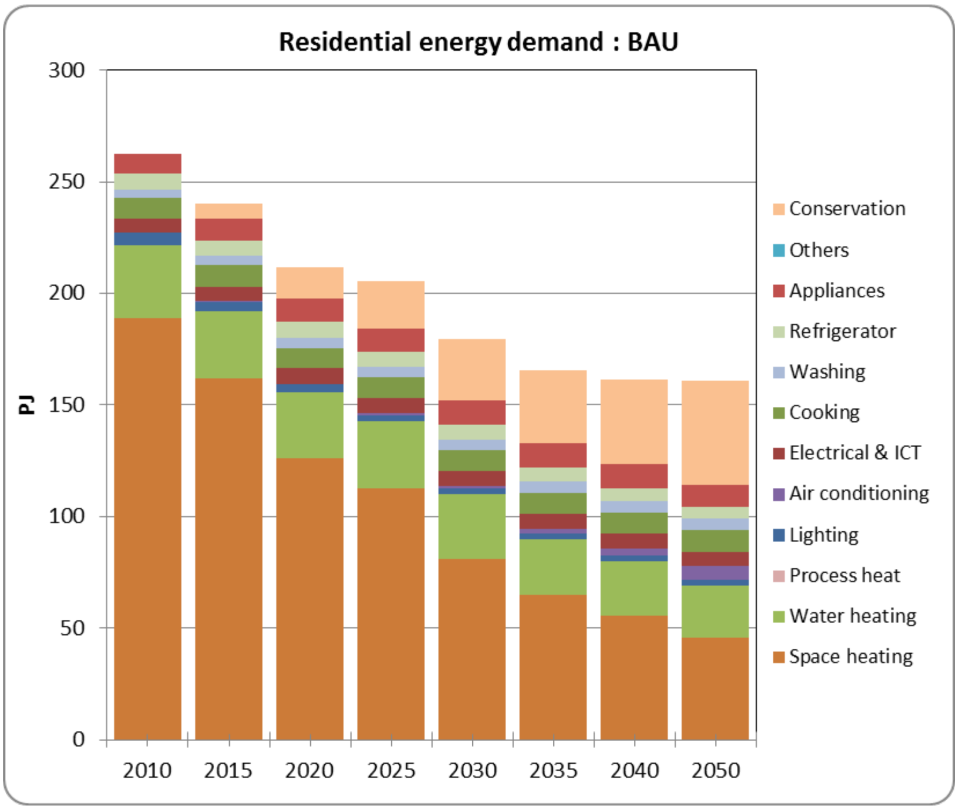


Figure 30: Residential energy use by end-use application in the *BAU* scenario

9.1.2. Services sector

Figure 31 shows the final energy demand in the services sector, which declines by about 15% between 2010 and 2050. Almost all of these reductions occur in space heating, which follows a similar trends as in the residential sector, i.e. existing oil-based heating systems are replaced by natural gas and then by heat pumps. Energy demand for space heating declines almost half while total floor area increases by 25% (Table 18) between 2010 and 2050. It is worth noting that in this scenario we have not assumed any building energy saving measures in the services sector, in contrast to the residential sector, so the future energy demand may be overestimated.

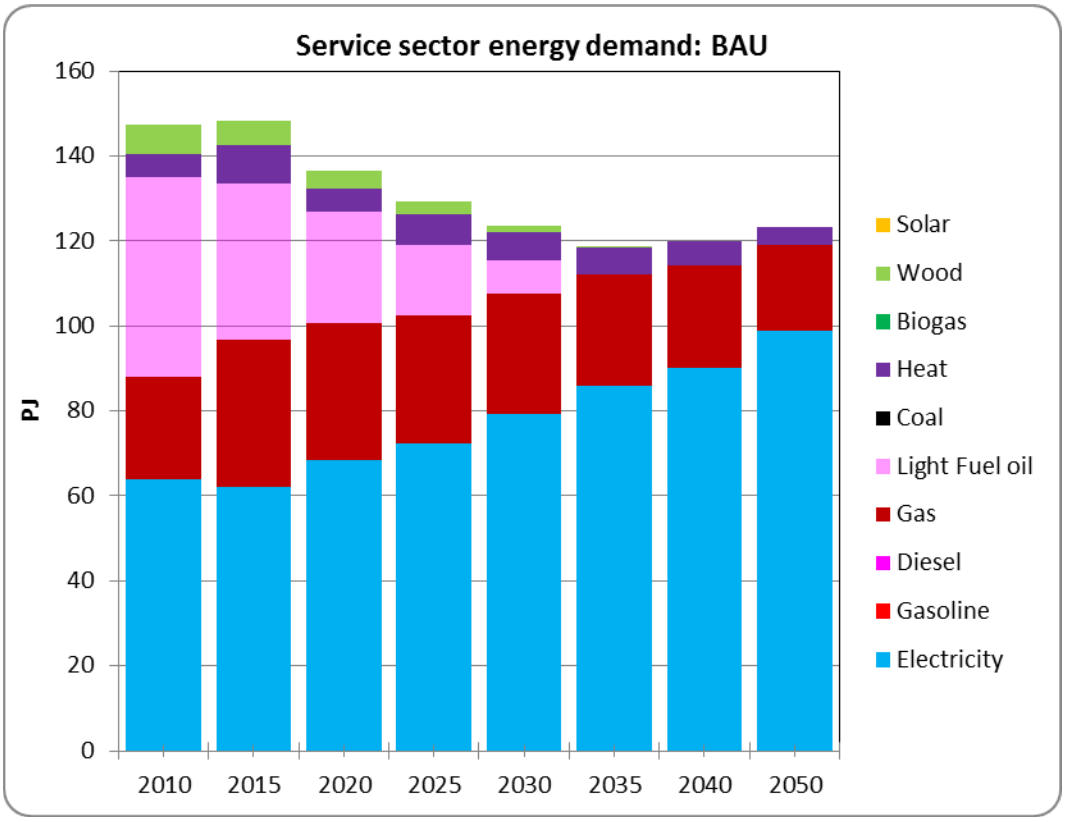


Figure 31: Energy demand in the services sector by fuel in the *BAU* scenario

Electricity demand in the services sector increases from 64 PJ in 2010 to 99 PJ by 2050 in the *BAU* scenario. Nearly one-third of the increase in the electricity demand arises from air conditioning (AC). The air-conditioned floor area is assumed to increase by 133% during 2010-2050, while the electricity demand for air conditioning increases by 62% (which is lower due to increases in efficiency, despite additional cooling-degree days). Electricity demand for lighting also increases by less than the lighted floor area (50% between 2010 and 2050 compared to 87%, respectively) due to uptake of efficient lighting technologies. The rest of the electricity demands (e.g., mechanical drive, ICT) increase 34% by 2050 in line with the ESD assumptions.

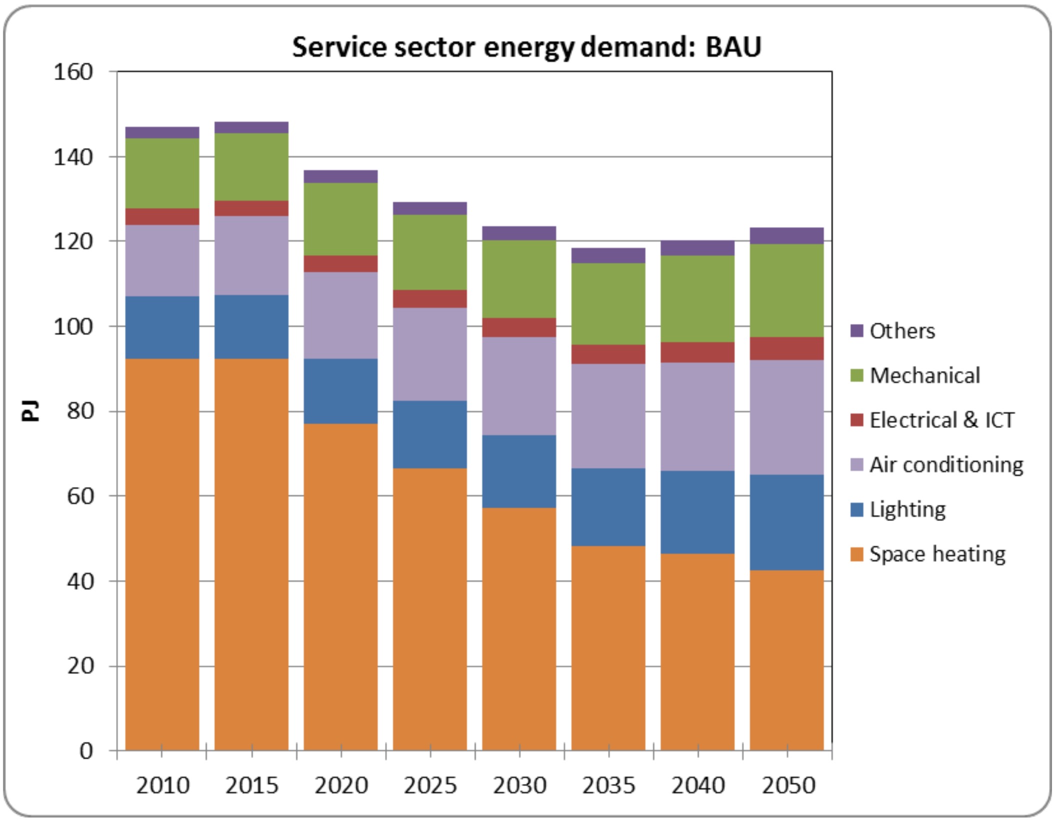


Figure 32: Services sector final energy use by end-use application in the *BAU* scenario

9.1.3. Industrial sector

Figure 33 shows industrial energy demand under the *BAU* scenario. In this sector energy demands are roughly constant while total ESDs increase by around 16% between 2010 and 2050. One of the more notable changes in the industrial sector over the projection period is an increase in the use of waste heat from centralised and decentralised CHPs, which increases three fold. This represents medium temperature (100-500 °C) waste heat which is assumed to be suitable for many process heat applications. As a result, in the *BAU* scenario existing oil-based process heating systems are phased out and replaced by natural gas based CHPs or direct process heat technology.

The other large changes are seen in the space heating and hot water demands which, although accounting for a small share of industrial demand (16% in 2010), provide options to reduce fuel consumption (Figure 34).

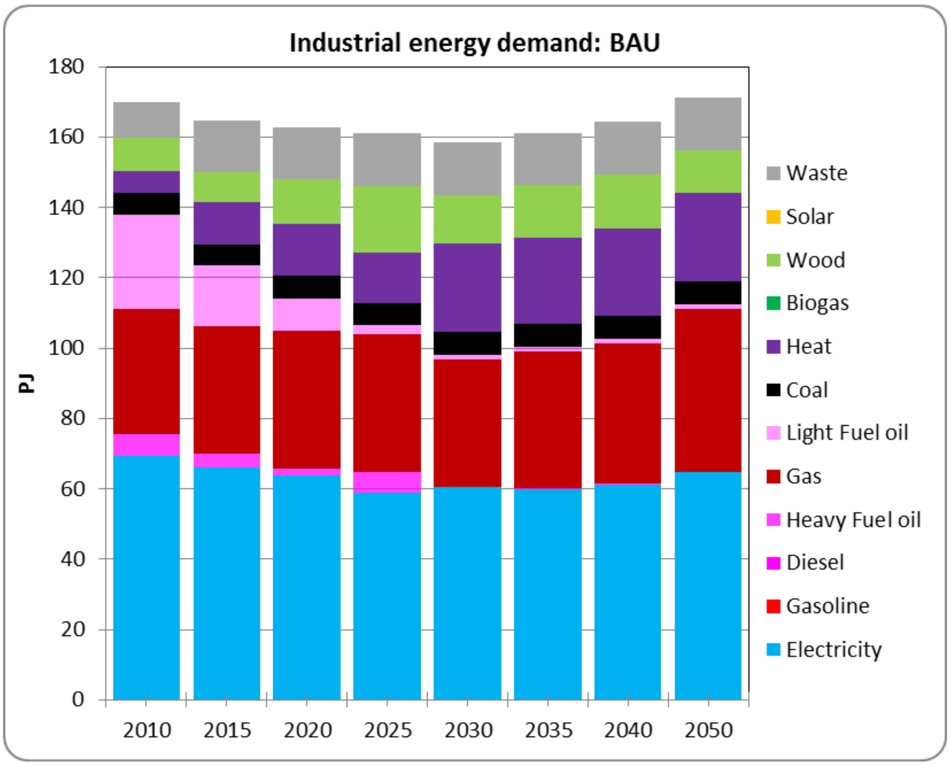


Figure 33: Final energy demand in industrial sector in the *BAU* scenario

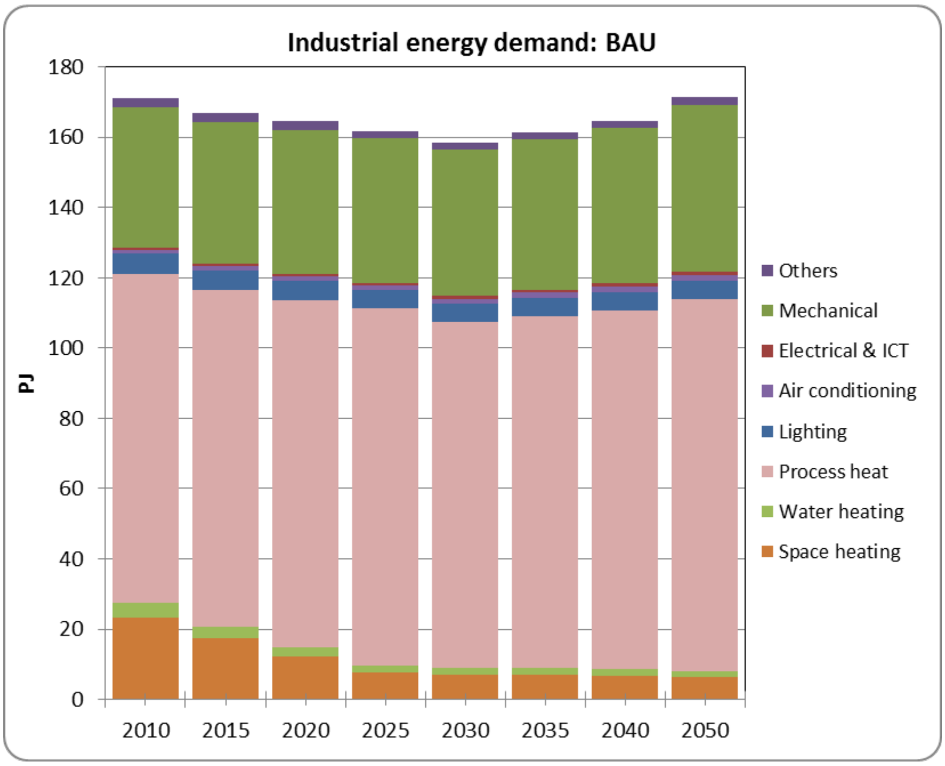


Figure 34: Industrial energy demand by end use in the *BAU* scenario

Looking in more detail at the industrial subsectors (Figure 35), the waste heat from CHPs is used predominantly in the food, paper and machinery subsectors (where medium-temperature process heat demands account for a significant share of total process heat requirements). In sectors assumed to have good access to biomass (e.g., food, paper and pulp), wood replaces natural gas and oil for heat production, and wood is also utilized directly in CHPs (see § 9.2.2). In the chemical industry, gas demand increases three-fold and electricity demand increases 60% because the sector (and thus ESDs) is assumed to grow strongly in this scenario (Table 19). Wastes continue to be used in the cement industry, although the sector itself is contracting so some is shifted to the chemical industry. In the construction sector, some of the light fuel oil is replaced by gas. We assume there is limited scope to replace the remaining light fuel oil used in construction machinery.

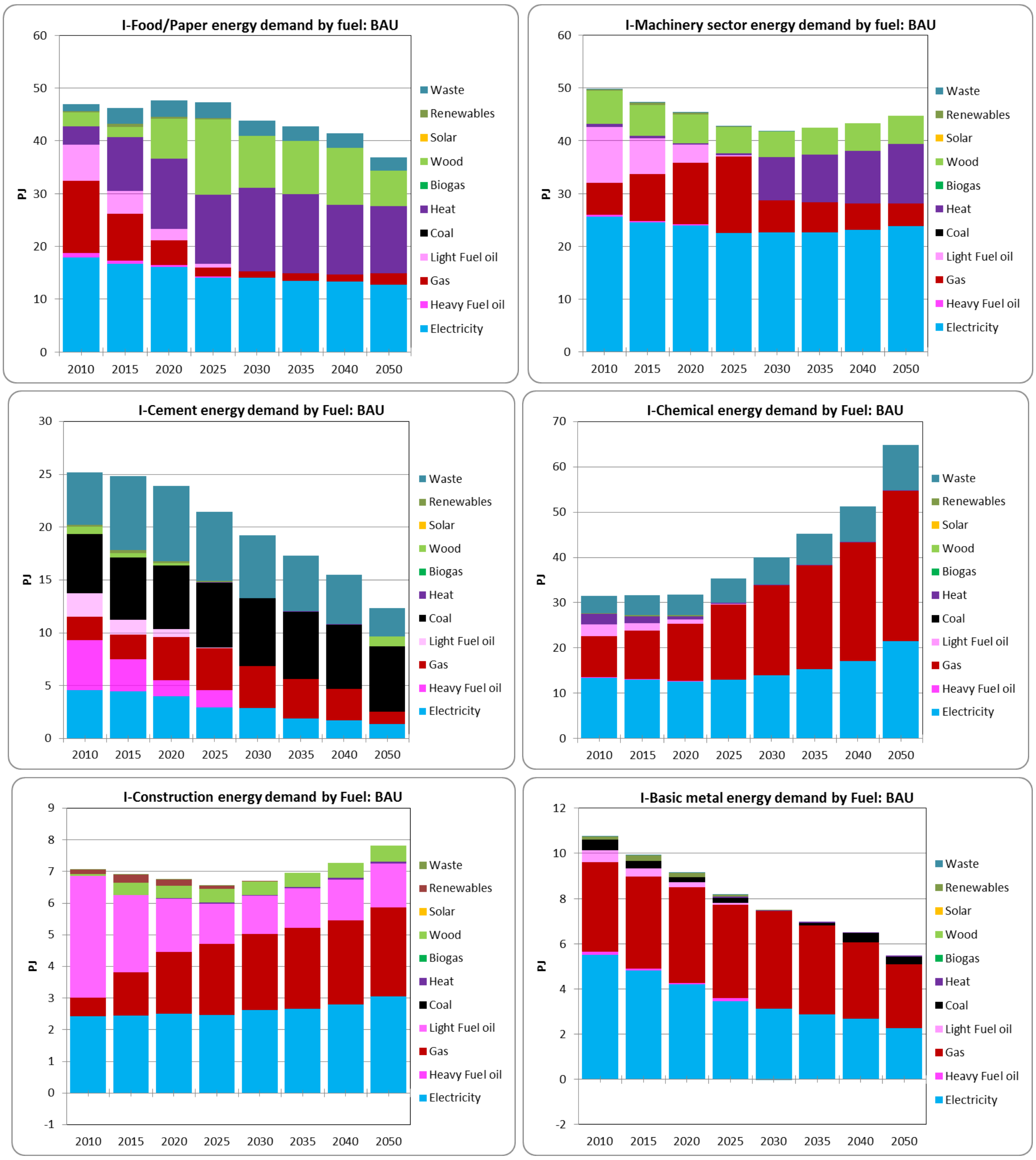


Figure 35: Industrial subsector energy demand in the *BAU* scenario

9.1.4. Transport sector

Figure 36 shows the transport energy demands in the *BAU* scenario, which decline about 30% by 2050. If fuel for international aviation is excluded, then the transport fuel demands decline by 44% and almost 85% of this reduction occurs in the car fleet (Figure 37).

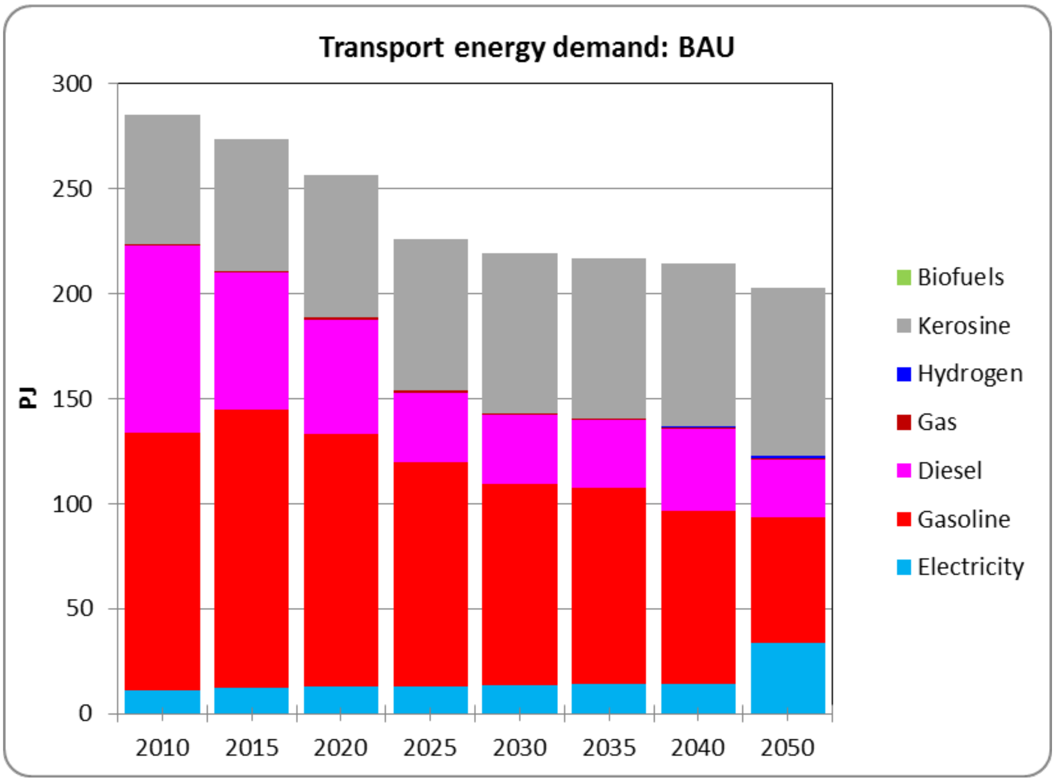


Figure 36: Transport fuel demands in the *BAU* scenario

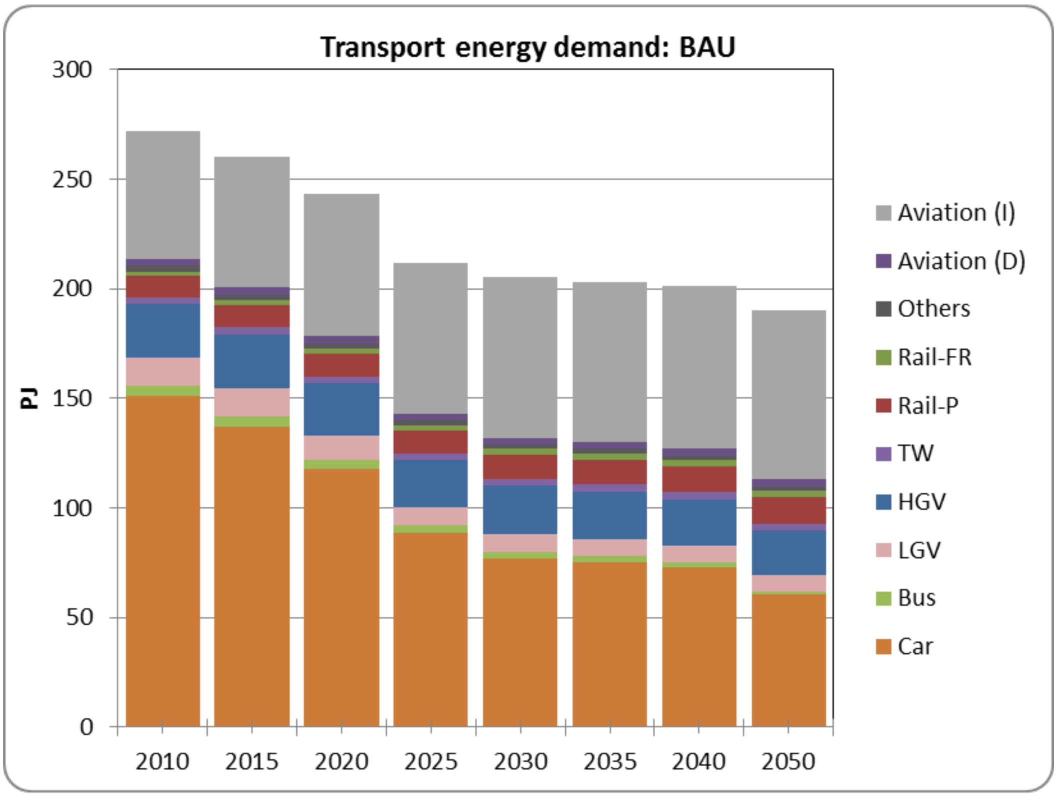


Figure 37: Transport sector fuel demand by mode in the *BAU* scenario

Fuel consumption in the car fleet is reduced 60% by 2050 from the 2010 level (Figure 37), despite increasing travel. Existing gasoline internal combustion engine (ICE) cars are replaced by advanced ICE cars in the short term. Gasoline hybrid cars penetrate more strongly from the low levels to today from 2020 (see Figure 38) and dominate the rest of the modelling period. Since the oil price increases throughout the time horizon (Table 21), battery electric vehicles (BEVs) become increasingly cost-effective towards 2050, by which time they account for about 40% of the car fleet (i.e. two million cars). The deployment of hybrids and BEVs results in a 30% reduction in gasoline demand by 2035 and 60% by 2050. The average CO_2 emission of the car fleet[18] decline from 208 g-CO_2/km in 2010 to 144 g-CO_2/km by 2020 and 45 g-CO_2/km by 2050 (shown Figure 38).

[18] Here we refer to the on-road tank-to-wheel driving emissions.

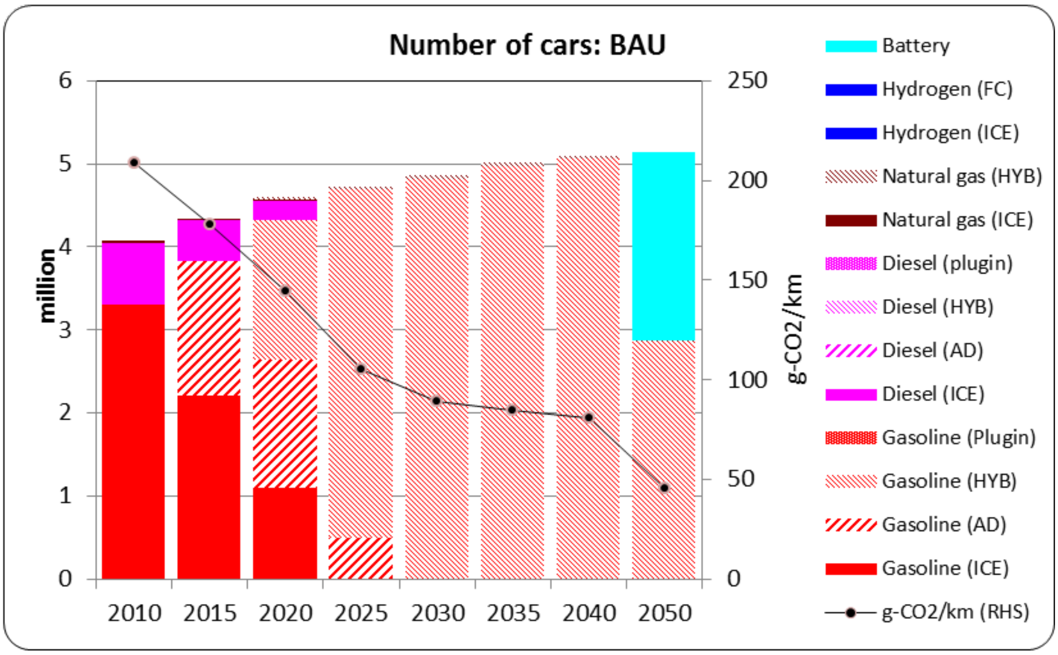


Figure 38: Car fleet in the *BAU* scenario

For other transport modes, improvements in efficiency offset some of the increases in demand leading to a moderate reduction in fuel demand (Figure 37). Conventional ICE buses are replaced with hybrid buses in the short and medium term and hydrogen in the longer term. This hydrogen is produced mainly from natural gas (see Figure 46). Heavy- and light goods vehicles begin to shift to hybrid diesel engines from around 2030. However, it should be noted that the representation of these other modes is less detailed than the car sector.

9.2. **Conversion sectors**

9.2.1. Electricity supply

Electricity demand in the *BAU* scenario increases from 215 PJ in 2010 to 288 PJ (or 80 TWh), representing a 34% (or 0.7% per annum) increase from 2010-2050. Figure 39 shows the electricity generation mix in the *BAU* scenario and installed electricity generation capacity is given in Annex-Fig. **1**. Electricity demand is also shown (blue marker) in the supply mix plot, representing the end-user demand excluding T&D losses and electricity used in pumped hydro plants. The consumption for pumped storage is shown as “Pumps” below the x-axis. Output from pumped storage hydro is 80% of the input, i.e. denoted ‘Hydro (P)’.

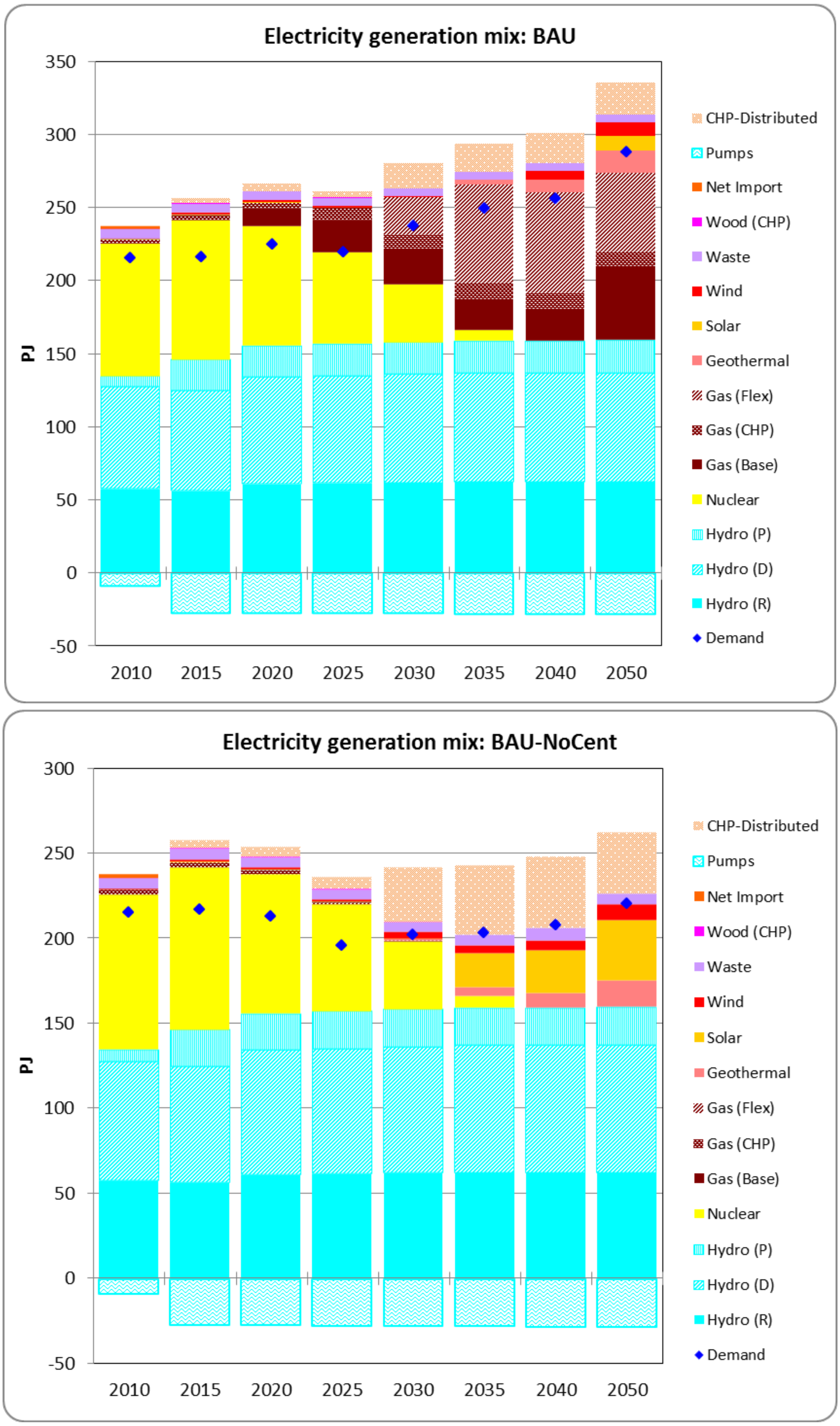


Figure 39: Electricity supply in the *BAU* and *BAU-NoCent* scenarios

The existing nuclear power plants are gradually replaced by natural gas turbine combined cycle (GTCC) power plants and CHPs, to supply increasing electricity demands. By 2035, one third of the electricity supply is from a combination of base load and dispatchable GTCC plants (denoted 'Gas (Base)' and 'Gas (Flex'), respectively).[19] Hydroelectric generation remains roughly constant throughout the period, though additional pumped hydro generation is deployed to profit from the cheap off-peak international electricity prices assumed in this scenario. In the longer run, some renewable technologies become cost effective because of (assumed) reductions in capital cost and increasing gas prices. By 2050, 12% of the electricity is generated from non-hydro renewables in the *BAU* scenario.

