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TRANSFORMATION STRATEGIES TOWARDS A SUSTAINABLE SWISS ENERGY SYSTEM: AN ENERGY-ECONOMIC SCENARIO ANALYSIS

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I dedicate this work to my parents.

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Acronyms and Abbreviations

AC	Air Conditioning
AF	Availability Factor
BAFU	Bundesamt für Umwelt
BAU	Business As Usual
b	billion
bbl	barrel
BFE	Bundesamt für Energie
BFS	Bundesamt für Statistik
bio	biomass
Btu	British thermal unit
bv-km/y	billion vehicle-kilometers per year
CARMA	CARbon MAnagement in power generation
CC1	Commercial Cooling
CCES	Competence Center Environment and Sustainability
CCEM	Competence Center Energy and Mobility
CCS	Carbon Capture and Storage
CCS-R	CCS with Retrofitting option
CH1	Commercial Heating
CHF	Swiss Francs
CHP	Combined Heat and Power
CHW	Commercial Hot Water
clim.	climate / climate target
climcorr	climate correction factor
CLA	Commercial Lighting
COE	Commercial Office Equipment
conv.	conventional
COT	Commercial Others
CO_2	Carbon Dioxide
CPH	Commercial Process Heat
CPP	Commercial Propulsion and Processes
DEM1	Demand scenario 1
DEM2	Demand scenario 2
DMD	Demand
dom.	domestic
EB	Business as usual fossil Energy prices
EEG	Energy Economics Group

EFF	Efficiency
EH	High fossil Energy prices
EL	Low fossil Energy prices
ELC	Electricity
EM	Medium fossil Energy prices
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat
EP	Energieperspektiven
ERFA	Energy Reference Floor Area
ESD	Energy Service Demand
ESM	Energy Saving Measures
ETH	Eidgenössische Technische Hochschule
ETP	Energy Technology Perspectives
ETS	Energie Trialog Schweiz
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EV	Erdölvereinigung
FC	Fuel Cell
FEC	Final Energy Consumption
FIXOM	Fixed operations and maintenance costs
FOEN	Federal Office for the Environment
GDP	Gross Domestic Product
Gen2	Generation 2 (nuclear technologies)
Gen3	Generation 3 (nuclear technologies)
Gen4	Generation 4 (nuclear technologies)
GHG	Greenhouse Gas
HDV	Heavy Duty Vehicle
hyb.	hybrid
ICE	Internal Combustion Engine
IEA	International Energy Agency
INVCOST	Investment costs
int.	international
IPCC	Intergovernmental Panel on Climate Change
I&C	Information and Communication
J	Joule(s)
LEA	Laboratory for Energy Systems Analysis
LDV	Light Duty Vehicle
LIFE	Lifetime
LCA	Life-cycle assessment
MARKAL	MARKet ALlocation
MFH	Multi-Family House
NEP	Neue Energiepolitik
NGA	Natural Gas
NGCC	Natural Gas Combined Cycle
NGCHP	Natural Gas Combined Heat and Power
NoCen	No Centralised power plants
nuc.	nuclear
NuExt	Nuclear Extension

NuPhs	Nuclear Phase-out
NuRep	Nuclear Replacement
OcCC	Advisory Body on Climate Change
O&M	Operations and Maintenance
PEC	Primary Energy Consumption
POM	Politische Massnahmen
POP	Population
pp	Percentage point
PSI	Paul Scherrer Institute
PV	Photo-Voltaics
R&D	Research and Development
RC1	Residential Cooling
RCD	Residential Cloth Drying
RCW	Residential Cloth Washing
RDW	Residential Dish Washing
REA	Residential other Electric Appliances
red.	reduction
repl.	replacement
RES	Reference Energy System
retrofit.	retrofitting option
RH	Residential Heating
RH1	Residential Heating old buildings single-family houses
RH2	Residential Heating new buildings single-family houses
RH3	Residential Heating old buildings multi-family houses
RH4	Residential Heating new buildings multi-family houses
RHW	Residential Hot Water
RK1	Residential Cooking
RL1	Residential Lighting
RRF	Residential Refrigeration and Freezing
SAAS	Swiss Academies of Arts and Sciences
SCT	Swisscleantech
SECO	State Secretariat for Economic Affairs
SFH	Single-Family House
SFOE	Swiss Federal Office of Energy
SHD	Specific Heating Demand
SMM	Swiss MARKAL Model
SMM-S	Swiss MARKAL Model version Schulz
SMM-W1	Swiss MARKAL Model version Weidmann 1
SMM-W2	Swiss MARKAL Model version Weidmann 2
SNB	Schweizerische Nationalbank
SNG	Synthetic Natural Gas
STEM-E	Swiss TIMES Electricity Model
t	time period in Swiss MARKAL Model
TAD	Transport Air Domestic
TAI	Transport Air International
TFC	Total Final energy Consumption
TIMES	The Integrated MARKAL-EFOM System

TOO	Transport Others
TRBC	Transport Buses Coaches
TRBU	Transport Buses Urban buses
TRC	Transport Road Car
TRL	Transport Road Light duty vehicles
TRH	Transport Road Heavy duty vehicles
TRW	Transport Road two Wheelers
TTR	Transport Train Rangieren (shunting)
TTP	Transport Train Passenger
TTF	Transport Train Freight
tv-km/y	thousand vehicle-kilometers per year
TWD	Transport Water Domestic (navigation)
UN	United Nations
USD	US Dollars
UNFCCC	United Nations Framework Convention on Climate Change
UVEK	Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation
VAROM	Variable operations and maintenance costs
vent.	ventilation
VSE	Verband Schweizerischer Elektrizitätsunternehmen
VSG	Verband der Schweizerischen Gasindustrie
W	Watt
Wh	Watt-hour
WWB	Weiter Wie Bisher
w/	with
w/o	without

The following suffix abbreviations are used with J, W, and Wh to denote larger quantities:

k	kilo-	10^3
M	Mega-	10^6
G	Giga-	10^9
T	Tera-	10^{12}
P	Peta-	10^{15}

Abstract

Key elements of a sustainable energy system comprise a sufficient, diversified, secure, economically and environmentally compatible energy supply and the efficient use of energy. Given its relatively high dependence on imported fossil fuels, the energy system in Switzerland today does not meet the criteria of a sustainable energy system. In order to achieve a more sustainable configuration of the energy system and cope with key challenges related to energy security, climate change mitigation, and the more rational use of energy, fossil fuel consumption would have to be significantly reduced. Additionally, the overall efficiency and the diversification of energy supply options would need to be increased in the energy system while deploying more environmentally friendly end-use technologies. The achievement of such targets is likely to require a major transformation of the configuration of the Swiss energy system. The realisation of such a transformation depends on a number of uncertain factors related to policy decisions, technological developments, and international energy prices, amongst others. The overall objective of this dissertation is to improve understanding of how a sustainable Swiss energy can be realised from a technology perspective.

Given the considerable levels of uncertainty that could affect the development of the future energy system, scenarios reflecting key uncertainties were developed, quantified, and analysed with the application of a technology-rich bottom-up model of the Swiss energy system, called Swiss MARKAL.

Different sets of scenarios based on key uncertainties were analysed within the scope of this dissertation. The first set comprises scenarios representing uncertainties related to political support for future electricity supply options including new nuclear power plants and large centralised fossil power plants and is analysed for different levels of climate change mitigation targets. In addition, the impact of changes in international prices for fossil fuels on the technological configuration of the energy system is investigated. Second, the potential role of low-carbon electricity sources such as carbon capture and storage (CCS) technologies in a nuclear- and climate-constrained Swiss energy system was analysed. In a third set, the impact of alternative socio-economic developments including economic and population growth on the energy system was investigated.

The scenario analysis conducted within the scope of this dissertation provided important insights into how the transformation towards a more sustainable Swiss energy system could be realised.

Coping with key challenges related to climate change mitigation will likely require significant reductions in domestic CO_2 emissions that can be realised with an increased deploy-

ment of energy efficiency technologies across all end-use sectors along with investments in energy saving measures in residential, commercial, and industrial buildings. Electrification could support the decarbonisation of the building sectors and reduce the need for more costly mitigation options in other parts of the energy system. Under stringent climate constraints, such an electrification will likely require the deployment of low-carbon electricity from renewable sources such as solar, wind, and biomass.

Given the limited potentials of domestic renewables and the recent decision on phasing out nuclear power in Switzerland, CCS technologies could provide an attractive complementary and almost abundant source for low-carbon electricity in the future energy system. However, the future availability of this technology is still highly uncertain since different technical, geological, and public acceptance issues will first have to be solved. Additionally, the fact that CCS technologies are likely to rely on fossil fuels can have consequences for the security of the energy supply.

The analysis of alternative projections of key socio-economic parameters showed that higher population and economic growth could result in higher energy service demands and possibly make the achievement of ambitious climate targets more challenging and more costly. However, there might be also positive aspects of an increased growth in population and GDP (e.g. with higher GDP, energy system costs could be carried more easily).

The results of this analysis provide insights into cost-effective technology combinations that could contribute to the transformation of the energy system towards a more sustainable configuration. However, barriers to the deployment of some of the cost-effective technology options can exist. In order to overcome these barriers, suitable policies need to be developed and successfully implemented.

Keywords: Swiss energy system; sustainable development; climate change; mitigation; nuclear policy; energy security; energy saving; efficiency; technologies

Kurzfassung

Wesentliche Elemente eines nachhaltigen Energiesystems beinhalten eine ausreichende, breit gefächerte, sichere, wirtschaftliche und umweltverträgliche Energieversorgung sowie eine effiziente Energienutzung. Aufgrund der relativ hohen Abhängigkeit von importierten fossilen Energieträgern, entspricht das heutige Schweizer Energiesystem nicht den Grundsätzen eines nachhaltigen Energiesystem. Um eine nachhaltigere Gestaltung des Schweizer Energiesystems zu erreichen und in der Lage zu sein, wichtige Herausforderungen im Zusammenhang mit Versorgungssicherheit, Klimaschutz und einem rationelleren Energieverbrauch zu meistern, müssen fossile Energieträger wesentlich reduziert werden. Zusätzlich sollte die Gesamteffizienz und die Diversifizierung der Energieversorgung im Energiesystem vergrössert und umweltfreundlichere Endnutztechnologien vermehrt zum Einsatz kommen. Das Erreichen solcher Ziele erfordert höchstwahrscheinlich eine bedeutende Umgestaltung des heutigen Energiesystems. Die Realisierung einer solchen Umgestaltung hängt von einer Anzahl von ungewissen Faktoren wie zum Beispiel politischen Entscheidungen, technologischen Entwicklungen, und internationalen Preisen von Energieträgern ab. Das Hauptziel dieser Dissertation ist es, das Verständnis, wie ein nachhaltiges Energiesystem aus technologischer Sicht realisiert werden kann, zu verbessern.

Um dem beträchtlichen Mass an Unsicherheiten, welche die Entwicklung des zukünftigen Energiesystems beeinflussen könnten, Rechnung zu tragen, wurden Szenarien für das zukünftige Energiesystem entwickelt, die wichtige Unsicherheiten abbilden. Diese Szenarien wurden mit dem Swiss MARKAL Modell, einem technologiereichen Bottom-up-Modell des Schweizer Energiesystems, quantifiziert und analysiert.

Verschiedene Gruppen von Szenarien, die wichtige Unsicherheiten repräsentieren, wurden im Rahmen dieser Dissertation analysiert. Die erste Gruppe umfasst Ungewissheiten bezüglich der politischen Unterstützung für zukünftige Stromversorgungsoptionen, einschließlich neuer Kernkraftwerke und zentralisierten fossilen Kraftwerken und wurde für verschiedene Klimaschutzziele analysiert. Zusätzlich wurden die Auswirkungen von Änderungen in internationalen Preisen für fossile Energieträger auf die Attraktivität von Technologien im Energiesystem untersucht. In einer zweiten Gruppe wurde die mögliche Rolle von Technologien zur Abscheidung und -Speicherung von Kohlenstoffdioxid (CO_2) (CCS) in einem künftigen Schweizer Energiesystem analysiert, das gleichzeitig Klimaschutzziele verfolgt und auf den Bau neuer Kernkraftwerke verzichtet. Eine dritte Szenariengruppe untersuchte die Auswirkungen von Wirtschafts- und Bevölkerungswachstum auf die zukünftige Entwicklung des Energiesystems.

Basierend auf der in dieser Dissertation durchgeführten Szenarienanalysen konnten wichtige Erkenntnisse, wie eine Transformation hin zu einem nachhaltigeren Energiesystem

realisiert werden könnte.

Um bedeutende Herausforderungen im Zusammenhang mit Klimaschutz meistern zu können, werden vermutlich signifikante Reduktionen domestischer CO_2-Emissionen nötig sein. Diese Reduktionen könnten mit einem intensiveren Einsatz energieeffizienter Technologien in allen Endnutzsektoren und mit Investitionen in energiesparende Massnahmen im Gebäudebereich realisiert werden. Eine Elektrifizierung könnte die Dekarbonisierung des Gebäudesektors unterstützen und die Notwendigkeit von teureren CO_2-Reduktionsmassnahmen in anderen Bereichen des Energiesystems vermindern. Unter einem ambitiösen Klimaschutzziel erfordert eine solche Elektrifizierung den Einsatz von CO_2-armer Stromerzeugung aus erneuerbaren Quellen wie zum Beispiel Sonne, Wind und Biomasse.

Aufgrund der limitierten Potentiale von domestischen erneuerbaren Energien und der Entscheidung, aus der Kernkraft auszusteigen, könnten CCS-Technologien eine attraktive komplementäre Quelle für kohlenstoffarme Elektrizität im Schweizer Energiesystem sein. Allerdings ist die zukünftige Verfügbarkeit dieser Technologieoption heute noch höchst ungewiss, da verschiedene Probleme im Zusammenhang mit technischer und geologischer Umsetzbarkeit und gesellschaftlicher Akzeptanz zuerst gelöst werden müssten. Zusätzlich könnte die Tatsache, dass CCS-Technologien höchstwahrscheinlich auf fossilen Energieträgern basieren werden, Konsequenzen für die Versorgungssicherheit des Landes haben.

Die Analyse von alternativen sozioökonomischen Entwicklungen hat gezeigt, dass ein höheres Wirtschafts- und Bevölkerungswachstum zu einer höheren Nachfrage nach Energiedienstleistungen führen, und möglicherweise das Erreichen ambitiöser Klimaschutzziele erschweren und verteuern könnte. Auf der anderen Seite könnte ein stärkeres Wachstum aber auch positive Skaleneffekte mit sich bringen.

Die Resultate aus dieser Arbeit gewähren Einblicke in kosteneffiziente Technologiekombinationen, welche die Transformation zu einem nachhaltigeren Energiesystem unterstützen können. Allerdings können Hindernisse zur Verbreitung dieser Technologien existieren. Um diese Hindernisse zu überwinden, müssen geeignete politische Strategien entwickelt und erfolgreich implementiert werden.

Stichwörter: Schweizer Energiesystem, nachhaltige Entwicklung, Klimawandel, Klimaschutz, Atompolitik, Energiesicherheit, Energie sparen, Effizienz, Technologien

Chapter 1

Introduction

Following Switzerland's concept of sustainable development (BFS, 2012) and the definition of sustainable development as used in the Brundtland report (UNWCED (United Nations World Commission on Environment and Development), 1987), a sustainable energy system can be understood as an energy system, that achieves "qualitative objectives of social solidarity, environmental responsibility and economic efficiency" (BFS, 2012, p. 5) and "seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" (UNWCED (United Nations World Commission on Environment and Development), 1987). Such an energy system is in line with Article 89 of the Federal Constitution of the Swiss Confederation (BSE, 1999) describing the Swiss energy policy aims of a "sufficient, diverse, safe, economic and environmentally sustainable energy supply" and an "economic and efficient use of energy".

Today's Swiss energy system with its relatively high dependency on imported and carbon-intensive fossil fuels such as oil and gas does not correspond to the abovementioned characterisation of a sustainable energy system. In order to achieve such an energy system and face key challenges related to energy security, climate change mitigation, and a more rational use of energy, fossil fuel consumption would have to be significantly reduced. Achieving this target will likely require a substantial transformation of the energy system, which is an ambitious undertaking in its own right. However, such a transformation is likely to be even more difficult to achieve given that Switzerland recently decided to phase-out nuclear power (BFE, 2011e), important electricity import contracts with France will expire, and domestic renewable energy sources (such as wind, solar, and biomass) have limited potentials.

Realizing the abovementioned transformation of the Swiss energy system will require decisions on the allocation of resources and an emphasis on research and development of suitable technologies supporting such a transition of the energy system. These decisions that have to be taken by policy-makers, stakeholders, and society are subject as a whole to considerable uncertainty in different aspects related to developments of international energy prices, availability of future electricity supply options, and developments of economic and population growth driving energy service demands. In order to take optimal decisions it is crucial to know and understand the main uncertainties and how they could affect the future energy system.

1.1 Scope of the analysis

The overall objective of this dissertation is to improve understanding of how a more sustainable Swiss energy system can be realised from a technology perspective and how key uncertainties could affect cost-optimal technology choice in the future energy system. In doing so, robust technology combination pathways until the middle of the century are identified and policy implications formulated in order to support policy-makers and stakeholders in decision making supporting the realisation of the transformation towards a sustainable energy system in Switzerland. In the scope of this thesis, key aspects of a sustainable energy system including CO_2 emissions, energy security, and economics are analysed. However, other aspects related to sustainability such as social impacts, ecosystem damages and others are not adressed in this analysis.

1.2 Methodology

For improving the understanding of the realisation of a sustainable Swiss energy system a set of scenarios representing major uncertainties related to the future energy system has been developed and analysed using the Swiss MARKAL energy system model (SMM) initiated by Labriet (2003), further developed by Schulz (2007), and further revised, updated, and restructured as part of this thesis. SMM is a technology-rich bottom-up perfect-foresight optimisation model of the entire Swiss energy system including energy supply, conversion, and end-use demand sectors including a highly detailed representation of energy efficiency technologies. SMM identifies the least-cost combination of fuels and technologies to satisfy energy service demands over a given time horizon by taking into account technical, policy and external constraints. The fact that the SMM covers the entire energy system allows the analysis of system-wide effects and cross-sectoral dependencies.

In the scope of this work, SMM has been further extended in different aspects including:

- The development and implementation of a Carbon Capture and Storage (CCS) module
- An update on technology parameters in the electricity sector and other parts of the model
- A recalibration of the entire energy system to 2010 statistics
- An update on energy service demands based on recent projections of socio-economic parameters
- A fundamental revision and rebuild of the industrial sector including energy efficiency, fuel switching, and cogeneration options

The extension of SMM with a representation of CCS technologies allowed to analyse the potential role of this technology option in the energy system. By updating technology parameters the consistency and actuality of the technologies could be improved. With the recalibration, assured that the model's start year is in line with current statistics. Further, the energy service demand update improves the consistency with more recent projections of economic and population growth. Additionally, the rebuild of the industrial sector including implementation of energy efficiency technologies allowed for a more detailed analysis of this sector.

The uncertainties analysed within this dissertation comprise different levels of support for new nuclear power plants and centralised fossil electricity generation technologies, different CO_2 emissions reduction targets, sensitivities on energy prices, the availability of alternative low-carbon electricity technologies such as gas plants with CCS, and alternative energy service demand projections.

1.3 Structure of the thesis

The work of this dissertation is organised in different chapters analysing and discussing the main uncertainties and their potential impact on the future energy system and the policy implications related to optimal technology combinations. Chapter 2 provides the motivation for this analysis. The methodology including a detailed description of the Swiss MARKAL modelling framework and key scenario and model assumptions is given in chapter 3. Further, a first part of model extensions and scenarios developed and analysed within this dissertation is presented.

Chapter 4 presents a scenario analysis of uncertainties related to future support for new nuclear power plants and large centralised fossil-based electricity generation technologies. These electricity supply options are tested for different climate mitigation targets. In addition, a sensitivity analysis on energy prices illuminates the impact of international fossil fuel prices on the future energy system. Some of the results presented in chapter 4 have been published in Weidmann et al. (2009) and Weidmann et al. (2012a). In chapter 5, the implementation of CCS technologies into SMM is described and the potential role of Carbon Capture and Storage supporting climate change mitigation is presented. Selected results shown in this chapter have been presented in various conferences (Weidmann and Turton, 2012a,b; Weidmann et al., 2012b) and at the Swiss Federal Office of Energy (Weidmann, 2012). Chapter 6 then describes extensive additional structural developments of key end-use sectors of SMM and chapter 7 includes an update on energy service demands based on recent population and GDP growth projections and the restructuring and rebuild of the industrial sector. Further, in this chapter a scenario analysis with the updated energy service demands is presented. Chapter 8 includes a summary and an overall discussion of the scenario analyses presented in chapters 4 to 7 and gives policy implications.

Chapter 2

Challenges for the future Swiss energy system

2.1 Introduction

A sustainable and safe energy system is the fundament of a society's wealth and quality of life today and in the future. In the coming years the Swiss energy system is likely to face major global and national challenges related to climate change mitigation, energy security, and economic and population growth that could endanger today's high levels of wealth and quality of life (e.g. due to electricity blackouts or fossil fuel delivery bottlenecks, amongst others). Successfully coping with these challenges requires a transformation of the Swiss energy system in the not so distant future implying that already now important (policy) decisions have to be taken and investments into infrastructure (e.g. electric grids) need to be done. As future developments are naturally subject to considerable uncertainty, developing the right strategies related to the transformation of the energy system becomes an even more difficult task.

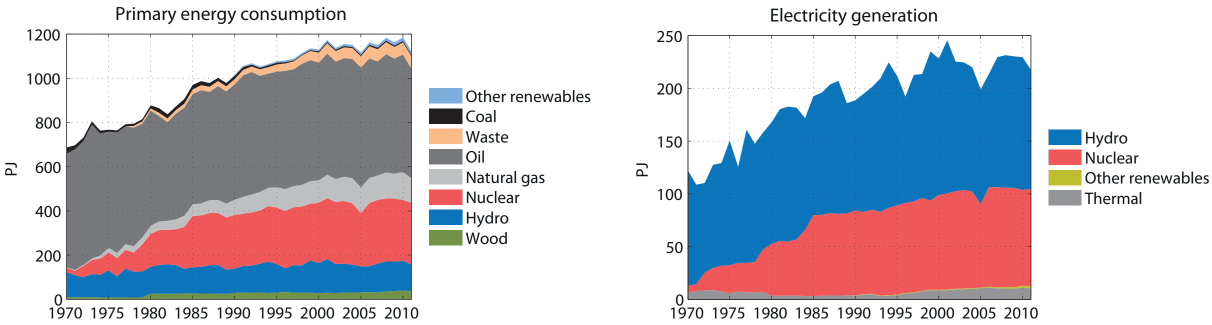
This chapter starts with a characterisation of today's Swiss energy system and a description of historical developments of energy consumption and their main drivers. Then, a selection of important challenges related to the realisation of a sustainable energy system and some background on current Swiss energy and climate policy is given. Further, an overview on energy system scenarios developed within other studies and a motivation for the work conducted within the framework of this dissertation is presented.

2.2 The Swiss energy system today and historical developments

Primary energy consumption (PEC) in Switzerland was 1097 PJ in 2010 (BFE, 2011f) accounting for only 0.2% of the total PEC worldwide (IEA, 2010). However, Swiss per capita consumption of 4786[1] Watt[2] (W) is almost twice the global average of 2452 W.