In the electricity supply variant scenario in which centralised GTCC plants and gas CHPs are restricted (*BAU-NoCent* in Figure 39), distributed CHPs and non-hydro renewable electricity generation play a larger role. Solar PV begins to penetrate from 2035 (vs. from 2050 in the *BAU*) and wind even earlier (from 2020). At the same time, distributed CHPs (mainly natural gas-based) contribute 15-20% of the total electricity supply during 2030-50. Given finite domestic renewable resources (Table 13) and the assumed restriction of net electricity imports (due self-sufficiency), electricity is a relatively scarce commodity in the *BAU-NoCent* scenario. As a consequence other fuels and additional efficiency options are cost effective. For instance, electrification is reduced in some of the end-use sectors compared to the *BAU* scenario. Total electricity demand in 2050 in the *BAU-NoCent* scenario is 61 TWh (vs. 80 TWh in *BAU*). The sectoral implications are further discussed in § 9.6.

9.2.2. Combined heat and power (CHP)

Figure 40 shows the deployment of CHP in the *BAU* and *BAU-NoCent* scenarios. Low temperature heat (dark purple) from CHPs is used for space and water heating, while medium temperature (100 – 500 °C range) heat (light purple) is used in some industrial processes. In the *BAU* scenario, electricity from CHP contributes 31 PJ in 2050 (or around 10% of the supply), increasing to 36 PJ in the *BAU-NoCent* scenario (16% of a lower total supply).

[19] The dispatchable GTCC plants are deemed to be attractive by STEM partly because their flexibility supports the balancing of supply and demand during weekdays, but also because they can be used to exploit hourly variations in international electricity prices (see

Figure 43). In other words, some of the flexible gas plants are mainly used for the export market (offset by importing off-peak electricity to fulfil the self-sufficiency constraint (see § 9.3)). The export of electricity during times of high prices generates revenue and reduces energy system cost (further discussed in § 9.3), although net annual electricity trade is zero.

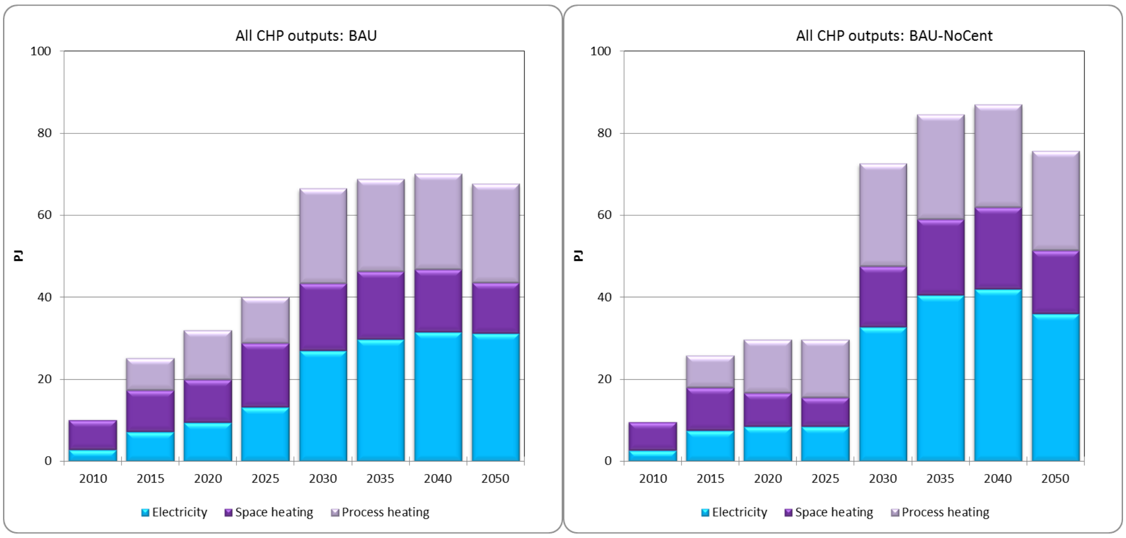


Figure 40: CHP in *BAU* and *BAU-NoCent* scenarios

The restriction on the deployment of centralised power generation in the *BAU-NoCent* scenario leads to higher deployment of distributed systems (Figure 41). In the *BAU* scenario, the heat from the distributed generation is mainly used for medium temperature industrial process heat (see § 9.1.3). However, in the *BAU-NoCent* scenario, the deployment of distributed CHPs is more widespread, and waste heat makes a significant contribution to residential sector space heating. Nonetheless, total electricity output from distributed CHPs in the *BAU-NoCent* scenario does not fully replace the electricity from centralised plants (GTCC and CHP) in the *BAU scenario*. This is partly because the heat demand is insufficient to support a larger scale of deployment of distributed systems, but may also be attributed to assumptions applied in the scenario that excess electricity generation from distributed plants cannot be exported from one end-use sector to another (on the other hand, there is no restriction on the use of this electricity throughout each end-use sector).

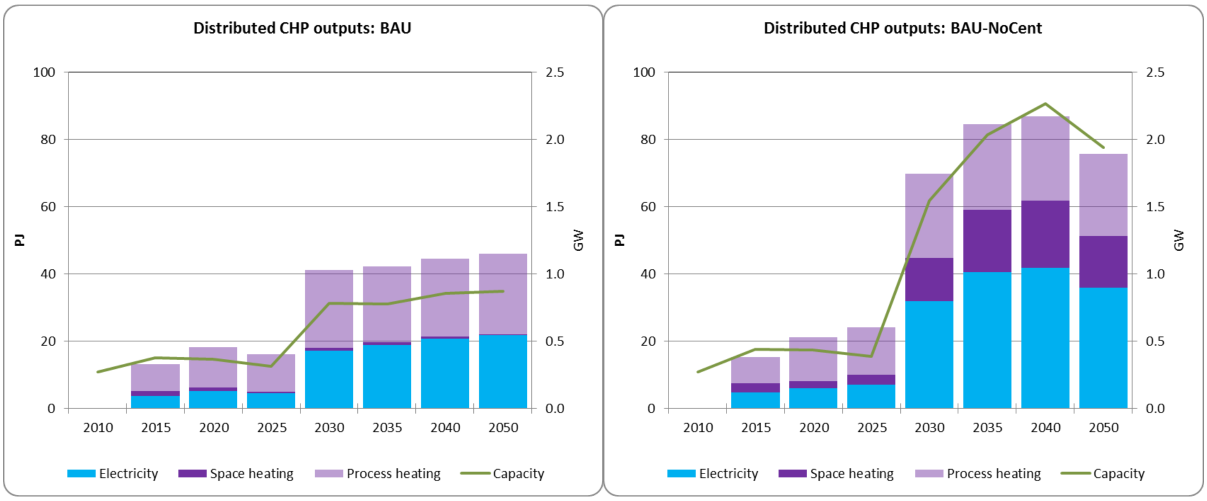


Figure 41: Distributed CHP in *BAU* and *BAU-NoCent* scenarios

In the both scenarios, natural gas-fired CHPs are chosen in the short and medium term, with wood-fired CHPs becoming more attractive in the long run. However, in the *BAU-NoCent* scenario, gas-based distributed CHP continues to play a role in the long run since centralised electricity generation is restricted.

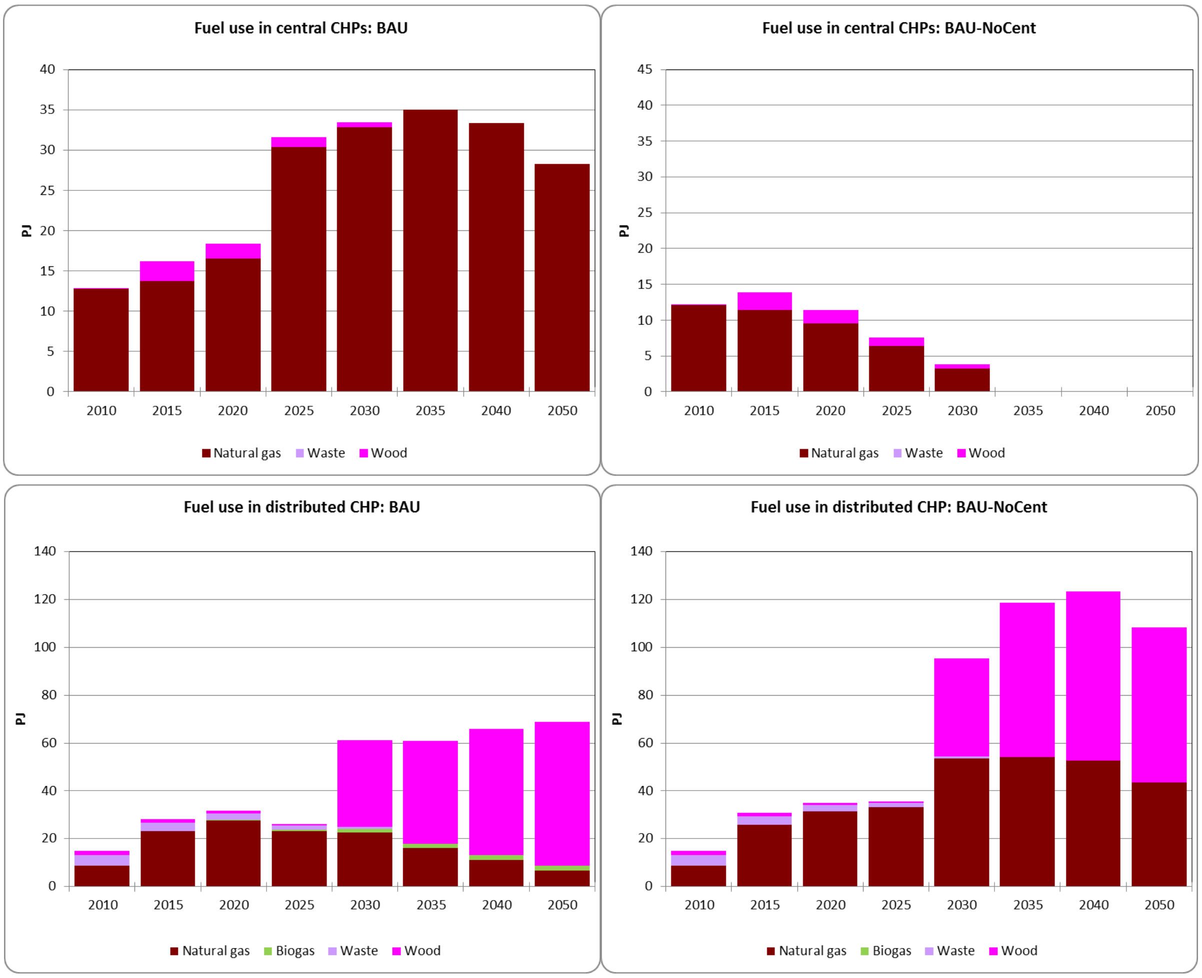


Figure 42: Fuel consumption in CHP in *BAU* and *BAU-NoCent* scenarios

9.3. **Electricity generation schedule**

A novel feature of STEM is its hourly time resolution, which has the potential to provide additional insights into electricity demand and supply balancing at the hourly level. As mentioned previously, the electricity demand and load curve are endogenous to STEM based on the choice of demand technologies.[20]

9.3.1. *BAU* scenario

Figure 43 shows electricity schedule from the *BAU* scenario in 2050 on summer and winter weekdays and weekends. In the *BAU* scenario, summer weekday demand peaks at 8.4 GW at 6:00[21] and stays in the 7-8 GW range during the day until late evening. The difference between the peak and lowest demand (which occurs at 2:00) is about 2.6 GW. The morning peak is due to charging of BEVs (brown shade in the export plot) using the cheap imported electricity assumed in this scenario. On the supply side, base-load plants like run-of-river hydro, gas, and CHPs contribute about 4.8 GW and the remaining demand is met with a combination of imported electricity (orange shade), dam hydro, solar PV, and others. Since international electricity prices are assumed to be relatively low on summer days, electricity imports are attractive from morning till noon. Some of this imported electricity is stored via pumped hydro (shown with in light blue shade in the lower plot) and BEVs. From 16:00, the stored electricity from pumped hydro and other flexible sources of electricity generation (dam hydro and gas plants) are scheduled to supply the demand; and the excess generation is exported. The total summer weekday exports account for 45% (or net exports, 21%) of total generation which eventually enables import during weekends and in winter (to fulfil the self-sufficiency constraint). The import and export patterns and quantities are highly dependent on the electricity price assumptions, which could also affect the choice of end-use technologies (e.g. the level of BEV deployment).

On winter weekdays, electricity demand peaks at 11.4 GW at 6:00 again due to charging of BEVs. The demand pattern is flatter than the summer weekday and the difference between peak and lowest demand (1:00) is 2.9 GW. Compared to summer, the output from run-of-river hydro plants is reduced but all base-load gas plants are operated at capacity. In addition, the contribution from CHPs is relatively high due to high heating demands. The total output from baseload plants (5.8 GW) is far below the lowest demand, and flexible gas plants are operated to meet the remaining demand. During 1:00–8:00, a small quantity (10% of demand) is imported and used for charging BEVs. From 14:00, dam hydro is scheduled, mainly for export. On winter weekdays, net exports accounts for 14% of the supply.

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[20] As described in Part I, demand profiles are specified for each ESD (e.g. Figure 9 and Figure 10) and then STEM determines the cost-optimal choice of fuel (and technology) and thereby the electricity demand profile (see [26] for further detail). Accordingly, the exogenous profiles of ESDs are critical inputs to the model. Some assumptions on the demand curve for these ESDs (especially the ‘residual’ demands discussed in section 3.2) need to be refined further.

[21] All times are given in 24-hour notation.

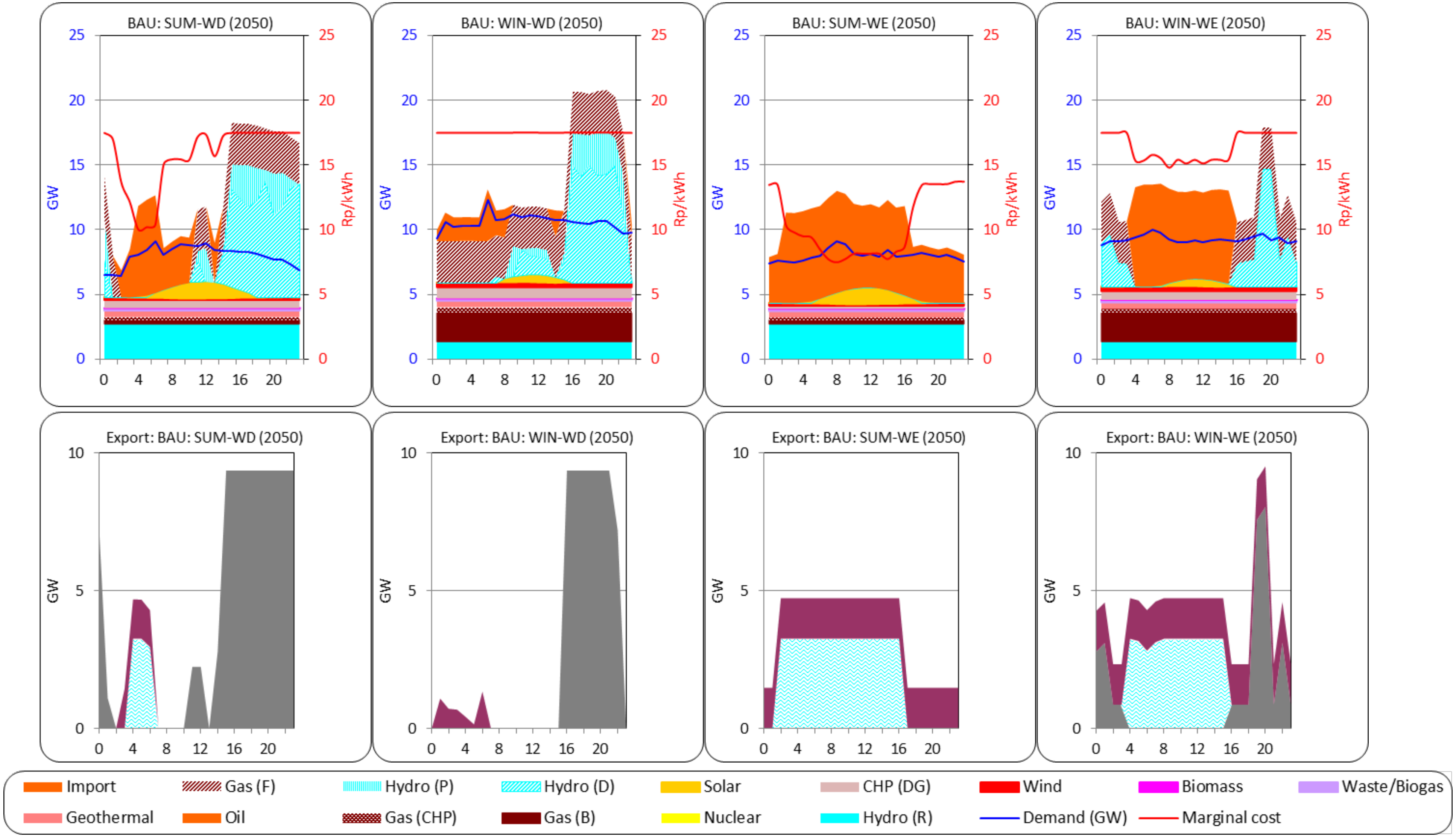


Figure 43: Electricity supply in winter and summer seasons in the *BAU* scenario

On weekends, electricity demand is similar to weekday demand because of the large load from charging BEVs, which are most cost-effectively charged during weekends. In both summer and winter, cheap electricity is imported during weekends and used to supply demand or stored via pumped hydro and BEVs. On summer weekdays, 70% of the demand is met with (net) imported electricity, while on winter weekends the figure is around 27%. The net electricity imports during the weekends facilitate net export (of dam hydro outputs) during weekdays.

It is important to emphasize that these patterns of electricity trade (and operation of pumped hydro reservoirs and deployment of BEVs) are partly driven by the scenario assumptions on the availability of cheap electricity imports in summer and on weekends (reflected in the relatively low marginal electricity cost seen at these times in Figure 42).

9.3.2. *BAU-NoCent* scenario

The electricity generation and demand schedule in the *BAU-NoCent* scenario is presented in Figure 44. Compared to the *BAU* scenario, electricity demand is lower in winter due to limited electrification of end-use sectors (explained in § 9.6). For example, heating in the residential and services sectors is not electrified (see Figure 45). The peak winter demand in *BAU-NoCent* is about 6.35 GW (vs. 8.9 GW in *BAU*) because there is less electric heating. Moreover, BEVs are not taken up in the *BAU-NoCent* scenario. While demand is lower in *BAU-NoCent*, so is the base-load supply. Daytime demand is met with imported electricity, while dam and pumped hydro plants are operated to optimise export revenue. Without gas plants, BEVs are less cost effective.

In summer, the electricity demands in *BAU-NoCent* scenario are similar to those in the *BAU* scenario, partly because there are relatively few summer electric demands that can be substituted with other fuels. However, on the supply side there is a larger contribution from solar PV in the *BAU-NoCent* scenario, and demand is almost fully met with domestic supply (whereas imports play a larger role in *BAU*). Like in the *BAU* scenario, output from dam hydro is optimised for export. On weekends (not shown), a large quantity of electricity is stored via pumped hydro and scheduled during weekday evenings, similar to *BAU*.

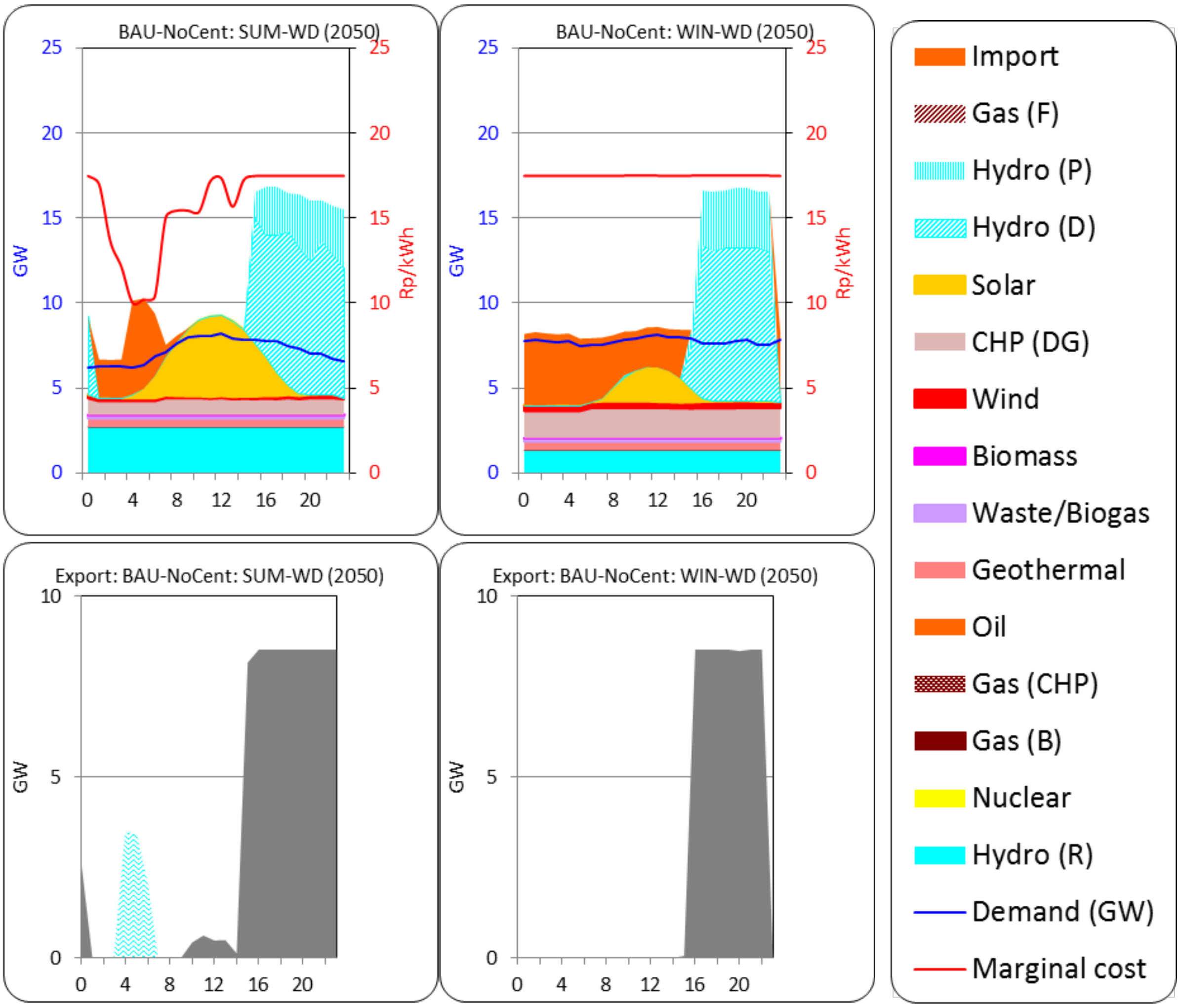


Figure 44: Electricity supply on winter and summer weekdays in *BAU-NoCent* scenario

9.3.3. Heat supply profile

Similar to the electricity supply-demand balance, other commodities can be tracked at the hourly level. For example, Figure 45 shows heat supply to residential buildings (for the *BAU* and *BAU-NoCent* scenarios). A substantial share of heat demand is offset by conservation measures. Note, the sectoral profile would provide additional insights with further developments of the model, including the introduction of demand-side storage.

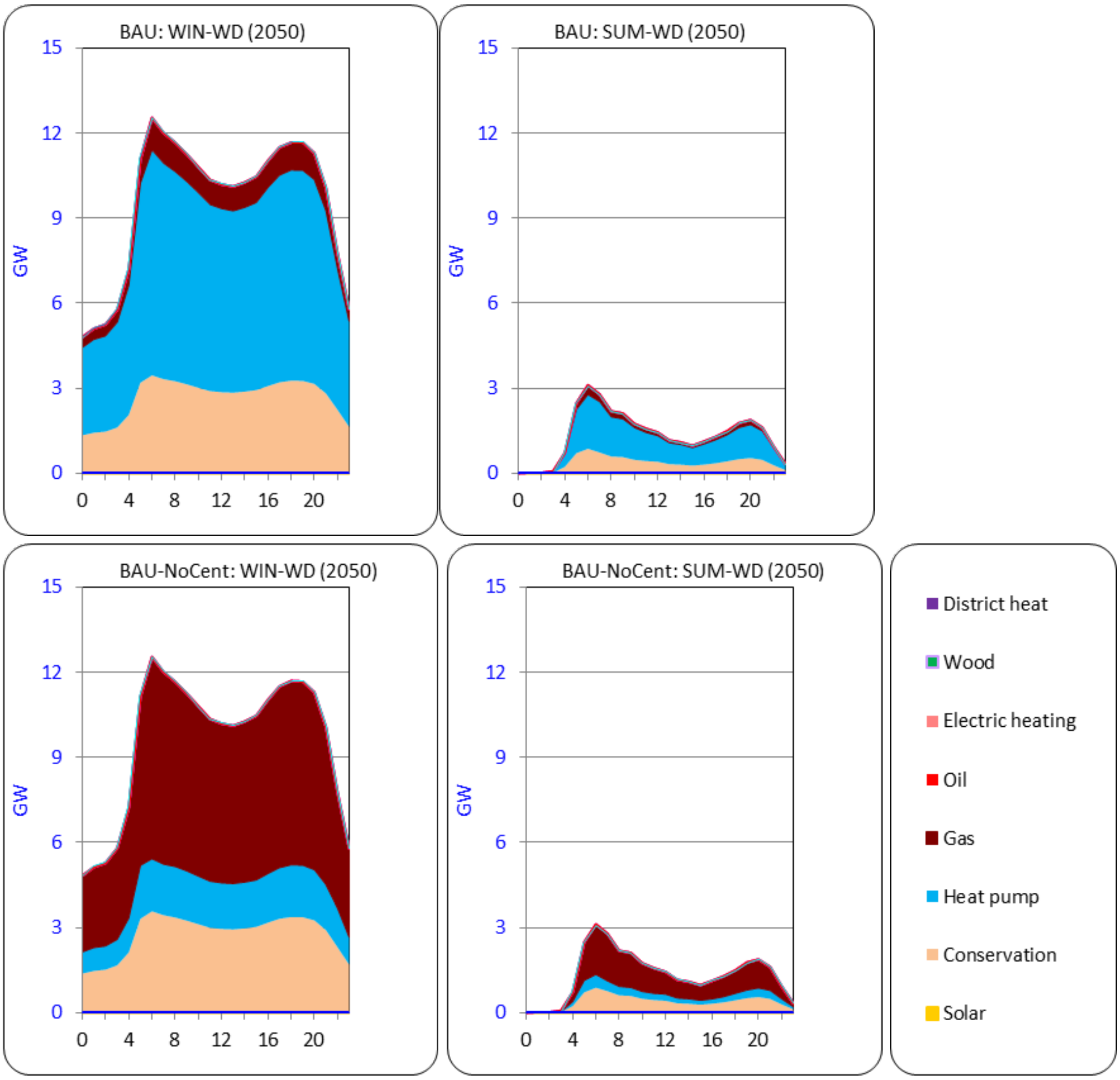


Figure 45: Heat supply on winter and summer weekdays in *BAU* and *BAU-NoCent* scenarios

9.3.4. Hydrogen production

Figure 46 shows fuel production for fuels other than electricity and heat under the *BAU* scenario. In the *BAU* scenario, a small quantity of hydrogen is produced from waste (manure) and in later periods hydrogen is produced from natural gas. The hydrogen is used in transport sector (Figure 36). Even though the option exists to store hydrogen and generate electricity with fuel cells, those are not cost effective in this scenario.

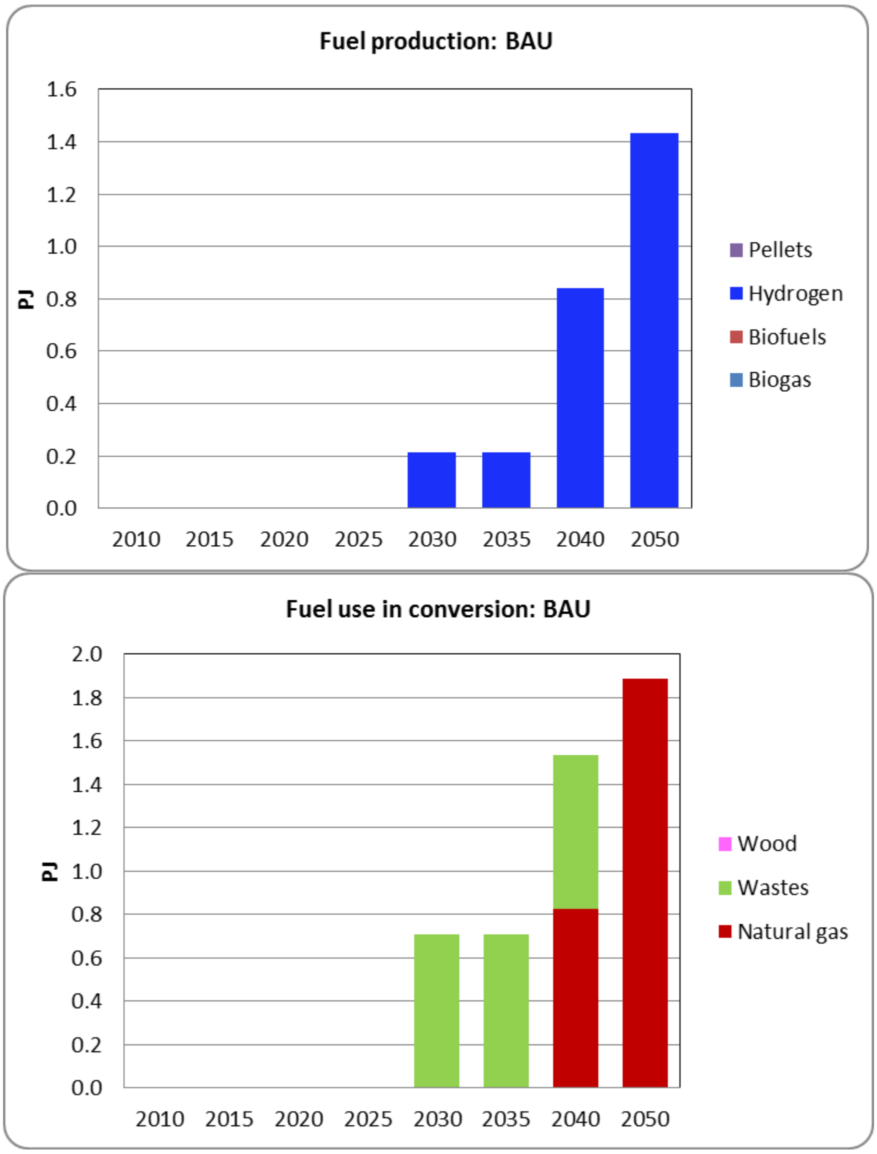


Figure 46: Hydrogen production in the *BAU* scenario

9.4. Carbon dioxide (CO_2) emissions

Figure 47 shows sectoral CO_2 emissions in the *BAU* scenario. Total CO_2 emissions in 2050 are reduced to 30 million tonnes (Mt-CO_2) from 43 Mt-CO_2 in 2010—an average annual reduction of 0.9%. Excluding CO_2 emissions from international aviation, the reduction is about 38%, or about 1.2% per annum. For the end-use sectors, emissions are reduced between 33% and 90%; however, emissions in the electricity sector are greatly increased (see §9.2.1)—that is, the electrification of end-use sectors (e.g. heat pumps for heating (see § 9.1.1) and BEVs (see § 9.1.4)) 'shifts' some the CO_2 emissions to the electricity sector. Also shown in Figure 47 (right panel) is the sectoral CO_2 emissions with the electricity (and other conversion) sector emissions allocated according to sectoral electricity use. This allocation shows a smaller reduction in sectoral emissions. For example, direct CO_2 emission from the residential sector are reduced by 90%, whereas the net emissions are reduced by about 60%

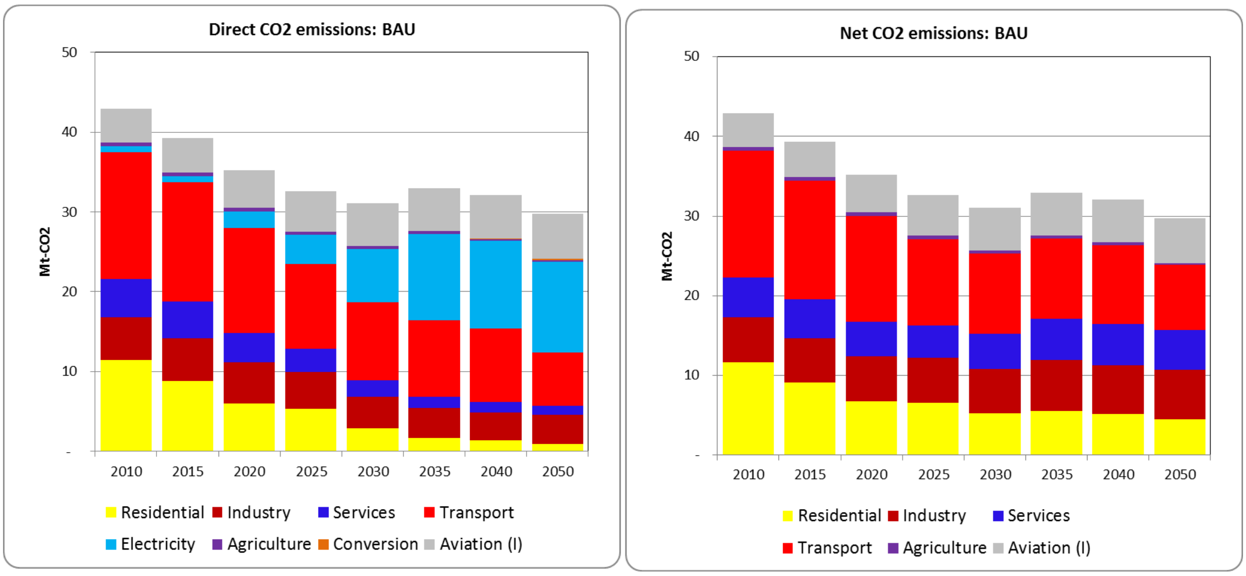
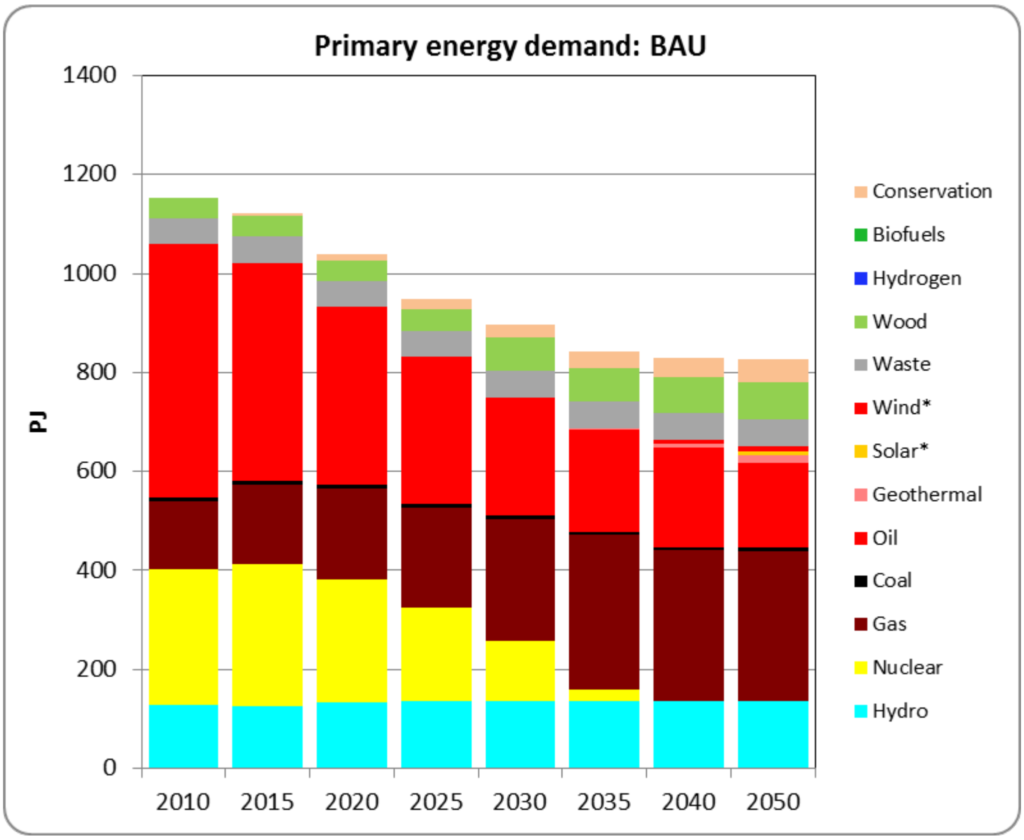


Figure 47: Sectorial CO_2 emissions in the *BAU* scenario

9.5. **Primary energy supply**

Figure 48 shows primary energy supply in the *BAU* scenario (see note in § 8.3.1). Oil includes crude oil and refined fuels like diesel, heating oil and gasoline. The share of oil declines due to fuel switching in heating and transport. However, the consumption of natural gas more than doubles from the 2010 level. Some of the natural gas supply is used in the electricity sector (to substitute nuclear fuels). The share of fossil fuels in primary energy declines by 56% (or 2% per annum) during 2010-2050. At the same time, the share of renewables increases. For the primary energy supply in 2050, a 2900 Watt society is realised. [22]

[22] Noting, however, that different accounting conventions can be applied for estimating primary energy for this target.



* see note in § 8.3.1

Figure 48: Primary energy supply in the *BAU* scenario

9.6. Parametric sensitivities—*BAU* scenario

The following subsections describe insights from the parametric sensitivities on fuel price assumptions, along with additional results from the no centralised gas electricity supply variant (*BAU-NoCent*).

9.6.1. Residential sector

With the low fuel price assumptions, heat pumps become less cost effective. As a result, the penetration of heat pumps is lower, and the deployed HPs are less efficient than in the *BAU* scenario. Heat is predominantly supplied with gas-based heating systems (see *BAU-FP-L* in Figure 49). Building energy conservation measures contribute to a reduction of 36 PJ by 2050 (vs. 47 PJ in the *BAU* scenario). Wood-based heating also is used for an extended period compare to *BAU*. Thus energy consumption for heating declines 48% by 2050, as compared to 69% in the *BAU* scenario. In contrast, with high fuel price assumptions (*BAU-FP-H*), there are no changes in the residential sector compared to the *BAU* scenario.

When the availability of centralised gas-fired electricity generation is restricted (*BAU-NoCent*) heat pumps are not taken up; and natural gas is used for heating (see Figure 49). The reduced generation from centralized gas plants cannot be made up by renewables, particularly because the supply patterns for renewable electricity do not coincide with high winter heating demands. Total residential energy demand declines only 31% compared to 56% in the *BAU* scenario (Figure 49).

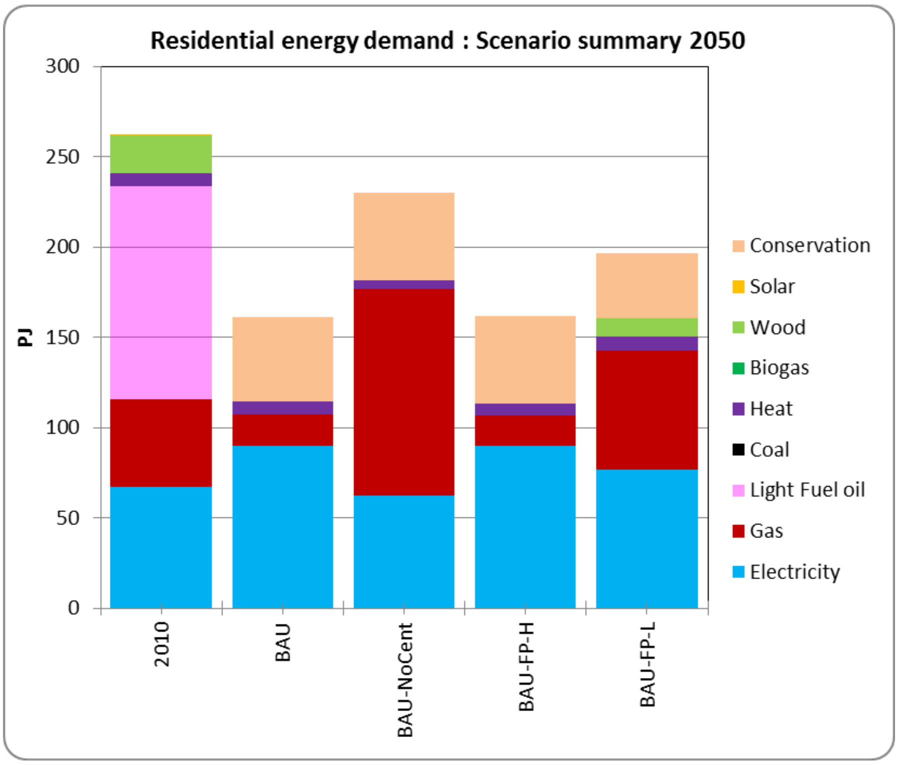


Figure 49: Residential energy demand in 2050 in *BAU* scenario variants

9.6.2. Services sector

Compared to the *BAU* scenario, the services sector energy demand is substantially higher with lower fuel price assumptions (*BAU-FP-L*), and heating demand is fully met with natural gas heating systems. A similar result is seen in the scenario with no centralised gas-fired power plants (*BAU-NoCent*) (Figure 50).

With high energy prices (*BAU-FP-H*), there is an accelerated switch from gas to heat pumps and the total service sector energy demand declines by 22% by 2050 (vs around 15% in *BAU*).

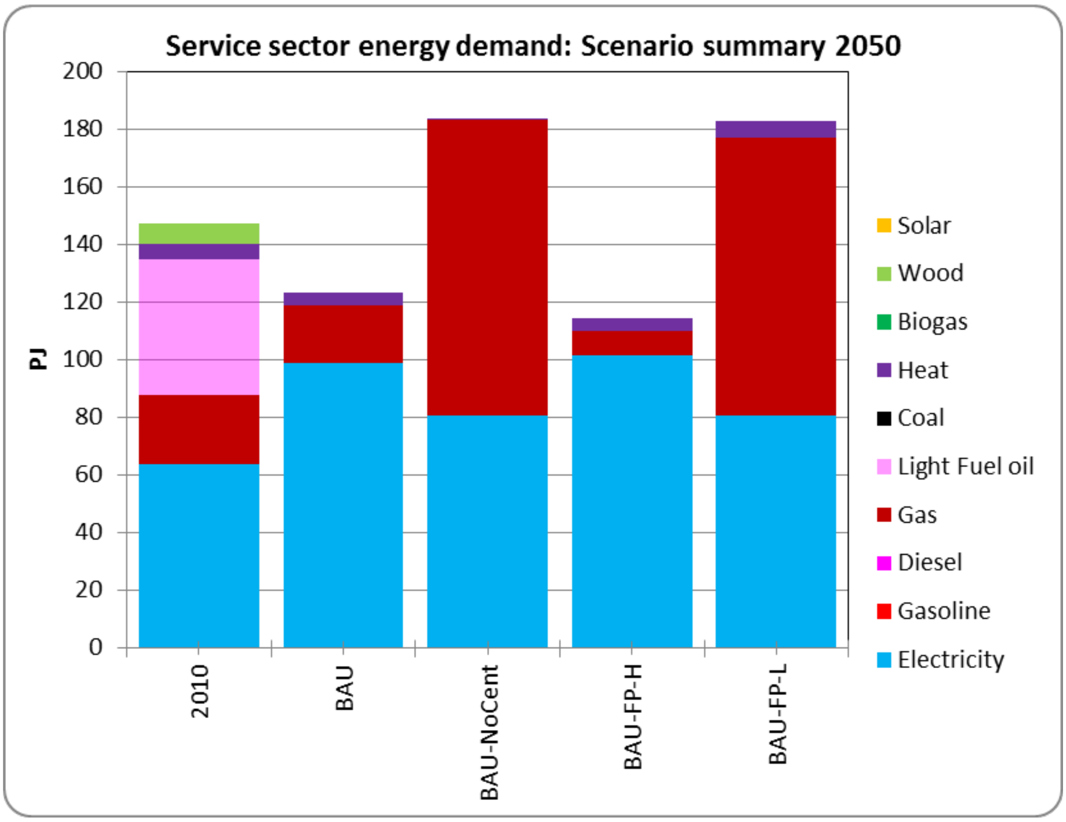


Figure 50: Services sector final energy demand in 2050 in *BAU* scenario variants

9.6.3. Industrial sector

Given limited options for fuel/technology substitution in the industrial sector, alternative fuel price assumptions have relatively less impact (Annex-Fig. **8**). Total fuel consumption remains unchanged with minor changes in technology and fuel mixes. With the low fuel price assumption (FP-L), the share of gas increases and uptake of CHP is lower (illustrated in Annex-Fig. **8** by the reduced quantity of heat in end use). On the other hand, with high fuel prices (FP-H), the energy mix is almost identical to *BAU*. However, without centralized gas power plants (*BAU-NoCent*), the role of (decentralized) CHP increases substantially as discussed in Section 9.2.2.

9.6.4. Transport sector

The penetration of BEVs depends heavily on future fuel price assumptions, the source of electricity supply and assumed cost improvements for the vehicle technology. With high fuel prices (*BAU-FP-H* in Figure 51) the share of BEVs increases to 70% by 2050 (vs. 40% in *BAU*) whereas BEVs are unattractive with the low fuel price assumptions (*BAU-FP-L*).

The source of electricity, or more specifically the availability of cheap electricity, is also important for the deployment of BEVs. In the *BAU* scenario, a substantial quantity of electricity is produced from natural gas (see §9.2.1, Figure 39). Without centralised gas-based electricity generation, the availability of electricity is reduced and advance gasoline hybrid vehicles dominate the market in 2050 (*BAU-NoCent* in Figure 51).

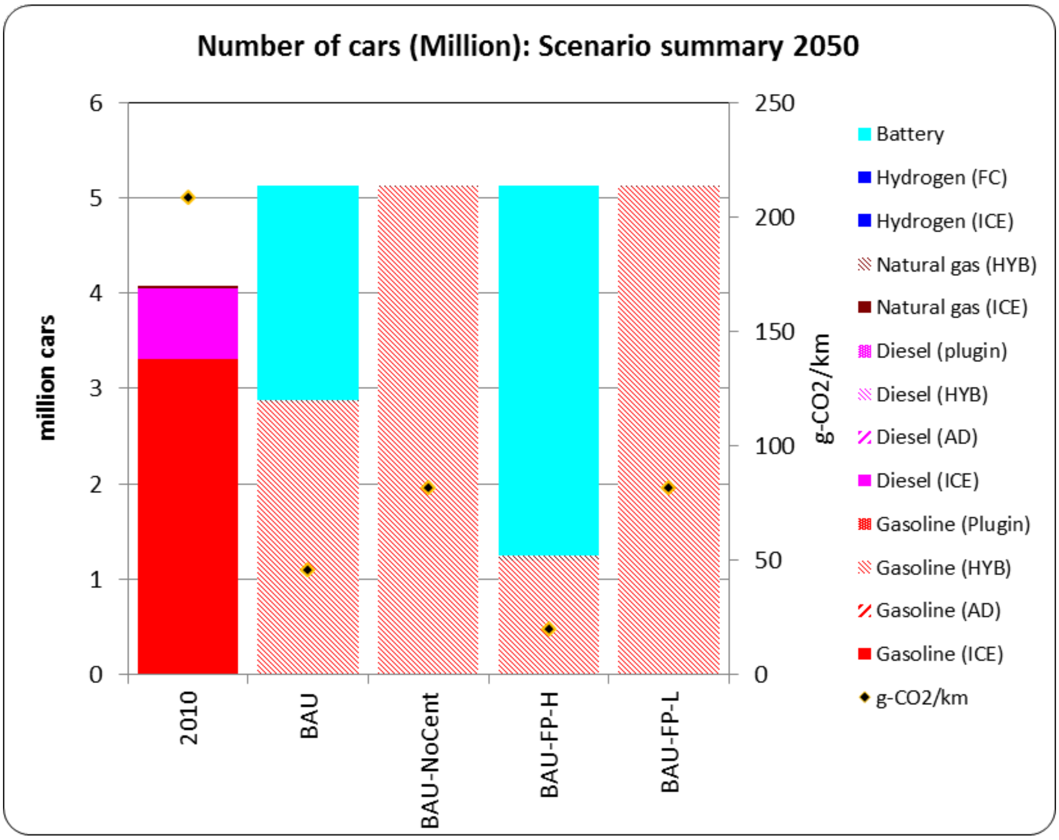


Figure 51: Car fleet in 2050 in *BAU* scenario variants

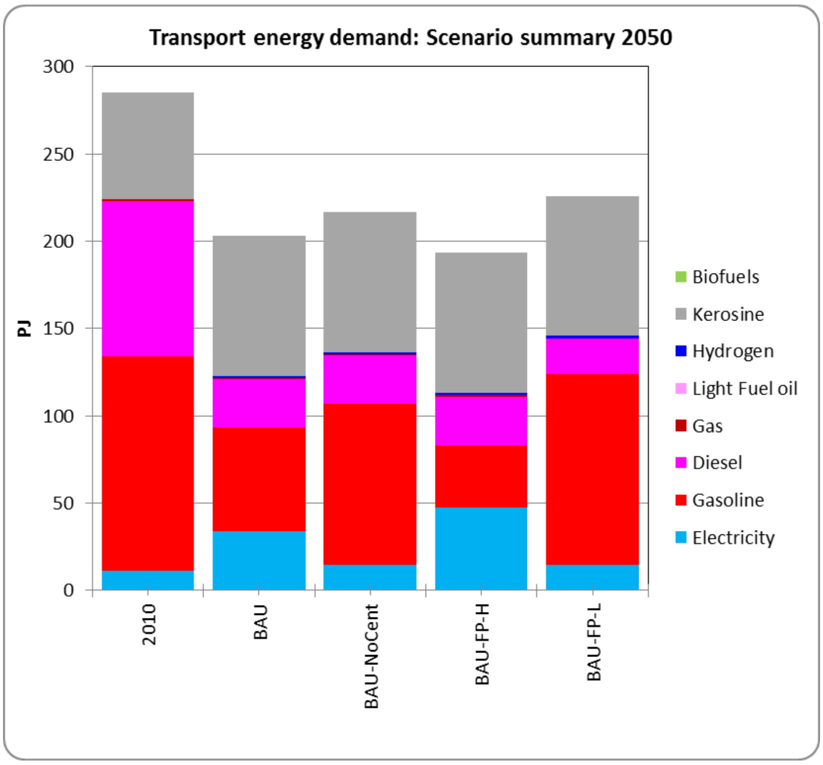


Figure 52: Transport sector fuel consumption in 2050 in *BAU* scenario variants

9.7. *BAU* scenario summary

For the given set of scenario assumption, the quantification from STEM illustrates potential transformations of the energy system from today to 2050. The transport and residential sectors undergo considerable changes in terms of fuel use and technology choice. Moreover, the whole-energy-system approach of STEM portrays strong interactions between the choice of technologies and fuels at the end-use sectors and supply side. For example, electrification of heating or car fleets is highly dependent on sources of electricity supply. Large-scale gas-based centralised electricity generation supports decarbonisation of some of the end-use sectors. On the other hand, restrictions on the deployment of central gas power plants push the use of natural gas to end-use sectors, and require a larger contribution of CHPs producing heat efficiently.

International energy prices are also a key uncertainty affecting the future configuration of the energy system. Low energy prices do not induce as much energy efficiency in the residential and transport sectors, nor require a major shift from conventional technologies. However, such a scenario raises additional challenges to meet any climate change mitigation policy goals (and would increase dependence on imported fuels), and thus likely requires additional policy intervention to support new technologies (e.g. heat pumps, insulation, electric vehicles, etc.). On the other hand, high energy prices induce more substantial technology shifts and improve overall energy efficiency (and indirectly support climate change mitigation). However, high energy prices naturally imply higher energy system costs, which raise economic and social challenges. In either case, policy intervention to lower barriers to the uptake of suitable technologies and support the conditions for investing in energy infrastructure is important.

9.7.1. Electricity demands

Future electricity demand trajectories are highly dependent on the level of electrification in end-use sectors, the sources (and costs) of electricity supply and climate policy goals. Figure 53 summarises the electricity demands from the *BAU* scenario, the supply and energy price variants. Without centralised gas power plants (*BAU-NoCent*), electricity demand declines in the short term (due to the phase-out of nuclear and initially high cost of renewable source of electricity supply) and then increases moderately over the medium to long term. This is explained by the limited availability of cheap sources of electricity supply, which limits the attractiveness of electrifying end-use sectors (heating demands, in particular). Electrification of end-use sectors also depends on the cost on non-electric alternatives. With a high fuel price (*BAU-FP-H*), some end-use sectors improve their energy efficiency by electrification (e.g. heat pumps, electric mobility). Thus, in the *BAU-FP-H* case, electricity demand increases by 40% by 2050 (vs. 20% in *BAU*) mainly due to a shift to electric mobility (§ 9.1.4). With low energy price assumptions (*BAU-FP-L*), the heating sector relies more on natural gas, reducing demand for electricity.

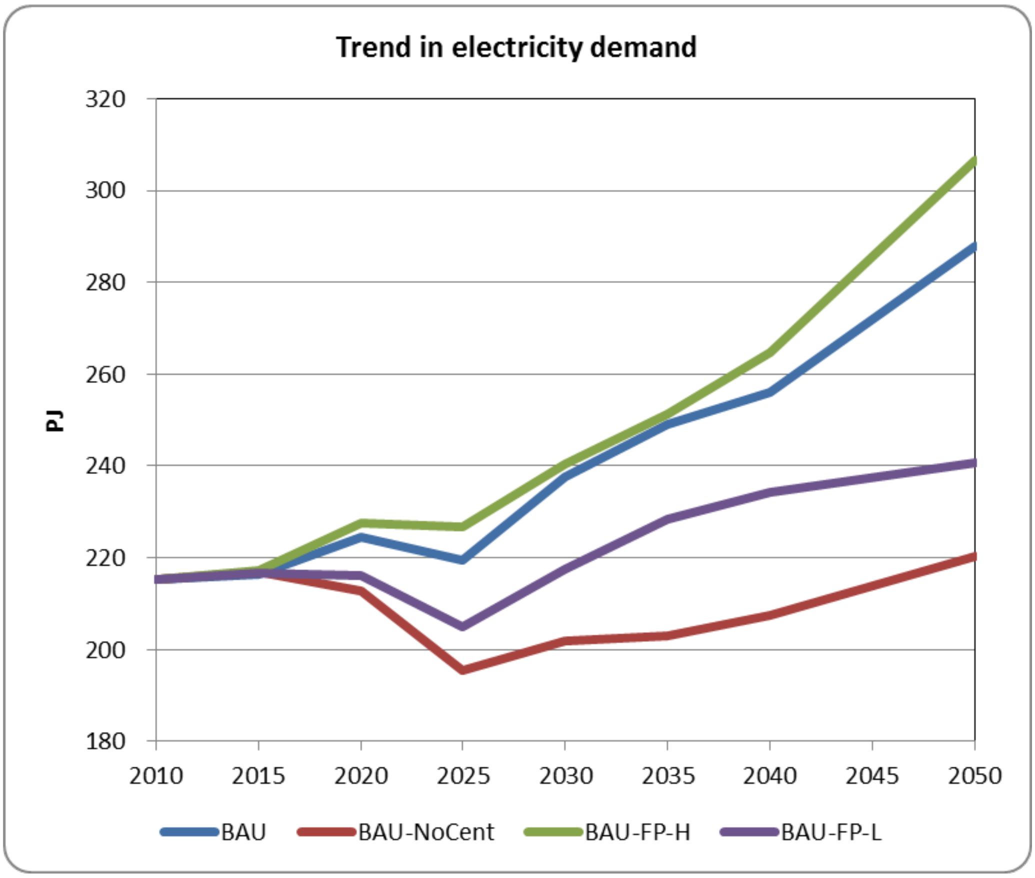


Figure 53: Electricity demand in *BAU* scenario variants

10. **Low carbon scenario**

In the low carbon (*LC60*) scenario, the energy system is constrained to realise a reduction in total[23] CO_2 emissions of approximately 60% in 2050 compared to 2010 (see § 8.2.3). Current end-use carbon prices and the assumed EU-ETS prices are also applied (see Table 23). For comparison, in the *BAU* scenario domestic CO_2 emissions decline by about 38% by 2050 (see Figure 47). The following subsection focuses on the additional changes in the energy system required to meet the more stringent CO_2 emissions target.

10.1. **Final energy demand**

In the *LC60* scenario, final energy demand declines by 38% between 2010 and 2050—an annual reduction of 1.2% (vs. 0.9% in *BAU*). Transport and heating fuel demand is reduced significantly, with the largest sectoral contribution from the residential sector (50%) followed by transport (32%) and services (18%). Uptake of conservation measures is almost 50% higher compared to the *BAU* scenario. Direct use of solar energy for thermal applications is also cost effective by 2050, and accounts for around 3.3% of final energy. In transport, gasoline and diesel demand declines significantly due to efficiency and a switch to efficient hydrogen-based technologies. Despite the higher electrification in end-use sectors, electricity demands increase to 287 PJ (79 TWh) by 2050—a level similar to the *BAU* scenario.

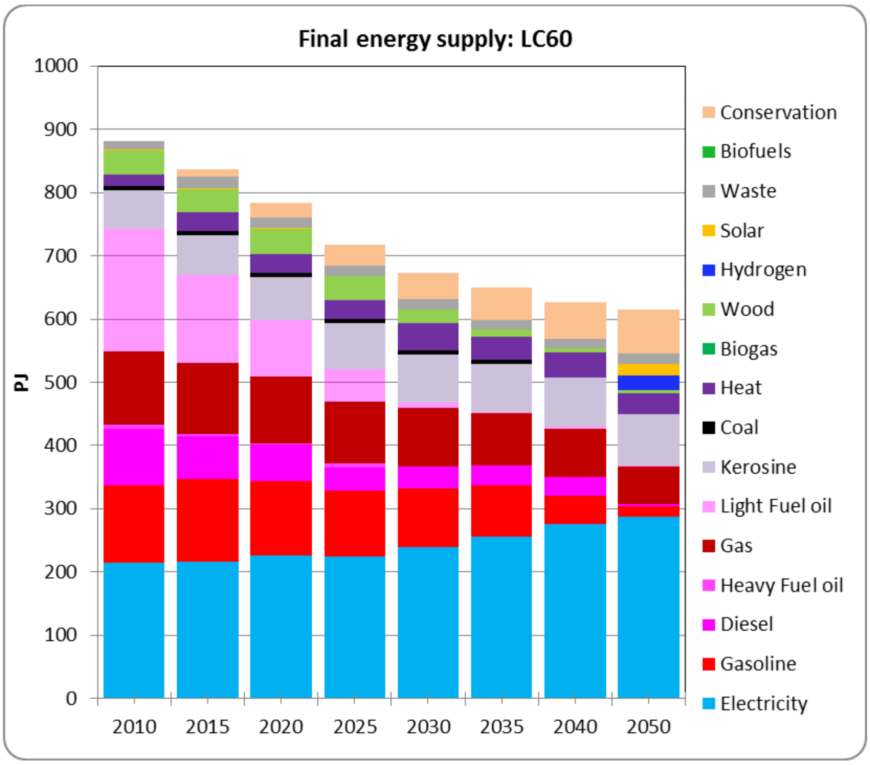


Figure 54: Final energy demand by fuel in the *LC60* scenario

[23] Including international aviation.

10.1.1. Residential sector

In the residential sector, existing oil- and gas-based heating systems are fully phased out by 2035 and 2050 respectively, whereas in the *BAU* scenario gas-based heating continues beyond 2050. As mentioned above, more building conservation measures are cost effective, contributing savings of around 70 PJ in 2050 compared to 47 PJ in the *BAU* scenario. Uptake of some of the more costly conservation measures is also important early in the projection period, even though the CO_2 target becomes stringent only later (Figure 55). This occurs because many conservation measures are assumed to be available only at the time of building renovation, and because of the long renovation cycle are deployed to ensure the long-term the carbon reduction target can be achieved. For residential heating, heat pumps become the dominant technology by 2050. Solar thermal systems also supply about one third of the heating (space and hot water) demand in 2050 and account for 18% of residential energy.