[1] The value for PEC in Switzerland doesn't include grey energy of roughly 4000 W/cap (PSI, 2007) used for the production of goods imported to Switzerland.

[2] The power unit 'Watt' is used here following the idea of the 2000 Watt society (Hirschberg et al., 2007) and corresponds to an annual consumption of 63 GJ.



(a) Primary energy consumption

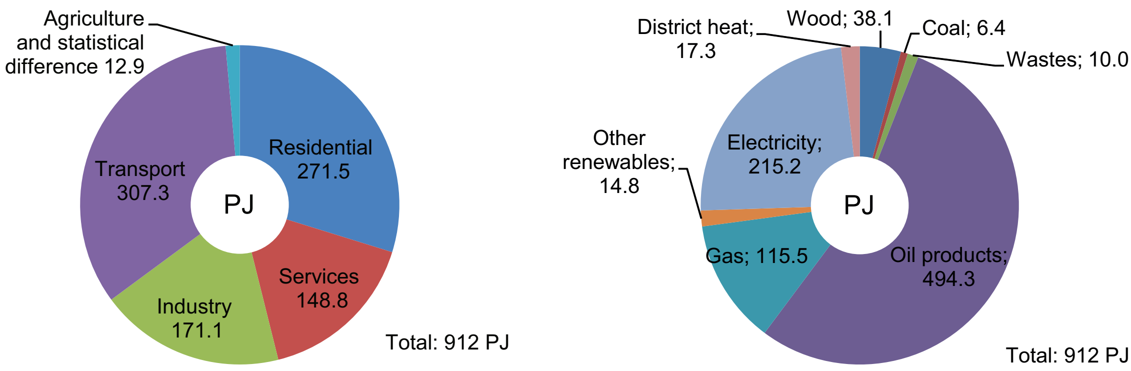
(b) Electricity generation

Figure 2.1: Historical primary energy consumption and electricity generation in Switzerland (Source: BFE (2011f))

As Figure 2.1(a) shows, Switzerland strongly relies on imported energy carriers such as nuclear and fossil fuels accounting for 79% of total Swiss PEC in 2010 (BFE, 2011f). Since fossil fuels such as oil and gas are largely sourced from politically unstable regions in the world there is a risk of scarcities along with sudden price increases of these energy carriers. This fact can have consequences for the security of and the access to affordable energy supply in the Swiss energy system (as discussed in section 2.3.2). Of the domestic resources, hydro has the largest share (11%) followed by the rest including wastes, biomass, and other renewables (10%).

Total Swiss electricity generation of 239 PJ in 2010 is mainly based on hydro (56.5%) and nuclear (38.0%) (BFE, 2011f) (Figure 2.1(b)). Conventional thermal and new renewable electricity production accounts only for about 5.4% of the total. Consequently, today's electricity generation mix is almost carbon-free. With its pumped storage capacities, Switzerland is able to "store" electricity. This allows imports when international electricity prices are low and exports at higher prices. Hence, trade of electricity plays an important role for the country. However, annual imports and exports are historically in a close balance. Beside their role in trade, the pumped storage plants also contribute to the control of the electric grid.

Swiss final energy consumption of 912 PJ in 2010 (BFE, 2011f) is mainly consumed in the transport (33.7%), residential (29.8%), industry (18.8%), and services (16.3%) sectors (Figure 2.2(a)). Agriculture along with the statistical difference only accounts for 1.4%. The breakdown into fuel types shows that oil products (54.2%) account for the largest share, followed by electricity (23.6%), and gas (12.7%) (Figure 2.2(b)). The rest, comprising wood, coal, wastes, and other energy carriers account for 9.5%. Approximately 36% of total final energy is consumed for space heating in buildings and one quarter for mobility (BFE, 2012a). Despite an increased deployment of alternative heating systems such as heat pumps, district heating, and solar thermal during the last decade the residential space heating sector still strongly relies on fossil fuels such as oil and gas, accounting for 75% of total final energy consumption in this sector. In the transport sector oil-based fuels (i.e. gasoline, diesel, and aviation fuels) play the dominant role (95%) while electricity and other fuels only account for around 5%. The current high penetration of diesel and gasoline in the car sector is partly related to the lack of cost-effective alternative drive-



(a) Final energy consumption by sector (b) Final energy consumption by energy carrier

Figure 2.2: Swiss final energy consumption by energy carrier and end-use sector in the year 2010 (Source: BFE (2011f))

train technologies such as natural gas, hydrogen, and electricity-based cars. Some of these technologies also have disadvantages in terms of range and longer refuelling (charging) times compared to the conventional gasoline and diesel cars.

The substantial use of fossil fuels in the Swiss energy system produced 39.54 million tons of CO_2 emissions in 2010 (BAFU, 2012a). The transport sector is the largest emitter of CO_2 with 44% followed by the residential sector (29%). The rest, including services (13%) and the industrial (14%) sector accounted for less than one third of the total CO_2 emissions in 2010.

For the outlook to the future energy system it can be helpful to consider historical developments and driving factors such as economic and population growth. In order to better understand the relation between Primary energy consumption and the gross domestic product (GDP) and population (POP), the PEC can be decomposed into the product of energy intensity (PEC/GDP)[3], income (GDP/POP), and population (Equation 2.1).

$$PEC = \underbrace{\frac{PEC}{GDP}}_{Energy\ intensity} \cdot \underbrace{\frac{GDP}{POP}}_{Income} \cdot POP \tag{2.1}$$

Between 1950 and 2010 Swiss total PEC grew by 662%, while the growth is slightly lower in the last 30 years compared to the time between 1950 and 1980 (Figure 2.3). While population shows a rather steady growth over the whole 60 years, the lower increase in PEC in the last decades seems to be related to the flattening of energy consumption per capita resulting from two opposed and balancing developments, an increase in income (GDP/capita) and a decrease in energy intensity (PEC/GDP). Given the rather constant energy consumption over the last decades population and income seem to be main drivers for the increase in primary energy consumption.

[3]The energy intensity PEC/GDP can be further decomposed into the product of primary per final energy consumption (PEC/FEC) and final energy consumption per gross domestic product (FEC/GDP).

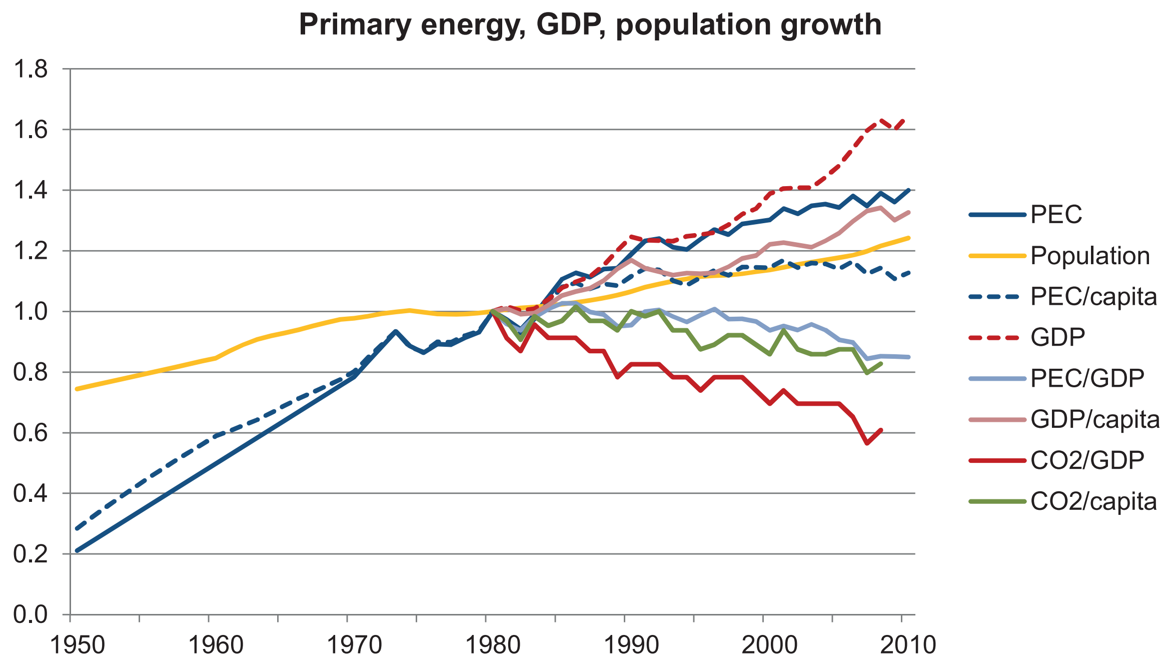


Figure 2.3: Historical growth of primary energy consumption, population, and GDP in Switzerland (1980=100%) (Source: BFE (2011f); www.gapminder.org)

As the historical development of Swiss CO_2 emissions in relation to economic and population growth shows, the emission intensities of the economic output (CO_2 per GDP) and population (CO_2 per capita) have decreased by 39% and 17% respectively between the years 1980 and 2008 (Figure 2.3). However, the dependency between CO_2 emissions and these key socio-economic parameters is still significant and it is unclear how they can be further decoupled during the coming decades.

2.3 Challenges related to the future energy system

The transformation to a sustainable Swiss energy system is affected by a number of challenges related to economic, social, and environmental issues. Many of these challenges have to be mastered in order to realize the goal of a sustainable energy system. Some of the main challenges are introduced below.

2.3.1 Climate change mitigation

The climate change effect caused by an increase in global temperature due to an excess of greenhouse gases (GHG) can have severe impacts on mankind related to rising sea-levels, damage to crops, and others (UNFCCC, 2011b). International action is needed to reduce anthropogenic CO_2 emissions being one of the main GHGs. Switzerland, as an Annex I party of the United Nations Framework Convention on Climate Change (UNFCCC), committed to reduce its GHG emission average level for the years 2008-2012 by 8% relative to the 1990 level (UNFCCC, 1998). Although Switzerland did not reach this target it intends continuing and intensifying its efforts (see section 2.4). A reduction in domestic

CO_2 emissions requires a transformation of today's relatively carbon-intensive energy system towards a more sustainable energy system less relying on fossil fuels. Particularly, in carbon-intensive end-use sectors such as space heating and transport, strong reductions are needed. However, transformations in these sectors can be most challenging since a number of barriers exist that hinder the realization of a low-carbon energy system while many abatement options are already cost-effective today. Some of the main barriers are discussed in section 2.3.6.

2.3.2 Energy security and energy price developments

Another important issue regarding the future energy system is supply security. With its high reliance on imported fossil energy carriers (i.e. crude oil, oil products, and natural gas) Switzerland strongly depends on foreign countries including some in politically unstable areas[4]. The instability of these regions can result in supply problems due to production disruptions or intentional suspension of deliveries (as a measure of political pressure). These interruptions of supply can lead to scarcity of energy carriers on international markets which again can cause an increase in energy prices. Such price volatilities decrease the planning reliability of the actors in an economy. One option of mastering the issue of security of supply and reducing the dependency on fuel imports from foreign countries is to decrease the need for fossil fuels in the energy system. While there are areas where these reductions can be realized more easily e.g. in the building sector where fossil fuels can be replaced by alternative non fossil-heating systems, there are other areas where fossil fuels are more difficult to substitute (e.g. for energy service demands relying on fuels with high energy densities such as road and air transport).

2.3.3 Policy decisions

Policy decisions can also be challenging for the energy system in many aspects. On one hand, decisions like the recently decided nuclear phase-out in Switzerland[5] or the Swiss commitment to the UNFCCC (UNFCCC, 1998) can impose additional constraints on the energy system. On the other hand, taking the right policy decisions and finding good strategies to reach the defined goals can be difficult. For example, even if a long term climate target is known, the cost-optimal CO_2 emissions reduction pathways can still be unclear. Suboptimal or even wrong policy decision can possibly result in missing the goals or causing additional costs for the energy system.

Besides energy and climate policy decisions there are also policy decisions related to other areas (e.g. commerce, environment, land-use planning, transport, industry, and others) that can have an indirect impact on the energy system. For example, policy decisions in land-use planning can change settlement patterns leading to changes in mobility demands of the population. Further, decisions on landscape protection can restrict the potentials for wind-based power generation. Environmental policies such as residual water restrictions in rivers can have an impact on hydro-electric generation levels.

[4] In 2011, Switzerland imported crude oil and oil products from Europe (64.3%), Africa (11.8%), and the rest of the world (23.9%) (EV, 2012). For natural gas, the imports source from the EU (43%), Norway (21%), Russia (22%), and Others (14%) (VSG, 2012).

[5] After the catastrophe of Fukushima in 2011 the Swiss government decided to phase-out nuclear power by not replacing existing nuclear power plants after they reach the end of their lifetimes (BFE, 2011e).

2.3.4 Uncertainty of availability and performance of future technologies

Given the strong need for a transformation of today's energy system towards a more sustainable and less carbon-intensive energy system, the availability of future technologies is likely to play a key role. Today, many promising technologies are not (yet) available or mature or cost-effective. If and when some of these technologies achieve the marketability and can be deployed on a large scale highly depends on different factors such as solving technical problems existing today and reducing costs to cost-effective levels by improvements in R&D, achieving enough social acceptance, and in many cases the required political support. There is a number of potential large-scale sources for providing low-carbon electricity in the Swiss energy system including geothermal energy, solar PV, wind, and gas plants with carbon capture and storage (CCS). While wind is today a mature and cost-effective technology, the future deployment mainly depends on the availability of suitable locations and public acceptance related to landscape protection. For a successful penetration of solar PV, it will be crucial how fast capital costs can be reduced. In the case of geothermal energy and CCS along with the issues related to costs and public acceptance also major technical and geological challenges have to be mastered before a commercial breakthrough can be realised. In order to account for the high uncertainty related to a future deployment of CCS in Switzerland the potential role of this technology option in the Swiss energy system is analysed in chapter 5.

2.3.5 Socio- and macroeconomic developments

As mentioned in section 2.2, energy consumption was in the past closely linked to socio- and macroeconomic factors such as population and economic growth. Given that these factors continue growing as projected in BFS (2010) and BFE (2012a) (i.e. 14.6% increase in population and 46.5% in GDP until 2050), a decoupling of future energy consumption and of these factors will most likely be necessary in order to cope with major challenges related to climate change mitigation and security of supply. Further, there is a trend in electrification of the energy system (the share of electricity in total final energy consumption has increased from 21.0% in 1990 to 23.6% in 2010) partially driven by an increased deployment of electric appliances (e.g. for I&C and entertainment) across many sectors. It is assumed that this trend of electrification will continue (Prognos, 2012) and hence the need for alternative low-carbon electricity sources would become even more important.

2.3.6 Potential barriers towards a transformation of the energy system

As mentioned above, there are barriers that prevent the deployment of technologies in the energy system although they are cost-effective from both the perspective of the entire energy system as a whole and from the individual consumer's point of view. Such barriers to technology diffusion, as also discussed for the case of compact fluorescent lamps in Lefèvre et al. (2006), can occur for many reasons:

- Split incentives: Often not the same person who does an investment also directly benefits from it. For example, in the residential buildings sector, the landlord of a multifamily house pays for a renovation with the result of a better insulated building but the renter benefits from economic savings due to the lower heating energy costs.

- Time horizon of investment: An individual investor might have a shorter time horizon for an investment (possibly due to his advanced age) than the technical lifetime of an investment. In such a case he might not do an investment since he will not experience the benefit from it.
- Lack of information: Although an investor would decide for an investment he doesn't due to a lack of information (e.g. because he doesn't know the existence of a certain technology).
- Level of investment costs: In some cases also the high investment costs hinder an individual from an investment, since the investment cost is too high and he cannot or is not willing to afford it.
- Technological, infrastructural barriers: There are technologies having certain advantages compared to others but also show some technical issues that are not (yet) resolved. While natural gas based passenger cars become more and more cost-effective, there are relatively few filling stations, preventing individuals from buying such cars.

2.4 Swiss energy and climate policy

There are important goals supporting a sustainable energy system including climate mitigation targets and guaranteeing the high level of security of energy and electricity supply. In order to achieve goals related to climate change mitigation according to the Swiss commitment to the UNFCCC (UNFCCC, 1998) there exists the CO_2 law comprising reduction targets for CO_2 emissions from the combustion of fossil heating and motor fuels[6] and measures to reach theses targets such as the CO_2 tax on fossil heating fuels. The CO_2 law has recently been updated for the time after 2012 (BAFU, 2013). Key points of the update include a 20%-reduction target for domestic CO_2 emissions for the year 2020 (relative to the 1990 level) and adjustments in the redistribution of the CO_2 tax, the relief for energy intensive enterprises, and an increased compatibility of the Swiss with the European emission trading system. Further, the updated CO_2 law foresees a possible increase in the CO_2 tax on fossil heating fuels of today CHF 36 per ton of CO_2 to CHF 60 per ton of CO_2 if intermediate reduction targets are not met.

After the catastrophe of Fukushima and the decision on phasing out nuclear power in Switzerland the government developed a strategy paper the "Energiestrategie 2050" (BFE, 2011d) including measures in order to achieve the abovementioned goals of climate change mitigation and security of supply under the new nuclear policy. The first package of measures of the "Energiestrategie 2050" is currently under consultation ("Vernehmlassung") and includes a 35% reduction of per capita energy demand until 2035 and a stabilisation of total electricity demand after 2020. For achieving these goals the deployment of efficiency measures across key sectors of the energy system is to be intensified. The reinforcement of

[6]Domestic CO_2 emissions from the energetic use of fossil fuels had to be reduced by 10% (heating fuels by 15% and motor fuels by 8%) relative to the 1990 level.

the building program ("Gebäudeprogramm") supporting energetic renovations and more stringent regulations for new and old buildings will play an important role. In the passenger car sector, more stringent emission prescriptions for new cars are foreseen. In the industrial sector, reliable agreements with enterprises are planned. In order to satisfy electricity demands when nuclear capacity falls away, hydro and new renewable capacities will be extended amongst others with an adaptation of measures related to the feed-in remuneration at cost ("Kostendeckende Einspeisevergütung"). If for the satisfaction of electricity demands more capacity is needed, fossil generation (combined heat and power plants and natural gas combined cycle plants) and electricity imports are allowed. The possible increase in power generation and the more decentralised character of the electricity system (due to significant deployment of new renewables such as wind and solar PV) will likely require an extension of the electric grid. All these measures are accompanied with intensification in energy research. For the time after 2020 further measures are planned including the combination of the CO_2 tax and the existing feed-in tariff tax into a new energy tax. Such an ecological tax reform will be developed and is planned to go under consultation mid-2014.

The abovementioned goals and measures of the current Swiss energy and climate policy are a needed framework to successfully coping with some of the challenges for the Swiss energy system described in section 2.3. Regulations and financial incentives to the deployment of energy efficient and low-carbon technologies will likely support the realisation of the transformation towards a more sustainable energy system successfully facing challenges related to energy security and climate change mitigation. However, it is uncertain if the policy measures and instruments are sufficient to meet the given targets, and, assuming that they are, if the policies are optimal from a cost perspective. One way of gaining some insight into these uncertainties related to cost-optimality of energy and climate policies can be the application of cost-optimisation models analysing scenarios of the future energy system.

2.5 Overview on scenarios of the future energy system

There exists a wide range of studies looking at different scenarios of the future energy system comprising some of the abovementioned goals related to climate change mitigation and security of supply. While several studies analyse the energy system as a whole, others focus on specific parts of it. For the electricity sector as one of the key sectors of the energy system a set of scenarios has recently been published. In order to give an overview on existing work and to identify possible areas that could be complemented by the analysis conducted within the scope of this dissertation results from five recent studies are compared. This comparison comprises a set of electricity generation mix scenarios for the year 2050 from the following studies.

- Bundesamt für Energie (BFE): Energieperspektiven 2050 (BFE, 2012a)
- Verband Schweizerischer Elektrizitätsunternehmen (VSE): Wege in die neue Stromzukunft (VSE, 2010)

- Swisscleantech (SCT): Energiestrategie (Barmettler et al., 2012)
- ETH Zürich (ETH): Energiezukunft Schweiz (Andersson et al., 2011)
- Energie-Trialog Schweiz (ETS): Energie-Strategie 2050 - Impulse für die schweizerische Energiepolitik. Grundlagenbericht (ETS, 2009)

Despite a lack of transparency, it seems that there are similarities and significant differences between the five studies in terms of their scopes and methodologies. According to their descriptions, it can be assumed that all studies use some sort of quantitative models fed with a set input assumptions partially based on expert judgements. As an example, for the ETS study, being an output of the extensive Energietrialog project[7], important input assumptions such as domestic potentials for renewable energy technologies were elaborated within a core group of experts. An important difference between the studies is related to their scopes. While the BFE, SCT, ETH, and ETS studies look at the entire energy system, the VSE study covers only the electricity sector. The BFE-scenarios are combinations of the "Weiter Wie Bisher" (WWB), the "New Energy Policy" (NEP), and the "Politische Massnahmen" (POM) scenarios with the electricity supply scenarios C (fossil centralised), E (renewable energy), and C&E (combination of fossil centralised and renewable energy) as described in Prognos (2012). The VSE scenarios were developed by 50 experts and are based on hourly model results of electricity demand until 2050. The SCT-scenarios were analysed with the Cleantech-model based on 100 parameters including potentials for domestic renewable resources and efficiency measures. The scenario presented in the ETH study is based on bottom-up and top-down modelling approaches in order to analyse technological and macroeconomic aspects of the energy system (see Andersson et al., 2011, p. 4). The scenarios in all studies include the recent policy decision on phasing out nuclear power in Switzerland (i.e. existing nuclear power cannot be replaced at the end of their lifetimes) (BFE, 2011e). Further, Carbon Capture and Storage (CCS)-technologies are assumed to not be available in the year 2050.

As one would expect, there are also significant differences between the scenario results of the five studies partially related to the diversity of the methodologies applied and the assumptions on key scenario input parameters such as resource potentials for renewables. Additionally, the studies are likely to have different assumptions on costs and/or policy support for some technologies. Figure 2.4 shows an overview on the electricity generation mix in the year 2050 for a set of scenarios from the studies introduced above. There are differences in total generation, levels of imported electricity, and resource potentials for new renewables such as solar PV, wind, geothermal, and biomass. In particular, the SCT-study assumes, with 22.5 TWh per year, a significantly higher potential for electricity from solar PV than other scenarios. While in some of the BFE scenarios (particularly in scenarios with electricity supply variant C) electricity from gas combined-cycle plants plays an important role, its use is significantly lower in most of the other scenarios. In contrast to the technologies mentioned, the levels of hydro-based power generation seem to be more similar across the scenarios analysed.

[7]The Energie Trialog project (2007-2010) involved representatives from science, economy, and society and aimed at contributing to the development of sustainable long-term energy policies and resulted in the publication of the Energie-Strategie Schweiz in 2009 (ETS, 2009). PSI's Laboratory for Energy Systems Analysis contributed to the project with an input study (Weidmann et al., 2009).

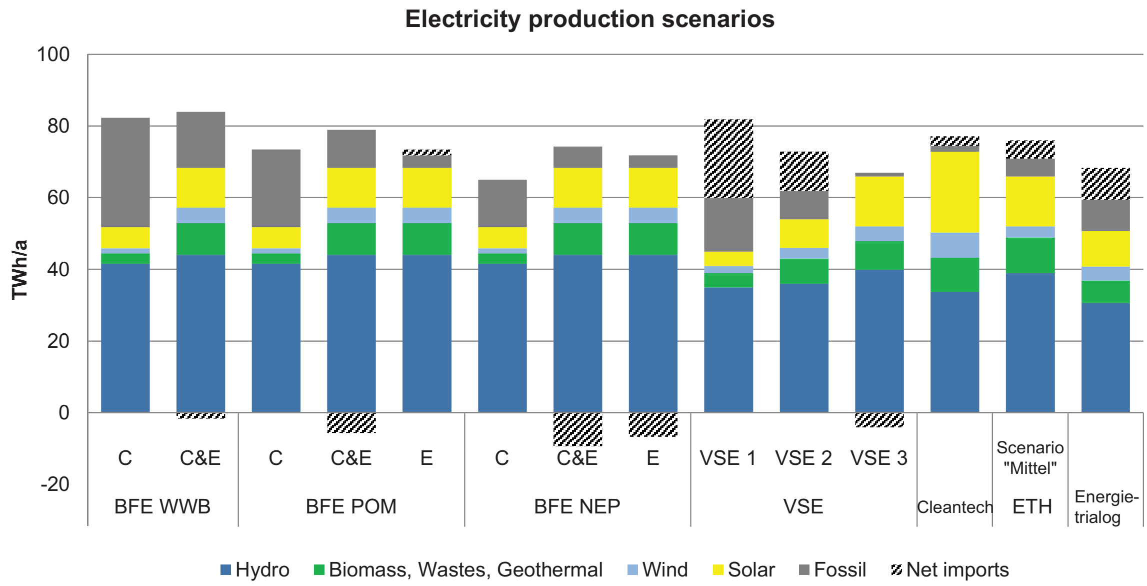


Figure 2.4: Electricity generation for the year 2050 from different scenarios in Switzerland (Sources: BFE (2012a), VSE (2010), Barmettler et al. (2012), Andersson et al. (2011), and ETS (2009))

The comparison of the different scenarios gives an interesting overview on how the future energy system could develop under a given set of assumptions. Unfortunately, based on the information available it is difficult to determine which assumptions are driving the differences between the scenario results in detail. For better understanding more information on the methodologies in general and the models in particular, as well as on the input assumptions including technology characteristics would be needed.

According to the information about these models I assume that the technology choices in the scenarios are driven by different factors but are most likely not a result from a pure cost-optimisation, implying that these technology choices are not necessarily cost-optimal with respect to the input assumptions. Non cost-optimal technology choices are related with additional costs that would have to be carried by the individual actors of the energy system or by the society as a whole. Further, the descriptions of the methodologies of the five studies imply that important technologies are represented in all the models. However, it seems that the level of technology detail could be limited in some models.

Due to the limitations related to non-cost-optimality and limited technology detail of the existing scenarios (including those presented above) further analysis using a technology-rich bottom-up cost-optimisation model of the entire Swiss energy system such as the Swiss MARKAL Model (SMM) could give additional insights related to the cost-effectiveness of technologies in the context of the entire energy system. Especially, the system-approach of SMM would allow for the analysis of cross-sectoral trade-offs between the different parts of the energy system. Doing so, least-cost pathways towards the future energy system under a given set of assumptions can be identified. Given the significant uncertainty related to the development of the future energy system (that is also indicated by the differences between the scenarios compared above) and the lack of analyses using technology-rich cost-optimisation models further analysis with SMM Model would add substantial value to the research field.

2.6 Motivation

For successfully coping with major challenges related to climate change mitigation and energy security a transformation of today's strongly fossil-based to a more sustainable Swiss energy system is required. After the policy decision on phasing out nuclear power in Switzerland the need for alternative technologies supporting the realisation of a low-carbon energy system has increased. The deployment of cost-effective technology combinations will likely play a key role in the upcoming transformation of the energy system. The significant uncertainty of future developments related to policy decisions, energy prices, availability of technologies, and resource potentials can have an impact on the choice of technologies. One way of resolving some of these uncertainties is development and analysis of scenarios of the future energy system. As shown in the last section a number of studies looking at scenarios of the future Swiss energy system has been presented. In order to extend this work and deepen the understanding of technology combinations supporting a sustainable energy system an extended version of the Swiss MARKAL Model has been developed and applied for the analysis of a number of scenarios in the course of this dissertation. The methodology in general and the description of the Swiss MARKAL Model is given in the next chapter.

Chapter 3

Swiss MARKAL energy system modelling framework: model description and key scenario assumptions

3.1 Introduction

The realization of a sustainable future Swiss energy system depends on a number of highly uncertain factors such as economic and population growth, the development of international energy prices, and the availability of low-carbon electricity generation technologies. Given that a small country like Switzerland has only insignificant influence on many of these (external) factors, it is crucial that Swiss policy makers and stakeholders take the right decisions to support technology choices that could support the realisation of a sustainable energy system. Due to the above mentioned uncertainties related to future developments and the complexity of the energy system, it can be most challenging for decision makers to elaborate the best long-term strategies supporting the pursued goal of a sustainable Swiss energy system.

One way of overcoming this challenge and resolving main uncertainties is the application of suitable analytical tools such as energy system models that are appropriate for the analysis of long-term scenarios related to developments of the future energy system. Under the large variety of energy system models looking at different energy related aspects, the Swiss MARKAL energy system model (SMM) has been considered to be the most suitable tool available to address the main questions within the scope of this work. The technology-richness of SMM allows the analysis in detail of technology options under different conditions and the identification of robust combinations of technologies and fuels that could play a role in the future Swiss energy system. Scenario analysis can be a useful instrument to improve the understanding of possible future developments of an energy system and explore "what-if"-type questions related to the configuration of the future energy system under a given set of assumptions. However, scenario analysis is less suitable to provide answers with predictive character.

This chapter introduces the Swiss MARKAL modelling framework including both the previous model version as presented in Schulz (2007) and further developments of model and scenarios. Section 3.2 presents an overview on the Swiss MARKAL Model including the model structure and key model and scenario assumptions. Sections 3.3 and 3.4 introduce main model and scenario developments conducted in the context of this thesis, and in the last section 3.5 methodological applicabilities and limitations are given.

3.2 Swiss MARKAL model[1]

The Swiss MARKAL[2] Model (SMM) is a technology-rich bottom-up perfect-foresight optimisation model of the entire Swiss energy system including energy supply, conversion, and end-use demand sectors. SMM identifies the least-cost combination of fuels and technologies to satisfy energy service demands over a given time horizon by taking into account technical, policy and external constraints. Some of SMM's strengths are its highly detailed representation of energy efficiency technologies in key end-use demand sectors and the fact that the model covers the entire energy system allowing the analysis of system-wide effects and cross-sectoral dependencies. The "perfect foresight" of the model means that the model optimizes based on full information about the future and takes cost-optimal decisions in each time-period. This leads to a least-cost energy system for the whole time horizon. In addition, the model acts as a single social planner so determines the least-cost options for the full energy system rather than individual consumers or a single sector.

Energy service demands are exogenous inputs to the model, along with a wide range of technical and cost details for different technology options for resource extraction, energy conversion, transmission and distribution, and end-use devices. Primary and final energy demands, electricity consumption, CO_2-emissions, and energy system costs are outputs of the model. Hence, SMM is an ideal tool to analyse potential impacts of policy decisions and other uncertainties on key economic and environmental indicators of the energy system.

The development of the Swiss MARKAL model was firstly initiated at the University of Geneva (Labriet, 2003) and subsequently extended by the Paul Scherrer Institute (Schulz, 2007). It has been further developed and extended in the course of this dissertation, and used for a number of analyses (e.g Weidmann et al. (2009, 2012b,a); Weidmann and Turton (2012a,b); Sceia et al. (2012)). In the course of this dissertation two recalibrations and a number of smaller and larger model and scenario updates have been undertaken. In order to keep transparency we distinguish between following three model versions *SMM-S*, *SMM-W1*, and *SMM-W2*:

- *SMM-S* is the previous version of SMM and has been developed and calibrated to historical data from SFOE and IEA for the years 2000 and 2005 within Schulz (2007). This model version doesn't include any changes or updates since then.

[1] Some parts of the model description in this section have been published in Weidmann et al. (2009, 2012a,b); Weidmann and Turton (2012a,b), and Weidmann (2012).

[2] The MARKAL modelling framework was developed in a cooperative multinational project by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (Loulou et al., 2004).

- *SMM-W1* includes a first recalibration of selected sectors of the energy system (e.g. electricity and passenger cars) to SFOE statistics from 2009 (BFE, 2010a), and minor adjustments of key assumptions to the reference scenario, undertaken as part of this dissertation. SMM-W1 is used for the analysis presented in chapters 4 and 5. For some analyses this model version has been extended with selected technologies of interest in the particular analysis. In such cases the changes are indicated at the beginning of the respective sections. The development of SMM-W1 is presented in section 3.3.1.

- For *SMM-W2* a major update including restructuring and calibration of the entire energy system to 2010 statistics has been conducted as part of this dissertation. The development of SMM-W2 is presented in chapter 6 and the results from analyses with SMM-W2 are presented in chapters 6 and 7.

3.2.1 Model structure and description

The basis of SMM is the so called Reference Energy System (RES) (Figure 3.1) that includes an extensive representation of technologies and energy carriers across all main sectors of the energy system (i.e. energy supply, conversion, and end-use demand sectors). The RES covers both, technologies existing today and others that are assumed to become available in the future. Many technologies of the RES show a broad variety in input fuel types (e.g. gas-based vs. biomass-based electricity generation), efficiencies and costs. Besides the technologies and energy carriers, also carbon dioxide (CO_2) emissions from the combustion of fossil fuels are represented in the model. Carbon dioxide emissions are tracked at the source level where they are emitted (e.g. from an internal combustion engine of a gasoline car).

Energy supply and conversion sectors

The supply sector includes extraction of domestic primary (mainly renewable) resources (e.g. hydro, wind, solar, biomass, and industrial and municipal wastes) as well as imports of fossil fuels from abroad (i.e. oil, natural gas, coal, nuclear fuels). In SMM, import and extraction of energy carriers are modelled as so-called resource processes representing inputs of energy commodities into the energy system. Imports of energy carriers are considered to have unlimited availability (relative to the size of Switzerland) at the given import price assumed in a scenario. The extraction processes comprise extraction costs as well as limitations on the potentials of domestic resources. Details about the assumptions on domestic resources are given in section 3.3.1

The energy conversion sector includes electricity and heat generation as well as production of secondary energy carriers such as hydrogen (e.g. from steam reforming) and oil products (from refineries). The electricity sector covers a set of different generation technologies such as natural gas combined cycle (NGCC) plants, natural gas- and biomass-based combined heat and power (CHP) technologies, waste incineration plants, and power generation from nuclear, hydro, wind, and solar photovoltaic (PV) technologies. The electricity generation technologies in SMM have been updated for both SMM-W1 and SMM-W2 (see sections 3.3.1 and 3.3.2).

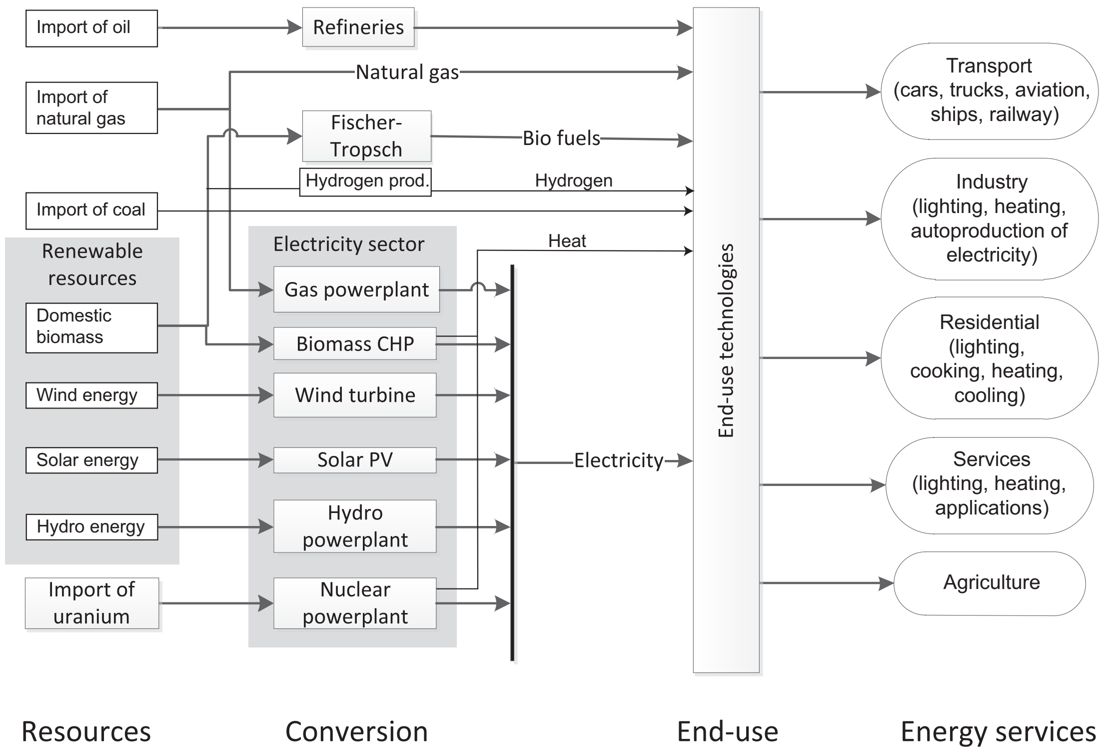


Figure 3.1: Simplified representation of the reference energy system in the Swiss MARKAL Model

End-use demand sectors

End-use demand sectors in SMM comprise the residential, transport, industrial, services, and agricultural sectors. These sectors as they are represented in SMM-S and SMM-W1 are shortly described below. For SMM-W2 the four sectors are restructured and updated. A description of this update is given in section 3.3.2 and chapter 6.

- The Swiss agricultural sector is small compared to the other end-use sectors (only around 1% of the total final energy consumption in 2010 (BFE, 2011f)) and is therefore represented in a rather simplified way without detailed representation of end-use technologies.

- The Services sector includes eight different energy service demands (ESD) namely cooling, cooking, space heating, hot water, lighting, office equipment, refrigeration, and other consumption. Each ESD can be satisfied by a set of end-use demand technologies that are different in technology type (e.g. heat pumps vs. resistance heaters), input fuel type (e.g. electricity vs. gas for hot water production), and other technology characteristics (e.g. higher/lower efficiencies, costs).

- Residential ESDs cover lighting, cooling, clothes drying, clothes washing, dish washing, refrigeration, other electric appliances (including information and communication and entertainment technologies, vacuum cleaners, micro waves, and others), space heating, and hot water. Unlike the services sector, the residential space heating sector also includes energy saving options representing technical measures to

Table 3.1: Residential heating demand categories in the Swiss MARKAL model

	Old buildings	New buildings
Single-family houses	RH1	RH2
Multi-family houses	RH3	RH4

reduce specific space heating demand (e.g. through investments in better insulated building envelopes). As described in detail by Schulz (2007) the energy saving options are based on marginal cost-curves of space heating saving technologies that have been developed in Jakob (2004) and Jakob et al. (2002). Due to the fact that space heating accounts for a relatively large share of total final energy demand in the residential sector, and the energy service demand technologies and saving options can be diverse for different sizes and vintages of buildings, this demand is divided into four categories RH1-RH4 addressing old and new buildings and multi- and single-family houses (Table 3.1).

- The industrial sector is disaggregated into six industrial branches, namely: chemicals, iron and steel, pulp and paper, non-ferrous metals, non-metals, and other industries. These industrial branch groups are modelled in SMM in a way that accounts for their different requirements for energy services such as steam, process heat, machine drives, electro chemical processes, and other services. For providing these services a set of industrial energy service technologies are available.

- In the transport sector, the following energy service demands are included: domestic and international air transport, buses, trucks, passenger cars, two-wheelers, passenger and freight rail, and domestic and international navigation. For each of the transportation demands a set of end-use demand technologies with different fuels and vintages is represented.

Time horizon and temporal resolution

The model has a time horizon of 50 years (2000 until 2050) that is divided into 11 five-year time periods. The temporal centre of a time period is January 1st of the time period's year (e.g. the time period of the year 2030 starts on July 1st, 2027 and ends on June 30, 2032. Each time period again is divided into six so-called "time slices" representing three seasons (summer, winter, and intermediate) and day and night to represent the temporal characteristics of demand and supply patterns.

3.2.2 Key model and scenario assumptions

There are a number of key model and scenario assumptions that typically can have a significant impact on the results of the scenario analysis. The most important assumptions are given in the following list:

- The exogenous energy service demands in SMM are based on projections for population ("A-trend" scenario presented in BFS (2001)) and GDP (SECO, 2004) growth projections. While GDP growth shows a rather steady increase by approximately 50% until 2050, population stays quite flat and increases from 7.2 million to 7.4

million and decreases again to 7.1 million people in 2050 (Figure 3.2). Besides population and economic growth there are also factors driving energy service demands in this analysis (e.g. projections of energy reference floor area, transport capacities). The demand projections based on these driver assumptions were adopted from Schulz (2007) and used for the analysis with model version SMM-W1. For the analysis with SMM-W2 updated demands based on recent socio-economic parameters were applied (section 3.3.2).

- Energy prices can have a significant impact on the cost-effectiveness of technologies and hence the configuration of the energy system. The prices for natural gas and crude oil for the references scenario were updated based on recent projections from the Energy Technology Perspectives (ETP) 2012 of the International Energy Agency (IEA) (IEA, 2012b). This update on energy prices in the reference scenario is described in section 3.4.1.

- For all scenarios analysed in this work it is assumed that annual electricity imports and exports stay balanced over the whole time horizon.

- Coal- and oil-based electricity generation are assumed not to be an option for the future Swiss energy system due to reasons related to climate change mitigation, high costs of oil, and practicability issues of transporting large amounts of coal from the extraction areas abroad to Switzerland.

- In the scenarios analysed geothermal-based electricity generation is not cost-effective and therefore also not mentioned in the results discussions. However, this technology option could play a role in the Swiss energy system depending on the political support and improvements in research and development.

- For the discounting of future energy system costs to present value the model uses a social discount rate[3] of 3% that reflects the real long-term yield on confederation bonds plus a risk premium for energy sector investments (SNB (Swiss National Bank), 2010).

- All cost assumptions in the model are in USD_{2000}, but the cost results are presented in CHF_{2010}[4] in this work.

3.3 Model developments

As mentioned in section 3.2, two major model updates and extensions resulting in model versions SMM-W1 and SMM-W2 have been conducted within the scope of this dissertation. Both model versions are described below.

[3] A social discount rate, as applied in this analysis, reflects a society's valuation of future costs compared to present costs and is typically different (lower) than the discount rate of an individual person or company. Some of the differences between the social and the individual discount rates come from the diverse types of risks a society and individuals are subject to in the future. Further, preferences for (investment) decisions can also be significantly different for individuals and for a society. For example: cost-effective installations in energy saving technologies in the building sector can be attractive from a society's point of view but are not from an individual's perspective due to the occurrence of investment barriers (see section 2.3.6).

[4] An exchange and inflation adjustment rate of 1.35 CHF_{2010} per USD_{2000} is used.

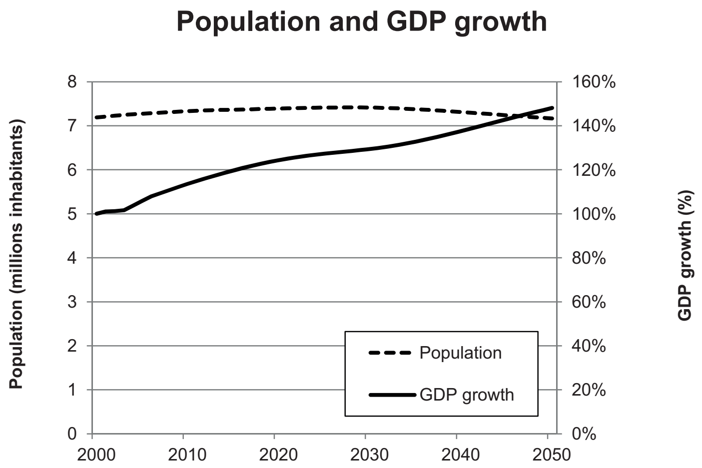


Figure 3.2: Swiss GDP and population growth projections in the Swiss MARKAL model (Sources: BFS (2001)), SECO (2004))

3.3.1 *SMM-W1*: electricity sector, resource potentials, CCS-module

Update of electricity generation technologies

In the electricity sector, the characteristics of generation technologies have been updated based on recent data from Hirschberg et al. (2010). In addition, more technology vintages have been added to the model to account for cost reductions and increase in efficiencies over time due to technology learning. Since only data for the years 2010, 2030, and 2050 were available, additional vintages for the years between these time-steps were interpolated. Table 3.2 shows the new set of electricity generation technologies after the update. It is important to note that the cost data of all electricity generation technologies as presented in Table 3.2 and used for this analysis reflect existing and future market prices of the technologies and do not include any kind of measures that reduce these prices (such as subsidies for renewable technologies).

Recalibration of the electricity sector

Since the previous model version SMM-S is calibrated to the years 2000 and 2005 a recalibration to more recent statistical data was considered to be necessary. For SMM-W1, the electricity sector as one of the key sectors in the energy system has been calibrated to 2009[5] energy statistics (BFE, 2010a). Table 3.3 shows the production of the electricity sector in the year 2009 used for the recalibration. The electricity sector of SMM-W2 is calibrated to the year 2010 based on BFE (2011f) as part of the recalibration of the entire energy system (see section 3.3.2 and chapter 6).

[5] Due to the five-year resolution of the Swiss MARKAL model the calibration was applied to the time-step of the year 2010.