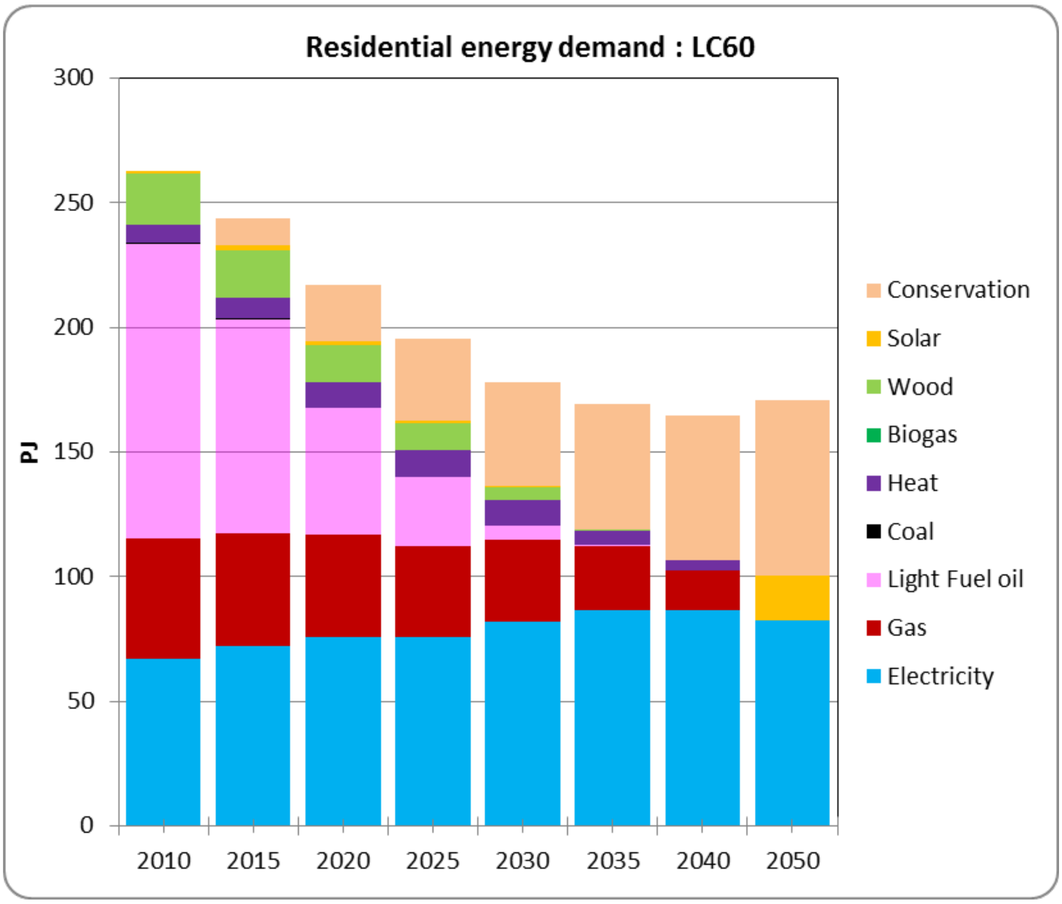


Figure 55: Residential energy demand in the *LC60* scenario

Compared to the *BAU* scenario, 50% less energy is consumed for space heating in 2050 in the *LC60* scenario due to the deployment of high efficiency (COP) heat pumps and large reductions in demand from conservation measures. There is also some reduction in energy consumption for air conditioning (AC) due to the uptake of efficient AC systems. Electricity demand for lighting also declines by 80% (vs 53% in *BAU*) due to a higher penetration of LED technologies. Energy demand for other applications is the same as in the *BAU* scenario because no alternative appliance technologies are represented in the current model (although, as mentioned earlier assumptions on autonomous energy efficiency improvements are incorporated).

10.1.2. Services sector

Total energy demand in the services sector declines by 42% from 2010 to 2050, while electricity demand increases by one-third (Figure 56). For heating, heat pumps penetrate extensively, covering almost the entire market by 2050. From 2040 onwards, very high efficiency heat pumps are deployed (COP of 3.89 vs. 3.51 in the earlier periods), contributing to a reduction in electricity demand from 2040 to 2050.

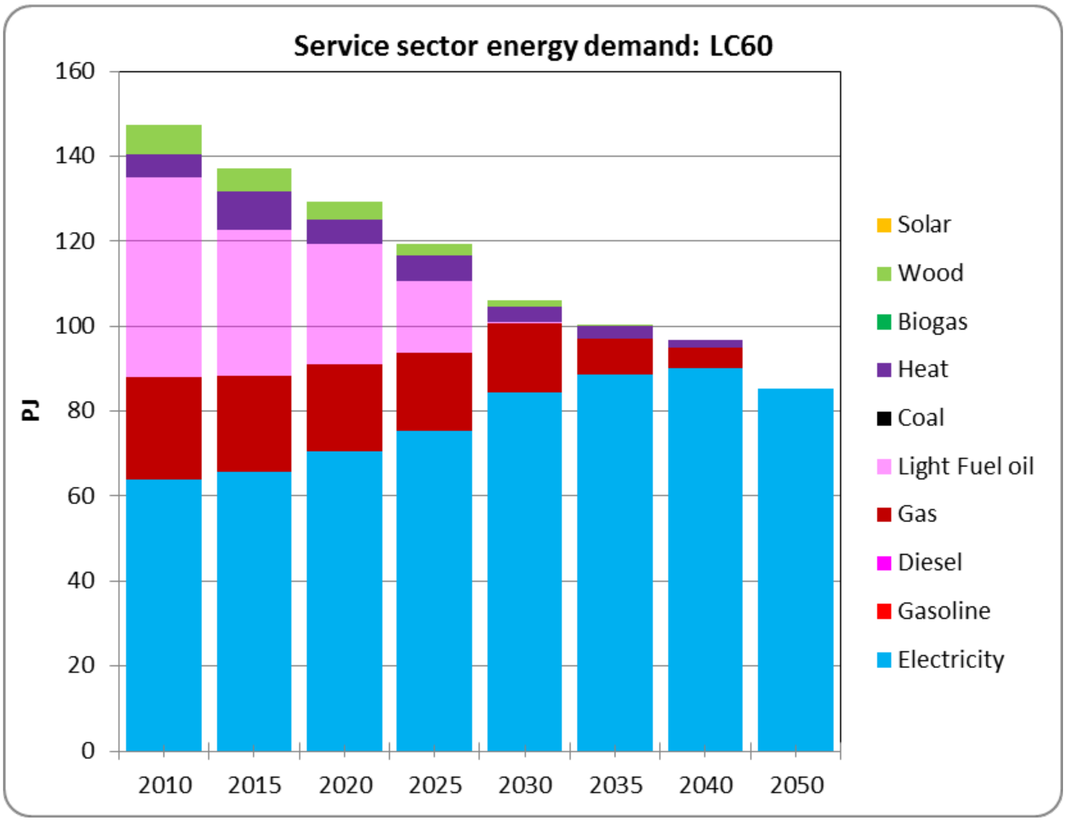


Figure 56: Energy demand in services sector in the *LC60* scenario

Similar to heat pumps, more efficient AC systems are deployed such that, despite the strong increase in demand for cooled floor area, electricity demand for AC increases only 15% (vs. 62% in the *BAU* scenario) by 2050. Electricity demand for lighting declines by 15% (vs. a 50% increase in the *BAU* scenario). For other ESDs, energy consumption remains the same as in the *BAU* scenario because alternative technology options are not represented in the current version of STEM for these (relatively smaller) demands.

10.1.3. Industrial sector

Figure 57 shows industrial energy demand in the *LC60* scenario. Compared to the *BAU* scenario (see Figure 33), there is relatively little change in total energy demand, although the fuel mix changes due to fuel switching within the industrial subsectors (Figure 58). For example, natural gas demand increases by 65% (compared to 30% in *BAU*) and the heat supplied from CHPs also increases (to 33 PJ vs. 25 PJ in *BAU*). Compared to the *BAU* scenario, direct utilization of wood (in the food and machinery subsectors) declines and is substituted by heat produced from CHPs (using natural gas and wood). This reallocation of biomass resources from direct utilization to CHP improves the overall resource efficiency. Coal in the cement and basic metal subsectors is replaced with natural gas (see Figure 59), whereas fuel demand in the chemical subsector is similar to the *BAU* scenario, although a small amount of heat is used in *LC60*.

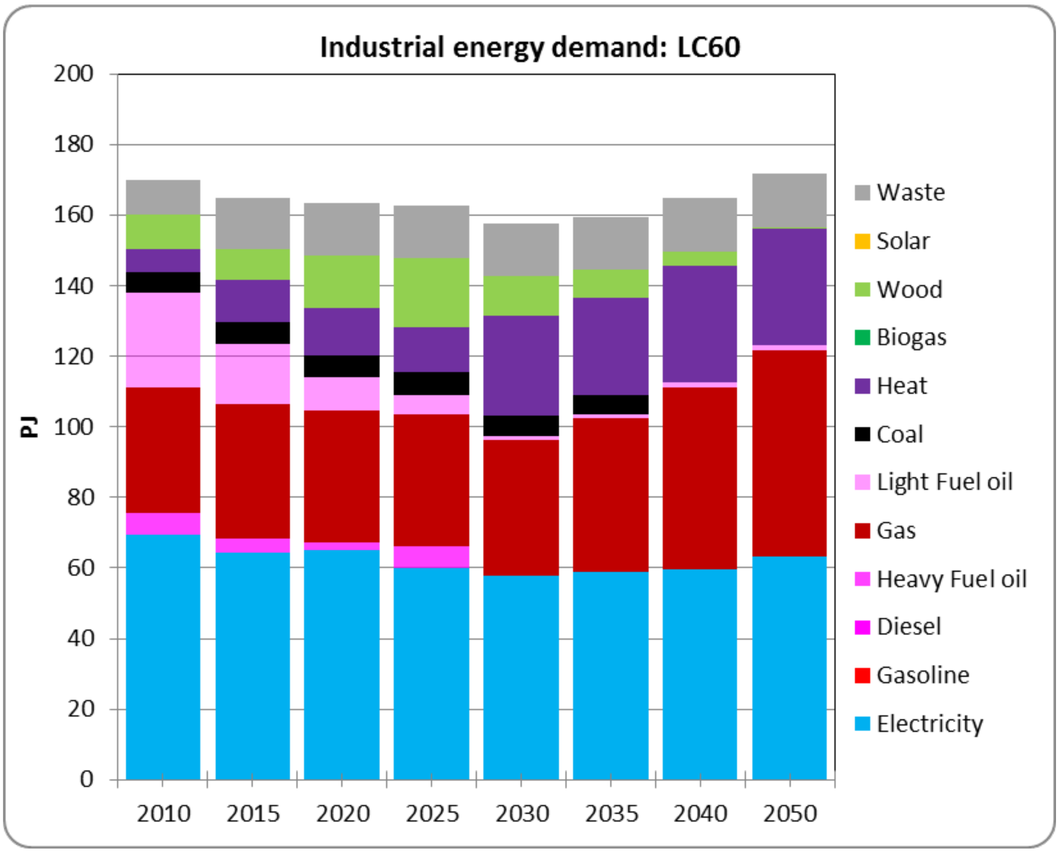


Figure 57: Industrial energy consumption in the *LC60* scenario

Though space heating demand is not significant in the industrial sector, heat pumps and district heating are deployed, resulting in a 50% reduction in space heating demand. Total electricity demand in the industrial sector declines by 10% (compared to 6% in the *BAU* scenario).

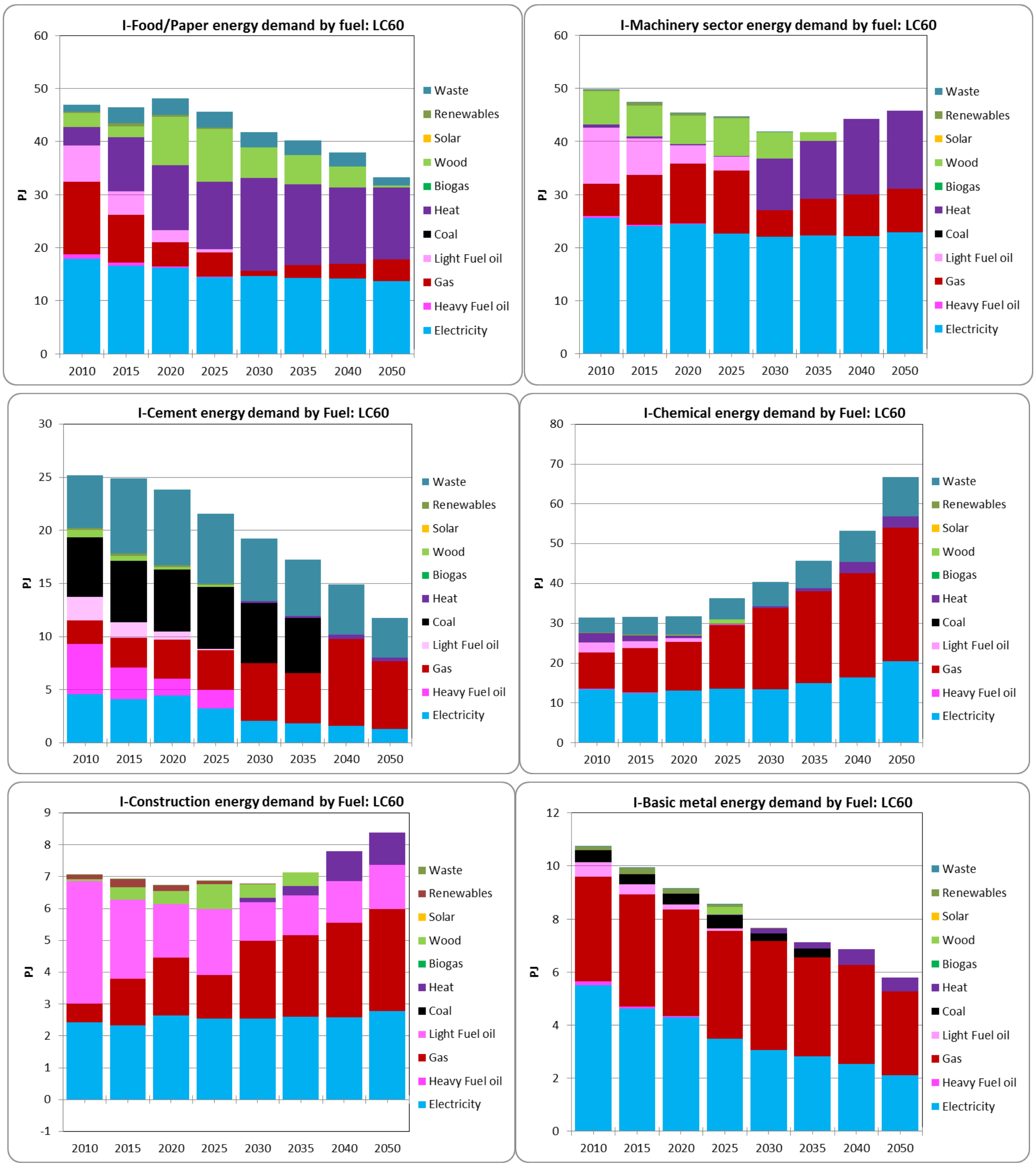


Figure 58: Industrial subsector energy demand in the *LC60* scenario

10.1.4. Transport sector

The transport sector's fuel demand (excluding international aviation) declines 55% by 2050 (Figure 59) vs. 44% in *BAU*. The sector is highly electrified, particularly the car, bus and LGV fleets, with electricity demand increasing to 56 PJ by 2050 (from 11 PJ in 2010). The HGV and LGV fleets also switch to hydrogen fuel by 2050 as the carbon constraint becomes very stringent. These developments lead to a concomitant decline in consumption of gasoline and diesel, contributing to a substantial reduction in CO_2 emissions (Figure 64).

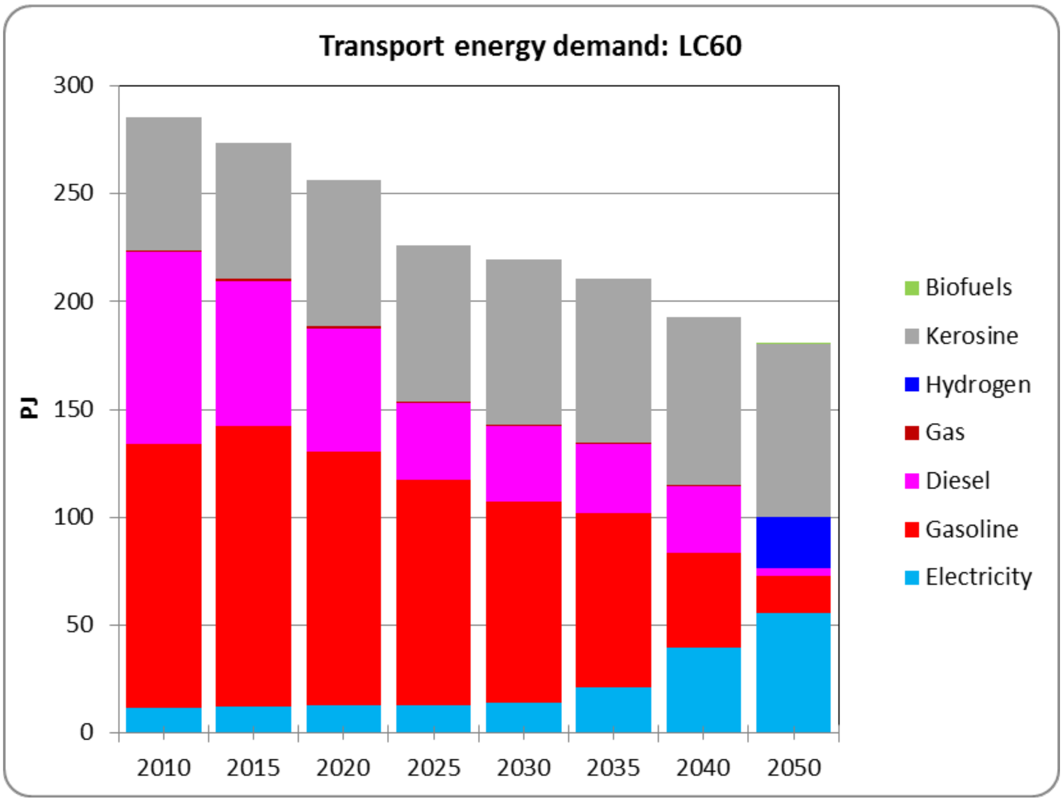


Figure 59: Transport fuel demands in the *LC60* scenario

In the short and medium term, the technology and fuel transition seen in *LC60* for the car fleet is similar to that in the *BAU* scenario (i.e., from ICEs to hybrid cars). In the long term, first plug-in hybrid electric vehicles (PHEVs) and then BEVs penetrate (see Figure 60). By 2050, all cars are either PHEV or BEV (see Figure 60). This deployment of PHEVs results in earlier decarbonisation of the car fleet, with average emissions in 2035 declining to 70 g-CO_2/km versus 84 g-CO_2/km in the *BAU* scenario. By 2050, the car fleet is fully decarbonized on a tank-to-wheel basis. The total energy demand of the car fleet declines at an average rate of 3% per year during 2010-2050.

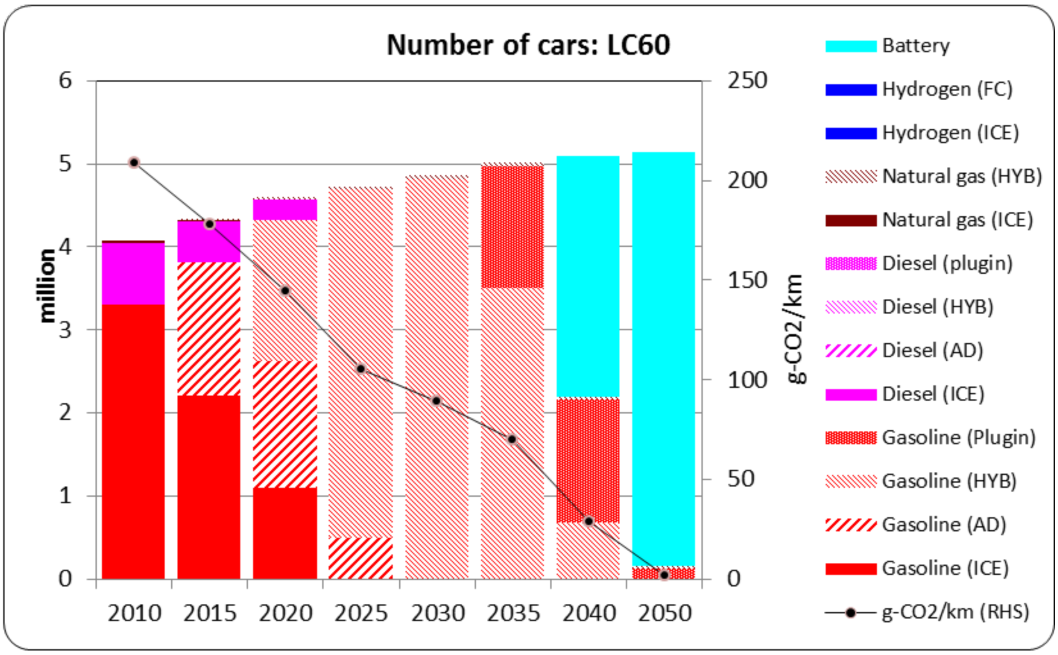


Figure 60: Car fleet in the *LC60* scenario

10.2. **Conversion sector**

10.2.1. Electricity supply

In the *LC60* scenario, electricity demand grows at 0.7% per annum and reaches to 287 PJ (79 TWh) by 2050 (Figure 54). Electricity supply is similar to the *BAU* scenario in the medium term, i.e. gas generation replaces the retired nuclear plants. As the carbon constraint becomes more stringent, renewable electricity generation becomes cost effective and contributes 12% of the total supply by 2030; and 22% by 2050 (vs. 12% in *BAU*). The remaining demand is supplied from gas-based generation since the domestic renewable potentials are fully exploited. The model chooses base-load-type GTCC plants, which are more efficient than the flexible/dispatchable plants (see Appendix-VI in [28]). The load variations are balanced by electricity storage in BEVs and by adapting to operation patterns of dam hydro plants (Figure 62). However, some of the pumped hydro storage is not used, even though the capacity is available, to reduce conversion losses. The contribution from CHPs increases in the short to medium term.

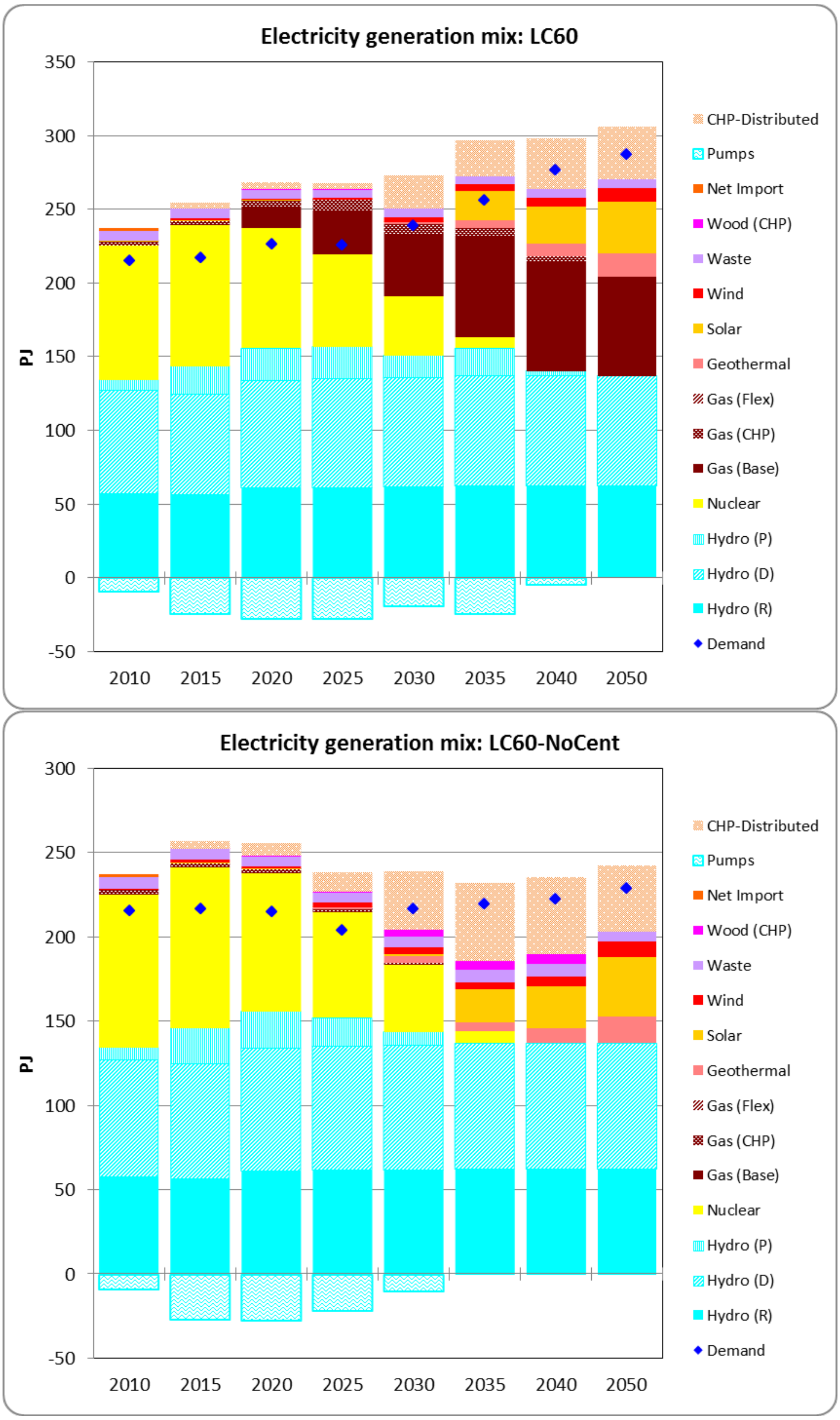


Figure 61: Electricity supply in the *LC60* and *LC60-NoCent* scenarios

Despite the carbon cap in the *LC60* scenario, centralised gas power plants are deployed to facilitate decarbonisation of end-use sectors (e.g. buildings and transport) (see Figure 64). Restricting centralised gas power plants (in the *LC60-NoCent* scenario) leads to reduction in total electricity demand due to an absence of alternative supplies, i.e. renewable potentials are assumed to be finite and net imports of electricity are assumed to be unavailable. Therefore, the electricity generation mix is similar to the *BAU-NoCent* scenario with an increased contribution from decentralised CHPs using natural gas and woody biomass.

10.3. **Electricity generation schedule**

Figure 62 shows the generation schedule in the *LC60* scenario. On summer weekdays, electricity supply exceeds the demand and the excess is exported. Dam hydro plants are mainly used for export during evenings and nights, while during 2:00–5:00 BEVs are charged with imported electricity.[24] Compared to *BAU* scenario, (peak) demand in the *LC60* scenario is low due to a lower load from air conditioning (because of the deployment of more efficient AC systems). The daytime peak is also curtained by the deployment of solar thermal systems for supplying hot water demand. However, a high peak demand still occurs in the evening due to loads from AC and hot-water demand.

On winter weekdays, demand peaks in the morning and evening due to the large deployment of electric heat pumps for space heating. Solar thermal systems supply a small quantity of heat during the day helping to reduce electricity demands during 8:00–15:00. Thus, the *LC60* scenario exhibits more predominant morning and evening demand peaks compared to the *BAU* scenario. CHPs significantly contribute to the winter demand as both electricity and heat demands are high. Again, a large share of the output from dam hydro is used for the export market. Unlike in summer, BEVs are also charged during the day time, which may be related to the availability of excess electricity from CHPs.

[24] On summer weekends, the BEVs are charged from solar PV outputs during the daytime and with imported electricity during evening and night. Again this charging pattern is driven by assumptions on electricity import prices.

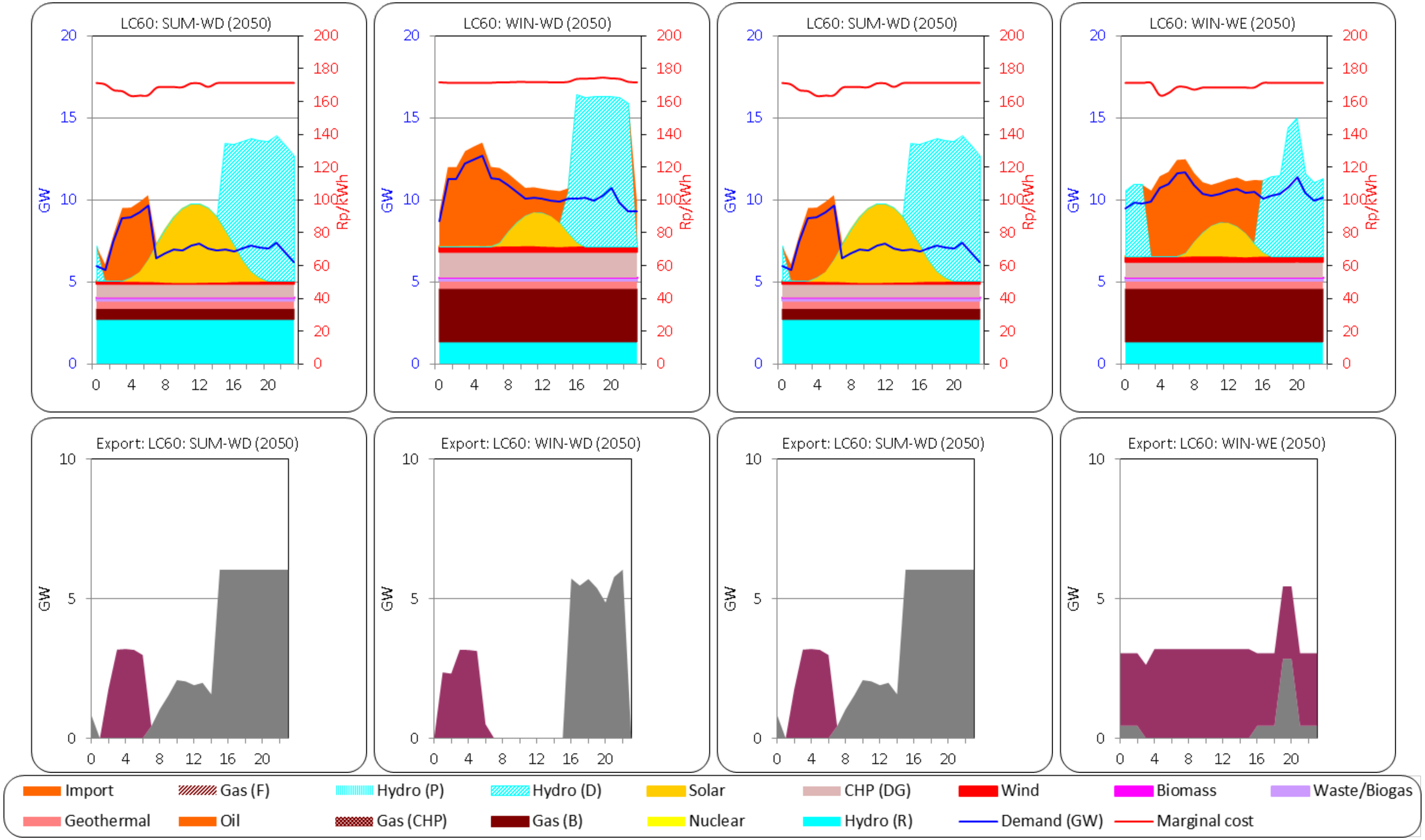


Figure 62: Electricity supply in winter and summer seasons in the *LC60* scenario

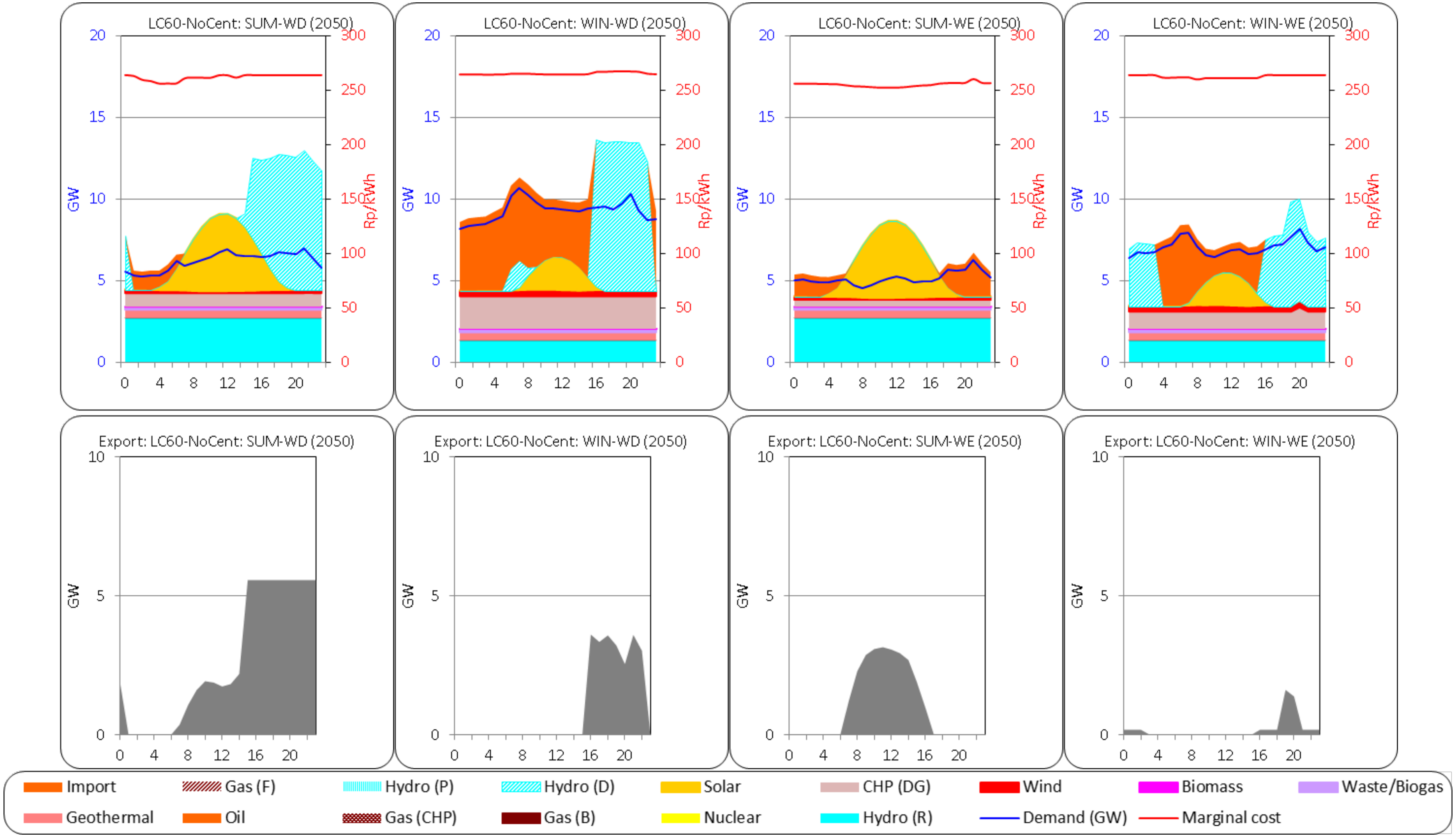


Figure 63: Electricity supply in winter and summer seasons in the *LC60-NoCent* scenario

The generation schedule of the *LC60-NoCent* scenario is similar to the *LC60* scenario. Since heating is not fully electrified in the *LC60-NoCent* scenario, electricity demand in winter is slightly lower than in *LC60*. At the same time, a higher share of solar thermal in heating reduces the peak electricity demand (see § 10.6 for detail). In both summer and winter, night-time imports are insignificant due to the absence of BEVs (Figure 66).

10.4. **Carbon dioxide emissions**

Figure 64 shows the CO_2 emission pathways in the *LC60* scenario. Both the residential and services sectors are fully decarbonised by 2050, partly because of electrification which shifts some of the emissions to the electricity sector (which, by 2050 accounts for half of the total emissions). The right hand panel of Figure 64 shows the sectoral emissions after allocating emissions from the conversion sector according to the end-use consumption of secondary energy carriers. This shows that, of the total emission reduction of 26 Mt-CO_2 between 2010 and 2050, transport (excluding international aviation) contributes 11.5 Mt-CO_2, with the residential (10 Mt-CO_2) and services (3 Mt-CO_2)[25] sectors contributing most of the rest.

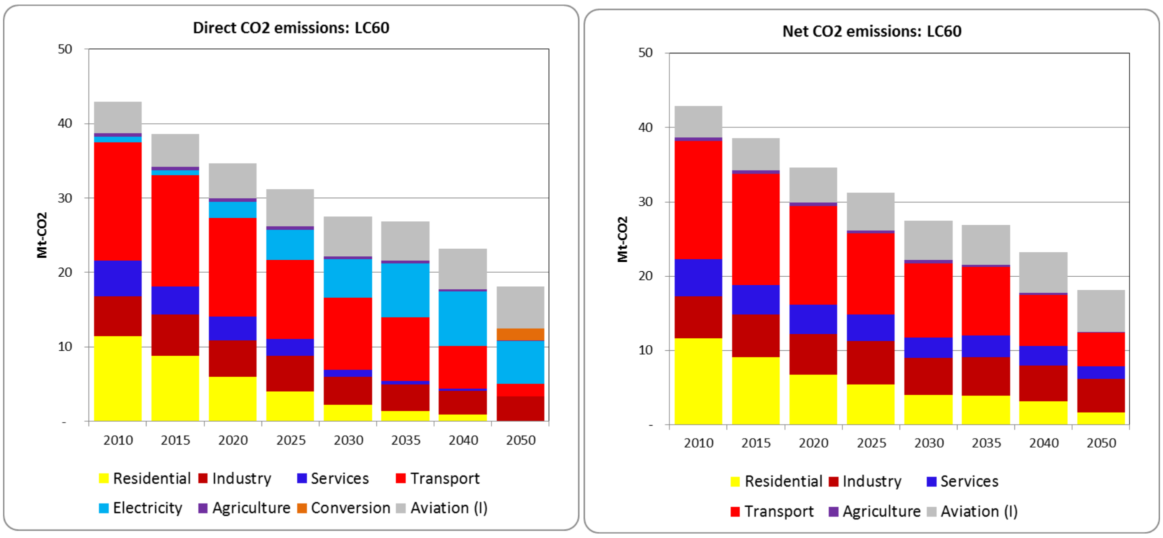


Figure 64: Sectorial CO_2 emissions in the *LC60* scenario

10.5. **Primary energy supply**

Figure 65 shows the primary energy supply in the *LC60* scenario. The primary energy supply of fossil fuels declines at an annual rate of about two percent. However, the supply of natural gas increases by 40% between 2010 and 2050, whereas oil declines by around 80%. Wood and solar increase significantly.

[25] Even though the heating systems in the services sector are electrified, higher electricity demands offset some of the reductions from fuel switching.

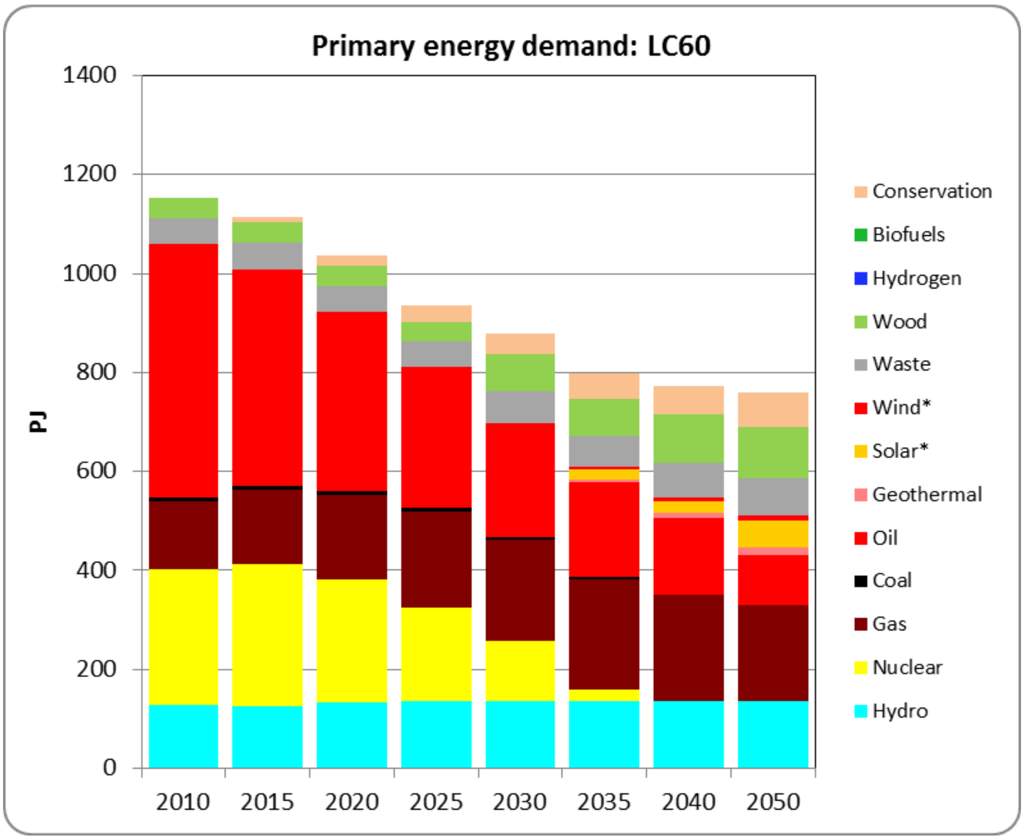


Figure 65: Primary energy supply in the *LC60* scenario

10.6. Sensitivity analysis of the *LC60* scenario

In the *LC60* scenario, alternative assumptions on international energy prices have almost no impact in terms of technology choice or fuel mix (see Annex-Fig. **5**), since the carbon constraint effectively determines the cost of using fossil fuels such as oil and gas. However, in the sensitivity analysis in which the availability of centralised gas-based generation is restricted (the *LC60-NoCent* scenario), system wide changes are seen. In the residential and services sectors, the rate of penetration of heat pumps is delayed since electricity is relatively scarce in winter. Thus, the use of conventional oil- and gas-based heating systems is prolonged (until 2040) before the switch to heat pumps. At the same time, district heating (from distributed CHPs) supplies 6% of the total heating demand in 2050. There is also a marginal increase in the (already-high) uptake of building conservation right from early in the time horizon (reaching 72 PJ in 2050 vs. 70 PJ in the *LC60* scenario). The contribution from solar thermal systems increases to 30% of residential heating in 2050. Accordingly, despite the lower availability of electricity, space heating is still decarbonized across all end-use sectors by 2050.

In absences of cheap centralized electricity supply, the transport sector also undergoes considerable changes. Instead of gasoline hybrids and PHEVs in the *LC60* scenario, the car fleet switches to natural gas hybrid vehicle (Figure 66). The average emissions decline to 60 g-CO_2/km in 2050 as against zero in the *LC60* scenario. The other transport modes extensively switch to hydrogen fuel, with the hydrogen produced from natural gas.[26] Total

[26] That is, when centralized electricity from natural gas is not available, centralized production of hydrogen from natural gas may be an attractive alternative for very ambitious mitigation targets.

electricity demand in this scenario increases to 229 PJ (63 TWh)—an increase of 6% from the 2010 level (Figure 70). It is worth noting that the *LC60-NoCent* scenario is an extreme scenario which requires the deployment of many exotic and expensive technology options (e.g., hydrogen in rail transport). However, it is worth reiterating that some of the end-use sectors do not represent all the technology options available for some of the less significant demands.

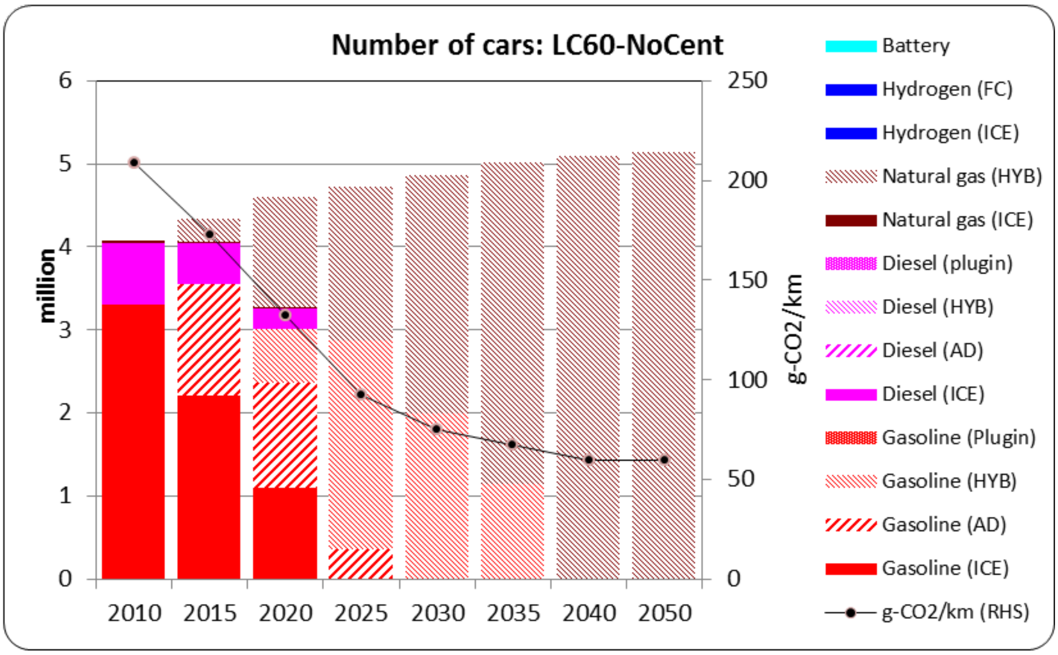


Figure 66: Car fleet in the *LC60-NoCent* scenario

10.7. ***LC60* scenario summary**

The *LC60* scenarios shed insights into options for realizing a reduction in emissions of about 26 Mt-CO_2 between 2010 and 2050. Most of the reductions in direct emissions are achieved in the transport (44%) and residential (38%) sectors—by a switch to BEVs in transport and deployment of heat pumps in buildings. The electrification of the car fleet and building heating leads to higher electricity demands. Despite the carbon target, electricity generation from GTCC is cost effective, along with new renewable sources (in addition to hydro). In 2050, gas-based generation contributes about 20% of the total electricity supply and about 5 Mt-CO_2 (or about half of the total emissions). Some of the other transport modes (buses and LGVs) switch from convention fuels to hydrogen, which is produced from natural gas (contributing about 1.6 Mt-CO_2). When the CO_2 emissions from electricity and hydrogen production are allocated to the end-use sectors, the residential and transport sectors contribute slightly less to the total reduction in emissions (but still 10 and 11.5 Mt-CO_2, respectively). In the services sector, a strong increase in electricity demand offsets some of the CO_2 emission reductions from a switch to heat pumps. The industrial sector contributes to about 4% of the total CO_2 emission reductions (~ 1 Mt-CO2), with coal fully replaced by gas and other fuels. Some of the industrial subsectors (e.g. food, paper) begin to deploy CHPs using natural gas and wood, which increase the fuel efficiency and contribute to CO_2 emission reductions.

The electrification of end-use sectors to reduce emissions contributes to a higher electricity demand, and creates challenges for supply. The demand in winter is supplied with centralised gas plants and CHPs. Both of these base-load plants are not scheduled in summer when the demand is low and output from hydro is high. The demand is balanced with imported electricity and dam hydro. However, the latter is significantly used for export, which enables import of cheap off-peak electricity (while fulfilling the self-sufficiency requirements stipulating an annual net balance in electricity trade). Cheap electricity imports assumed on weekends are used for charging BEVs (and the uptake of BEVs appears to be sensitive to these assumptions on the availability of cheap electricity imports on weekends). As a general remark, the assumed international electricity price, and our implicit assumption that there is an unlimited supply of electricity imports (or an unlimited market for exports) are highly uncertain and represent an area for further sensitivity analysis.

11. Security scenario

The energy security (*SEC*) scenario aims to explore the energy system implications of reduced dependence on imported fossil fuels (which is one element of energy security). In the *SEC* scenario, imports of fossil fuels are reduced by 55% between 2010 and 2050; an average of two percent per annum (Annex-Fig. **16**). Even though this reduction applies to fossil fuel supply, it indirectly implies a reduction in carbon emissions, although it does not distinguish between higher- and lower-carbon fossil fuels.

Total final energy consumption in the *SEC* scenario follows a pathway in between the *BAU* and *LC60* scenarios (Figure 67). However, final consumption of fossil fuels declines about 69% in this scenario compared to 84% in *LC*60 scenario or 65% in *BAU* scenario, and the energy system uses more diesel and gasoline fuels compared to the *LC*60 scenario (Figure 69). Zero-carbon fuels (e.g. heat, wood, hydrogen, etc.) increase by only 77% from 2010 compared to 130% in the *LC60* scenario. Electricity demand in 2050 is about 255 PJ—12% lower than the *LC60* and *BAU* scenarios.

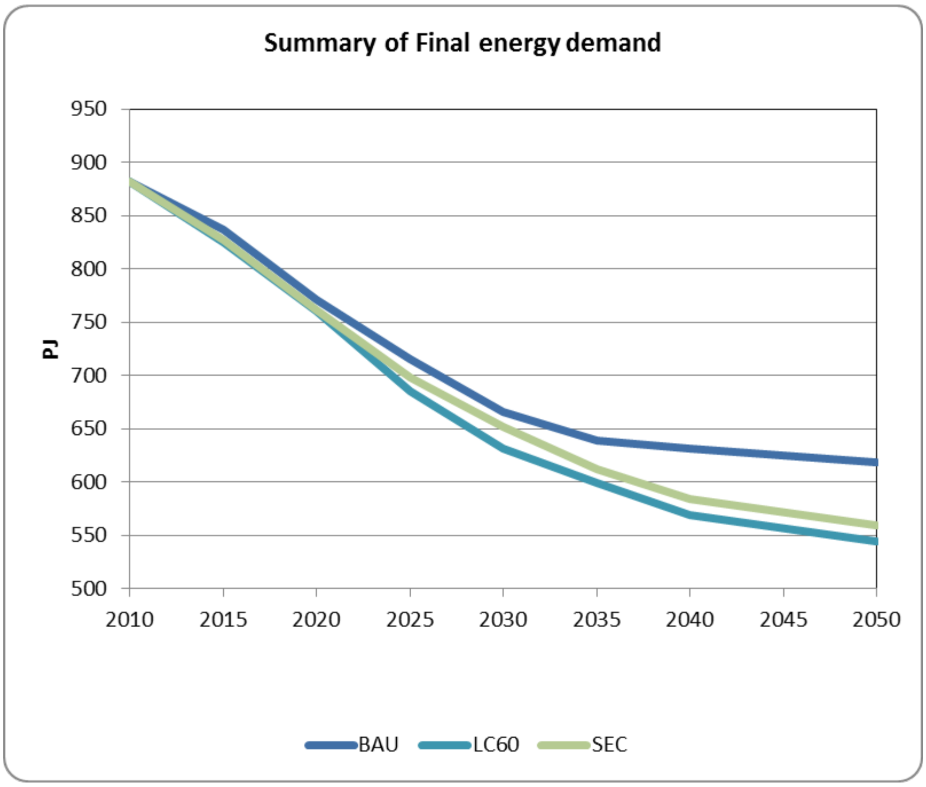


Figure 67: Final energy consumption in the core scenarios

Oil- and gas-based heating contribute for a longer period (to 2040) in the residential and services sectors, although by 2050 both sectors are fully decarbonised (Annex-Fig. **6**, Annex-Fig. **7**). In the residential sector, the demand reduction from conservation measures is only 66 PJ (vs. 70 PJ in *LC60* and 47 PJ in *BAU*). Solar thermal penetrates by 2050, but stays at much lower level, <1% of the final energy vs. 3.3% in *LC60*.

In the *SEC* scenario, the car fleet switches to plug-in hybrid electric vehicles (PHEVs) (see Figure 68) rather than BEVs seen in the *BAU* and *LC60* scenarios (Figure 71). Similarly, other transport modes continue to use diesel with efficient drivetrains (e.g. hybrid vehicles), whereas hydrogen is extensively used in the *LC60* scenario (see Annex-Fig. **9**).

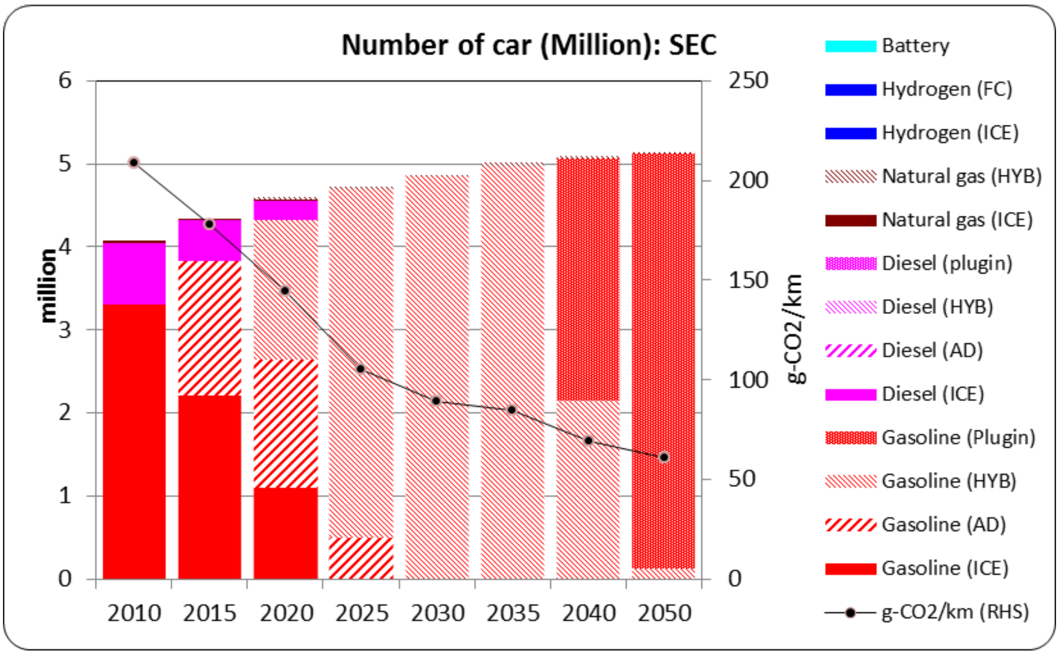


Figure 68: Car fleet in the *SEC* scenario

Electricity supplies in *SEC* are similar to the *LC60* scenario (Annex-Fig. **3**). Since electricity demand in this scenario is low (because of limited deployment of BEVs), electricity generation from GTCC plants is also lower. However, renewables are still exploited to their full potential in the *SEC* scenario (see Figure 73).

The total primary energy supply reflects the assumptions on reduced fossil imports, but exhibits a higher share of oil and lower share of natural gas compared to the *BAU* and *LC60* scenarios (Figure 75). This difference reflects the higher use of gasoline and diesel in transport, and lower electricity generation from gas.

Total CO_2 emissions are reduced by 54% between 2010 and 2050 in the *SEC* scenario, compared to 60% in *LC60* or 31% in *BAU*. In absolute term, emissions in *SEC* are about 1.5 Mt-CO_2 above those in *LC60* scenario in 2050, with most of the difference in the transport sector (Figure 74).

In the absence of centralised gas-based generation (*SEC-NoCent* scenario), electricity demand reaches only 233 PJ (vs. 255 PJ in the *SEC* scenario). Instead, gas is used in CHPs which enable the use of more heat in final energy (~10 PJ). At the same time, gas is also used for hydrogen production, similar to the *LC60-NoCent* scenario.

12. Scenario comparison and synthesis

Final energy consumption in 2050 from the core scenarios is compared in Figure 69. Across all scenarios, final energy demand in 2050 declines between 13% and 38%. In all scenarios, oil-based heating systems are phased out, except cases where energy prices are very low and no climate mitigation policy is in place (e.g. *BAU-FP-L* in Annex-Fig. 5). On the other hand, electricity demand increases in all scenarios in the range of 2–33% depending up on availability of centralised gas-based electricity generation (see Figure 70). There are clear linkages between the availability of centralised gas-based electricity generation and the choice to utilize natural gas in end-use sectors. For example, centralized gas plants support the deployment of heat pumps (and BEVs) in end-use sectors—that is, the cost effectiveness of end-use technologies (e.g. cars, heating system) depends on policy decisions in the electricity sector. Without centralised power plant, some of the end-use sectors are not electrified and therefore growth in electricity demand is moderated (see Figure 70); penetration of CHPs is also affected by the availability of centralized plants.

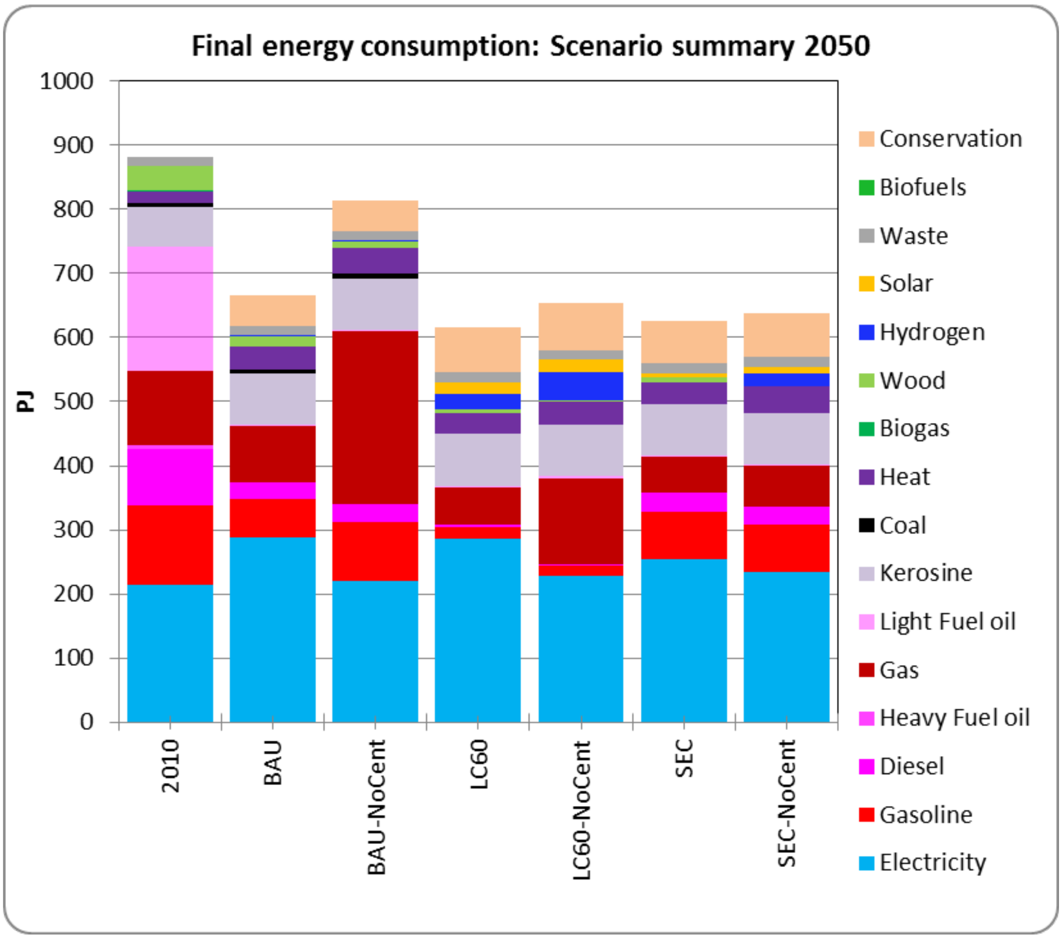


Figure 69: Comparison of final energy consumption in 2050

Across all scenarios, some building conservation measures are cost effective—a minimum of 47 PJ in *BAU*. To achieve a more stringent climate change mitigation target or ameliorate security concerns, additional conservation measures are attractive.

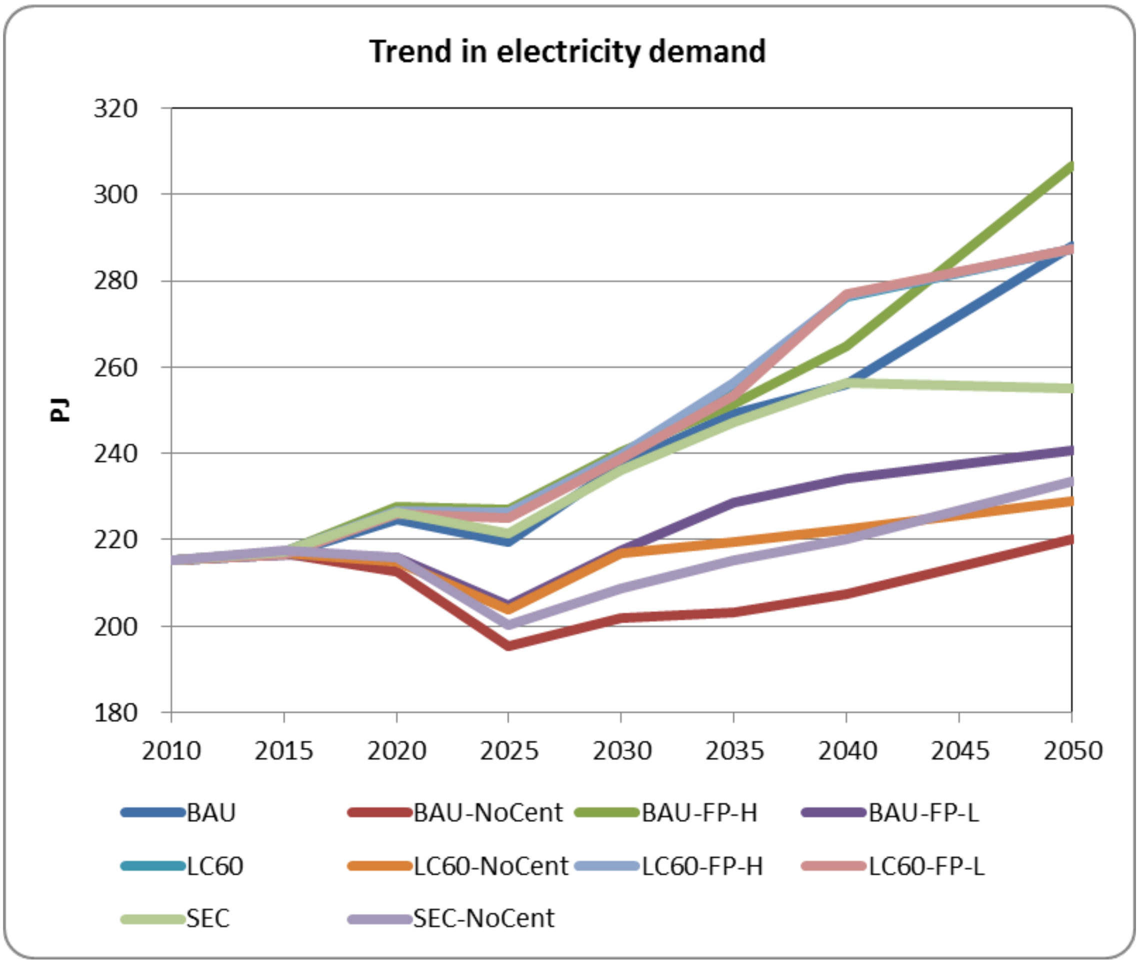


Figure 70: Electricity demand pathways across scenarios

Given that the car fleet accounts for a significant share of final energy use and CO_2 emissions, future vehicle technology and fuel choice plays a crucial role in the development of the energy system. Across all scenarios, efficiency improvements are seen through the deployment of gasoline hybrid vehicles. The long-term transition of the car fleet depends however on the availability of cheap source of electricity, i.e. gas based generation, which enables electrification (see Figure 71). On the other hand, stringent abatement targets without centralised gas-fired power plants render electric mobility less attractive, with natural gas hybrids becoming attractive. International oil prices are also a critical factor in technology and fuel choice in the car fleet (see Annex-Fig. **10**).