Table 3.2: Updated electricity generation technologies in SMM-W1. The natural gas combined cycle (NGCC) and the natural gas combined heat and power (NGCHP) technologies are centralised. (Sources: Hirschberg et al. (2010) and own assumptions)

Technology	AF	INVCOST [CHF_{2010}/kW]	FIXOM [CHF_{2010}/kW]	VAROM [Rp_{2010}/kWh_e]	EFF elec.	EFF therm.	LIFE
Solar PV 2010	11%	6500	5	0.2	32%		40
Solar PV 2015	11%	5588	5	0.2	32%		40
Solar PV 2020	11%	4675	5	0.2	32%		40
Solar PV 2025	11%	3763	5	0.2	32%		40
Solar PV 2030	11%	2850	5	0.2	32%		40
Solar PV 2035	11%	2625	5	0.2	32%		40
Solar PV 2040	11%	2400	5	0.2	32%		40
Solar PV 2045	11%	2175	5	0.2	32%		40
Solar PV 2050	11%	1950	5	0.2	32%		40
Wind 2010	14%	2150	44	5.0	32%		20
Wind 2015	14%	2050	40	4.6	32%		20
Wind 2020	14%	1950	36	4.1	32%		20
Wind 2025	14%	1850	32	3.7	32%		20
Wind 2030	14%	1750	28	3.2	32%		20
Nuclear Gen2	91%	4250	23	1.2	32%		50
Nuclear Gen3	91%	4250	12	0.7	35%		60
Nuclear Gen4	90%	4750	55	0.1	40%		40
NGCC 2010	82%	1150	8	2.4	58%		25
NGCC 2030	82%	1050	8	2.4	63%		25
NGCC 2050	82%	1050	8	2.4	65%		25
NGCHP 2010	82%	1380	12	3.6	55%	25%	25
NGCHP 2030	82%	1260	12	3.6	58%	25%	25
NGCHP 2050	82%	1260	12	3.6	60%	25%	25

AF: Availability factor
INVCOST: Investment cost
FIXOM: Fixed O&M cost
VAROM: Varibable O&M cost
EFF: Efficiency
LIFE: Lifetime

Table 3.3: Swiss electricity generation in 2009 as used for the recalibration of the electricity sector in SMM-W1 (Source: BFE (2010a))

	[PJ]	[TWh]
Hydro	133.7	37.1
Nuclear	94.0	26.1
Conventional thermal	10.2	2.8
Renewables	1.5	0.4
Total	239.4	66.5

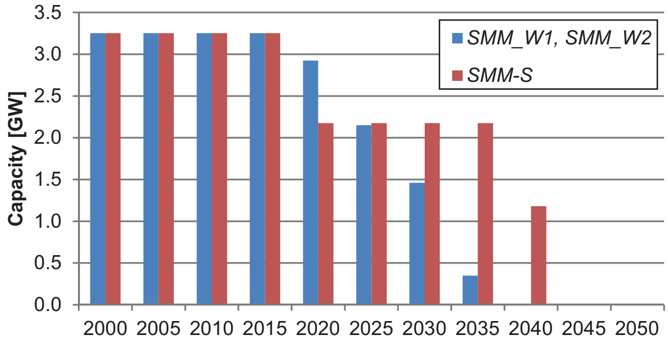


Figure 3.3: Residual capacity of existing nuclear power plants in SMM-S and SMM-W1 + SMM-W2 model versions. (Source: BFE (2011d))

Update of the nuclear power sector

Another area were an extension has been made is the nuclear power sector. In SMM-S the five existing Swiss nuclear power plants (i.e. Mühleberg, Beznau 1+2, Gösgen, and Leibstadt) are represented by one technology with a residual capacity decreasing over the time horizon according to assumptions on the lifetimes of the individual plants (i.e. between 45 and 55 years).

After the accident in Fukushima the Swiss government intensified the discussion about lifetimes of existing nuclear power plants and presented scenarios with 40- and 50-year lifetimes (BFE, 2011d). For our analysis we adopt the 50-year lifetime that is considered by the government as a business-as-usual scenario. The 50-year lifetimes lead to shutdown dates that are not in line with the five-year time periods of SMM. Hence, the nuclear residual capacity of a five-year time period had to be adjusted and averaged in a way that the total product of the residual capacity and the number of years of the time period it is available is equal to the averaged capacity times five (for the total number of years in one time period). Based on the new assumptions for lifetimes of nuclear power plants the total residual capacity in SMM-W1 has slightly changed compared to the assumptions in SMM-S. Figure 3.3 shows the total nuclear capacities before the update (SMM-S) and after the update (SMM-W1). As can be seen, the three small power plants (i.e. Beznau 1+2 and Mühleberg) are shut down earlier in SMM-S (between 2015 and 2020) than in SMM-W1 due to the five year lower assumptions on lifetime in SMM-S compared to SMM-W1. On the other hand in SMM-S the nuclear plants in Gösgen and Leibstadt are assumed to have a longer lifetime (around 55 years) than in SMM-W1 (50 years).

In addition to the update of total nuclear residual capacity also some structural adjustments were conducted. While in SMM-S the five existing nuclear power plants were combined in one technology, for SMM-W1 they are modelled as single plants. This adjustment opens for future work the possibility to differentiate between the five plants and their assumptions on technology parameters (e.g. costs, lifetimes, efficiencies etc...) and analyse them individually.

Potentials of domestic renewable sources

Domestic renewable potentials are limited by a number of factors including physical, technical, environmental, economic, and social aspects. Depending on the point of view, assessments of future renewable potentials can provide diverse results. Additionally, there is a significant level of uncertainty related to the projections of future potentials. These circumstances and the fact that assumptions on renewable potentials are important input parameters for scenario analysis were the reason for a revision and partial adjustments of the renewable potentials underlying SMM. Table 3.4 shows potentials for domestic renewables including wind, solar PV, biomass, and hydro before (SMM-S) and after the update (SMM-W1 and SMM-W2)[6]. All potentials presented in Table 3.4 and used in this study represent technical potentials that could be realistically implemented. However, for some technologies, supportive measures (e.g. feed-in tariffs) are likely required in order to overcome potential barriers to exploit the full potentials (see section 2.3.6 for a short introduction to potential barriers to the deployment of cost-effective technologies in the energy system).

Table 3.4: Domestic renewable potentials in Switzerland for the year 2050 as used in the Swiss MARKAL model before (SMM-S) and after (SMM-W1, SMM-W2) the update. (Sources: BFE (2012c), Schulz (2007), BFE (2012a), BFE (2004))

	SMM-W1/-W2		SMM-S	
	[PJ]	[TWh]	[PJ]	[TWh]
Hydro	137.2	38.1	136.0	37.8
Solar	49.3	13.7	49.3	13.7
Wind	15.1	4.2	14.4	4.0
Wood	62.8		103.0	
Biogas	36.7		7.5	

Carbon capture and storage (CCS) module

As introduced in the last section, there is significant uncertainty related to the future availability of Carbon Capture and Storage (CCS) technologies providing an alternative low-carbon electricity source. To resolve some of this uncertainty and analyse the potential role of CCS in the future Swiss energy system a CCS-module has been developed and implemented to the electricity sector of SMM-W1. The CCS-module represents a number of CCS technologies including natural gas combined cycle (NGCC) with CCS and natural gas combined heat and power (NGCHP) with CCS. Additionally, an option to decouple investments in the generation capacity and the CO_2 capture units has been added to the CCS module. In particular, this option allows retrofitting of earlier-built NGCC and NGCHP plants when capture units become available and cost-effective. In order to represent technological and cost improvements of CCS-technologies over time, different vintages for the years 2030 and 2050 have been included. For the CCS-ready gas plants (with the option to be retrofitted at a later time) a 2010-vintage has been

[6]For hydro, solar, and wind, the electric potential, and for wood and biogas, the thermal potential is given.

added. A detailed description of the CCS module implemented in SMM-W1 is given at the beginning of chapter 5, which also includes a scenario analysis of the potential role of CCS technologies in the future Swiss energy system.

Extension of passenger car sector

The passenger car sector in SMM-S includes car technologies with a wide range of drivetrain types such as gasoline, diesel, and natural gas internal combustion engines (ICE), and hydrogen fuel cells. Besides the variety in drive train types there is also a large set of different technological characteristics (higher/lower efficiencies and costs) represented in many cases. In order to further improve the technologies richness of the passenger car sector, two advanced car technologies have been added to the model. Both cars (i.e. a battery electric car and a highly efficient gasoline hybrid car) are based on the car technology database presented by Gül (2008) and updated in Densing et al. (2012). Table 3.5 shows the technological specifications of both the two new car technologies and a selection of some of the existing cars of SMM-S.

Table 3.5: Technological characteristics of existing and new (**bold**) car technologies added to the Swiss MARKAL model. (Source: Gül (2008))

Car technology	INVCOST [CHF_{2010}/ tv-km/y]	FIXOM [CHF_{2010}/ tv-km/y]	EFF [bv-km/y]
Gasoline hyb. advanced	2076	36	0.77
Gasoline conv.	1639	33	0.48
Gasoline hyb.	1789	36	0.56
Diesel conv.	1374	27	0.51
Diesel hyb.	1481	30	0.62
NGA conv.	1810	36	0.48
NGA hyb.	1892	38	0.63
Hydrogen fuel cell	5860	117	0.98
Battery electric	2488	50	1.41

INVCOST: Investment cost
FIXOM: Fixed O&M cost
EFF: Efficiency
tv-km/y: thousand vehicle kilometers per year
bv-km/y: billion vehicle kilometers per year

3.3.2 *SMM-W2*: Restructuring, recalibration, end-use demand update

The second update resulting in the model version SMM-W2 comprises major developments in three aspects. First, some of the key sectors of the energy system have been restructured in order to improve consistency with statistical data and projections of future developments that were available and to increase the level of technological and sectoral detail. Within the second update also a recalibration of the four main end-use demand sectors (i.e. residential, industrial, transport, and services sectors) and the electricity sector to 2010 statistics has been conducted in order to be consistent with recent developments of the energy system. After the calibration, the energy service demands (ESD) were updated based on recent projections of socio-economic parameters such as GDP and population growth. The ESD update is allocated to the model developments section rather than to the scenario developments since it is closely linked to purely structural model developments such as restructuring and reallocating of end-use demand categories, amongst others. The extensive model developments that have been conducted for SMM-W2 are described in detail at the beginning of chapter 6 before the scenario analysis from SMM-W2 is presented.

3.4 Scenario developments

Within the scope of this dissertation a number of scenarios reflecting key uncertainties related to the future Swiss energy system has been developed, quantified, and analysed with the SMM. While some scenarios are used only for specific analyses (e.g. analysis of the potential role CCS technologies in the future energy system) there are other scenarios that are used across a wide range of analyses presented in this thesis. These general scenarios comprise uncertainties related to climate change mitigation targets and support of new nuclear power plants. Other more specific scenarios include uncertainties related to the future availability of centralized fossil electricity generation technologies, different types of CCS technologies, stagnation in energy service demands, and alternative climate targets. While the general scenarios are described in this section the specific scenarios are introduced at the beginning of the chapters 4, 5, and 6 before the respective scenario analysis presented in each chapter.

3.4.1 Reference scenario

For the analysis of scenarios reflecting future uncertainties a reference scenario is generally defined as a basis for comparison. Often, a reference scenario is a business as usual type scenario under given assumptions related to future developments. Depending on the diverse foci of the analyses in this work the specifications of the reference scenario can slightly change amongst the chapters. For example, when analysing uncertainties related to future energy prices in a world that assumes a Swiss nuclear phase-out then the reference scenario reasonably includes a nuclear phase-out. On the other hand, when analysing the impact of a potential nuclear phase-out in a nuclear supportive world, then the reference scenario should allow investments in new nuclear capacities. In order to provide transparency on the reference scenario that is used for the scenario analysis in a particular chapter key assumptions of the reference scenario are given at the beginning of each chapter.

As mentioned in section 3.2.2, the energy prices of the reference scenario of SMM-1 and SMM-2 have been updated based on recent projections from the Energy Technology Perspectives (ETP) 2012 from the International Energy Agency (IEA) (IEA, 2012b). For the reference scenario in SMM the *ETP 2012 6 DS* scenario representing a business-as-usual development of future oil and gas prices has been adopted. As for SMM-S a linkage between prices for oil and gas and other energy carriers is assumed. Figure 3.4 shows projections for oil and gas prices in the references scenario for the updated model versions

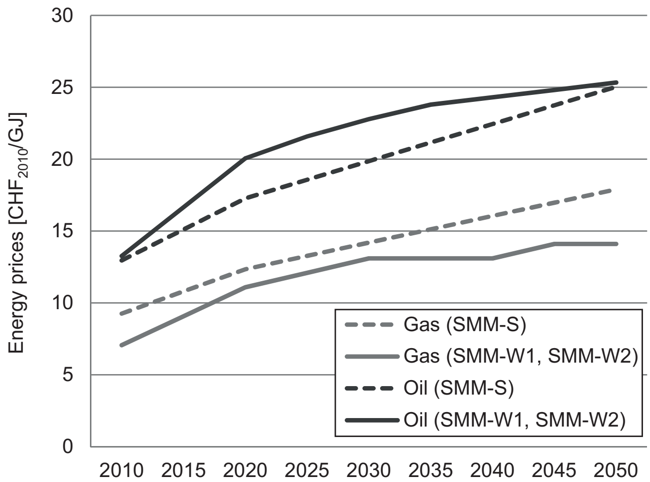


Figure 3.4: Oil and gas prices used in the new (SMM-W1, SMM-W2) and old (SMM-S) Swiss MARKAL model. (Sources: Schulz (2007), IEA (2012b))

SMM-W1 and SMM-W2 in comparison to SMM-S.

3.4.2 OcCC climate target scenario

The OcCC climate target scenario assumes a climate policy in which domestic CO_2 emissions are reduced by 20% by 2020, and by 60% by 2050 relative to the level of the year 1990. These emission targets are similar to the recommendations of the Swiss Academies of Arts and Sciences (SAAS) (SAAS, 2009) and the Advisory Body on Climate Change (OcCC) (OcCC, 2007). The abovementioned emission targets are implemented as cap on total emissions across the entire energy system in SMM. In addition to the OcCC target also alternative climate mitigation targets including higher CO_2-reductions and more flexible reduction pathways have been analysed in chapters 4,5, and 7.

3.4.3 Nuclear phase-out scenario

In the nuclear phase-out scenario it is assumed that the five existing nuclear power-plants are not replaced at the end of their 50-year lifetimes (the definition of the residual capacity is given in section 3.3.1). This scenario is roughly in line with the policy announced by the Swiss Parliament (BFE, 2011e).

3.5 Methodological applicability and limitations of the modelling framework

Similar to other analytical tools used to model complex systems, there are limitations in the MARKAL framework. One has to be aware of the following important points when considering the results:

- As mentioned at the beginning of section 3.2, the SMM is a cost-optimisation tool that is suitable for what-if type analyses of scenarios of the future energy system. Based on the cost assumptions given to the model, cost-effective technology combinations of the future energy system can be identified. While costs are well represented in SMM there are other factors that are likely to have significant impact on the development of the future energy system that are less represented in the model (e.g. decision making based on social behaviour). Since many non-economic aspects cannot be analysed with SMM the model is inappropriate for any kind of prediction of future developments that are by nature also driven by non-economic factors.

- For our analysis we assume perfect information, well-functioning markets and economically rational decisions. In the real world these stylised conditions often do not exist. As described in section 3.2 energy service demands and modal shares are exogenous inputs to the model. In the real economy it is observed that demands can change with changes in costs for services (e.g. increase in energy prices or decrease in technology costs). There are also services that can be substituted by others. For example a modal shift can occur between rail passenger transport and car transport when fuel prices increase. These modal shifts are also not included in the model but rather incorporated in scenario input assumptions.

- There are many model input assumptions that are highly uncertain such as energy price developments and projections of future technology characteristics (e.g. efficiencies and costs). For example, different assumptions on future cost reductions of technologies could change their cost-effectiveness relative to other options. Scenario analysis (and sensitivity analysis) can explore some of this uncertainty. However, there are unpredictable uncertainties such as an economic crisis that are more difficult to analyse.

- In contrast to other modelling frameworks (e.g. TIMES) the MARKAL models only include six different time periods or time slices (i.e. winter, summer, intermediate and day and night) to represent seasonal demands and supply of energy and services. Hence, in SMM the electricity load and supply curve at different times of the day and season are represented in an aggregated way. Other analysis of hourly electricity load curves has been conducted with the Swiss TIMES electricity model (*STEM-E*) (Kannan and Turton, 2013; Weidmann et al., 2012a).

- SMM is a single region model representing only Switzerland. In reality the Swiss energy system is not isolated and has interactions with other countries (e.g. trade of electricity). While the analysis of such interactions cannot be analysed with SMM there are models looking at the interplay between the Switzerland and other countries at European and global levels (Marcucci and Turton, 2012; Reiter, 2010).

3.6 Summary

In this chapter, the methodology including the Swiss MARKAL energy system modelling framework and the scenario development are presented. The previous model developed by Schulz (2007) is shortly described. Then, the developments and extensions conducted within the scope of this dissertation and resulting in the two model version SMM-W1 and SMM-W2 are introduced. These include a recalibration and restructuring of large parts of the energy system and the development of a Carbon Capture and Storage (CCS) module. Further, key model and scenario assumptions are given and scenario developments including different levels of support for future nuclear power plants, and availability of alternative low-carbon electricity sources are described. Finally, the applicability and limitations of the modelling framework are given. The scenario and model developments elaborated in this dissertation enable the analysis of scenarios representing the high uncertainty related to future electricity supply options (i.e. possible availability of future nuclear power plants, centralised fossil gas plants, carbon capture and storage technologies) under different levels of climate mitigation targets (see chapters 4, 5, 6, and 7).

Chapter 4

The Swiss energy system under electricity supply uncertainty and climate constraints

4.1 Introduction

Some of the key challenges for the Swiss energy system are related to climate change mitigation and security of the future energy and particularly electricity supply (see chapter 2). The reduction target for domestic CO_2 emissions of 20% (relative to the 1990 level) included in Switzerland's commitment to the UNFCCC (UNFCCC, 2011a,b) and longer-term targets of 60% to 80% reduction for the year 2050 suggested by the Advisory Body on Climate Change (OcCC) (OcCC, 2007, 2012) and the Swiss Academies of Arts and Sciences (SAAS) (SAAS, 2009) are likely to require a substantial technological transformation of today's relatively carbon intensive Swiss energy system. The need for such a rebuilding of the energy system has also been emphasized in other studies (e.g. ETS (2009)). The realisation of the transformation to a low-carbon energy system strongly depends on a number of highly uncertain factors such as the development of the power sector and the future availability of cost-effective low-carbon electricity sources that would allow maintaining today's low emission levels in the electricity sector and could support the decarbonisation due to electrification in other parts of the energy system.

Particularly, the uncertain political support for some of the future electricity generation options is crucial. In the case of nuclear power, the public and political acceptance has drastically decreased (mainly due to a loss of trust into safety aspects of the technology) after the catastrophe of Fukushima in 2011, and finally led to the decision of the government to phase out nuclear power after existing power plants reach the end of their lifetimes (BFE, 2011e). Despite this decision it is still unclear for how long the existing nuclear power plants will be running (based on the question how long they are considered to be safe) and if the ban on new power plants will hold for any new nuclear technologies or if breakthrough technological improvements were allowed in the future. Further, the decision on phasing out nuclear is not carved in stone and could theoretically be reversed.

As for nuclear power plants, the political support is also uncertain for some of the renewable sources including wind and solar. Wind is today a relatively mature technology that is widely accepted; however, there is significant uncertainty related to the domestic potential of this technology due to controversial opinions about the relevance of landscape protection for the identification of suitable locations for wind turbines. Solar photovoltaic is currently still a relatively expensive technology and needs to be supported with subsidies to be deployed. Policymakers disagree about the benefit of such subsidies and if the money should not better be spent in other ways to support the abovementioned transformation of the energy system. Another electricity technology option that could be interesting especially under the absence of nuclear power are centralised natural gas combined cycle plants (NGCC). If the waste heat from NGCC plants is used (e.g. in a natural gas combined heat and power (NGCHP) plant) this technology option has the advantage of a high overall efficiency beside the relatively low costs compared to other options including new renewable sources such as wind and solar (see Table 3.2). On the other hand, there is the disadvantage that NGCHP technologies rely on natural gas causing CO_2 emissions while increasing the issue related to supply security. Given these disadvantages, the political support for NGCHP technologies is not undisputed.

Other uncertainties that can have an impact on the configuration of the future energy system include the stringency of CO_2 reduction targets, and future developments of energy prices. On the latter, Switzerland has almost no influence, since Swiss energy prices are dependent on developments of highly uncertain international market prices for energy commodities. Especially, prices for fossil fuels (particularly oil) are typically very sensitive to their availability on the market or the expectations of their future availability. Unlike for energy prices, the Swiss government has direct influence on climate policies and CO_2 reduction targets. The uncertainty here comes from the fact that a CO_2 reduction target constrains the energy system and consequently the economy which can cause substantial additional costs for the society. Therefore, there exist controversial opinions about quantitative climate mitigation targets for the country resulting in high uncertainty regarding future climate policies. While the reduction target for domestic CO_2 emissions for the year 2020 of 20% (as mentioned above) is defined and part of the Swiss CO_2 law (BAFU, 2013), there exists considerable uncertainty related to longer-term targets until the middle of the century and beyond. While quantitative reduction targets for the year 2050 of 60%, 80%, or more have been recommended by OcCC (2007, 2012) and SAAS (2009), there is also uncertainty in respect to the (cost-)optimal reduction pathways to reach these targets. In this regards, developing optimal policies, that could reach given targets in the most efficient way, can be of a major challenge.

Addressing the overall objective of this PhD thesis of improving understanding of how some of the key uncertainties could affect the future energy system (see chapter 1), a set of scenarios is developed and analysed using the Swiss MARKAL model version 1 (*SMM-W1*) (see chapter 3). In doing so, cost-effective technology combinations will be identified and their robustness across the different scenarios tested. Based on these results, policy implications and recommendations for stakeholders will be deducted and formulated.

The next section (4.2) in this chapter defines a number of scenarios based on key uncertainties discussed above. Section 4.3 presents results for of a set of different electricity supply constraints. In section 4.4 results for scenarios incorporating climate mitigation pathways are shown. Section 4.5 illuminates the potential role of the development of energy prices in the four electricity supply cases with and without climate target while in section 4.6 the energy system costs of the sensitivity analysis are shown. In section 4.7, the results are discussed and policy implications for the future energy system are given.

4.2 Scenario definitions

Scenarios were defined based on three sets of uncertainties, related to availability of electricity supply options, climate policies, and international energy prices.

4.2.1 Electricity supply constraints

In order to analyse the uncertainty related to future electricity supply options we defined four constraints representing different levels of support for nuclear and large centralised fossil electricity generation technologies:

- *Nuclear Replacement (NuRep)*: Investments in new nuclear capacities are possible when existing power plants reach the end of their lifetimes of 50 years. However, the total capacity cannot exceed current levels over the entire time horizon. This constraint represents the preservation of today's situation by maintaining the existing capacity level.

- *Nuclear Extension (NuExt)*: Investments in new nuclear power are allowed up to a total annual production of 150 PJ (41.7 TWh) representing the output of a total capacity of roughly 5 GW. The nuclear extension constraint accounts for the original plans from parts of the society and of the energy sector to build two to three new nuclear power plants. However, these plans have been suspended after Fukushima.

- *Nuclear Phase-out (NuPhs)*: After the retirement of existing nuclear capacities no new nuclear power plants can be built. This constraint is roughly in line with the current nuclear policy to phase-out nuclear power (BFE, 2011e).

- *No Centralised power plants (NoCen)*: This constraint assumes a nuclear phase-out and additionally forbids investments in centralised fossil power plants (particularly NGCC and NGCHP). However, as in all other electricity supply constraints, decentralised fossil power generation (e.g. from gas CHP) is allowed. This constraint represents the uncertain acceptance of large centralised fossil-based electricity generation technologies in the society.

4.2.2 Climate target constraints

To reflect the uncertainty related to future climate change mitigation policies (as introduced in section 4.1) the following climate policy constraints are developed and analysed:

- *No climate policy*: This scenario assumes that no climate change mitigation action taken during the entire time horizon.

- *60% reduction of domestic CO_2 emissions (60)*: In this scenario total domestic CO_2 emissions have to be reduced relative to the 1990 level by 20% in the year 2020 and by 60% in 2050. The reduction targets for the years in between are linearly interpolated. The 20% reduction goal in 2020 is in line with the current Swiss CO_2 law (BAFU, 2013). The 60%-target in 2050 bases on recommendations by OcCC (2007).