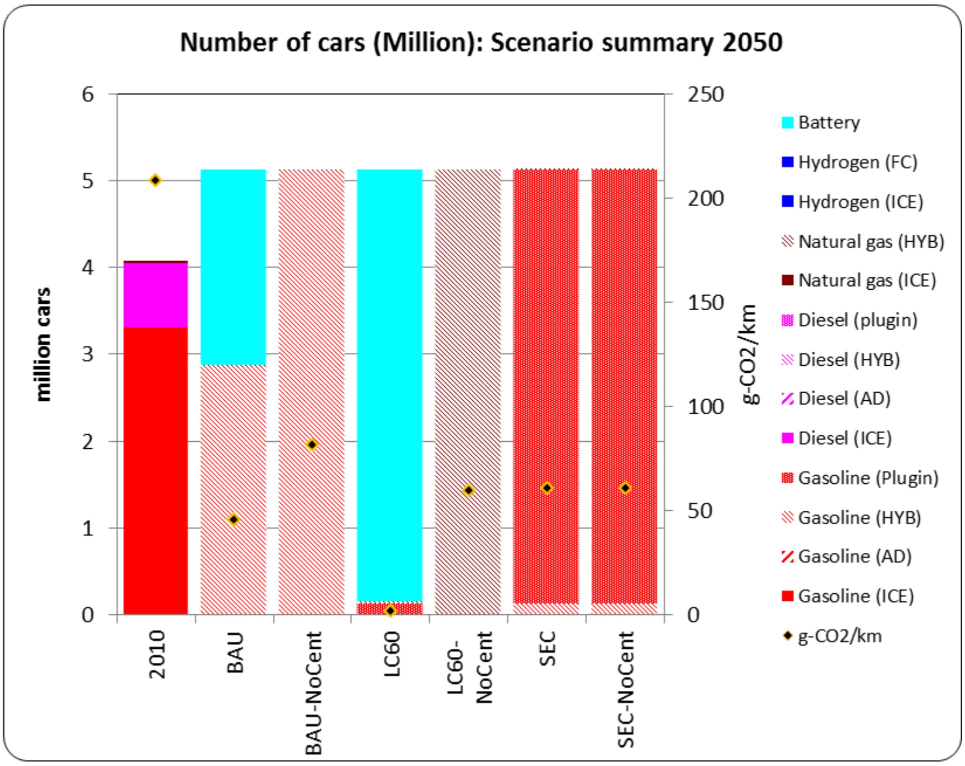


Figure 71: Comparison of car fleet in 2050

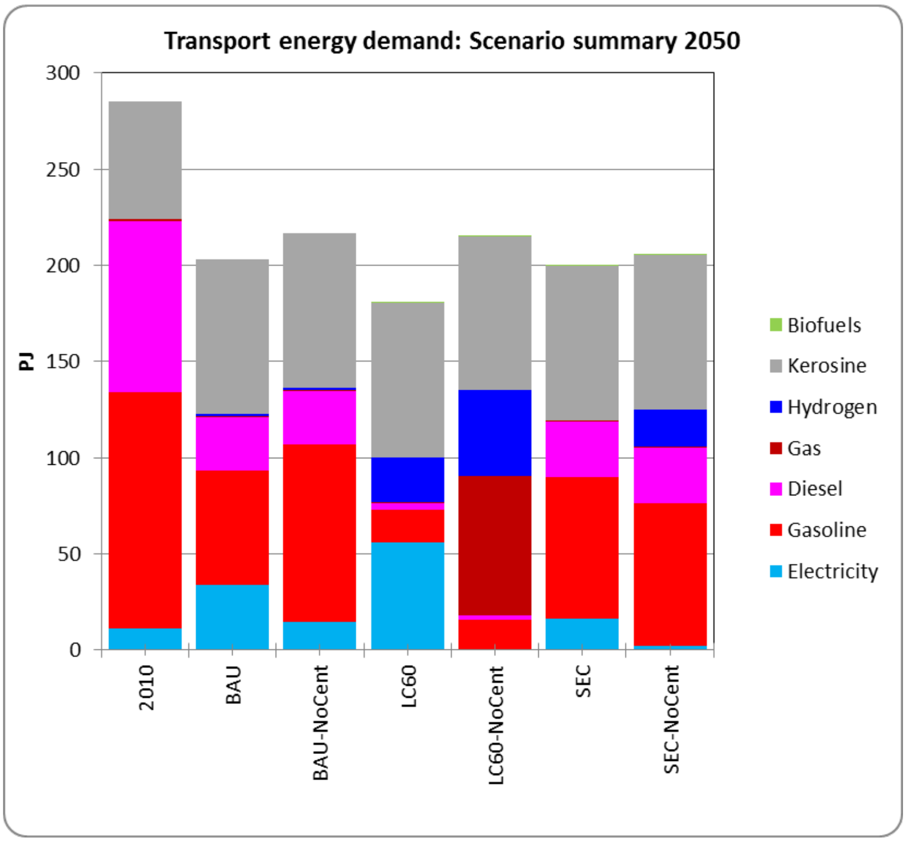


Figure 72: Comparison of transport fuel demand in 2050

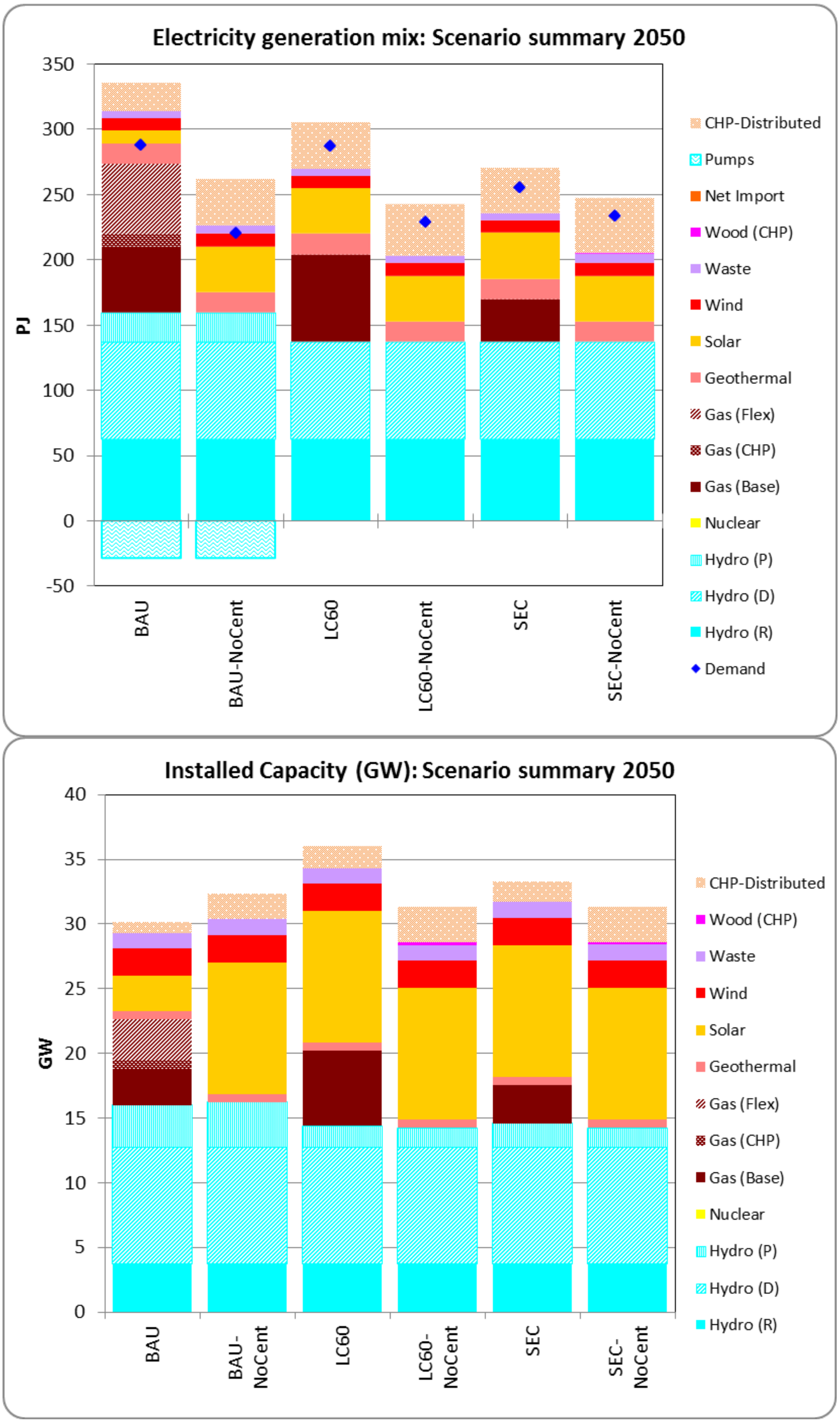
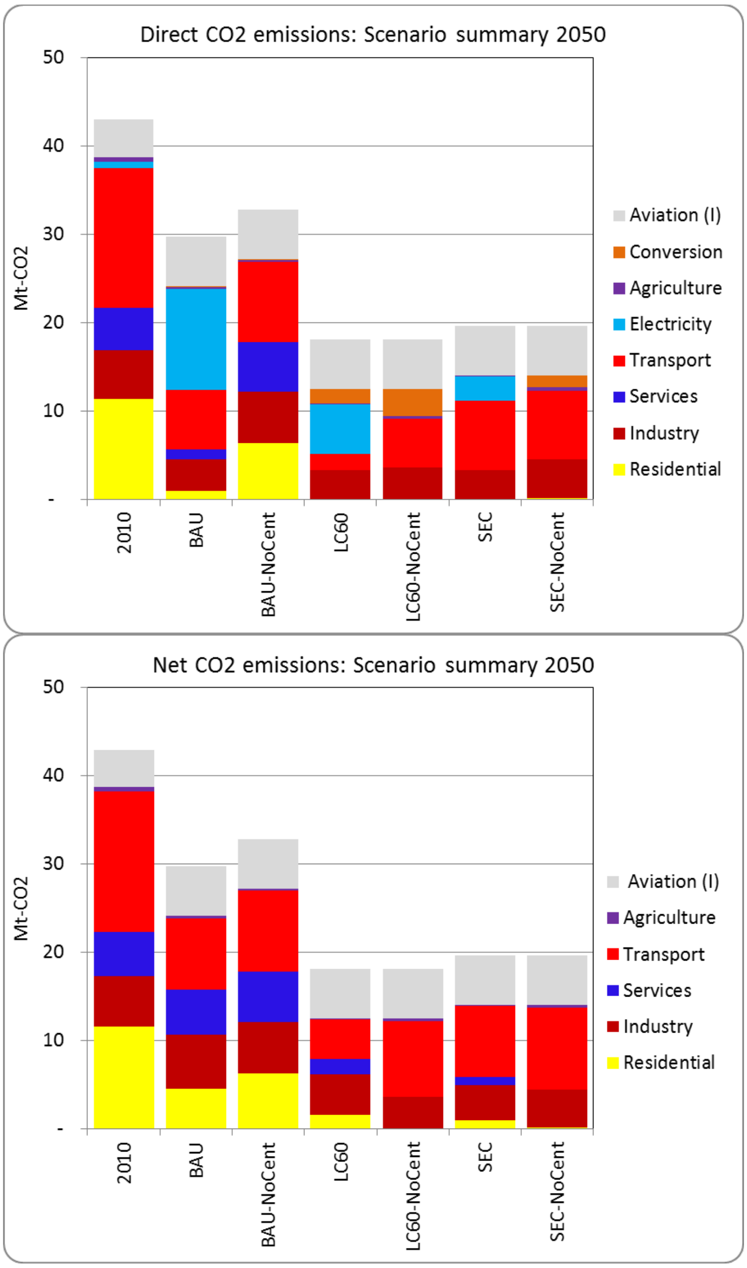


Figure 73: Comparison of electricity supply and installed capacity in 2050

In terms of CO_2 abatement, the phase out of oil-based heating in end-use sectors is seen in all scenarios (due to the higher price of oil relative to natural gas, among other factors) reducing end-use emissions. However, some of these reductions are offset by growing demands in ESDs, e.g. air conditioning. To meet a stringent climate target, further measures like accelerated electrification of transport or deployment of renewables are required. In all scenarios, expansion of gas-based power generation enables the decarbonisation of the end-use sectors.



Note: in both figures, emissions from decentralized electricity generation (i.e., CHPs) are included in the estimates for the end-use sectors

Figure 74: Comparison of direct and net CO_2 emissions in 2050

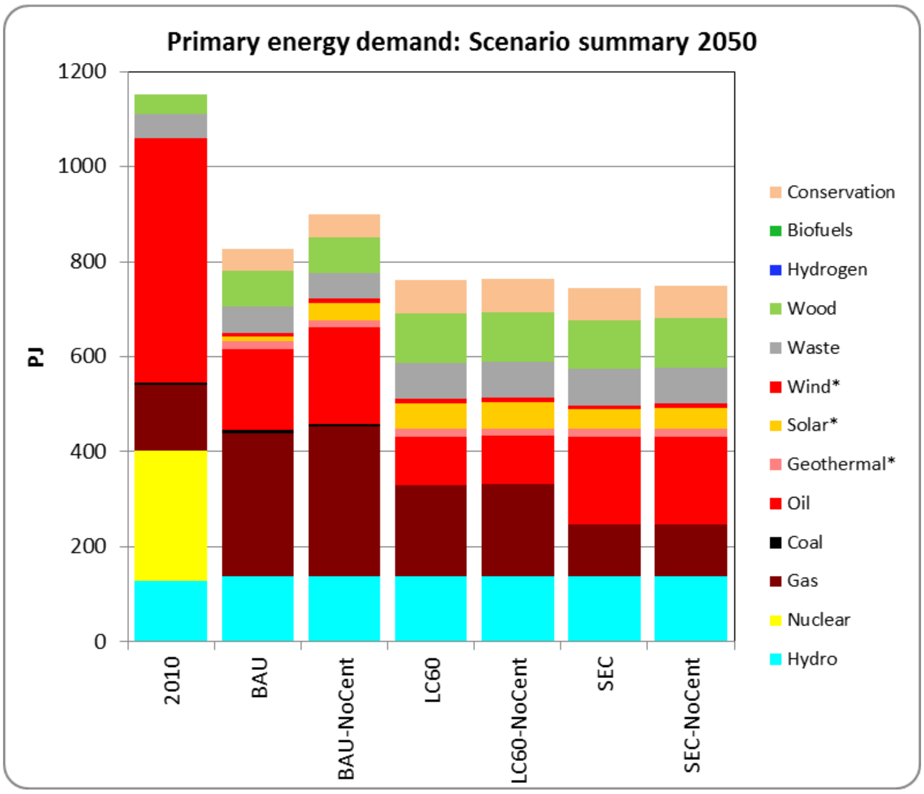
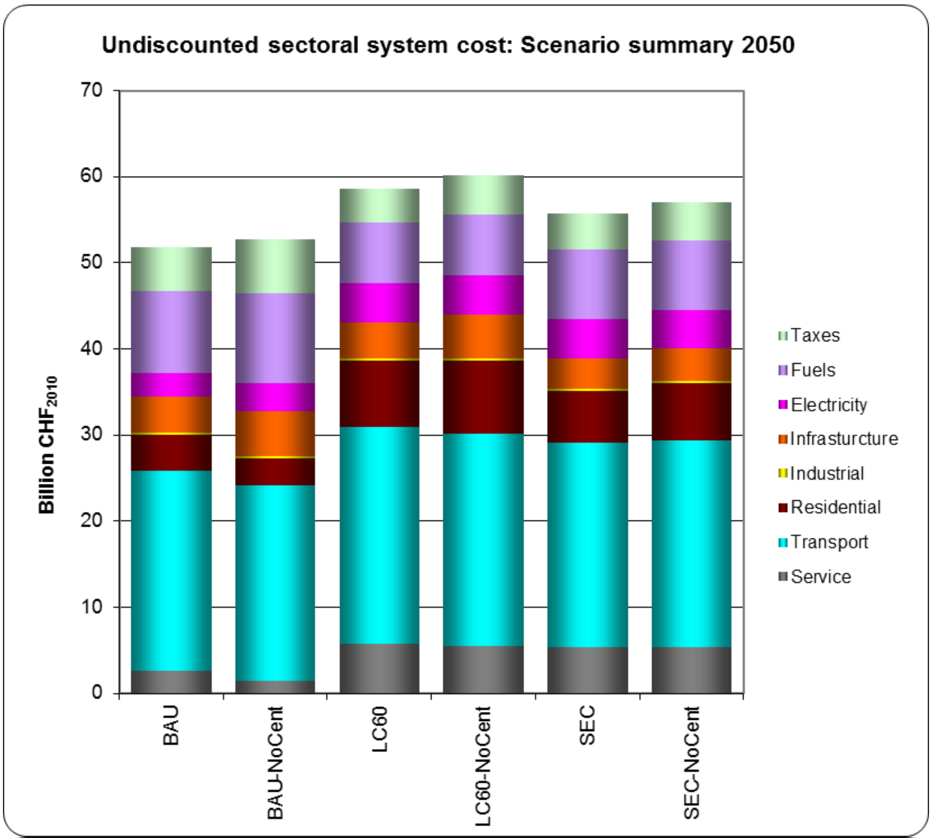


Figure 75: Comparison of primary energy supply in 2050

Figure 76 shows the annual undiscounted energy system costs for year 2050. Compared to the *BAU* scenario, additional annual (undiscounted) costs in the *LC60* scenario are about CHF 6.81 billion in 2050 (or 13% more than in the *BAU* scenario). Most of this additional cost occurs in end-use sectors, with around CHF 3 billion in both the residential and services sectors (excluding reductions in expenditure on fuels, which appear in 'Fuel' in Figure 76). This additional cost is related mainly to capital expenditure on conservation measures, heat pumps, efficient air conditioning and efficient lighting. The additional cost in the transport sector is about CHF 2 billion, which includes the cost of vehicles. Given the reduced consumption of conventional fuels in the *LC60* scenario, fuel costs and taxes[27] decline about CHF 2.4 and 1.3 billion respectively; and a large share this cost reduction occurs in the transport sector. Additional costs in the electricity sector are about CHF 2 billion because of deployment of capital-intensive renewables. Total capital expenditure in the *LC60* scenario alone increases about 8.7 billion compared to *BAU*. However, some of this additional expenditure is offset by reductions in fuel expenditure/taxes. As can be seen, the trade revenue from electricity also declines by about one billion CHF. The cumulative cost over the period 2010-2050 is about CHF 112 billion more than in the *BAU* scenario (or 4.7%) (see Figure 77).

[27] Although, presumably this revenue reduction will need to be made up elsewhere by governments via increases in other taxes, reduced expenditure on services or increased debt.



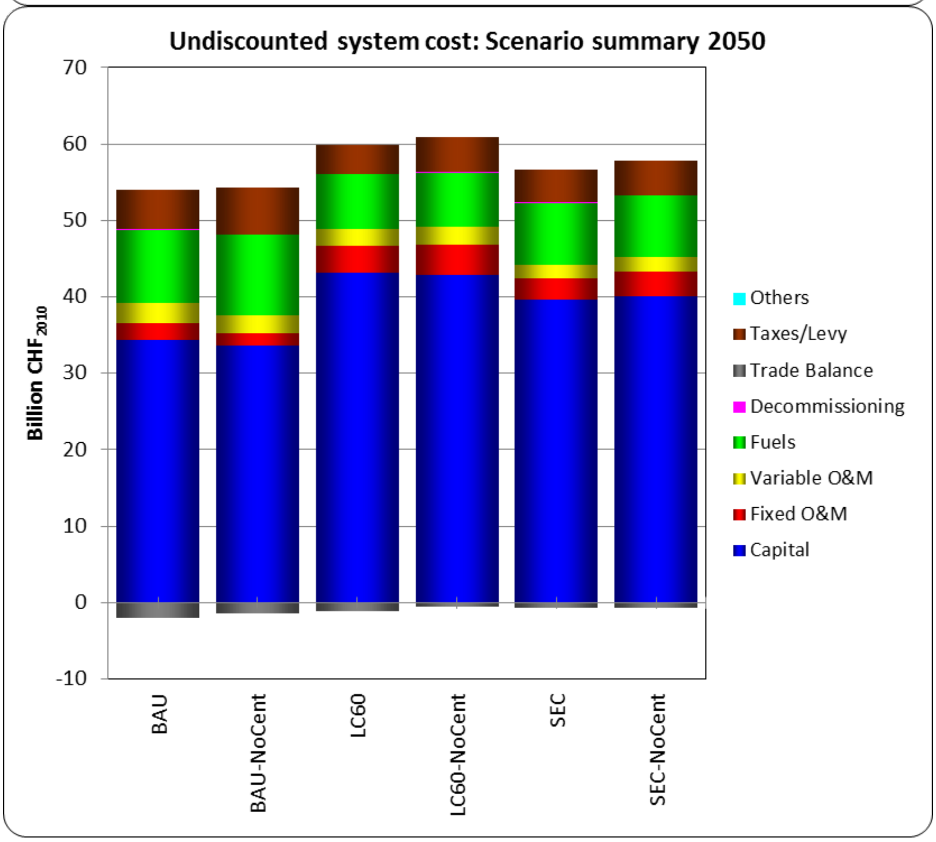


Figure 76: Comparison of annual undiscounted energy system cost in 2050

The additional annual cost in 2050 for the security scenario is about CHF 4 billion, mostly in the services sector where heat pumps are deployed. The cumulative cost of the *SEC* scenario is CHF 64 billion more than the *BAU* scenario, and about CHF 49 billion lower than the *LC60* scenario (see Figure 77).

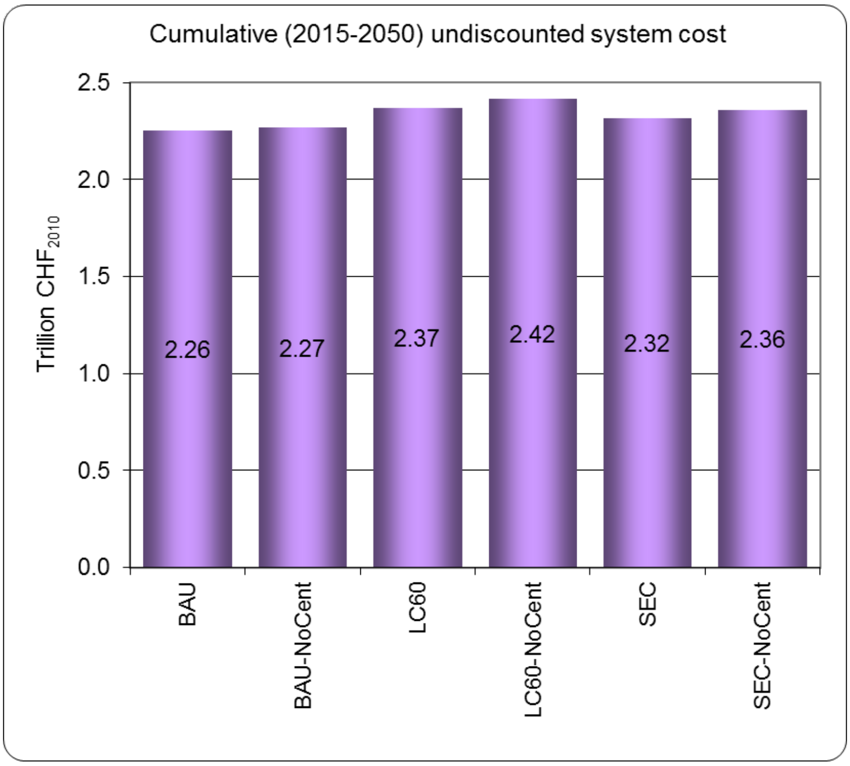


Figure 77: Comparison of cumulative (undiscounted) energy system cost (2015-2050)

12.1. **Selected indicators**

Table 24 provides a summary of selected per capita and economic indicators in 2050 for the core scenarios and supply variants. Average electricity use per household in 2050 varies between 4 and 5.9 MWh compared to 5.2 MWh in 2010. The *LC60* scenarios realise a 2700 W society in 2050, compared to 2900 W in the *BAU* scenario, and would cost about CHF 750–950 per person in 2050. The energy system cost increases to 7.3–7.5% of GDP in the *LC60* scenarios compared to 6.5% in the *BAU* scenario.

Table 24: Scenario indicators in 2050

Indicators	Units	2010	*BAU*	*BAU-NoCent*	*LC60*	*LC60-NoCent*	*SEC*	*SEC-NoCent*
Per capita electricity consumption	*MWh*	7.6	8.9	6.8	8.8	7.0	7.8	7.2
Per capita final energy consumption	*MWh*	32	21	26	20	21	20	21
Per capita CO_2 emission (excluding international aviation)	*t-CO_2*	4.91	2.67	3.01	1.38	1.38	1.55	1.55
Residential electricity use per household	*MWh*	5.3	5.7	3.9	5.2	5.1	5.6	5.2
Cumulative total CO_2 emissions* (2010–2050)	*M.t-CO_2*	43	1559	1649	1294	1300	1348	1380
Average CO_2 intensity of car fleet	*g-CO_2/km*	208	45	81	2	59	61	61
Per capita primary energy use	*Watt*	4634	2903	3158	2667	2682	2609	2632
Electricity intensity^	*MWh per M.CHF*	109	100	76	100	79	88	81
Final energy intensity^	*MWh per M.CHF*	456	239	294	225	239	229	235
Industrial sector energy intensity	*MWh per M.CHF*	371	265	276	266	270	267	271
Services sector energy intensity	*MWh per M.CHF*	110	62	92	43	42	44	43
CO_2 intensity*	*t-CO2 per M.CHF*	79	37	41	23	23	25	25
Total energy cost**	*% of GDP*	4.5%	6.5%	6.6%	7.3%	7.5%	7.0%	7.1%
Per capita undiscounted energy costs**	*CHF_{2010}*	3'108	5'732	5'826	6'485	6'650	6'167	6'298

* including international aviation

** The 2010 energy cost does not include investment costs of existing technology stock

^ Based on all end-use sectors, including residential.

13. **Discussion of key findings and policy implications**

13.1. **Summary of key findings**

Key results across the scenarios include:

- End-use sectors and demands
    - Several factors are driving the development of energy demands, including the electrification of end-use sectors and international energy prices, along with climate and energy security policy. Final energy demand declines 0.35–0.88% per annum during 2010–2050 under the set of business as usual (*BAU*) scenarios, and 1.1–1.2% per annum in the low carbon and security scenarios. The reduction in final energy is realised through a range of measures such as electrification of heating demands and transportation, and adoption of building conservation measures, among others.
    - Electricity demand in 2050 varies between 61 and 80 TWh compared to 60 TWh in 2010—an annual growth of 0.06–0.73% during 2010–2050.[28] Electricity use per household increases from around 5.25 MWh in 2010 to 5.7 MWh in *BAU*, but declines slightly to 5.2 MWh in the low carbon scenario (with centralized gas plants).
    - A 2900 W society is realised in the *BAU* scenario by 2050, whereas the *LC60* scenario achieves 2700. [22]

- Electricity and conversion sectors
    - Under the assumptions applied in this analysis, new investment in combined cycle gas generation is a cost-effective way to supply future electricity demand, without net imports. Combined cycle gas generation produces up to 15–25 TWh by 2035 and 9–30 TWh in 2050, depending on the electricity demand pathway. However, new investment in GTCC leads to increased dependence on imported natural gas and create a range of trade-offs in importing electricity versus natural gas.
    - Realising a low-carbon or secure energy system without net imports would require large scale exploitation of renewable based electricity (~19 TWh by 2050—the maximum assumed potential).

- Climate change and dependence on fossil fuel imports
    - In the *BAU* scenario CO_2 emissions are reduced by 30%, and thus additional abatement is required to realise a 60% emission reduction.
    - Centralized gas generation produces additional CO_2 emissions of between 6 and 11 Mt CO_2 in 2050 across the scenarios. However, the electricity from these plants can substitute direct use of fossil fuels in end-use sectors (e.g., heating and transport), resulting in a net reduction in emissions.
    - Depending on the scenario, the share of fossil energy in total final energy declines to 13–53%, compared to 61% in 2010. The share of fossil fuels in the primary energy mix declines to 43–70%, compared to 73% in 2010.

- Energy system costs
    - The incremental annual (undiscounted) cost in 2050 of achieving a low-carbon scenario (realising 1.4 t-CO_2 per capita, excluding international aviation) is CHF

[28] In the same period, GDP and population increases at 0.96% and 0.34% per annum respectively.

6.8–8.3 billion or CHF 750–950 per person in 2050, based on the assumptions applied here. This additional cost includes investment in efficient buildings and heating systems, vehicles and other infrastructure costs, offset by reduced fuel costs.

- For a low-carbon scenario, energy system cost as a percentage of GDP increases to 7.3–7.5% compared to 6.5% in the *BAU* scenario (or 3.1% in 2010, excluding the capital costs of the existing technology stock).

13.2. **Discussion and policy implications**

13.2.1. Model features and strengths

The analysis with STEM illustrates the importance of a system-wide approach for understanding future energy transitions. As described in Sections 9 to 12, there are extensive interactions across sectors in terms of technology and fuel choice. This is seen not only in the impact of electricity sector technology choice on the availability of low-cost electricity for electrification of end-use sectors, but also in the allocation of other energy carriers, such as biomass or natural gas under a CO_2 cap. This system-wide approach is a key strength of the STEM framework.

In addition, the results also illustrate the strength of the high time resolution of STEM. This appears to be critical for understanding the technical feasibility and trade-offs of future technology choice for electricity, heating and transport (esp. electric mobility). This feature can be exploited further for other ESDs which are currently represented with a more aggregate time resolution.

13.2.2. Specific technology-policy implications

The scenario analysis identifies a number of key technology transitions in the long-term development of the Swiss energy system that are important for realising a range of energy policy goals. Some technology-related findings and policy implications include:

- **Heat pumps** (HP) are cost effective across the scenarios, and realising a high level of deployment may require policy support through the incorporation of appropriate incentives in building standards, for both new and renovated buildings.
- Cost-effective **building conservation** measures can significantly contribute to demand reductions. Policy can support the realisation of this potential by ensuring decisions on conservation during building renovation account for the long term—that is, to overcome barriers to the adoption of conservation measures that may not be cost effective in the short term, but which are critical to achieve long-term goals—through appropriate standards.
- **E-mobility** has the potential to decarbonise substantially the car fleet, which alone contributes to a significant reduction in total CO_2 emissions across the scenarios. However, the uptake of e-mobility faces a number of hurdles, in particular the availability of **charging infrastructure**[29] (but also the availability of cheap electricity—see next bullet). This indicates a possible role for policy in supporting the initial development of charging infrastructure and, where necessary, supporting grid expansion.

[29] i.e., where a critical mass of vehicles is required to make investment in charging infrastructure attractive, and *vice versa* where a minimum level of charging infrastructure is required before the technology is attractive to mainstream consumers.

– Increasing electrification of end-uses is seen across the scenarios, resulting in continuous growth in electricity demands. Given the phase out of nuclear generation, there is need for additional capacity in both the short [30] and long term.
    - **Clear policy signals for electricity sector** are required to ensure this capacity is built to achieve low-carbon and energy security goals. This includes signals for continued expansion of renewable generation.
    - Moreover, it is essential to ensure **consistency between electricity sector and end-use energy policies** (e.g., promotion of end-use electrification of buildings and transport *verses* support for new centralised power plants), for example:
        - cheap electricity is critical for the deployment of e-mobility; without centralized gas plants, other fuels (notably natural gas) are cost-effective in car transport, and thus different types of sector-specific policy support and infrastructure is then appropriate.
        - similarly, natural gas fired CHPs may be attractive in the industrial sector without centralized gas generation, again with different policy implications.

– Realising the high deployment of some capital-intensive end-use technologies (heat pumps, BEVs) observed in the scenarios may be challenging given the high upfront capital outlays faced by consumers. Though cost effective from a social perspective, policy support may be necessary to provide households and small enterprises with **access to capital for investing in new efficient technologies**.

– Finally, a broader observation across the scenarios is that the substitution of fossil fuels with electricity in many end-use sectors, along with increasing efficiency, has the potential to lead to **reduced revenues from fuel taxation**. While this may be relatively insignificant over such a long timeframe, it nonetheless implies a need to reduce expenditure or raise revenue from other sources.