- *Alternative climate policies* with higher mitigation target of 80% and cumulative targets comprising the same total CO_2 emissions between 2010 and 2050 as for the 60% reduction target have been tested within the scope of this analysis. A more detailed description of these alternative targets and insights from this analysis are given in paragraph 4.4.2.

4.2.3 Fossil fuel prices sensitivities

The energy price sensitivities applied for this analysis are based on the oil and gas prices of three scenarios of the Energy Technology Perspectives (ETP) 2012 IEA (2012b) of the International Energy Agency (IEA). The natural gas and oil prices of the three scenarios[1] comprising the ETP 6° Scenario (6DS), the ETP 2012 4° Scenario (4DS), and the ETP 2012 2° Scenario (2DS) are presented in Table 4.1. For our analysis we use the ETP 6DS scenario as a business as usual energy prices sensitivity, the 4DS as a medium energy price, and the 2DS as low energy prices sensitivity. Further, we complement these scenarios with an additional "high energy price" scenario assuming that the energy prices of the 6DS are multiplied with a factor linearly increasing between 1.0 in 2010 and 1.5 in 2050 (i.e. 50% increase relative to 6DS in 2050).

Table 4.1: Oil and gas prices of the ETP 6DS, 4DS, and 2DS scenarios including an own "high energy price" scenario (6DS+50%). (Source: IEA (2012b))

		2010	2020	2025	2030	2035	2040	2045	2050
Oil (IEA crude oil	2DS	78	97	98	98	98	92	89	87
import price)	4DS	78	109	114	117	120	119	119	118
(USD_{2010}/bbl)	6DS	78	118	127	134	140	143	146	149
	6DS+50%	78	133	151	168	184	197	210	224
Gas (Europe	2DS	7	10	10	10	9	9	9	8
import price)	4DS	7	10	11	12	12	12	12	12
(USD_{2010}/Mbtu)	6DS	7	11	12	13	13	13	14	14
	6DS+50%	7	12	14	16	17	18	20	21

4.2.4 Scenario combinations

The four electricity supply constraints (*NuRep*, *NuExt*, *NuPhs*, and *NoCen*), the no-climate policy and the climate mitigation constraints (*60*), and the four energy price sensitivities (low, medium, business as usual (BAU), high) introduced above are combined with each other to analyse the uncertainties discussed above (Table 4.2).

[1] The IEA describes the 6DS scenario as reflecting a business as usual type scenario where no policy action is assumed to be taken to address issues related to climate change and energy security. In the 4DS scenario concerted efforts in order to achieve reductions in both energy demands and emissions compared to the 6DS are represented. For the 2DS even stronger actions leading to a transformation towards a sustainable energy system are assumed.

Table 4.2: Scenario combinations of the three sets of uncertainties related to availability of electricity supply options, climate policies, and international fossil fuel prices.

	Energy price sensitivity	**Nu**clear **Rep**lacement	**Nu**clear **Ext**ension	**Nu**clear **Ph**ase-out	**No** **Cen**tralised
	Low	*NuRep_EL*	*NuExt_EL*	*NuPhs_EL*	*NoCen_EL*
No clim. policy	**M**edium	*NuRep_EM*	*NuExt_EM*	*NuPhs_EM*	*NoCen_EM*
	BAU	*NuRep_EB*	*NuExt_EB*	*NuPhs_EB*	*NoCen_EB*
	High	*NuRep_EH*	*NuExt_EH*	*NuPhs_EH*	*NoCen_EH*
	Low	*NuRep_EL_60*	*NuExt_EL_60*	*NuPhs_EL_60*	*NoCen_EL_60*
Climate target (60% red.)	**M**edium	*NuRep_EM_60*	*NuExt_EM_60*	*NuPhs_EM_60*	*NoCen_EM_60*
	BAU	*NuRep_EB_60*	*NuExt_EB_60*	*NuPhs_EB_60*	*NoCen_EB_60*
	High	*NuRep_EH_60*	*NuExt_EH_60*	*NuPhs_EH_60*	*NoCen_EH_60*

BAU: Business as usual

4.3 Scenario analysis of future electricity supply uncertainty

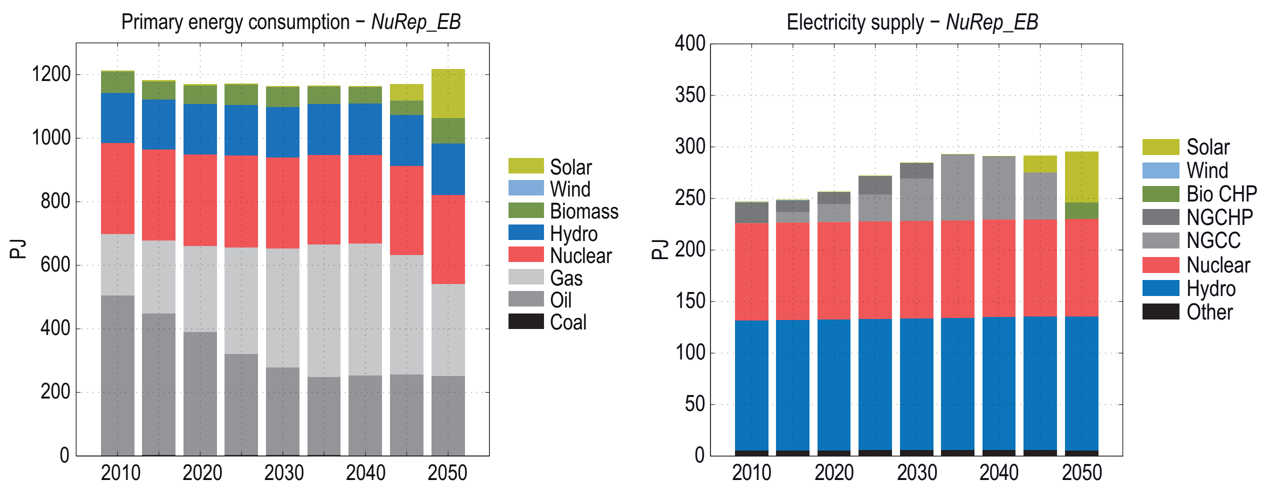
The 32 scenarios defined in Table 4.2 were quantified and analysed with *SMM-W1*. In this section we focus on the four different electricity supply options and their implications for the entire energy system. Initially, we consider the case with business as usual energy prices based on the ETP 6DS scenario (Table 4.1) and no climate target (i.e. scenarios *NuRep_EB*, *NuPhs_EB*, *NoCen_EB*, *NuExt_EB*).

4.3.1 Nuclear replacement (*NuRep_EB*)

In a scenario where Swiss nuclear power plants can be replaced after reaching the end of their lifetimes and no climate target is applied to the energy system (*NuRep_EB*), total primary energy consumption stays on a relatively constant level over the whole time horizon (Figure 4.1(a)). This result occurs despite the fact that GDP (as one of the key drivers for energy service demand growth) grows by more than 20% between 2010 and 2050 (while population stays rather constant over the time horizon). This implies that the energy intensity of the energy system (i.e. PEC/GDP) is reduced. Despite the relatively flat development of total PEC, in the last decade a slight increase can be seen when natural gas is partly replaced by solar[2]. In the first decades of the observation period a shift from oil to natural gas can be seen, mainly driven by the relatively higher prices for oil compared to natural gas. However, this shift from oil to gas is stabilized after the year 2035 due to limited availability of cost-effective substitution options between those energy carriers. Hydro and nuclear energy are cost-effective over the entire time horizon and therefore used up to assumed potentials described in chapter 3.

While primary energy consumption more or less maintains its level over the time horizon, total final energy consumption (TFC) slightly decreases partially related to an increased

[2]This increase in primary energy consumption at the end of the time horizon is mainly related to the lower conversion efficiency of solar energy compared to natural gas.



(a) Primary energy consumption (b) Electricity generation

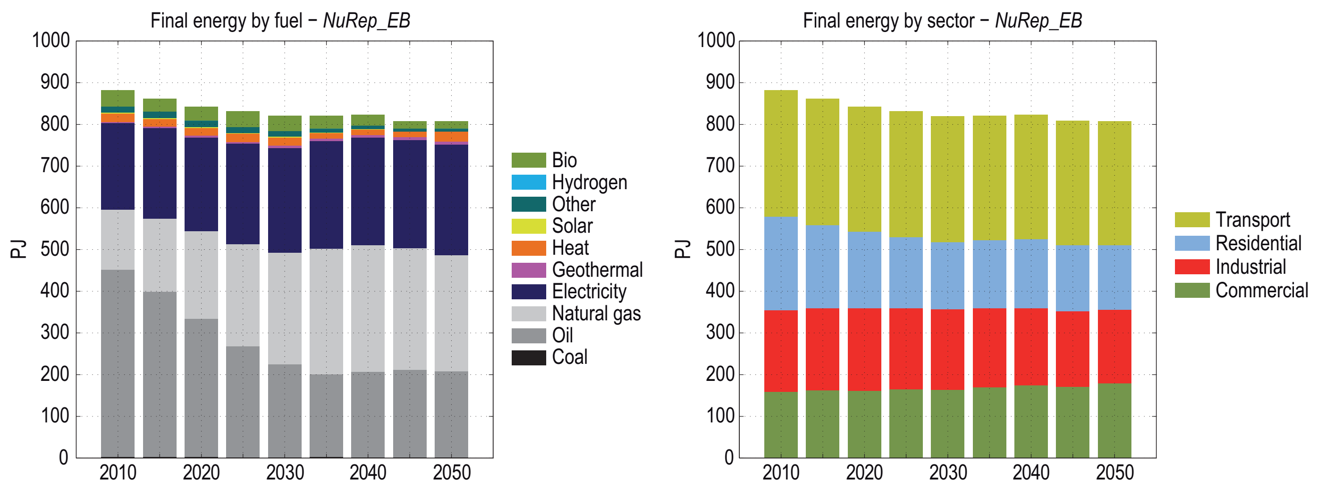
Figure 4.1: Primary energy consumption and electricity generation, Nuclear replacement scenario (*NuRep_EB*)

electrification of the energy system by 20% (Figure 4.2(a)). Subsequently, the losses in the electricity sector are not accounted in the electricity share in the final energy balance. The decrease in TFC is realised while energy service demands are increased in average. This implies improvements in energy efficiency in the end-use demands technologies. While the use of oil halves, the consumption of natural gas doubles between the years 2010 and 2040. Other energy carriers, such as district heat, solar thermal energy, and coal play only a small role in this scenario. The decrease in total final energy consumption is mainly driven by a decrease in the residential heating sector where energy saving measures including insulation of the building envelopes are cost-effective and installed at a large scale (Figures 4.2(b) and 4.3(b)). Along with the uptake of energy saving technologies in the residential heating sector, also a fuel shift from oil- to natural gas-based heating systems (mainly related to the lower fuel costs of natural gas compared to oil) (see Figure 3.4) and electric heat pumps (due to their high efficiency) takes place (Figure 4.3(b)). Other sources such as district heat and biomass only play a minor role in residential space heating.

Another sector contributing to the lower TFC in the energy system is transport. Particularly in the passenger car sector a shift from gasoline to diesel (due to the higher efficiency of diesel compared to gasoline cars) and natural gas (due to the lower price for NGA compared to gasoline) and a deployment of highly efficient car technologies including hybrids is taking place (Figure 4.3(a)).

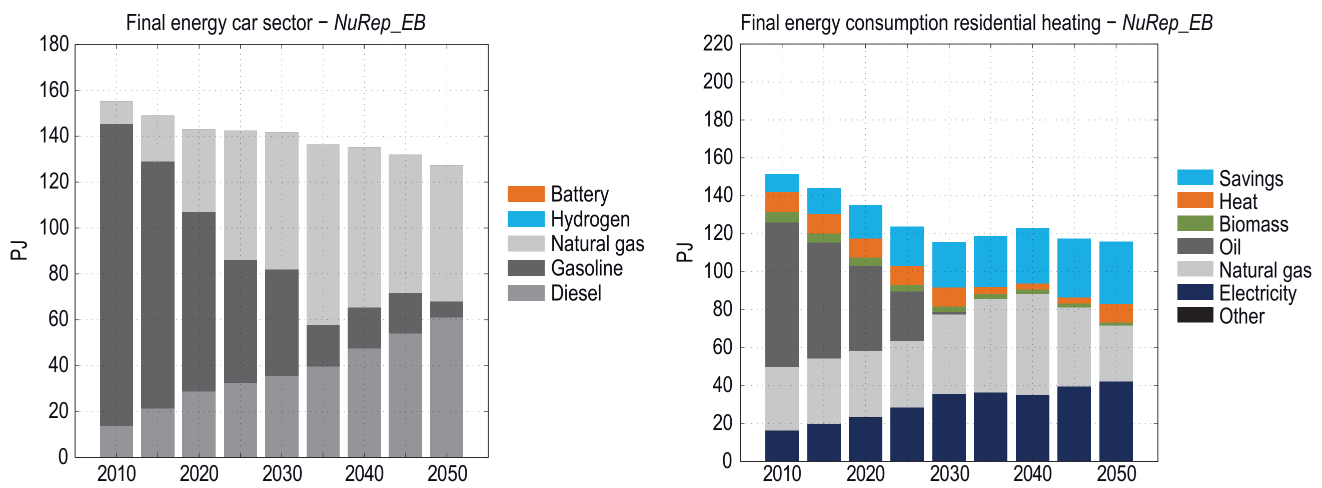
The increased share of electricity in TFC shown in Figure 4.2(a) is realised with a deployment of NGCC technologies, while hydro and nuclear capacities are used up to their assumed potentials[3] (Figure 4.1(b)). Electricity production increases to 2035, then stabilises. This stabilisation and the shift from NGCC to solar PV technologies in the last decade are driven by the increase in gas price (see Table 4.1) consequently raising the costs

[3]These potentials are given in Table 3.4.



(a) Final energy consumption by energy carrier (b) Final energy consumption by sector

Figure 4.2: Final energy consumption, Nuclear replacement scenario (*NuRep_EB*)



(a) Final energy consumption car sector (b) Final energy consumption residential heating

Figure 4.3: Final energy consumption in the car and residential heating sectors, Nuclear replacement scenario (*NuRep_EB*)

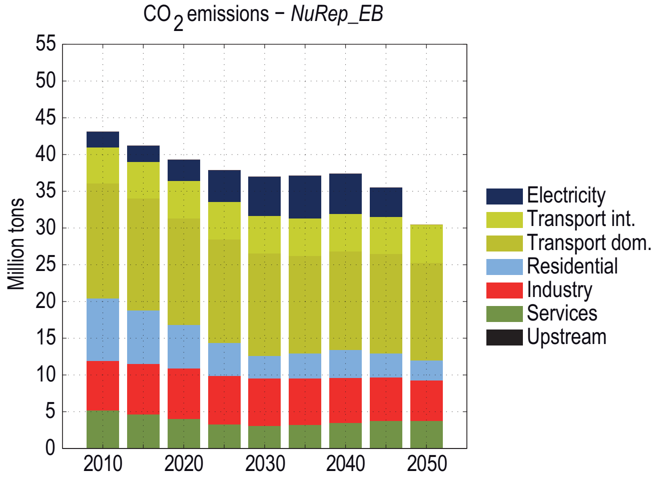


Figure 4.4: CO_2 emissions by sector, Nuclear replacement scenario (*NuRep_EB*)

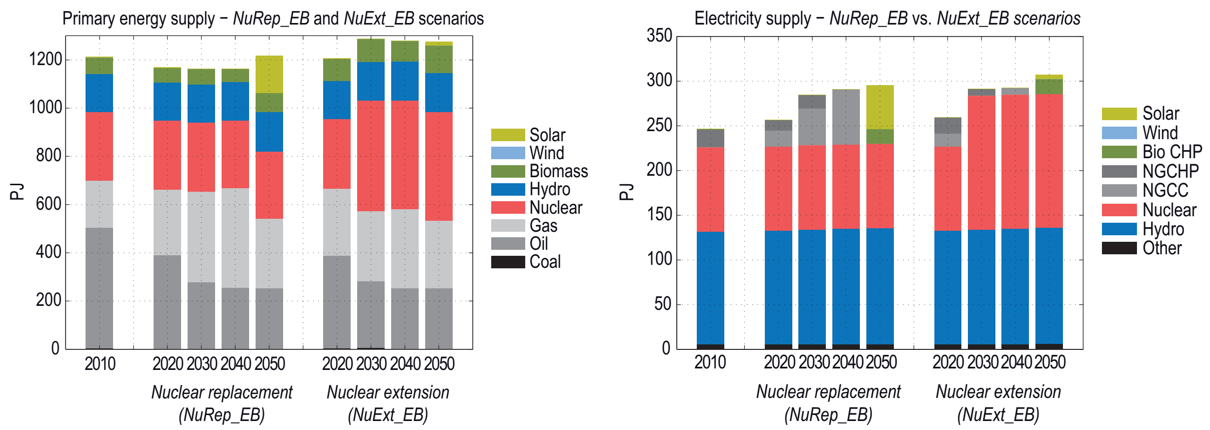
for electricity generation by NGCC and a decrease in capital cost of solar PV technologies (see Table 3.2).

The decline in use of fossil energy carriers such as oil and gas (Figure 4.1(a)) implies a reduction of CO_2 emissions in the energy system. As can be seen in Figure 4.4 significant reductions are taking place in the residential sector (as mentioned, partially due to a shift from oil to electric heat pumps and the deployment of energy saving technologies). Emissions are also reduced in other end-use sectors (i.e. transport, industry, and services). In the electricity sector, CO_2 emissions increase due to the deployment of NGCC technologies but are reduced to zero in the last time period when fossil generation is completely replaced by new renewables such as solar PV and biomass.

4.3.2 Nuclear extension (*NuExt_EB*)

If the installed capacity of nuclear generation can be expanded to a total capacity of 5 GW (as described in section 4.2.1) this technology option is cost-effective[4] and used up to the assumed maximum replacing significant capacities of NGCC compared to the nuclear replacement scenario (Figure 4.5(b)). Only when investments in nuclear technologies are not yet available (before 2025) or cannot satisfy the entire electricity demand in the energy system (i.e. in the years 2035 and 2040) NGCC technologies are partially installed. The increased deployment of nuclear power accelerates and intensifies the electrification of the energy system and reduces the need for the more expensive solar PV technologies in the last periods compared to the case with constant nuclear capacity (*NuRep_EB*). While the higher use of nuclear power increases the primary energy consumption in the energy system (mainly due to the lower thermal efficiency of nuclear compared to NGCC technologies) (Figure 4.5(a)) its impact on final energy consumption is less significant. The CO_2 emission reductions in the building sector and the shift from NGCC to nuclear technologies in the electricity sector support a further decarbonisation of the energy system in

[4]Cost-effective means here that electricity generation from nuclear technologies is economically more attractive than from other competing power technology options (including NGCC, wind, and solar PV) and also more attractive than reducing the energy system's demand for electricity by still satisfying given energy service demands.



(a) Primary energy consumption (b) Electricity generation

Figure 4.5: Primary energy consumption and electricity generation, Nuclear replacement (*NuRep_EB*) and Nuclear extension (*NuExt_EB*) scenarios

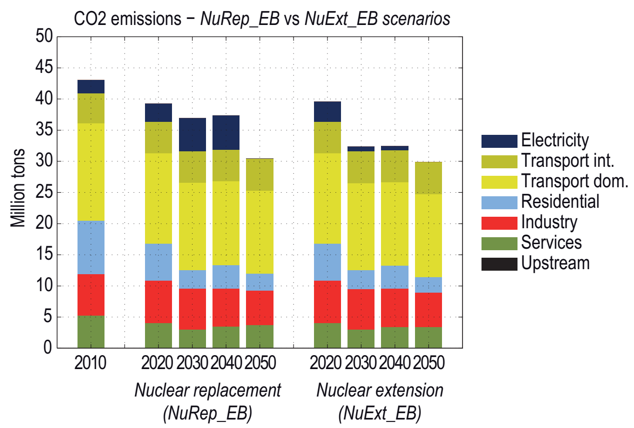
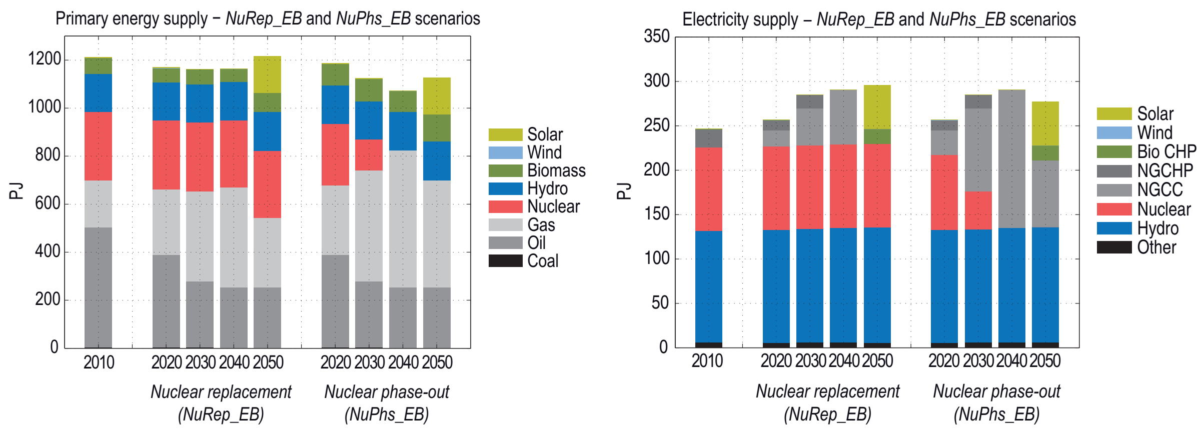


Figure 4.6: CO_2 emissions by sector, Nuclear replacement (*NuRep_EB*) and Nuclear extension (*NuExt_EB*) scenarios

the middle periods of the time horizon (see Figure 4.6). The car sector is not affected by the additional electricity production since car technologies relying on fuels that could be produced with electricity (i.e. battery and hydrogen cars) are not cost-effective due to the relatively high investment costs of these technologies (see Table 3.5) and the assumptions on fossil fuel prices in this scenario (that are too low to compensate the high investment costs).

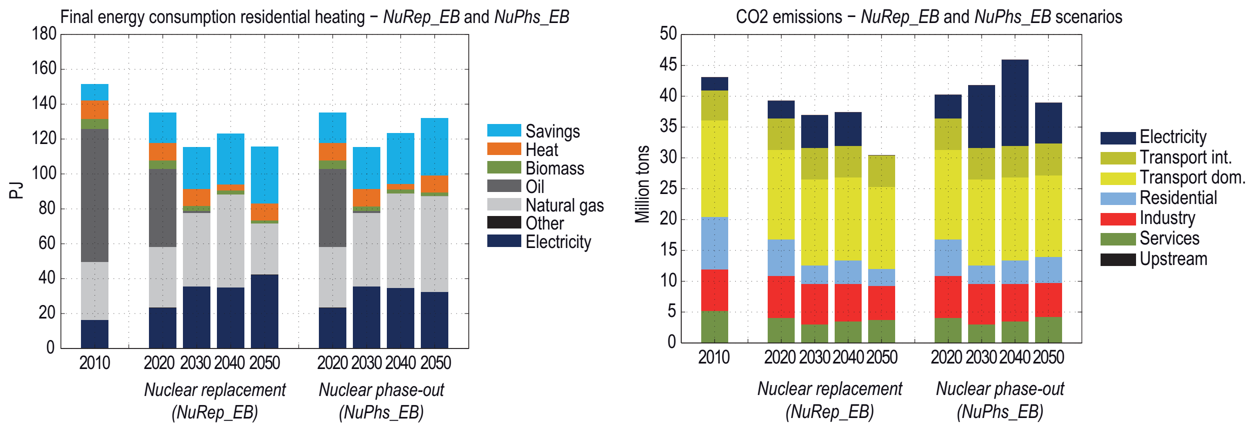
4.3.3 Nuclear phase-out (*NuPhs_EB*)

Assuming that no deployment of new nuclear capacity is allowed (*NuPhs_EB*), the decline in nuclear generation is offset by additional electricity generation first from NGCC and an accelerated deployment of solar PV at the end of the time horizon (i.e. in the year 2045) (Figure 4.7(b)). While total final energy and electricity supply show similar levels (with a slight shift from electricity to gas in the residential heating sector though (see Figures 4.7(b) and 4.8(a))) compared to the nuclear replacement scenario, primary energy consumption is lower in the second half of the observation period, primarily because of the



(a) Primary energy consumption (b) Electricity generation

Figure 4.7: Primary energy consumption and electricity generation, Nuclear replacement (*NuRep_EB*) and Nuclear phase-out (*NuPhs_EB*) scenarios



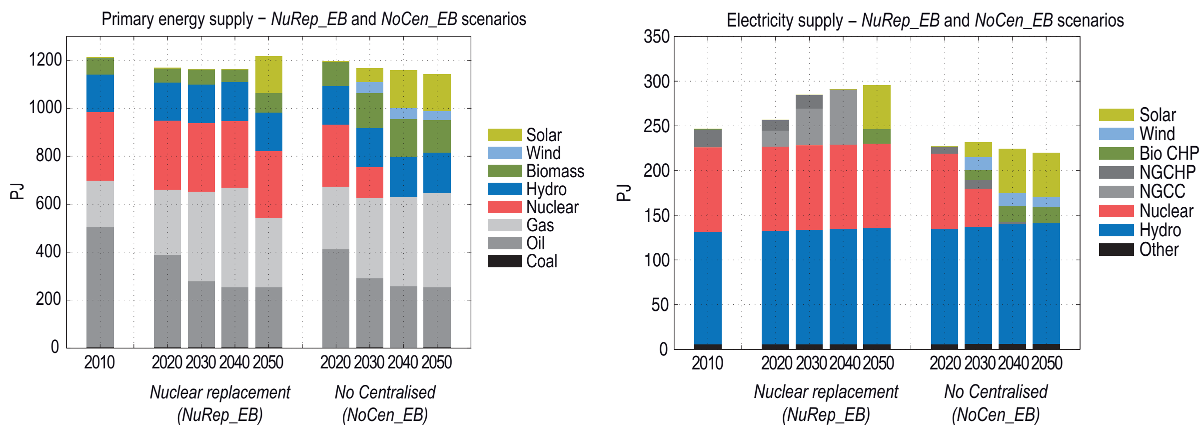
(a) Final energy residential heating (b) CO_2 emissions

Figure 4.8: Final energy consumption residential heating and CO_2 emissions, Nuclear replacement (NuRep_EB) and Nuclear phase-out (NuPhs_EB) scenarios

higher thermal efficiency of the natural gas generation compared to nuclear (Figure 4.7(a)). While the lower electrification in the last periods has some impact on the residential sector (i.e. lower uptake of electric heat pumps), it seems not to affect the car sector for the same reasons as for the *NuExt_EB* scenario. The extensive use of natural gas in power generation and the partial shift from electricity to gas in the residential sector contribute to significantly higher CO_2 emissions in an energy system with nuclear phase-out relative to the nuclear replacement case (Figure 4.8(b)).

4.3.4 Nuclear phase-out and no centralised fossil power plants (*NoCen_EB*)

If in addition to the nuclear phase-out also investments in centralised fossil power plants (i.e. NGCC and NGCHP) are not allowed (*NoCen_EB*), only decentralised fossil (i.e. small gas CHP's) and renewable technologies are available. Since electricity generation



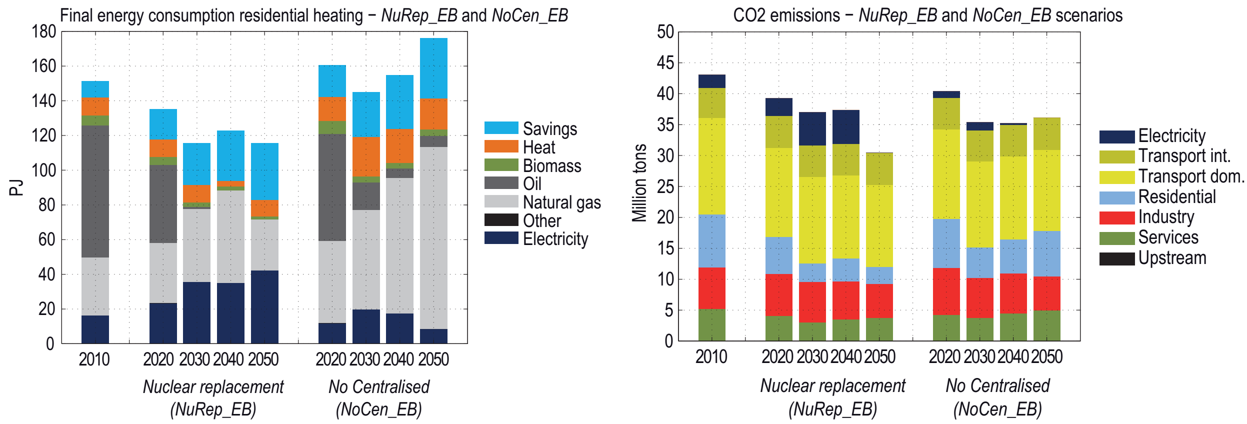
(a) Primary energy consumption (b) Electricity generation

Figure 4.9: Primary energy consumption and electricity generation, Nuclear replacement (*NuRep_EB*) and No centralised (*NoCen_EB*) scenarios

costs from decentralised fossil technologies are considerably higher compared to the centralised fossil power plants and renewable generation is limited by the domestic potentials, electrification of the energy system is less attractive compared to the direct use of fossil energy in some of the end-use sectors (Figure 4.9(b)). This can be illustrated when looking at final energy consumption in the residential heating sector (Figure 4.10(a)) showing a strong shift from electricity to natural-gas based heating system compared to the nuclear phase-out scenario where electrification is supported by deployment of centralised fossil electricity generation. In addition, the scarcity of electricity in the energy system and the high energy prices at the end of the time horizon in *NoCen_EB* support an increased deployment of energy saving measures and district heating (from small gas and centralised wood CHP's) in the residential heating sector (Figure 4.10(a)). The higher generation costs has a direct impact on the electricity supply mix. In contrast to *NuRep_EB*, *NuExt_EB*, and *NuPhs_EB* scenarios presented above, in the *NoCen_EB* scenario total electricity production decreases from 2010. During the nuclear phase-out the retired nuclear capacities are partially replaced by decentralised NGCHP's, centralised wood CHP's, wind, and solar PV to maintain the generation level. The lower fossil electricity generation and the higher direct use of fossil energy carriers in the end-use sectors cause changes in the sectorial allocation of CO_2 emissions. While the electricity sector is almost decarbonised in *NoCen_EB*, emissions in the building sectors are increased while overall emissions have decreased compared to the *NuPhs_EB* scenario (Figures 4.10(b) and 4.8(b)).

4.4 Climate change mitigation

In this section we present and analyse scenarios illustrating how climate change mitigation targets could affect the configuration of the future energy system under the uncertainty related to future electricity supply. Specifically, this scenario presents scenarios *NuRep_EB_60*, *NuExt_EB_60 NuPhs_EB_60*, and *NoCen_EB_60* (see Table 4.2).



(a) Final energy residential heating

(b) CO_2 emissions

Figure 4.10: Final energy consumption and CO_2 emissions, Nuclear replacement (*NuRep_EB*) and No centralised (*NoCen_EB*) scenarios

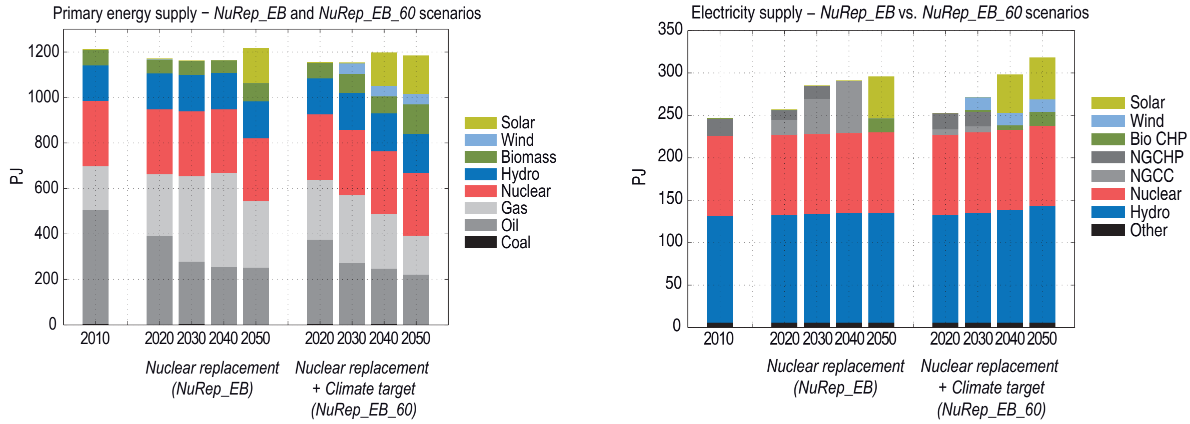
4.4.1 60% CO_2 reduction target by 2050

Nuclear replacement with 60% CO_2 reduction by 2050 (*NuRep_EB_60*)

In the nuclear replacement scenario with climate policy (*NuRep_EB_60*) the energy system has to reduce its use of fossil fuels in order to meet the climate target. As Figure 4.11(a) shows, wind, solar, and biomass are therefore deployed earlier compared to the case without climate target (*NuRep_EB*) and partially replace oil and gas in the second half of the time horizon. The lower availability of gas also limits the electricity generation from NGCC that significantly contributes to the electrification of the energy system in the *NuRep_EB* scenario (see section 4.3.1). In the *NuRep_EB_60* scenario NGCC technologies are only marginally used as a bridging technology until the climate target becomes more stringent and solar PV and wind technologies are cost-effective (Figure 4.11(b)). The uptake of wind in addition to solar PV and biomass CHP technologies leads to slightly higher electricity production in order to electrify and hence decarbonize some of the end-use demand sector in the energy system in the *NuRep_EB_60* scenario compared to the *NuRep_EB* scenario at the end of time horizon (Figure 4.11(b)). Fossil fuel use is reduced in end-use sectors (e.g. Figure 4.13(a)) through electrification and deployment of efficient demand technologies.

In order to contribute to the improvement of the overall efficiency of the energy system reduction in final energy consumption are seen in all end-use demand sectors (Figure 4.12(a)). However, the residential sector shows the strongest reductions supported by increased installations of heat pumps, district heat, and energy saving technologies (Figure 4.13(a)). In the car sector the reduction in total final energy is realised by a deployment of highly-efficient car technologies including hybrids. At the end of the time horizon a very small (and only barely visible) number of battery and hydrogen cars are deployed (Figure 4.13(b)).

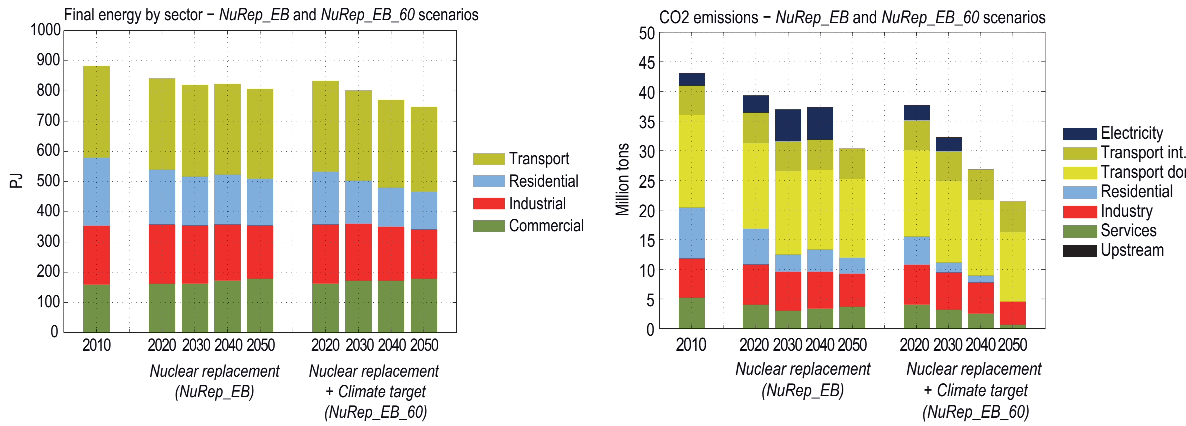
The reduction in the use of fossil fuels due to the climate target has consequences for CO_2 emissions in many sectors across the energy system. While electricity, residential,



(a) Primary energy consumption

(b) Electricity generation

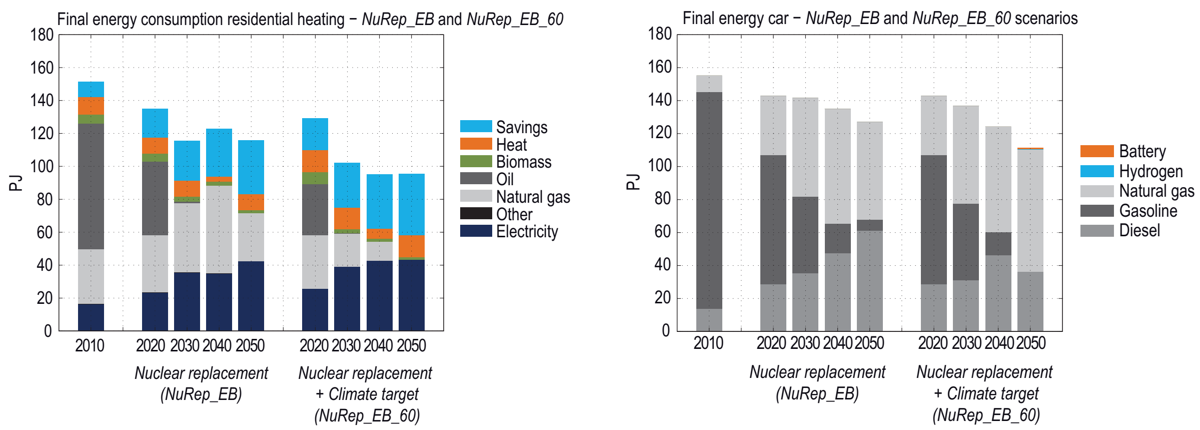
Figure 4.11: Primary energy consumption and electricity generation, Nuclear replacement scenarios without (*NuRep_EB*) and with climate target (*NuRep_EB_60*)



(a) Final energy consumption

(b) CO_2 emissions

Figure 4.12: Final energy consumption and CO_2 emissions, Nuclear replacement scenarios without (*NuRep_EB*) and with climate target (*NuRep_EB_60*)



(a) Final energy residential heating

(b) Final energy consumption car sector

Figure 4.13: Final energy consumption residential heating and car sectors, Nuclear replacement scenarios without (*NuRep_EB*) and with climate target (*NuRep_EB_60*)

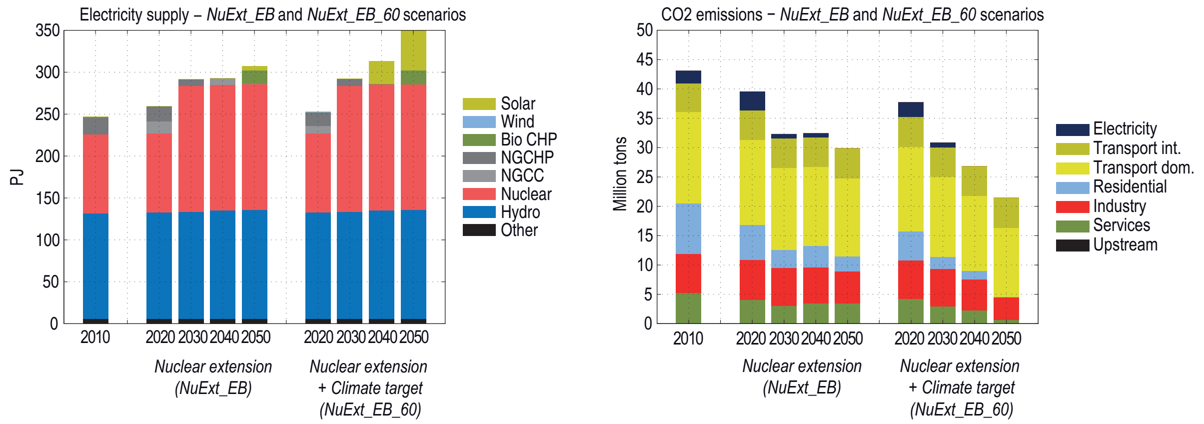
and services sectors are almost decarbonized between 2040 and 2050, industry shows a reduction of around 41% and transport of 25% (excluding international transport) (Figure 4.12(b)). Particularly in the latter cost-effective climate change mitigation options seem to be limited.

Nuclear Extension with 60% CO_2 reduction by 2050 (*NuExt_EB_60*)

Applying a climate target to a scenario where nuclear power can be extended shows similar results as for the nuclear replacement scenario. The limitations on the use of fossil fuels due to the climate target promote an electrification of the energy system by deploying low-carbon electricity from solar PV and wind (in addition to nuclear) as shown in Figure 4.14(a). When nuclear capacity can be extended the additional electrification (i.e. between *NuExt_EB* and *NuExt_EB_60*) to support climate change mitigation is higher compared to the scenarios where nuclear capacity is maintained (i.e. *NuRep_EB_60* compared to *NuRep_EB*). This additional electrification is mainly taking place in the residential and industrial end-use sectors. Further, when nuclear capacity can be expanded the need for new renewable technologies (with their higher cost-assumptions compared to nuclear), as a measure for climate mitigation, is reduced (compare *NuExt_EB* and *NuExt_EB_60*). Hence, the installations of renewable technologies are delayed until the climate target becomes most stringent at the end of the time horizon.

Nuclear phase-out with 60% CO_2 reduction by 2050 (*NuPhs_EB_60*)

As for the Nuclear Replacement scenario with climate target (*NuRep_EB_60*), reaching a 60% emission reduction target under a nuclear phase-out requires a earlier deployment of new renewables such as wind, solar, and biomass at the end of the time horizon. However, compared to the nuclear replacement case, an earlier deployment of these renewable sources is needed due to the retirement of nuclear capacities (compare Figures 4.15(b) and 4.14(a)). Furthermore, although fossil fuels are limited by the climate target, a small amount of electricity generation from centralised NGCC and NGCHP is needed to meet the energy system's electricity demands, even when the potential of solar and wind is fully



(a) Electricity generation mix

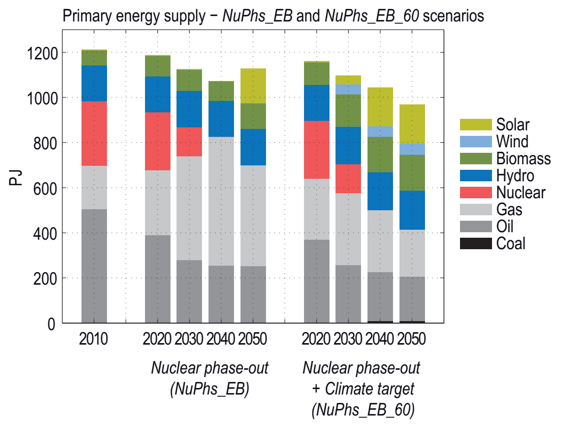
(b) CO_2 emissions

Figure 4.14: Electricity generation mix and CO_2 emissions, Nuclear extension scenarios without (NuExt_EB) and with climate target (NuExt_EB_60)

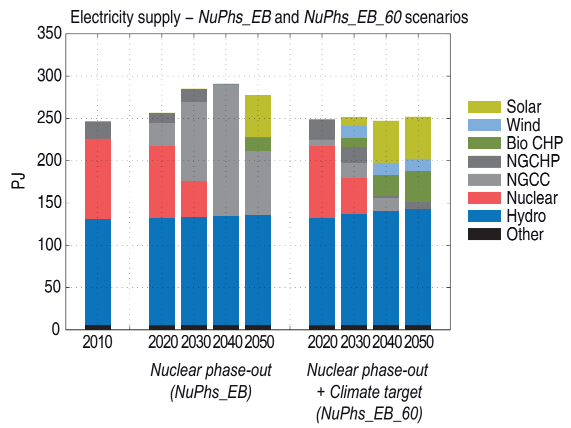
exploited. Given the constraints on new renewable and fossil power generation, the level of electrification of the energy system is reduced compared to the case where nuclear can be replaced (*NuRep_EB_60*) (compare Figures 4.15(b) and 4.14(a)). For example, in the residential heating sector district heating and intensified investments in energy saving options play a larger role (Figures 4.16(a) and 4.13(a)). The use of gas in the electricity sector necessitates a further shift away from fossil fuels in the rest of the energy system in order to meet the climate target. For instance, in the passenger car sector hydrogen and battery electric vehicles are deployed and account for more than 14% of the car fleet in 2050 (Figure 4.16(b)). With the higher efficiency of these alternative drivetrains relative to the conventional ICE car technologies consequently the reduction in final energy consumption in transport driven by the climate target is significantly higher under the nuclear phase-out compared to the nuclear replacement scenario (compare Figures 4.16(b) and 4.13(b)). The efficiency improvements in the car sector as well as in other end-use demand sectors contribute to the overall decrease in total final energy consumption (compare Figures 4.17(a) and 4.12(a)). The technological changes mentioned above also have consequences for the sectoral allocation of CO_2 emissions across the energy system. While the power sector shows an increase in emissions due to the uptake of NGCC and NGCHP technologies in the *NuPhs_EB_60* compared to the *NuRep_EB_60*, significant reductions can be seen in the domestic transport sector (e.g. compare Figures 4.16(b) and 4.13(b)).