14. Outlook

14.1. STEM development

The model described in this report provides a framework with high flexibility for further refinements, in terms of data and structural refinements. On the data side, a number of options for improvement have been noted throughout the report. Among these, a high priority is to improve the representation of the hourly and seasonal demand profile for demands other than heating, cooling and lighting (i.e., the ‘residual’ category). Also of high priority is to further refine technology data for some end-uses (e.g. appliances, industrial process heating, industrial motors), storage (e.g. hydrogen, power-to-gas) and more exotic conversion processes (hydrogen/biofuel production). In the case of storage, although electricity storage is represented (via pumped hydro, batteries in electric vehicles), there is scope to improve the representation of other options (e.g. power to gas with seasonal storage, for storing the output from solar PV in summer for use in winter). Similarly, the representation of daily thermal storage can be improved to account for the potential to combine heat pumps and hot water storage to shift peak electricity demands (and thereby potentially affect the optimal electricity supply mix). There is also a potential to update the characteristics and costs of residential conservation measures, and implement a similar

[30] It is worth noting that we do not allow net electricity imports due to the self-sufficiency constraint. However, electricity imports options are available for Switzerland under the long term contracts (i.e. bestehende Bezugsrechte) 111.

representation of conservation measures in the services sector.[31] All of these potential model developments are, however, highly dependent on the availability of suitable data.

On the supply side, carbon capture and storage (CCS) is not currently represented in STEM, but can be introduced relatively quickly to explore scenarios in which this technology is assumed to be acceptable. Direct use of geothermal for end-use applications, along with geothermal CHP, is also currently excluded from the model (although both geothermal heat pumps and electricity generation are included).

Possible further structural development options for STEM could be aimed at addressing some of the limitations identified in Section 7, related to behavioural, spatial, temporal, and other factors. For instance, to improve the capability of STEM to account for behavioural factors, price-elastic demands could be introduced (rather than assuming a fixed ESD). This would enable STEM to account for the impact of changes in energy prices not only on appliance or fuel choice (currently represented), but also on demand for energy services (e.g. driving less for leisure or resetting thermostats for space heating). Ideally, such an extension of STEM could also exploit the hourly time resolution to elicit hourly demand responses (although data availability is also a challenge in this context). Over the longer term, further model developments could seek to represent spatial factors, among others. However, for any extension a key consideration is computational requirements, particularly given the long horizon and high intra-annual time resolution of STEM.

14.2. **Scenario analysis**

The limited set of scenarios presented in this report shed important insights into the development of the Swiss energy system, and illustrate potential applications of STEM to further scenario analyses. A wide scope exists for future scenario development accounting for additional uncertainties on technology availability and characteristics, domestic and international policy goals, and/or ESD (e.g. scenarios of alternative behaviour, or different patterns of economic growth). Some specific questions that can be answered with the current framework of STEM include:

- How dependent is the future role of e-mobility on the availability of cheap electricity during night and weekends? This question is motivated by the results presented in this report, which were derived from one set of (highly uncertain) assumptions of electricity trade. Additional scenario analysis using different international boundary conditions on electricity trade can be explored.[32]
- How do the end-use sectors respond if electricity supply is highly constrained, e.g. no imports at any time (compared to no net import in the above analysis)?
- How does availability of capital affect deployment of technologies and the realisation of specific policy objectives? This could be implemented using sector- or technology-specific discount rates to reflect consumer behaviour, costs of capital and other factors.
- How does uncertainty on macroeconomic development affect development of the energy sector and CO_2 emissions? (i.e., via a different set of macroeconomic drivers)
- Is there a more cost-effective (but environmentally equivalent or superior) CO_2 reduction pathway for the next 40 years?

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[31] In this context, additional policy options could also be analysed, such as an endogenous analysis of the cost-optimal allocation of KEV revenue for promoting conservation or renewables.

[32] In this context, it is possible to take advantage of development of the Cross-border Swiss TIMES electricity sector model (CROSSTEM), representing different international policy environments, re-striction on availability of off-peak imports and available markets for exports.

Additional policy questions could be analysed with the model extensions mentioned in Section 14.1. They include, but are by no means limited to:

– How could alternative technology cost developments for renewables affect energy demand in end-use sectors (through both behaviour change and the uptake of energy efficiency)?
– Could emerging storage options (thermal and seasonal electricity storage) be a game changer for balancing electricity supply and demand, and integrating large shares of intermittent renewables?
– How could CCS contribute to a sustainable energy system?

15. **Conclusions**

This report outlines the development of a new model of the Swiss energy system—the Swiss TIMES energy system model (STEM)—and presents selected analyses exploring long-term energy policy challenges confronting Switzerland. Models such as STEM represent a useful methodology for energy research aimed at evaluating future energy supply options and generating insights into some of the associated uncertainties.

The key features and strengths of STEM include: i) a high level of technology detail, ii) representation of the entire energy system of Switzerland, iii) a long time horizon, and iv) a high time resolution covering seasonal/diurnal variations in energy demand and supply. The high level of technology detail ensures that the future energy pathways identified by the model account explicitly for the characteristics of the necessary technology options, and thus are feasible from an engineering perspective; moreover, the inclusion of end-use technology detail ensures the analysis considers the provision of energy services rather than energy *per se*. The representation of the entire energy system ensures that STEM accounts for cross-sectoral interactions and competition for the allocation of energy carriers (for instance, the implications of electricity sector technology choice for the electrification of end-use sectors; or the allocation of biomass to electricity, heat or transport). The 'whole energy system' approach is also essential for identifying cost-effective CO_2 abatement options. The long time horizon of STEM facilitates the analysis of long-term goals and challenges, and accounts for the long lifetimes of energy-related capital infrastructure. Finally, the high level of time resolution enables STEM to account for the temporal variations in supply and demand, which are likely to become increasingly critical with continuing deployment of intermittent renewables, electrification of transportation and heating, and an emerging need for storage and/or additional flexibility in imports and exports. These developments have also pushed the state of the art among the international TIMES modelling community, particularly through the implementation of a high level of temporal resolution.

To illustrate these and other features, results from STEM are presented analysing alternative scenarios of energy system development, focusing on selected uncertainties related to policy (climate change mitigation, energy security, and the acceptability of new centralized electricity generation) and international fuel price volatility. Even without strong climate change mitigation policy, a number of other driving forces (energy prices, economic structural change, and improvements in technology performance/cost) are expected to reduce energy demand and CO_2 emissions through increasing efficiency and electrification of end uses. However, achieving more ambitious targets such as a 60% or greater reduction in line with European goals requires substantial changes to the energy system. Key technology options on the demand side include further electrification of heating and transport, and an aggressive adoption of building conservation measures. On the supply side, the large-scale exploitation of renewable resources is a key requirement to avoid increasing dependence on net imports. In addition, the acceptability of new centralized generation options, namely gas combined cycle plants, is critical for realising climate change or security goals at lowest cost. Despite its reliance on natural gas, this technology supports (further) efficient electrification of end uses, substituting direct use of fossil fuels.

Policy support will be critical in realising many of these developments, despite uncertainty regarding the exact nature of future domestic climate change and energy security policies, and international developments. Based on the scenario analysis, key areas for policy support include: measures promoting building efficiency; incentives to support deployment of heat pumps for space heating and decentralized generation options like solar PV (where there may be high upfront capital costs); and promotion of combined heat and power systems, particularly in industry. In the transport sector, advanced and hybrid conventional vehicles represent a cost-effective technology choice in the medium term across the scenarios analysed, which can likely be realized with continuing price signals (along with incentives in the EU on vehicle standards). However, over the longer term the choice, particularly the role of electric vehicles, depends on policy choices related to the availability of cheap electricity (either in the form of imports or domestic generation from new centralized plants). In this context, policy certainty will ultimately be required to support investment in new infrastructure and larger-scale technology options (like centralized gas plants).

The development of STEM described in this report provides a basis for further modelling enhancements, to enhance the technology representation of new options such as storage or incorporate features related to additional behavioural factors driving energy transitions. Moreover, the scenario analysis presented here illustrates the capability to apply STEM to a wide range of additional scenario analyses to explore key policy questions and uncertainties confronting decision makers in Switzerland.

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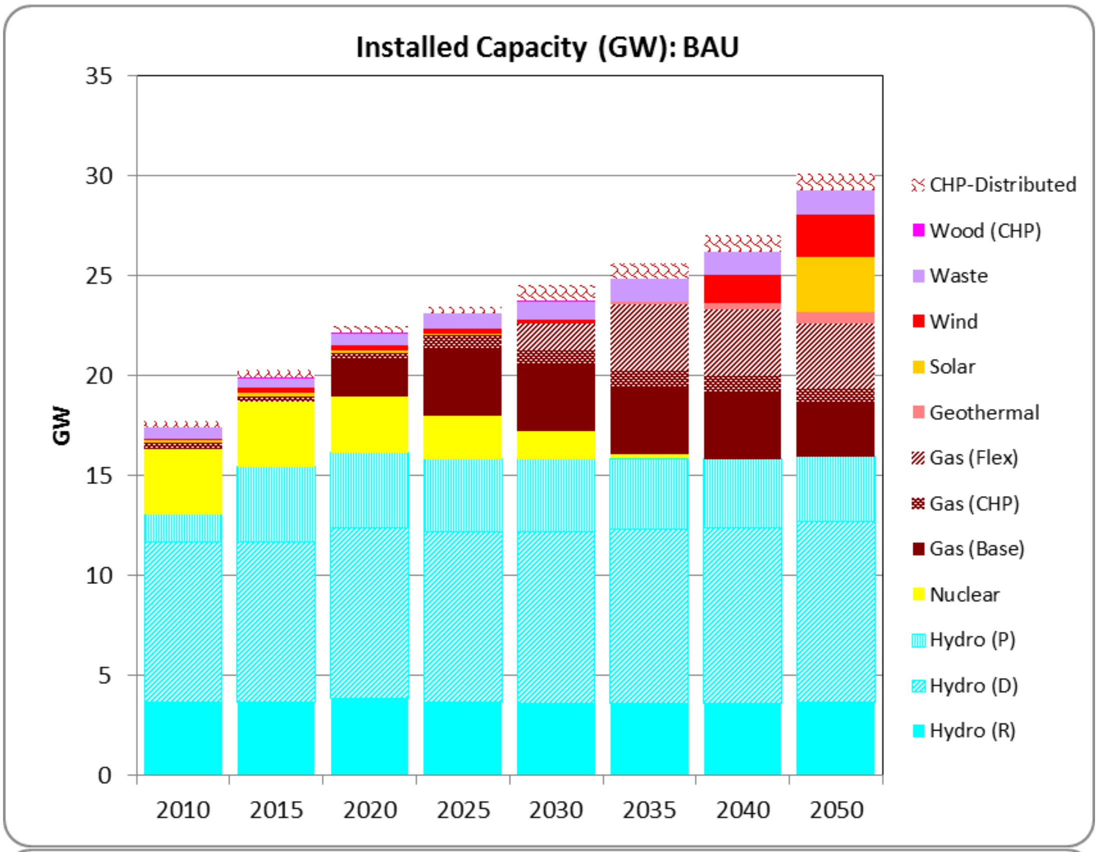
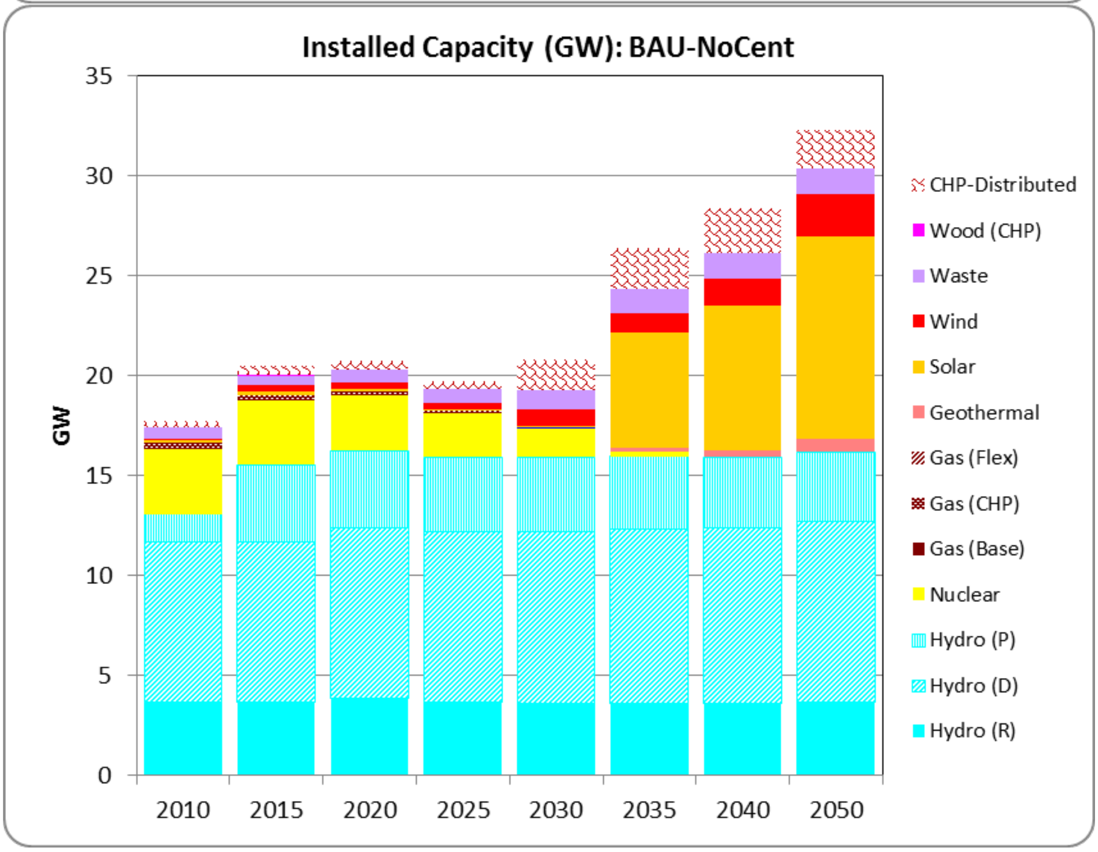
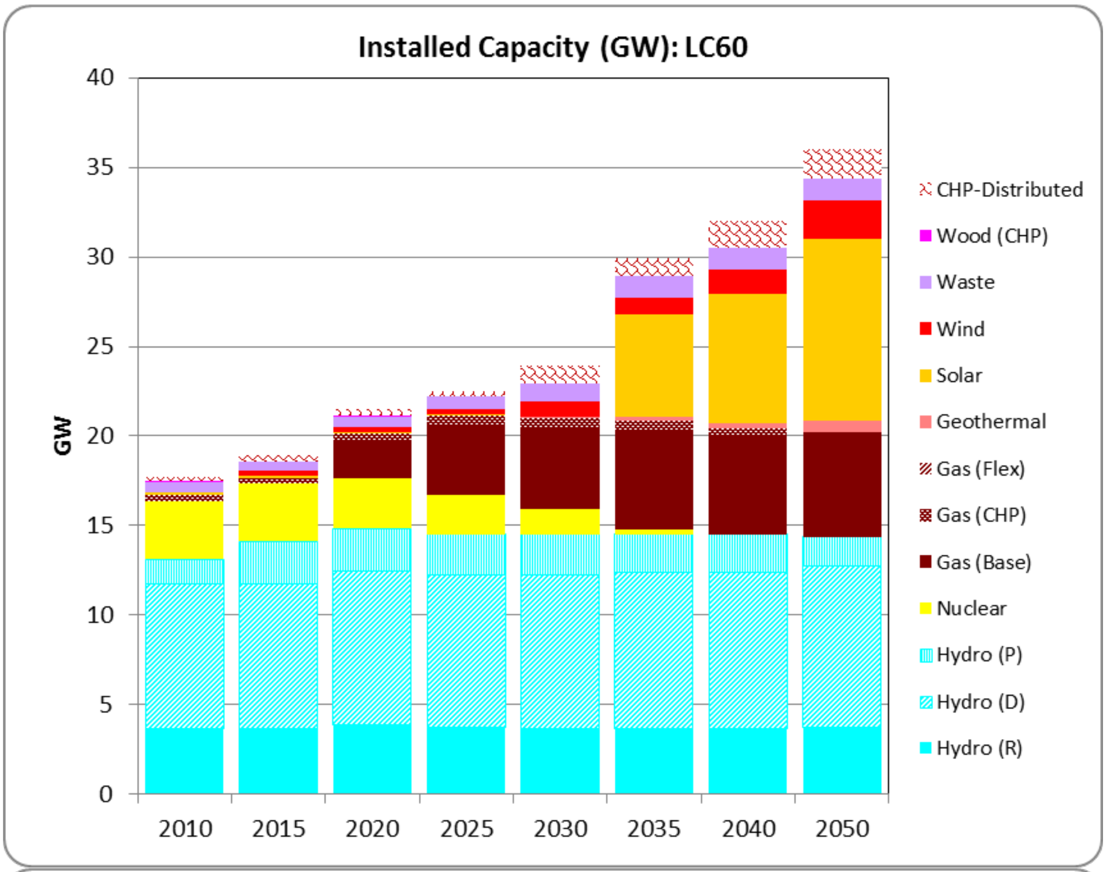
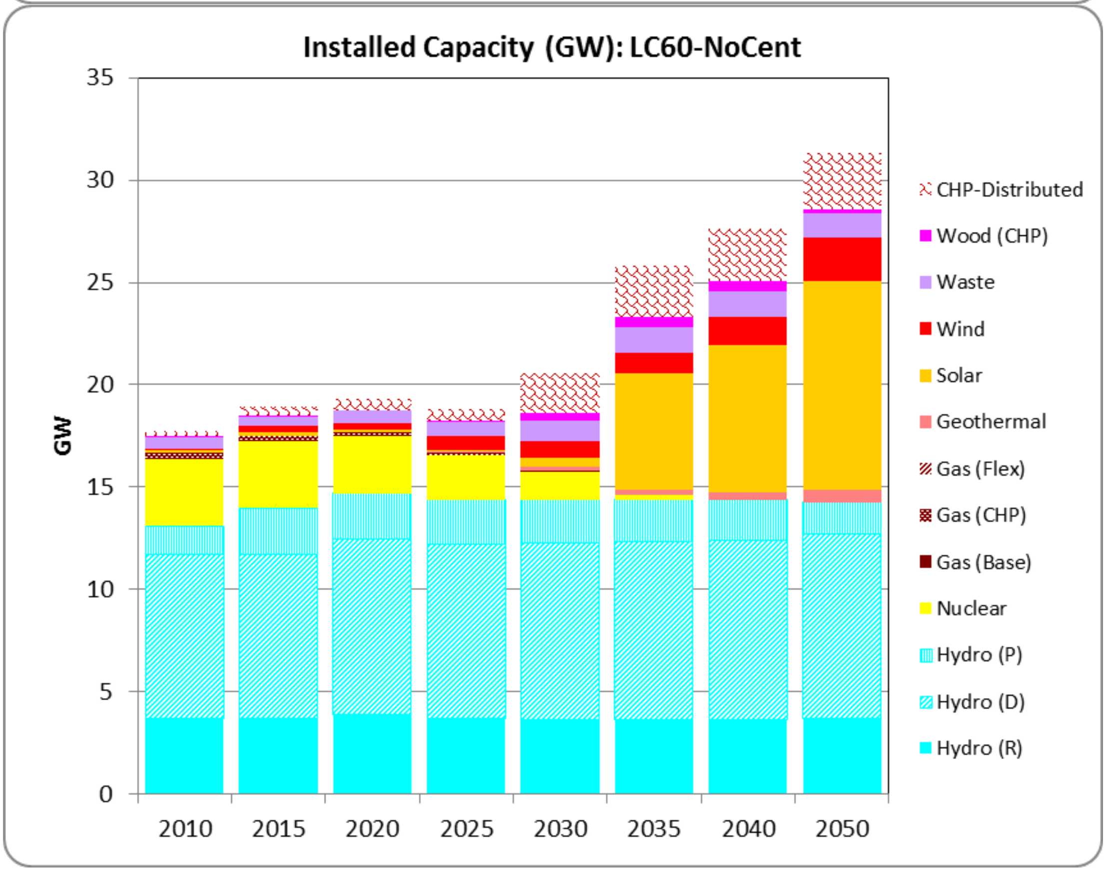
PART IV: Annexes



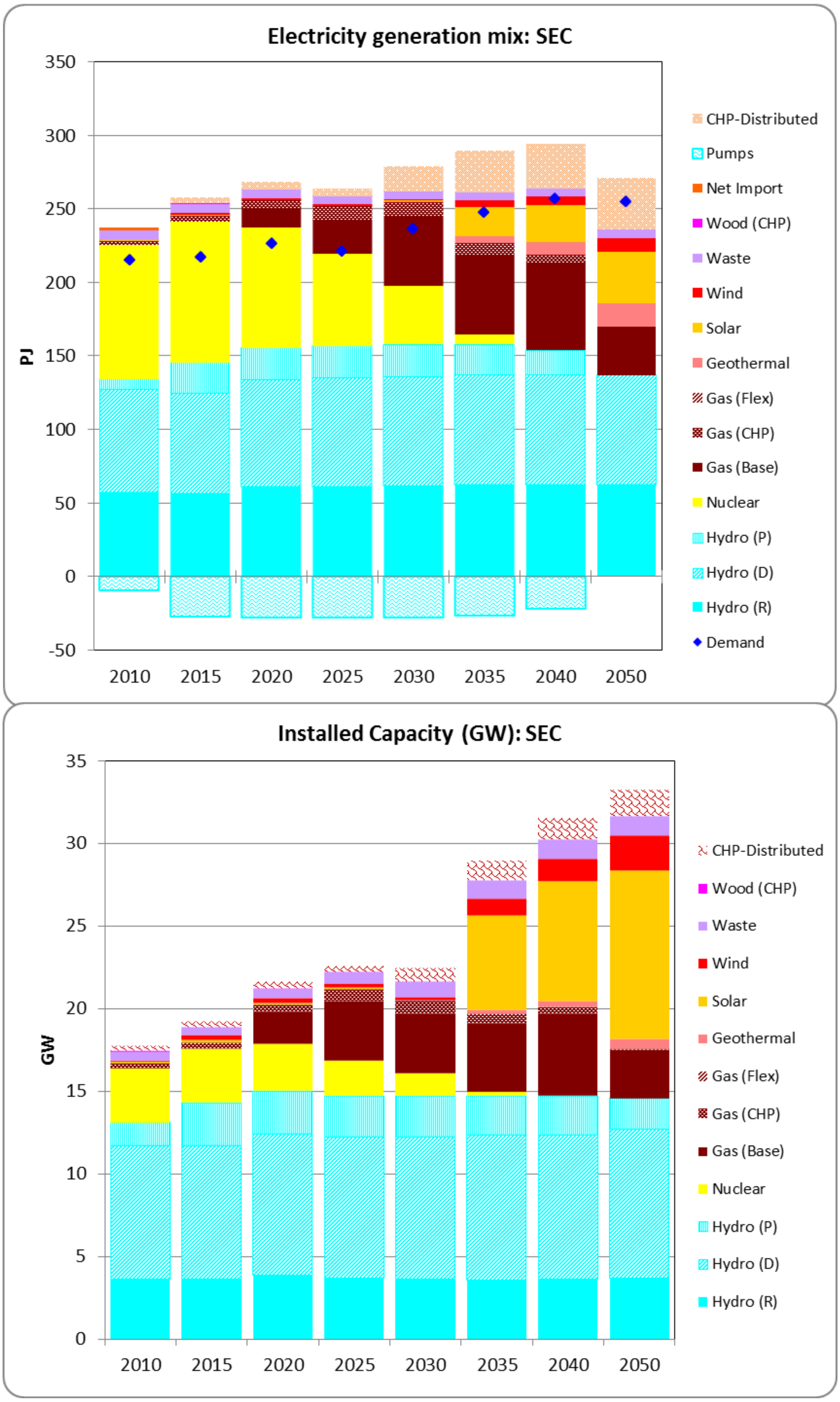


Annex-Fig. 1: Installed capacity in *BAU* and *Bau-NoCent* scenarios

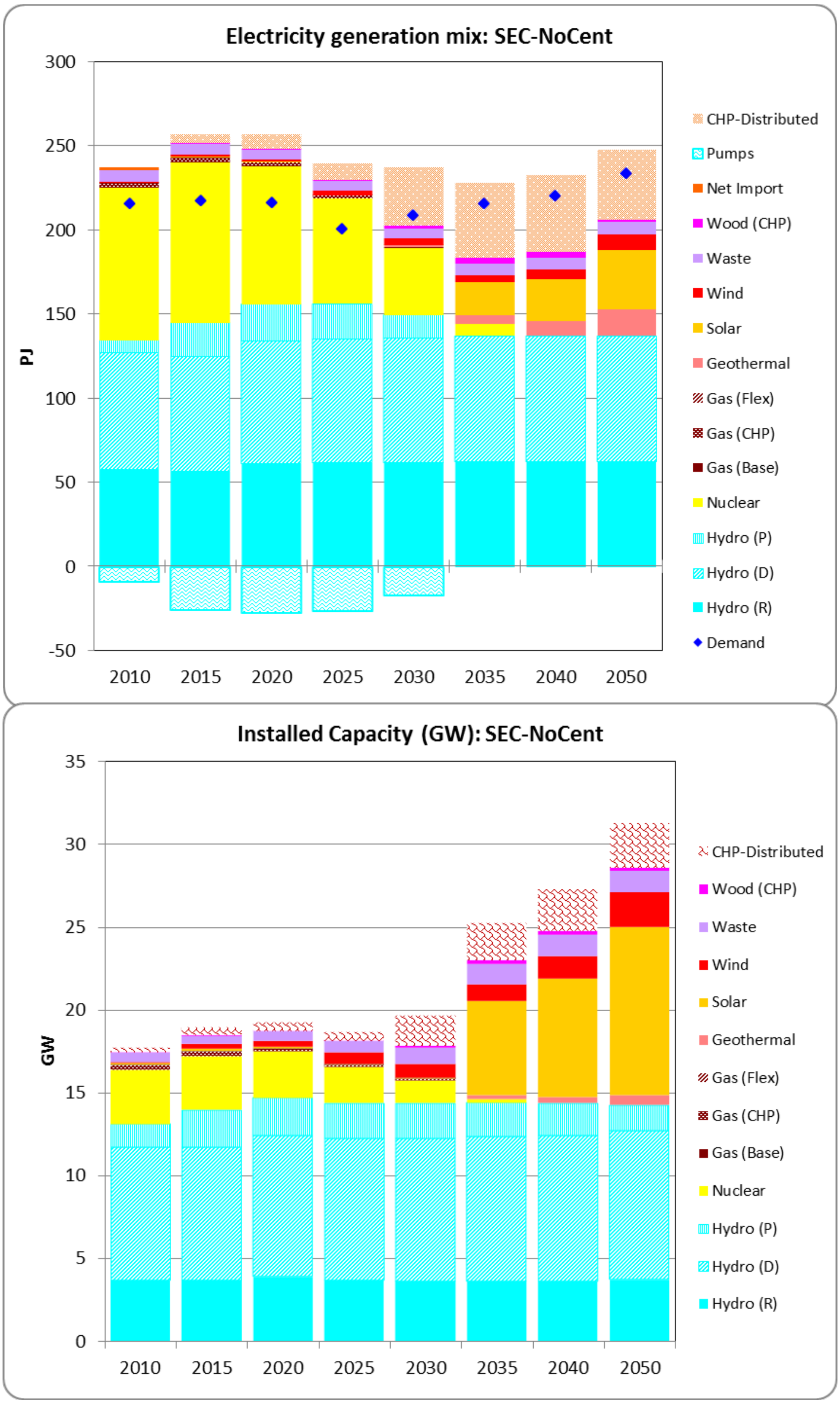




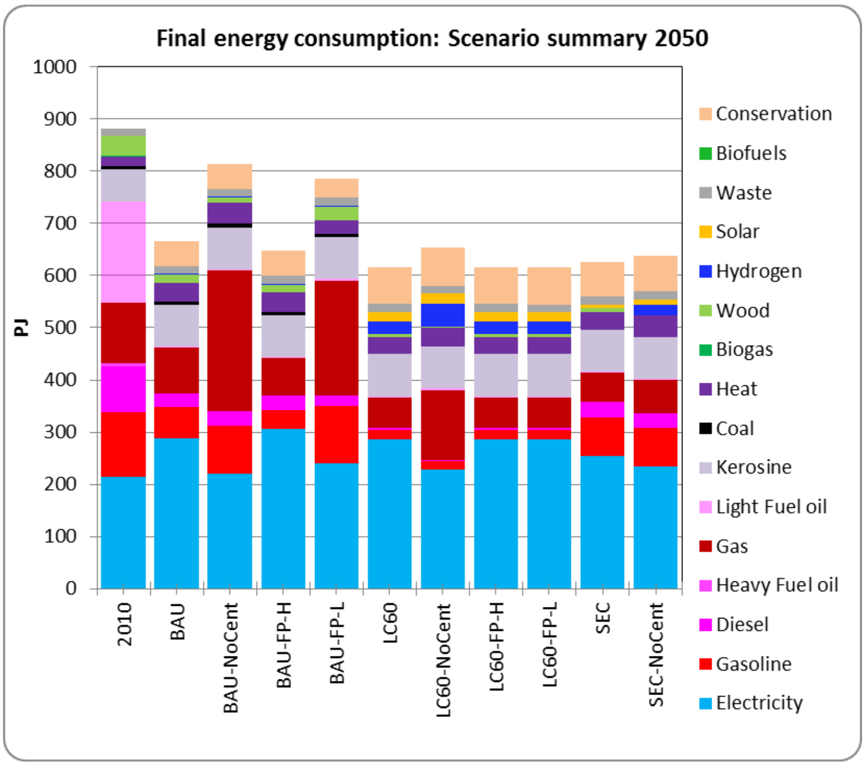
Annex-Fig. 2: Installed capacity in *LC60* and *LC60-NoCent* scenarios



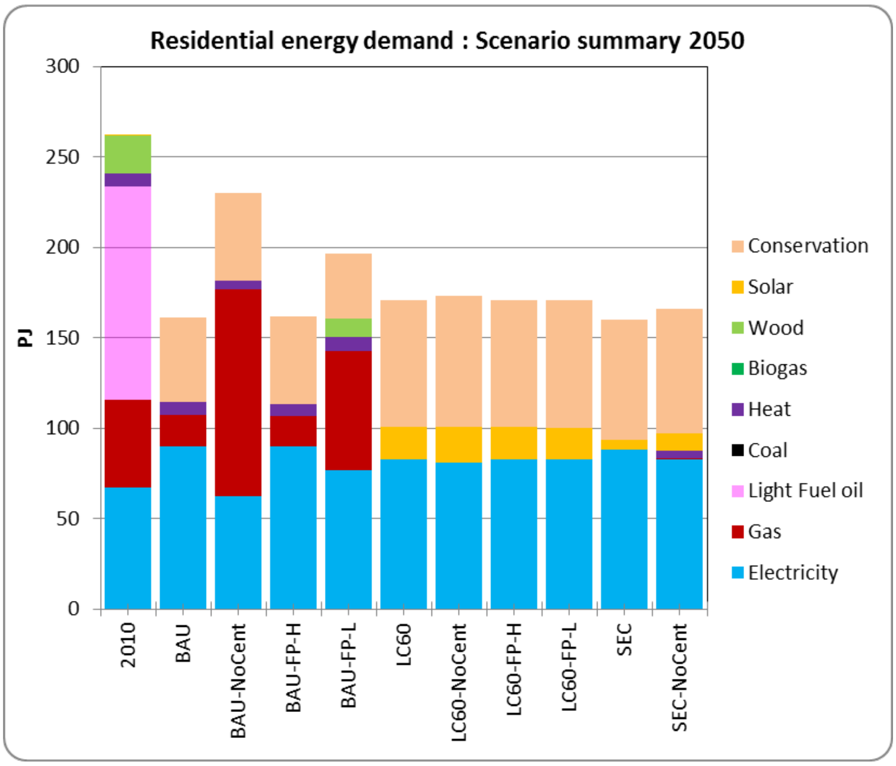
Annex-Fig. 3: Electricity supply and installed capacity in *SEC* scenario