No centralised power plants with 60% CO_2 reduction by 2050 (*NoCen_EB_60*)

The absence of centralised fossil and nuclear power plants in a climate target scenario enforces the trend that has been observed in the nuclear phase-out case. Based on the higher electricity generation costs (due to the diseconomies of scale of smaller decentralised generation units compared to larger centralised technologies), electrification of the energy system becomes less attractive and is further decreased. The deployment of decentralised NGCHP technologies increases the production of district heat partially replacing electric heat pumps in the buildings sectors. The lower availability of electricity in the energy system reduces the electrification and decarbonisation of the commercial building sector

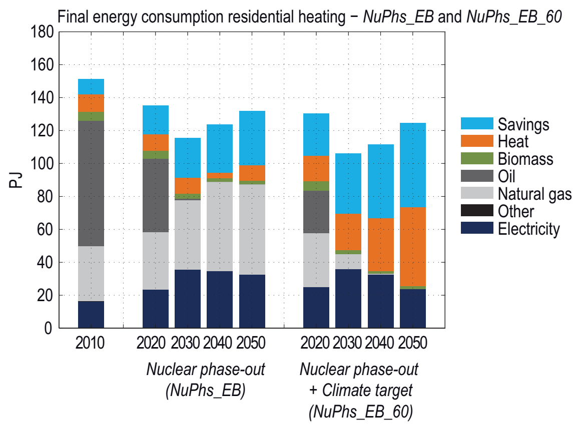


(a) Primary energy consumption

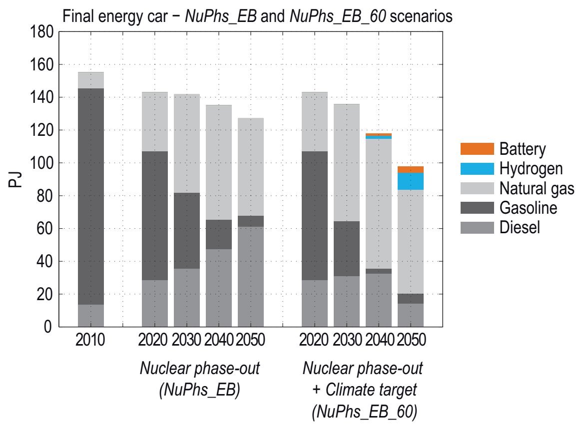


(b) Electricity generation mix

Figure 4.15: Primary energy consumption and electricity generation mix, Nuclear phase-out scenarios without (*NuPhs_EB*) and with climate target (*NuPhs_EB_60*)

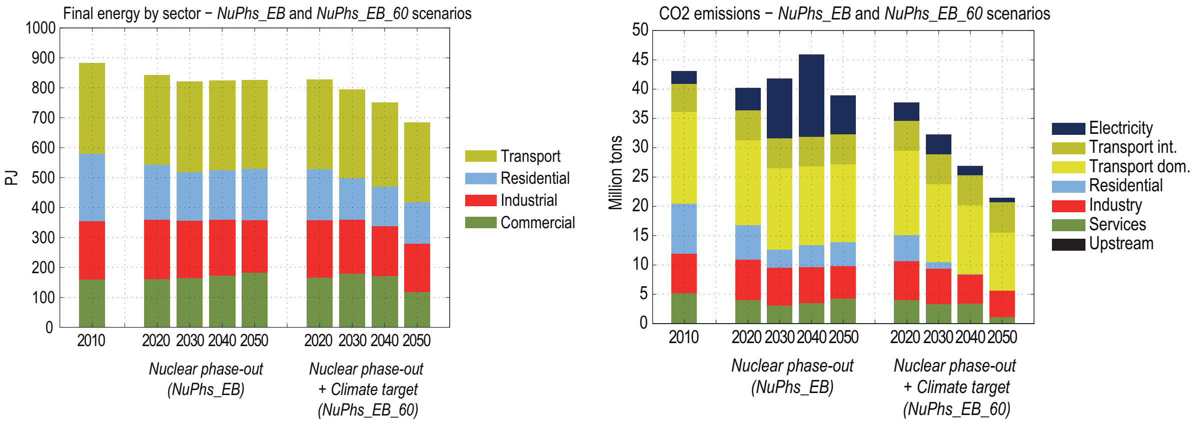


(a) Final energy consumption residential heating



(b) Final energy consumption car sector

Figure 4.16: Final energy consumption in residential heating and car sector, Nuclear phase-out scenarios without (*NuPhs_EB*) and with climate target (*NuPhs_EB_60*)



(a) Final energy consumption by end-use sector

(b) CO_2 emissions

Figure 4.17: Final energy consumption by sector and CO_2 emissions, Nuclear phase-out scenarios without (*NuPhs_EB*) and with climate target (*NuPhs_EB_60*)

compared to the *NuPhs_EB_60* scenario. In order to meet the climate target the higher emissions in the commercial sector are partly compensated by a further decarbonisation of the transport sector (in *NoCen_EB_60* compared to *NuPhs_EB_60*) which is realised with a slightly higher deployment of hydrogen cars partially replacing gasoline and diesel vehicles. The hydrogen used in the car sector is produced from wood gasification.

4.4.2 Alternative climate mitigation targets

Within the scope of this work also alternative climate mitigation scenarios were investigated with *SMM-W1*. Tests have shown that more stringent climate targets than 60% reduction of domestic CO_2 emissions in 2050 could be achieved. With the given set of assumptions on renewable potentials, annual net electricity imports, and the assumed absence of other low-carbon electricity sources such as gas based electricity generation with carbon capture and storage (CCS) or deep heat geothermal power, for the *NuRep* and *NuExt* electricity supply options a CO_2 reduction target of 75%, and for the *NuPhs* and *NoCen* scenarios a 65% reduction target were feasible in 2050. In the latter, the level of low-carbon electricity generation is not sufficient to decarbonise also transport and industrial sectors in order to achieve higher mitigation targets (such as a 70% reduction). The picture will drastically change if CCS or other technologies providing an additional source for low-carbon electricity became available. The role of CCS in the future Swiss energy system is analysed in chapter 5.

The 60% CO_2 reduction target presented above implies a fixed upper bound on the trajectory of domestic CO_2 emissions and doesn't allow flexibility in terms of the timing of CO_2 mitigation over the time horizon. Therefore there might be more cost-effective CO_2 reduction pathways that could achieve the same cumulative CO_2 emissions over the time horizon of 40 years. In order to analyse this, two CO_2 reduction scenarios were defined assuming the same cumulative emissions as in the 60% reduction target with either full flexibility or full flexibility with only the requirement to achieve a 60% reduction in 2050 to meet the climate reduction target as recommended by OcCC (2007). In both scenarios

CO_2 reductions are intensified earlier in the time horizon mainly by decarbonising the building sectors in order to avoid higher reductions (in the second half of the time horizon) including more expensive mitigation options in the transport sector. Although the model generally tends to push investments to the end of the time horizon due to their lower net present value compared to earlier investments, it seems to be more cost-effective to invest earlier (at higher net present costs) in order to forgo the higher mitigation costs due to more stringent targets later.

4.5 Sensitivity analysis on fossil fuel prices

The future development of energy prices, particularly of imported fossil fuels, is likely to have a significant impact on the configuration of the future Swiss energy system. Since there is large uncertainty related to the development of international energy prices and Switzerland has almost no influence on it a sensitivity analysis on fossil fuel prices is conducted within the scope of this analysis. As introduced in section 4.2 four different fossil prices sensitivities based on three energy price scenarios from the IEA Energy Technology Perspectives (ETP) IEA (2012b) of the International Energy Agency (IEA) are analysed in this section.

4.5.1 No climate target

In the absence of a climate target high prices for imported fossil fuels lead to lower demand for these fuels (especially oil and gas) and promote an earlier and stronger deployment of new renewables such as solar and wind compared to scenarios with lower fossil fuel prices (Figure 4.18). This effect that can be observed in all four electricity supply scenarios. In addition, final energy consumption decreases with higher energy prices indicating an increase in overall efficiency of the energy system.

The impact of fossil fuel prices on electrification of the energy system is different across the four electricity supply options. When nuclear can be replaced or expanded high fuel prices seem to promote electrification particularly towards the end of the time horizon when prices are highest. The increase in non fossil-based electrification in these scenarios allows to substitute fossil fuels with electricity in other parts of the energy system (Figure 4.19). When nuclear power is phased out electrification is less attractive when fossil fuel prices are high since only gas-based electricity generation is left when limited domestic renewable potentials are exhausted. Hence, in contrast to the nuclear replacement and extensions scenarios, in the nuclear phase-out scenario electricity production is reduced when fossil prices are high. In the No Centralised case, the level of electrification shows a similar pattern as for the Nuclear replacement and Nuclear Extension scenarios (i.e. higher electrification for high fossil fuel prices). However, additional electrification is mainly realised with renewable sources due to the diseconomy of scale of the decentralised fossil electricity generation technologies.

The increased electrification in the *NuExt_EH* scenario occurs mainly in the commercial and residential building sectors where gas-based heating systems are partly replaced by electric resistance heaters and heat pumps. The residential heating sector is one of the parts of the energy system that is very sensitive to changes in energy prices in all four

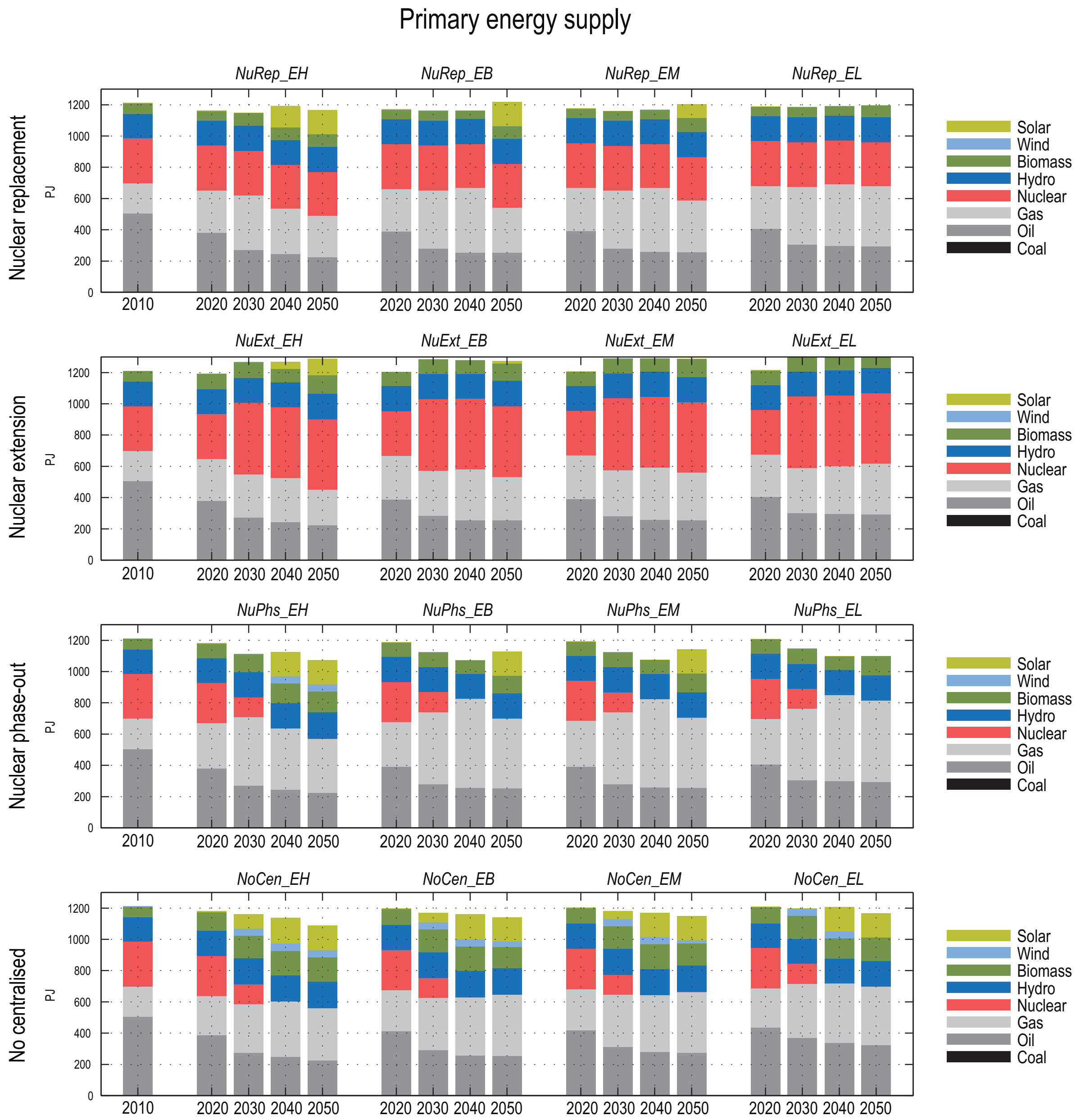


Figure 4.18: Impact of fossil fuel prices (High, Business as usual, Medium, and Low) on primary energy consumption in four electricity supply scenarios Nuclear replacement, Nuclear extension, Nuclear phase-out, and No centralised (without climate policy)

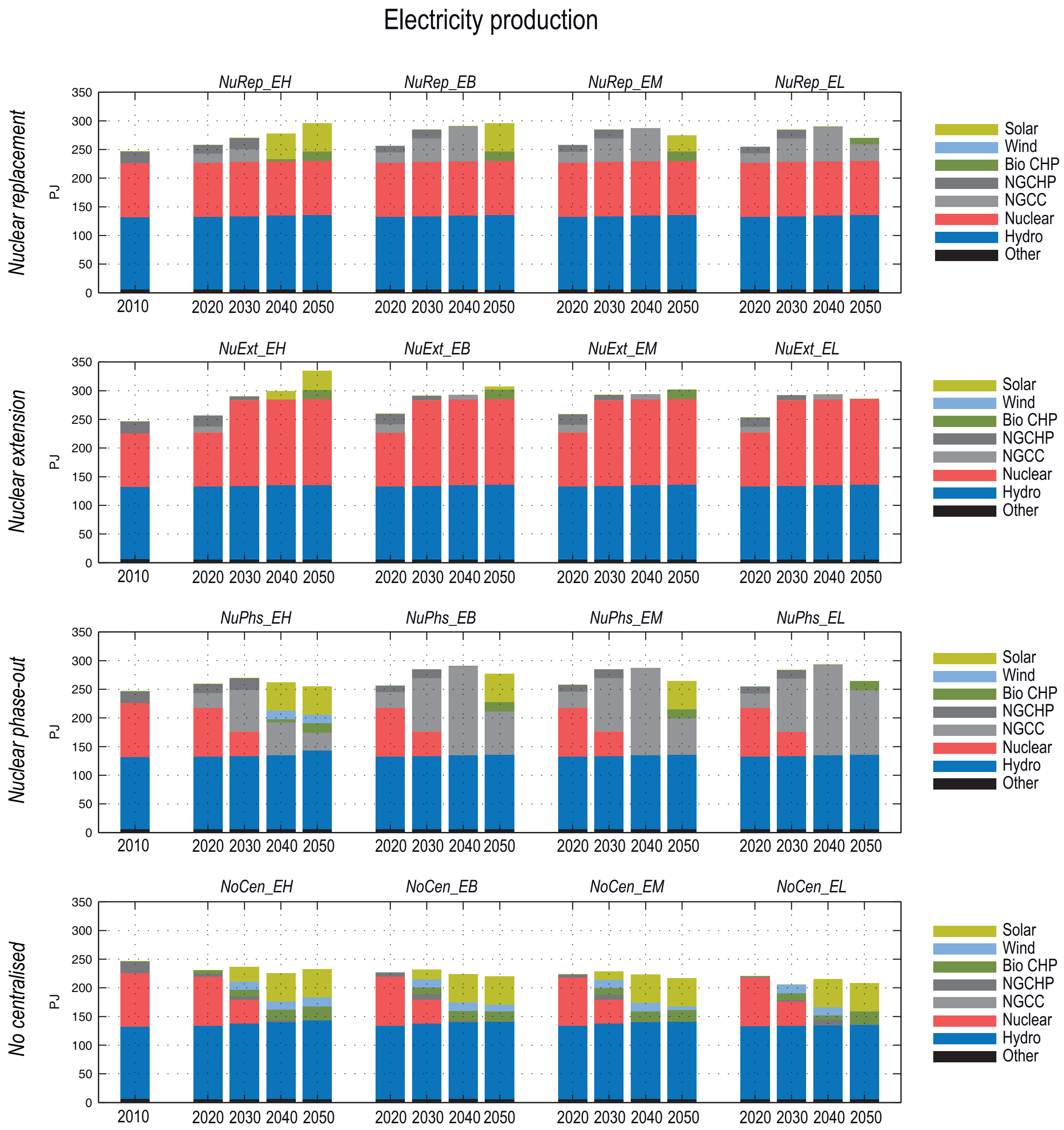


Figure 4.19: Impact of fossil fuel prices (High, Business as usual, Medium, and Low) on electricity generation in four electricity supply scenarios Nuclear replacement, Nuclear extension, Nuclear phase-out, and No centralised (without climate policy)

electricity supply cases. While the low fossil fuel prices promote the use of gas and oil used longer for space heating (in scenarios *NuRep_EL*, *NuExt_EL*, *NuPhs_EL*, and *NoCen_EL*), in the high price scenarios these fossil fuels are replaced by district heating, electric heat pumps and significant installations of energy saving technologies. In the passenger car sector we observe a faster deployment of gas technologies at the expense of gasoline and diesel cars when fossil fuel prices are high. The shift from oil based fuels to gas in the car sector goes along with a decrease in final energy consumption related to the deployment of more efficient car technologies. As a concomitant effect the high energy prices also support the decarbonisation of the energy system. However, there are sectors that seem to be more cost-effective to decarbonise than other. For example in all electricity supply scenarios we observe that the building sectors decarbonise before the industrial and transport sectors, since they are assumed to have more cost-effective options to substitute fossil fuels (e.g. heat pumps and solar thermal in space heating).

4.5.2 Climate target

In contrast to the scenarios without CO_2 reduction target presented above, changes in fossil fuel prices have a less significant impact on a climate constrained energy system. For the four electricity supply scenarios the use of fossil fuels in particularly oil and gas is already restricted by the climate constraint, with only small changes for different energy prices. Given the limit on the total carbon emissions there is only little flexibility in the use of oil and gas. According to the increasing relative price difference between oil and gas for higher energy price scenarios (due to the faster increase of the oil price compared to natural gas (see Table 4.1)), we observe a slight shift from oil to gas with higher fuel prices. However, for the nuclear supportive scenarios (i.e. *NuRep_E∗_60* and *NuExt_E∗_60*) the flexibility seems to be slightly higher than for the *NuPhs_E∗_60* and *NoCen_E∗_60* scenarios. Similar to the case without a climate target, in the E_60_x scenarios higher energy prices promote a slightly higher electrification of the energy system. While technology choice in the residential sector seems to be rather insensitive to changes in energy prices, the car sector shows that the shift from oil-based fuels to gas cars is accelerated when energy prices are high. This effect is partially driving the abovementioned change of the relative shares of oil and gas in primary energy consumption.

4.6 Energy system costs

One of the aims of scenario analysis presented in this chapter is to deepen understanding of the future energy system and provide knowledge supporting policy decision making. In this regard, the costs of realising different future energy systems and particularly of policy options are of great interest and deserve to be analysed in detail.

As introduced in chapter 3, Swiss MARKAL determines the combination of technologies and fuels for each scenario with the lowest possible discounted cost over the entire time horizon of 40 years. In doing so, cost-optimal combinations of technologies and energy carriers are identified. The discounted total system costs are a meaningful indicator of the economic costs of the pathway towards a specific energy system. In order to understand possible implications on costs of the different scenarios presented in this chapter, the costs of all scenarios are compared and analysed.

4.6.1 Costs of electricity supply options

Figure 4.20 presents the relative changes in energy system costs of the three electricity supply options Nuclear Extension, Nuclear Phase-out, and No Centralised relative to the Nuclear replacement option for the set of fossil fuel price sensitivities and for the cases with and without CO_2 emission target. In order to reach a nuclear phase-out in a no climate policy scenario the energy system costs increase by more than 1% compared to the case where nuclear can be replaced. If in addition to the nuclear phase-out also investments in centralized technologies are restricted, the additional costs are even higher (>2%) due to the more expensive decentralized electricity technologies. If nuclear capacities can be extended leading to a higher electrification of the energy system, the costs can be reduced by more than 1% compared to the nuclear replacement case.

Figure 4.20 also shows that under a climate target the costs of a nuclear phase out significantly increase up to more than 3% compared to the no-climate target case. This rise in costs is partially driven by the replacement of the relatively cheap gas combined cycle technologies by the more costly new renewables including solar PV and wind. While the restrictions on centralized fossil power plants significantly increase the costs of a nuclear phase-out in a no-climate policy scenario the additional costs are only small when a climate target has to be reached. Similarly, the cost reductions of a nuclear extension are only slightly higher in a climate target scenario compared to the case without climate target. This is partially related to the fact that already in the no climate scenario due to the high electrification (from nuclear power) the energy system is largely decarbonized and only moderate efforts are needed to meet the climate target.

Looking at Figure 4.20, the analysis of the impact of energy prices on the additional costs of the three electricity supply options (relative to the Nuclear replacement case) shows that when there is no climate target increasing fossil fuel prices generally increase the costs of all supply scenarios due to the higher fuel costs. However, there seems to be an exception in the case of the no centralized option where the incremental costs of 2.2% of this supply option relative to the nuclear replacement case seems to be lower for higher energy prices. In this case in the nuclear replacement scenario the use of fossil fuels in the power sector is already reduced by the high energy prices (while new renewables are deployed) resulting in higher system costs. Hence, the restrictions on nuclear and centralized fossil power plants have a smaller impact on the energy system compared to the scenarios with lower energy prices.

While higher fossil fuel prices increase the system costs in most cases in the absence of a climate policy, we can observe the opposite effect if the energy system has to reach a climate target. The incremental system costs of all electricity supply options analysed are lower for higher energy prices due to the same reasons as described above for the no centralized scenario without climate target: Due to the high fossil fuel prices the energy system invests already in the nuclear replacement case into relatively expensive non fossil-based technologies (e.g. solar PV) and hereby reducing the dependency on fossil fuels while increasing the system costs. When constraining the energy system with the nuclear phase-out or no centralised electricity supply option less additional efforts are needed since many options needed to replace the retired nuclear capacity is already attractive in the nuclear replacement case.

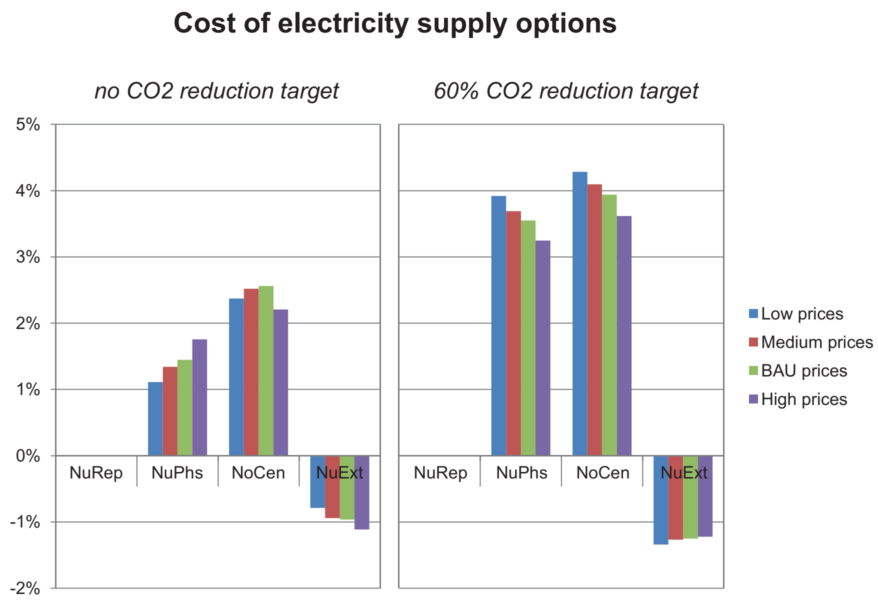


Figure 4.20: Additional cost of electricity supply options (Nuclear phase-out, No centralised, Nuclear extension) relative to Nuclear replacement option without and with CO_2 reduction target.