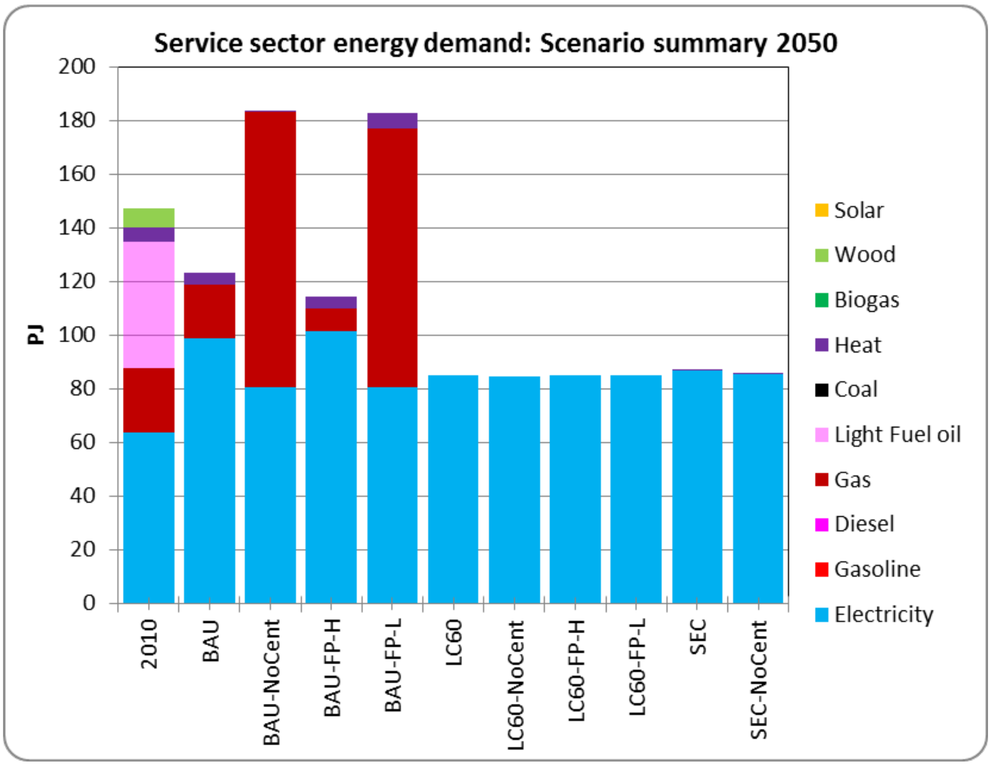
Annex-Fig. 4: Electricity supply and installed capacity in *SEC-NoCent* scenario



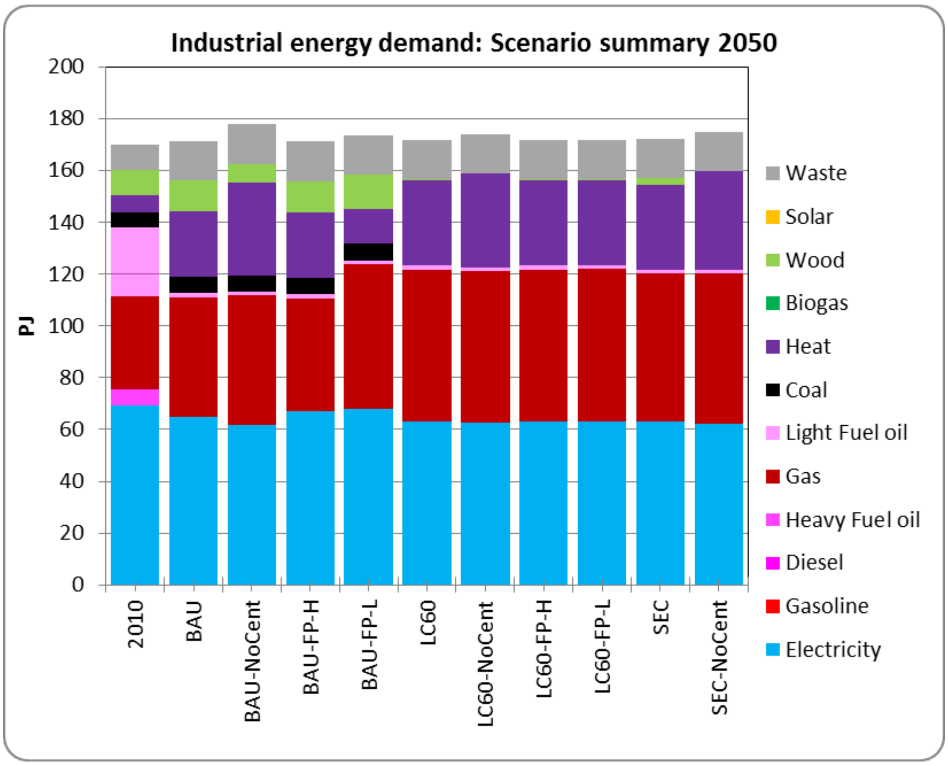
Annex-Fig. 5: Final energy demands in 2050—scenarios comparison



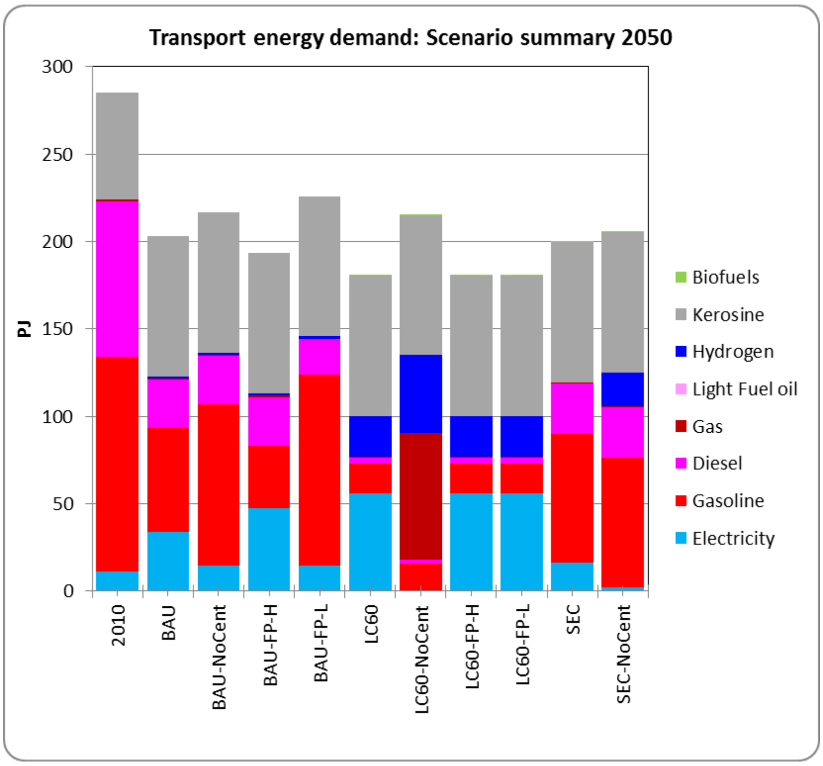
Annex-Fig. 6: Residential energy demand in 2050—scenarios comparison



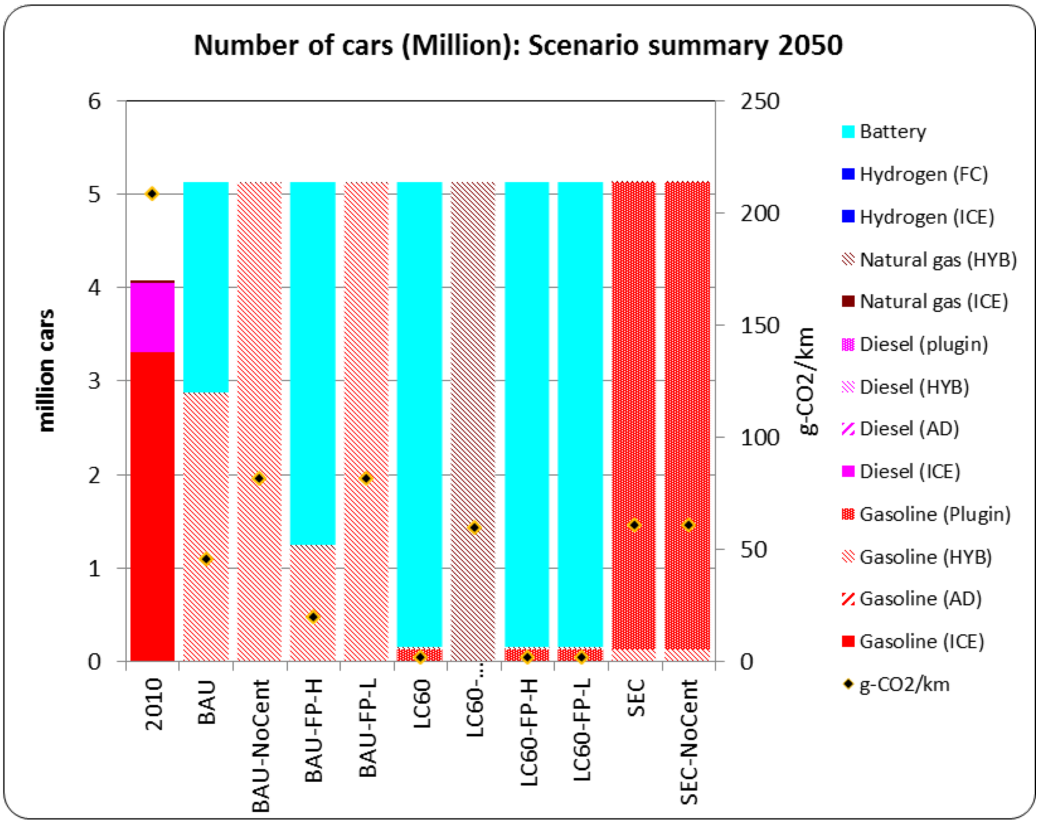
Annex-Fig. 7: Services sector energy demand in 2050—scenarios comparison



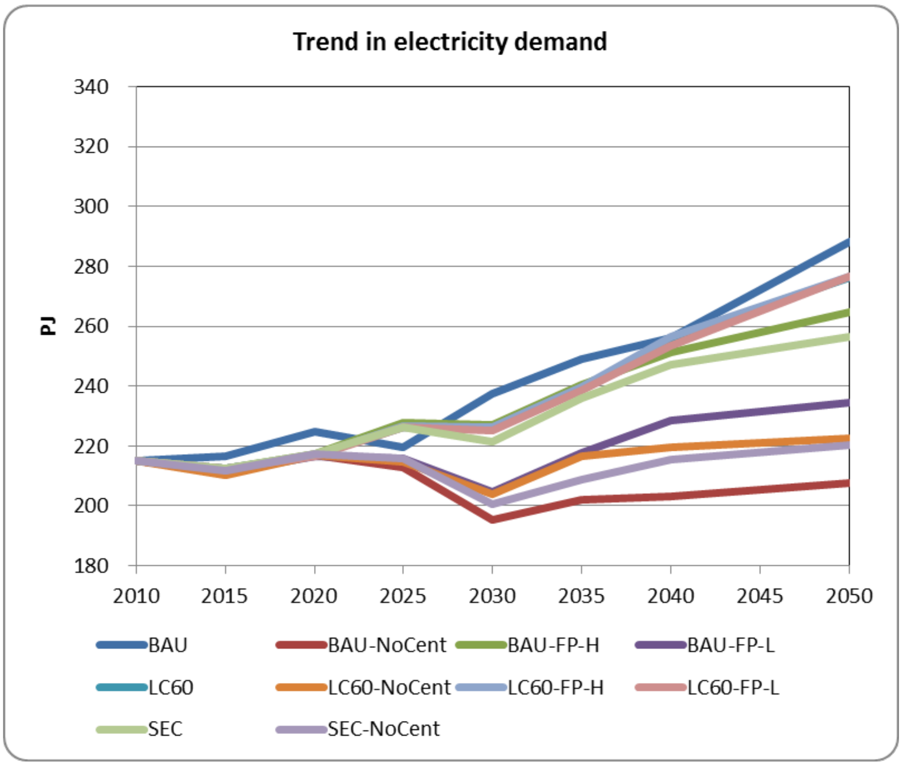
Annex-Fig. 8: Industrial energy demand in 2050—scenarios comparison



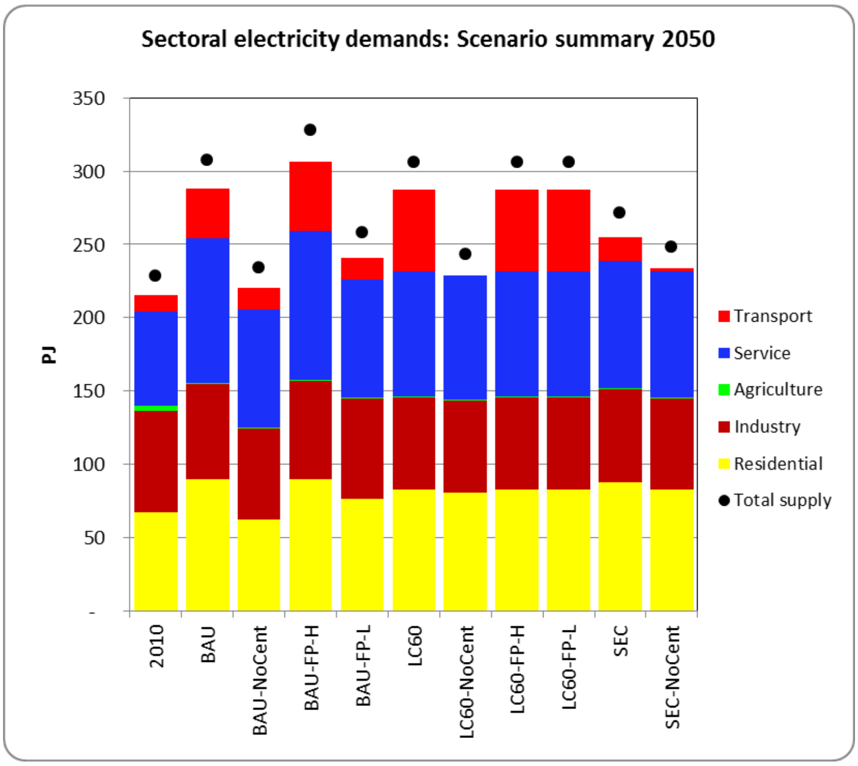
Annex-Fig. 9: Transport sector fuel demands in 2050—scenarios comparison



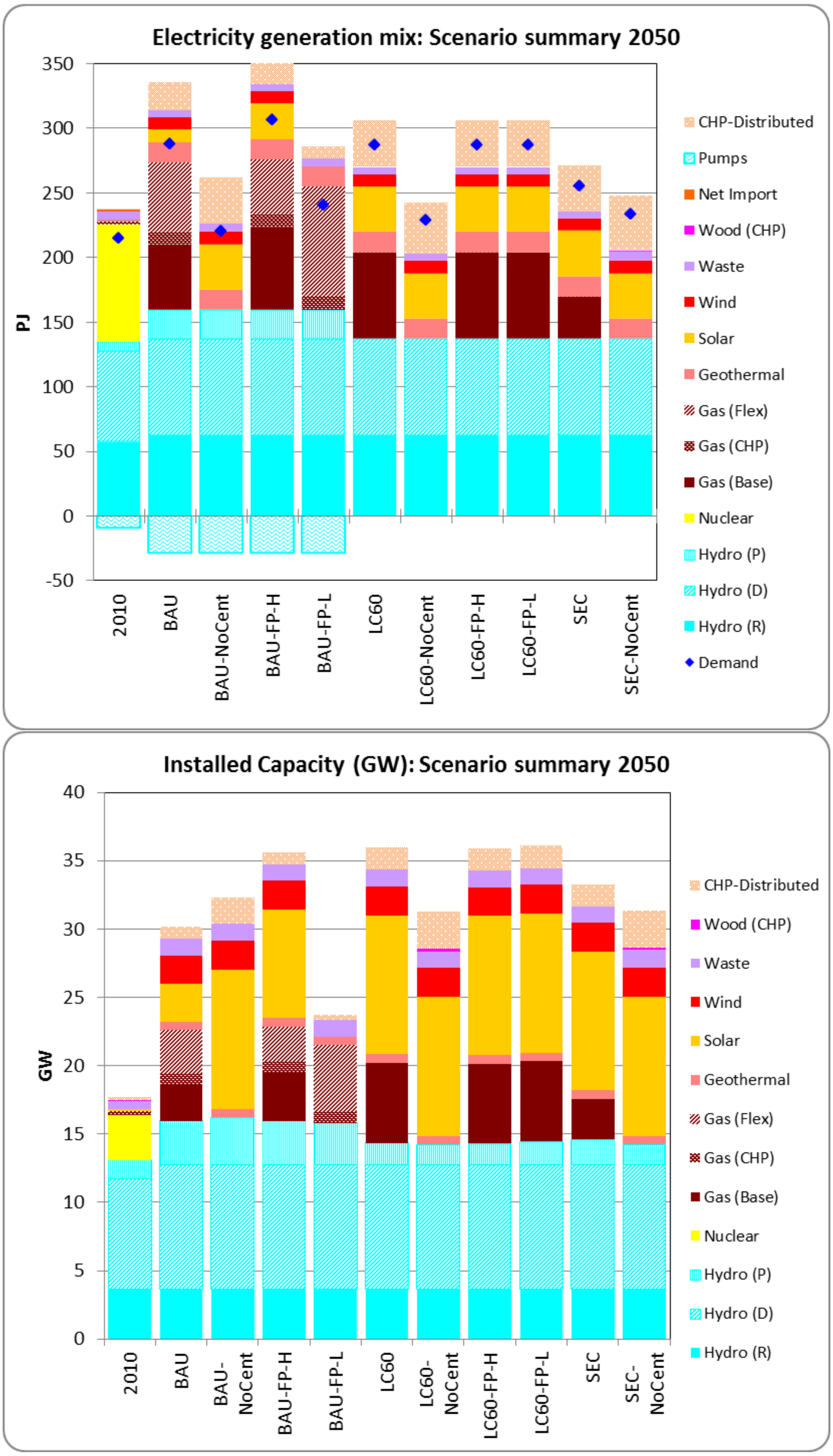
Annex-Fig. 10: Car fleet in 2050—scenarios comparison



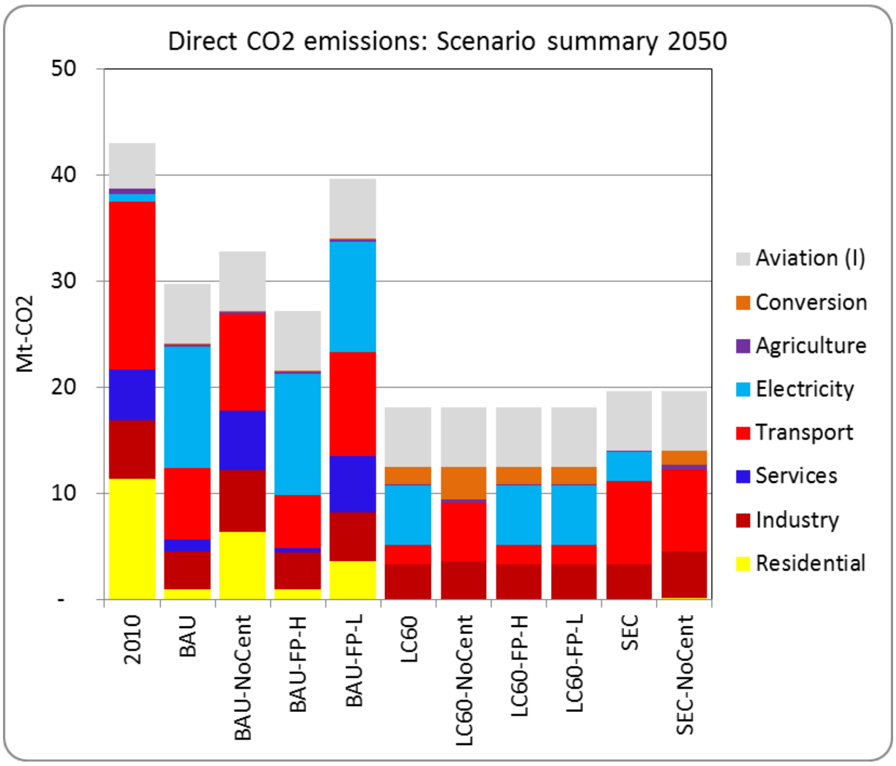
Annex-Fig. 11: Electricity demand development—scenarios comparison

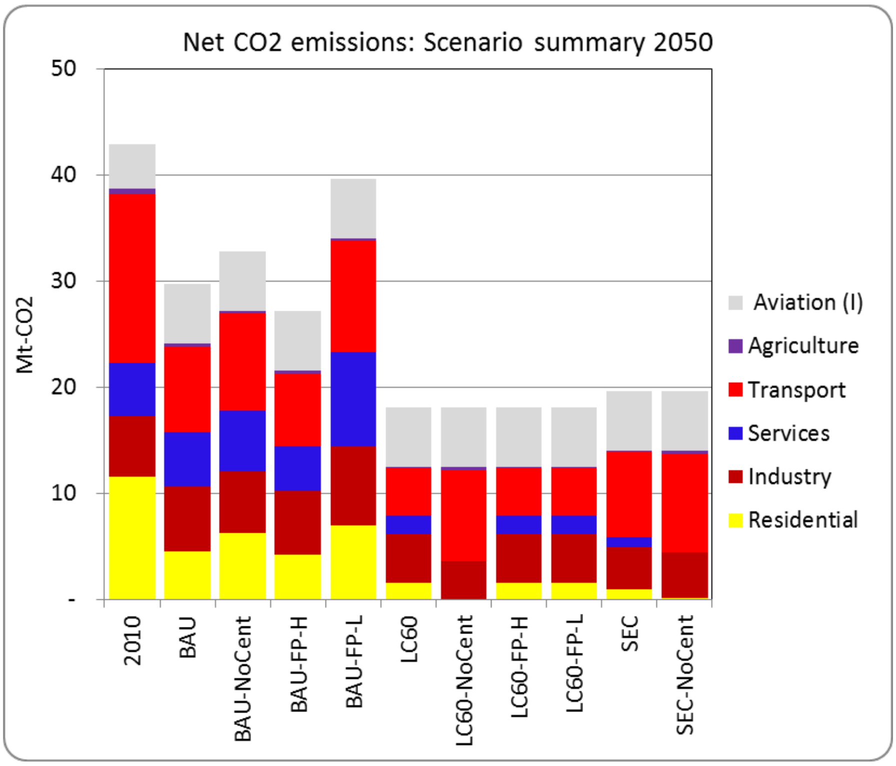


Annex-Fig. 12: Sectoral electricity demands in 2050—scenarios comparison

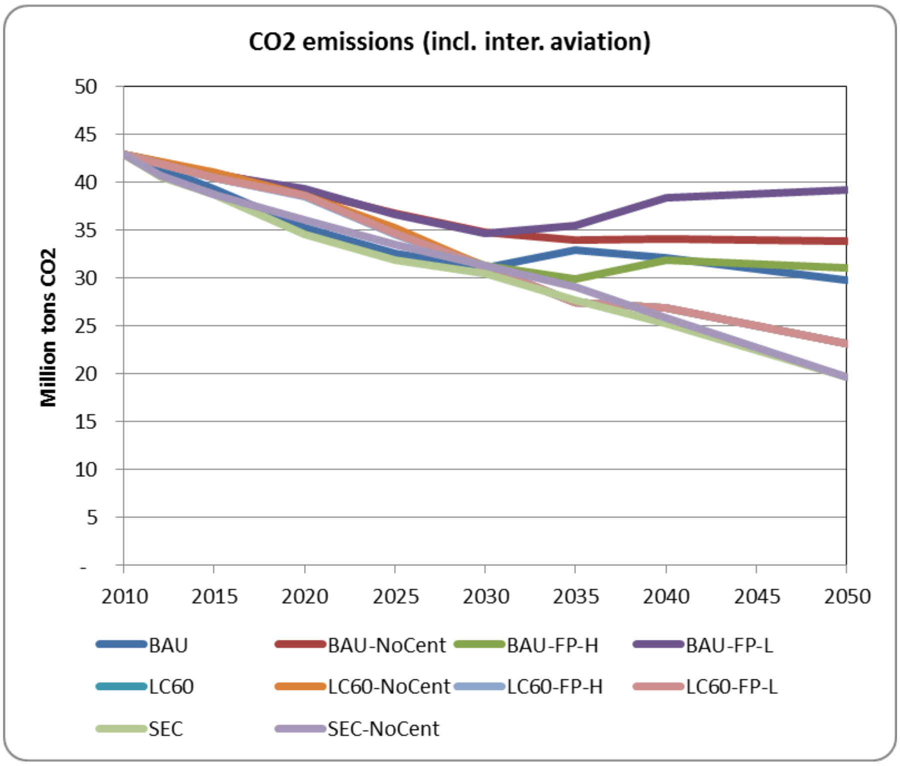


Annex-Fig. 13: Electricity supply mix and installed capacity in 2050—scenarios comparison

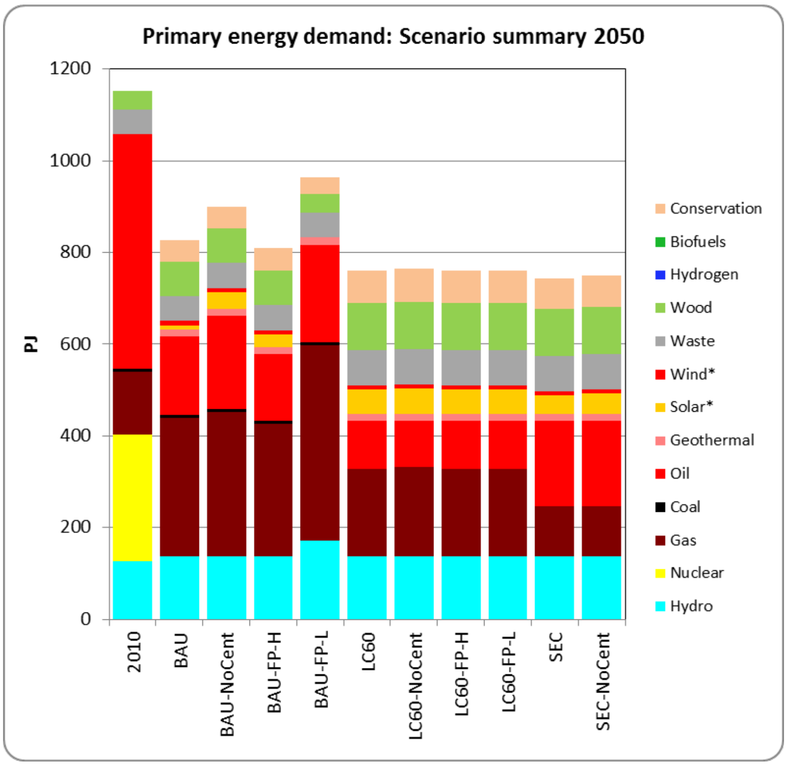




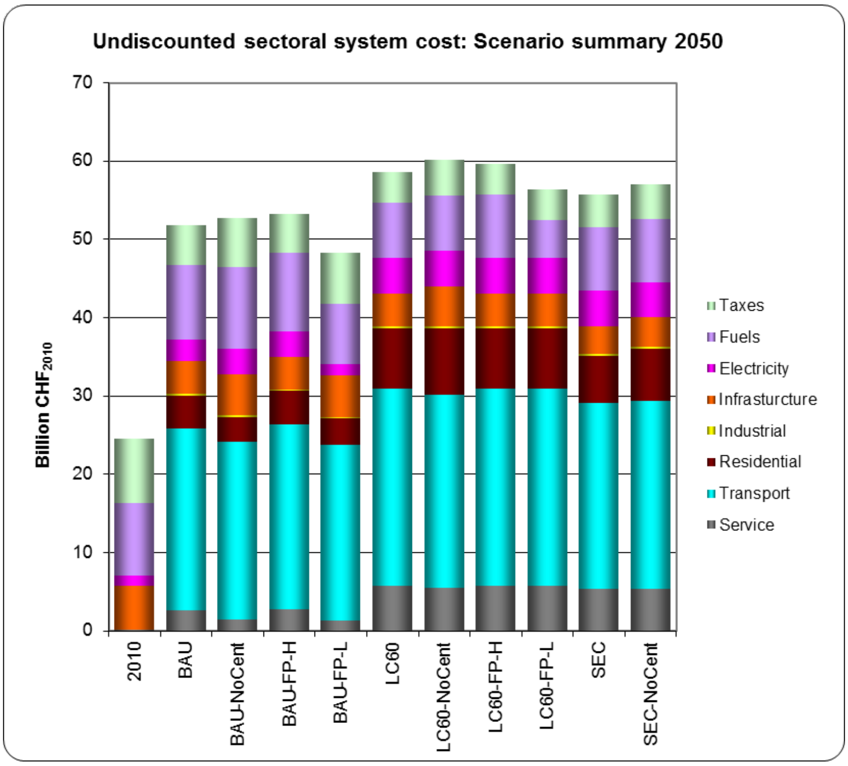
Annex-Fig. 14: Direct and net CO2 emissions in 2050—scenarios comparison

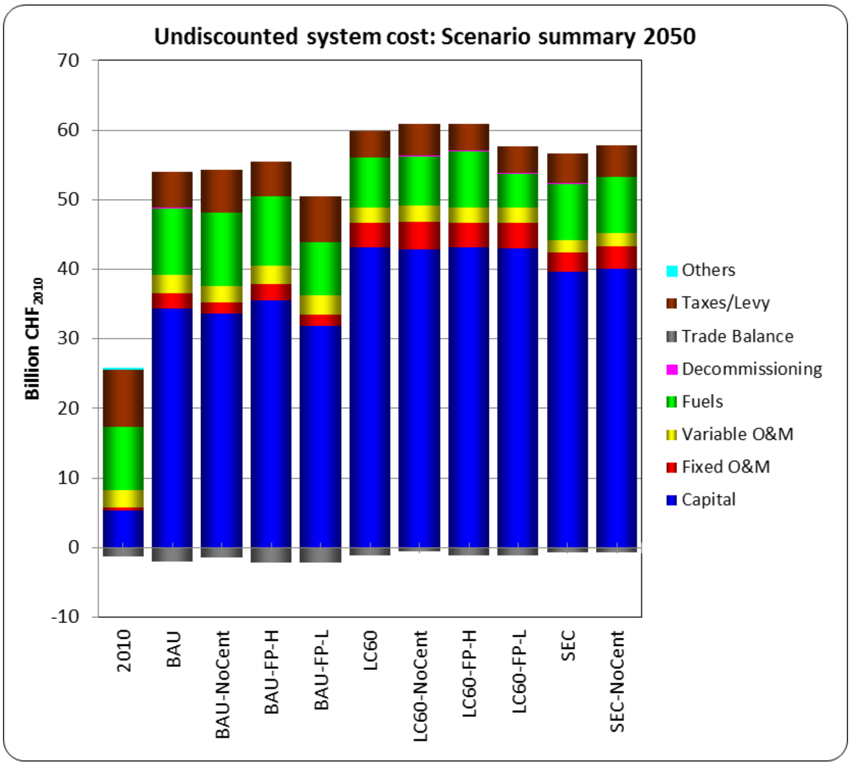


Annex-Fig. 15: Total CO_2 emission pathway—scenarios comparison



Annex-Fig. 16: Primary energy supply in 2050—scenarios comparison





Annex-Fig. 17: Undiscounted energy system cost in 2050—scenarios comparison

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