4.6.2 Costs of the climate target

Reaching a climate target such as the 60% reduction in domestic CO_2 emissions increases the costs of the energy system. However, there are differences across the four electricity supply options and the energy prices sensitivities. As Figure 4.21 shows that, the costs for climate mitigation are highest for the nuclear phase-out since in such a scenario relatively cheap gas power plants replacing the phased-out nuclear capacities have to be replaced by the significantly more expensive new renewable technologies in order to meet the climate target. Slightly lower climate mitigation costs occur for the no centralized scenarios, where a number of mitigation options are already attractive in the no climate policy case due to relatively higher costs of the decentralised fossil generation technologies compared to the less expensive centralized gas combined cycle plants in the nuclear phase-out scenarios. Significantly lower costs for climate mitigation are seen when nuclear power can be replaced (*NuRep*) or extended (*NuExt*).

4.6.3 Impact of energy prices on system costs

A comparison of energy system costs for the four electricity supply options with and without climate target for each of the four fossil fuel price sensitivities shows that fuel prices have a significant impact on costs in all cases. Compared to the business as usual fossil fuel price scenario (*EB*) the medium (*EM*) and low (*EL*) price scenarios imply reductions in system costs of 4 to 5% (*EM*) 9 to 10% (*EL*). On the other hand the high energy prices of the *EH* scenarios show an increase in costs of 8 to 9.5% compared to the *EB* scenarios. For all scenarios it can be seen that under a climate target the differences tend to be slightly smaller than for the case without climate policy mainly related to the fact that the climate constraint generally reduces the dependency on fossil fuels in the energy system and hence the impact of changes in energy prices.

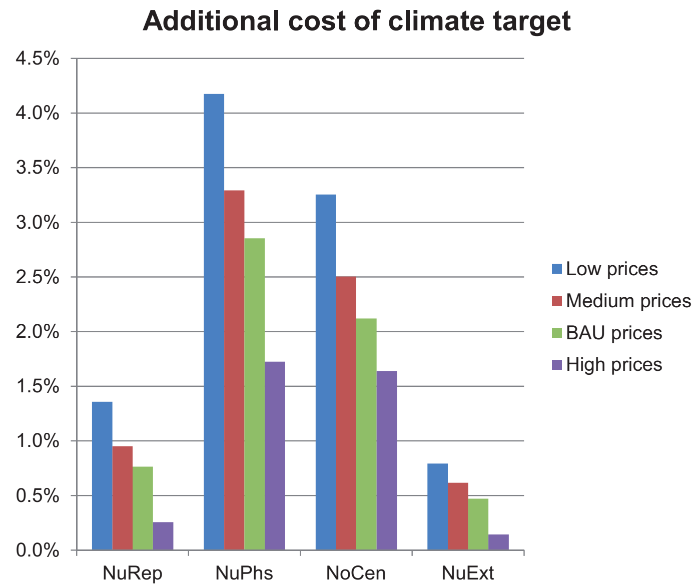


Figure 4.21: Cost of climate mitigation for the four electricity supply options (Nuclear replacement, Nuclear phase-out, No centralised, and Nuclear extension) for different levels of fossil fuel prices.

4.7 Summary and discussion

After the decision of the Federal Council to phase-out Swiss nuclear power plants at the end of their lifetimes, there still exists large uncertainty related to the future electricity supply in particular, and the energy system in general. Some of this uncertainty is related to the open question of how Switzerland will continue following ambitious climate change mitigation targets when substantial capacity of low-carbon electricity from nuclear falls away. The results of this analysis show that phasing out nuclear power and at the same time reducing domestic CO_2 emissions by 60% in 2050 is possible under the assumptions used here (see chapter 3). However, in order to reach these goals a transformation of today's energy system towards a more sustainable configuration is inevitable and requires tremendous efforts in many respects.

4.7.1 Electricity supply

In this chapter, major uncertainties related to future electricity supply options and the development of fossil fuel prices have been analysed for scenarios with and without CO_2 reduction target. Four electricity supply options including a nuclear phase-out, replacement of today's nuclear capacities after reaching the end of their lifetimes, a ban on centralized fossil power plants (including a nuclear phase-out), and a possible extension of nuclear power have been analysed in this chapter. It has been shown that the fundamental diversity of these four electricity supply scenarios is likely to have a significant impact on the configuration of many parts of the future energy system such as some of the end-use sectors. Based on the technology assumptions used in this analysis, hydro

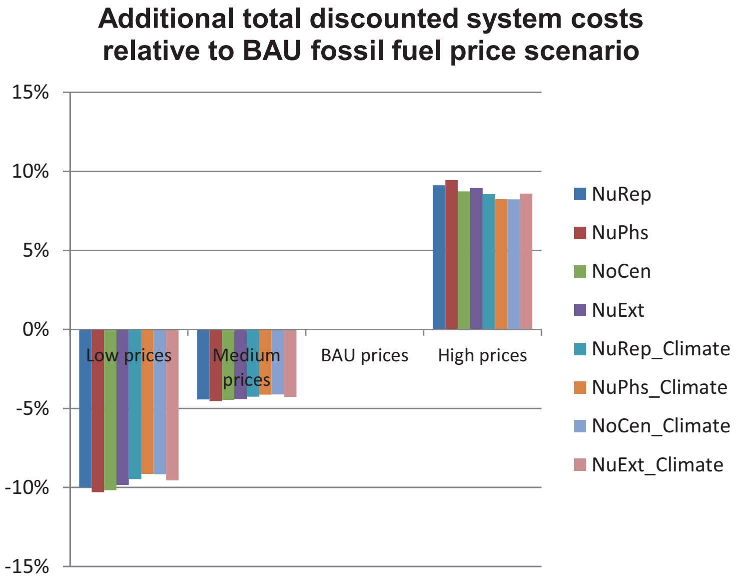


Figure 4.22: Impact of fossil fuel prices on energy system cost for the four electricity supply options (Nuclear replacement, Nuclear phase-out, No centralised, and Nuclear extension) without and with climate target.

and nuclear power are used up to assumed potentials or scenario limits across all four supply scenarios. Additional electricity is produced by NGCC, gas CHP's, solar PV, wind, and biomass CHP. However, the level and the mix of the residual generation strongly depend on the assumptions on the availability of nuclear power, fossil fuel prices, and climate policy constraints. While NGCC technologies seem to be an attractive option to support the increasing electrification of the energy system in the nuclear phase-out and nuclear replacement scenarios without an emission reduction target, in the nuclear extension scenario it is only marginally used due to the higher deployment of nuclear power. In the no centralized scenario where NGCC technologies cannot be built more expensive decentralized CHP plants are used. However, due to the high costs of these decentralized technologies the electricity production of the energy system is more or less stabilized on current levels in scenarios with and without an emission reduction target. Focussing on the scenarios with a climate target, fossil-based power generation plays only a small role while new renewables such as solar PV and wind are deployed in the second half of the time horizon.

As mentioned above, fossil fuel prices can have a significant impact on the attractiveness of many electricity supply technologies. While the cost-effectiveness of fossil-based power generation technologies (i.e. NGCC and NGCHP) is directly influenced by energy prices, new renewables are only indirectly linked to changes in prices. Given the assumptions on annual net electricity import levels, and nuclear and hydro potentials used in this analysis, the attractiveness of new renewable technologies increases when fossil-based electricity generation are less cost-effective due to high energy prices. Beside the competition between electricity generation technologies, fossil fuel prices can also have an impact on the competition between their use for electricity production and their direct use as final energy carriers in the end-use sectors. For example, when fossil fuel prices are high, the efficiency of a conversion technology becomes crucial and could lead to the result (given that this efficiency is low) that it is more cost-effective to use the fuel directly in the demand technology (than converting it first to electricity).

As the results in this analysis show, in the electricity sector the full potential of many domestic renewable electricity sources including new hydro, wind, and solar needs to be exploited in order to compensate the phased-out nuclear capacity and stabilize today's electricity supply levels. Further, the intermittent character of wind and solar energy has to be taken into account when planning the future electricity supply system. In order to meet electricity demands at all times in the year (taking into account significant seasonal and day-night fluctuations in electricity demand) either electricity import and export activities have to be increased (still allowing that annual imports and exports stay balanced) or storage capacities for electricity need to be extended (e.g. pumped storage hydro). While the former would increase the dependence on other countries the latter is related with additional high investment costs assuming that suitable locations are available. Another important issue is the electric grid. With an extensive uptake of decentralized new renewable technologies the capacities of the electric grid will need to be adjusted and increased in order to prevent local black outs. The costs of such infrastructure changes (that are not included in this analysis) could be significant.

4.7.2 End-use demand sectors

The different levels of electrification, the changes in fossil fuel prices, and the CO_2 reduction target have implications for the technological configuration in some of the end-use sectors. In the absence of a CO_2 emission target the residential sector favours gas-based heating systems in the second half of the time horizon for medium and low energy prices. In emission reduction scenarios and when energy prices are high, gas-based heating is replaced by electrical heat pumps, district heat, and a massive deployment of energy saving measures compared to scenarios with lower fuel prices or no climate target. In particular, under climate constraints, district heat is used in nuclear phase-out and no centralized scenarios, in which low-carbon electricity is limited. In such cases, highly efficient natural gas and biomass CHP technologies are attractive. Energy-saving technologies representing insulation of building envelopes are cost-effective across all scenarios analysed in this chapter. However, there are differences in the level of the deployment, since some of the more expensive measures are only deployed when fossil fuel prices are high or an ambitious CO_2 reduction target is applied to the energy system.

In the car sector it can be observed that a climate policy target reducing emissions by 60% supports the deployment of gas vehicles, while in the absence of a climate target diesel and gasoline cars play the dominant role over the entire time horizon. Hydrogen and battery cars are only attractive under a nuclear phase-out when low-carbon electricity becomes scarce and has to be complemented with gas-based generation. The increase in emissions in the power sector is then compensated with higher mitigation efforts in other parts of the energy system such as the transport sector. This implies that the direct use of natural gas in the car sector is more attractive than converting the gas into electricity or hydrogen) to be used in these relatively expensive car technologies.

In order to achieve the presumed climate mitigation targets all end-use sectors will likely have to reduce CO_2 emissions. Especially the residential and commercial building sectors need to exploit most of their potentials to decarbonise by insulating the building envelopes, replacing fossil-based heating systems with district heating and heat pumps. In the transport sector the most part of the passenger car fleet has to move from oil based fuels to natural gas (and possibly low-carbon fuels such as hydrogen and electricity). Depending on the technological changes in the car fleet massive investments in refuelling infrastructure would be required.

There are many energy efficiency and climate change mitigation options in the end-use demand sectors that are cost-effective already today but not deployed due to the existence market barriers related to insufficient knowledge, missing investment support in case of capital intensive measures, or missing incentives due to long amortization times. Some of these barriers could be overcome if policy makers improve the legal framework supporting investments in energy efficiency measures (e.g. by increasing the current limits on subsidies for energy efficiency measures in the building sectors) and intensify efforts in increasing public knowledge related to energy efficiency and climate change mitigation technologies.

4.7.3 Energy system cost

The impact on energy system costs has been analysed for three uncertainties related to future electricity supply, development of fossil fuel prices, and CO_2 reduction targets. From these factors, Switzerland can only decide on the reconfiguration of the electricity system and future climate policies but has only insignificant influence on the development of international energy prices. Given the range of uncertainty analysed, the comparison of these three factors shows that fossil fuel prices have by far the strongest impact on energy system costs (i.e. variations of +/- 10% depending on the price level) compared to the electricity supply and the climate target (with ranges of around 5% and 4% respectively depending on the electricity supply option and the CO_2 reduction target). The negative impact of high fossil fuel prices on costs could be reduced by reducing the dependence on fossil fuels in the energy system (e.g. due to a CO_2 reduction target). This would support climate change mitigation and relaxing energy security issues at the same time, both contributing to the required transformation of the energy system towards a sustainable configuration. While a CO_2 target can reduce the impact of fossil fuel prices on the energy system, (high) prices could in return lead to a decarbonisation of the energy system and support climate change mitigation. However, this (highly uncertain) contribution from possibly high fossil fuel prices will most likely not be sufficient to meet higher CO_2 reduction targets (particularly in the absence of future nuclear power plants) and would require policy action to reduce domestic CO_2 emissions (i.e. by higher taxes on carbon intensive fuels or technologies). The impact of a nuclear phase-out is relatively small (i.e. 1-2% cost increase with the absence of a CO_2 reduction target) compared to the fossil fuel prices. However, the impact on the incremental cost of a nuclear phase-out can significantly increase upto 4% under a stringent climate policy.

Chapter 5

Carbon capture and storage in Switzerland

This chapter is based on and includes substantial elements of the conference paper *"Potential Role of CCS in Post-Fukushima Nuclear Policy Scenarios under Climate Constraints in Switzerland"* written by Nicolas Weidmann and Hal Turton (Weidmann and Turton, 2012b), submitted to and presented at the 12^{th} IAEE European Energy Conference in Venice, Italy, 2012.

5.1 Introduction

After the decision of the Federal Council to phase out nuclear power (see chapter 2), the availability of alternative low-carbon electricity sources will likely be crucial for the realisation of the transformation of the Swiss energy system towards a more sustainable configuration as mentioned in chapters 1 and 2. Apart from new renewable technologies (such as wind, solar, and biomass), which have limited potentials, natural gas combined-cycle plants with carbon capture and storage (CCS) (see Box 5.1) could potentially provide a large-scale source of low-carbon electricity and support successfully coping with challenges related to climate change.

While CCS seems to be an attractive technology option for realizing climate change mitigation targets, its deployment is dependent on various highly uncertain factors such as technical and geological feasibility for capture and storage[1], cost-effectiveness including the future price of natural gas, and public acceptance. Additionally, policy decisions related to the exact timing of the nuclear phase-out and the CO_2 reduction pathway could be crucial to the cost-effectiveness of CCS.

[1]From today's perspective it is uncertain, if Switzerland has enough suitable geological long-term storage capacities for a large-scale use of CCS technologies. Further, it is unclear if the process of capturing CO_2 emissions will become cost-effective.

Box 5.1 Carbon Capture and Storage

Following the descriptions of the International Energy Agency (IEA, 2013) and the CO_2 Capture Project (CCP, 2008), Carbon Capture and Storage (CCS) is a group of technologies and techniques aiming at capturing carbon dioxide (CO_2) from point sources such as energy-related fuel combustion or industrial processes before it enters the atmosphere (CCP, 2008). Then, the CO_2 is compressed, transported, and injected deep underground in secure geological formations (e.g. in depleted gas fields and deep saline aquifers), so that it remains stored there indefinitely (generally in supercritical form) (CCP, 2008). Figure 5.1 illustrates the main processes related to CCS as mentioned above. The key motivation for undertaking CCS is the need for cost-effective solutions to cope with the global challenge of climate change by reducing CO_2 emissions (CCP, 2008).

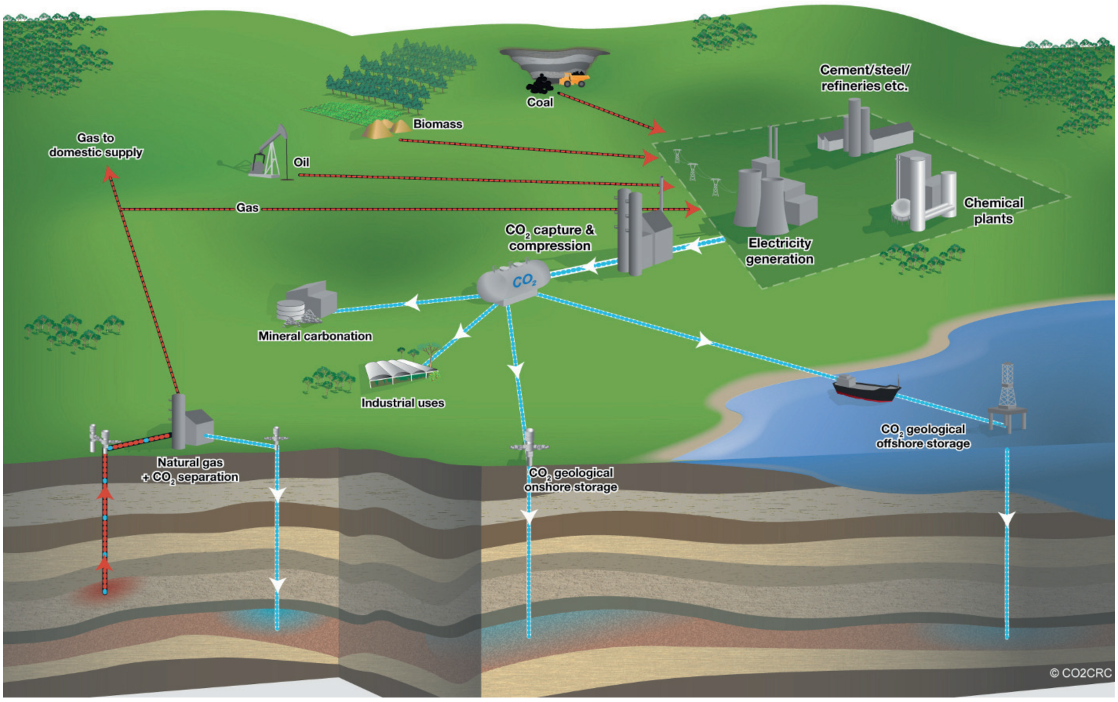


Figure 5.1: Capture, transport, and storage of CO_2 (Figure courtesy of CO2CRC (CO2CRC (Cooperative Research Centre for Greenhouse Gas Technologies), 2013)).

A possible implementation of CCS in Switzerland has been investigated in the scope of the CARMA (CARbon MAnagement in power generation) project, that was supported by the Competence Center Energy and Mobility (CCEM), the Competence Center Environment and Sustainability (CCES) (both from the ETH domain), and Swisselectric Research. Amongst others, the Paul Scherrer Institute (PSI) participated in this project. A part of PSI's contribution comprised the work on scenario analysis of the potential role of CCS in the future Swiss energy system as presented in this chapter. Other research partners involved in the CARMA project (e.g. Diamond et al. (2010)) investigated potential areas for CO_2 storage in Switzerland. As can be seen in Figure B.1, areas with higher potential for CO_2 storage within deep saline aquifers (with a total theoretical (unproven) storage capacity of approximately 2680 million tonnes of CO_2) have been located in the sector Fribourg-Olten-Lucerne. *http://www.carma.ethz.ch/*

There are many areas where CCS technologies could be applied. Beside the electricity sector, CO_2 emissions could also be captured in the cement industry and from the production of fossil-based hydrogen, both possibly representing point sources where CCS could be cost-effective. In the electricity sector there exists a number of different CCS technologies including CCS pre-combustion (with natural gas) and post-combustion (e.g. with gas, coal, or biomass) technologies. Since coal seems not a realistic option for future electricity generation due to reasons related to climate change mitigation and transport issues, for this analysis, we focus on CCS technologies in combination with natural gas-combined cycle (NGCC) plants with post-combustion capture technologies.

In this chapter, conditions are identified under which CCS could be an attractive solution for CO_2 mitigation in Switzerland (and herewith supporting the abovementioned transformation of the energy system), accounting for the phase out of nuclear generation. Further, possible impacts of a deployment of CCS on technology and fuel choice in some of the end-use demand sectors are explored. For this purpose, a number of scenarios reflecting key uncertainties including a set of different fossil fuel price assumptions (as given in Table 4.1), the availability of CCS retrofitting technologies[2], different levels of CO_2 emission reduction targets, and an increased support for nuclear power. These scenarios are analysed with the Swiss MARKAL Model version 1 (*SMM-W1*), as described in chapter 3[3]. For the analysis of CCS technologies in the Swiss energy system, *SMM-W1* has been extended with a CCS module representing a set of different CCS technologies.

Substantial parts of the analysis presented in this chapter have been undertaken within the CARMA (CARbon MAnagement in power generation) project (see Box 5.1). Results from this work have been also presented in different conferences (Weidmann et al., 2012b; Weidmann and Turton, 2012a,b) and at the Swiss Federal Office of Energy (Weidmann, 2012).

The remainder of this chapter is organized as follows: In section 5.3 the scenarios analysed in this chapter are defined. Section 5.2 describes the CCS module that has been developed and implemented into the model. Section 5.4 presents results from a scenario analysis looking at the potential role of CCS when nuclear power is phased-out under the abovementioned sets of uncertainties. Section 5.6 presents a sensitivity analysis on fossil fuel prices and their impact on the attractiveness of CCS in the energy system. In section 5.7 the analysis is discussed and conclusions from the results are drawn along with possible policy implications supported by this work.

5.2 CCS module

SMM-W1 has been extended with a detailed CCS-module representing different types of gas power plants in combination with CCS (i.e. combined-cycle and combined heat

[2]Retrofitting technologies as also described in (IEA, 2012a) allow the temporal decoupling of investments into the power plant and the capture units.

[3]The assumption on hydro potential in 2050 of 33 TWh used for the analysis presented in this chapter is slightly lower than the 37.1 TWh (see Table 3.3) used in chapters 4, 6 and 7, since the analysis on CCS was conducted before the update on the hydro potential. However, this change in hydro potential does not change the overall findings of the analysis.

and power for different vintages)(see Table 5.1) and also includes the option to deploy and later retrofit CCS-ready plants. Beside the plants and the capture technologies, CO_2 transport and storage[4] processes are also represented in the CCS module. The structure of the CCS module applied in *SMM-W1* is shown in Figure 5.2.

Table 5.1: NGCC and NGCHP CCS technology data parameters. (Sources: Hirschberg et al. (2010) and own assumptions)

Technology	AF	INVCOST	FIXOM	VAROM	EFF		LIFE
		[CHF_{2010}/kW]	[CHF_{2010}/kW]	[Rp_{2010}/kWh_e]	elec.	therm.	
NGCC 2030	82%	1700	16	4.8	56%		25
NGCC 2050	82%	1500	16	4.8	61%		25
NGCHP 2030	51%	2040	23	7.2	52%	25%	25
NGCHP 2050	51%	1800	23	7.2	56%	25%	25

AF: Availability factor
INVCOST: Investment cost
FIXOM: Fixed O&M cost
VAROM: Varibable O&M cost
EFF: Efficiency
LIFE: Lifetime

5.3 Scenario definitions

In order to analyse the potential role of CCS in the Swiss energy system under nuclear and climate constraints, a set of scenarios reflecting some of the main uncertainties related to the possible future energy system in general, and the availability of CCS in particular, was developed:

5.3.1 Availability of CCS technologies

For analysing the role of CCS and the option to retrofitting earlier-built gas plants, three cases representing different levels of availability of CCS technologies have been developed:

- CCS not available: In this case, CCS technologies are fully restricted in the energy system.
- CCS available (CCS): Here, centralised natural gas combined cycle (NGCC) technologies with CCS and centralised natural gas combined heat and power (CHP) technologies with CCS are available from the year 2030 on. Other types of CCS technologies (e.g. in coal-based electricity generation or in non-electricity sectors including the cement industry) are not assumed to be available.

[4]The theoretical storage capacity in Switzerland of 2680 million tons of CO_2 as presented by Diamond et al. (2010) is used for this analysis. However, the results of the analysis show that less than 10% of this potential will be used until the year 2050.

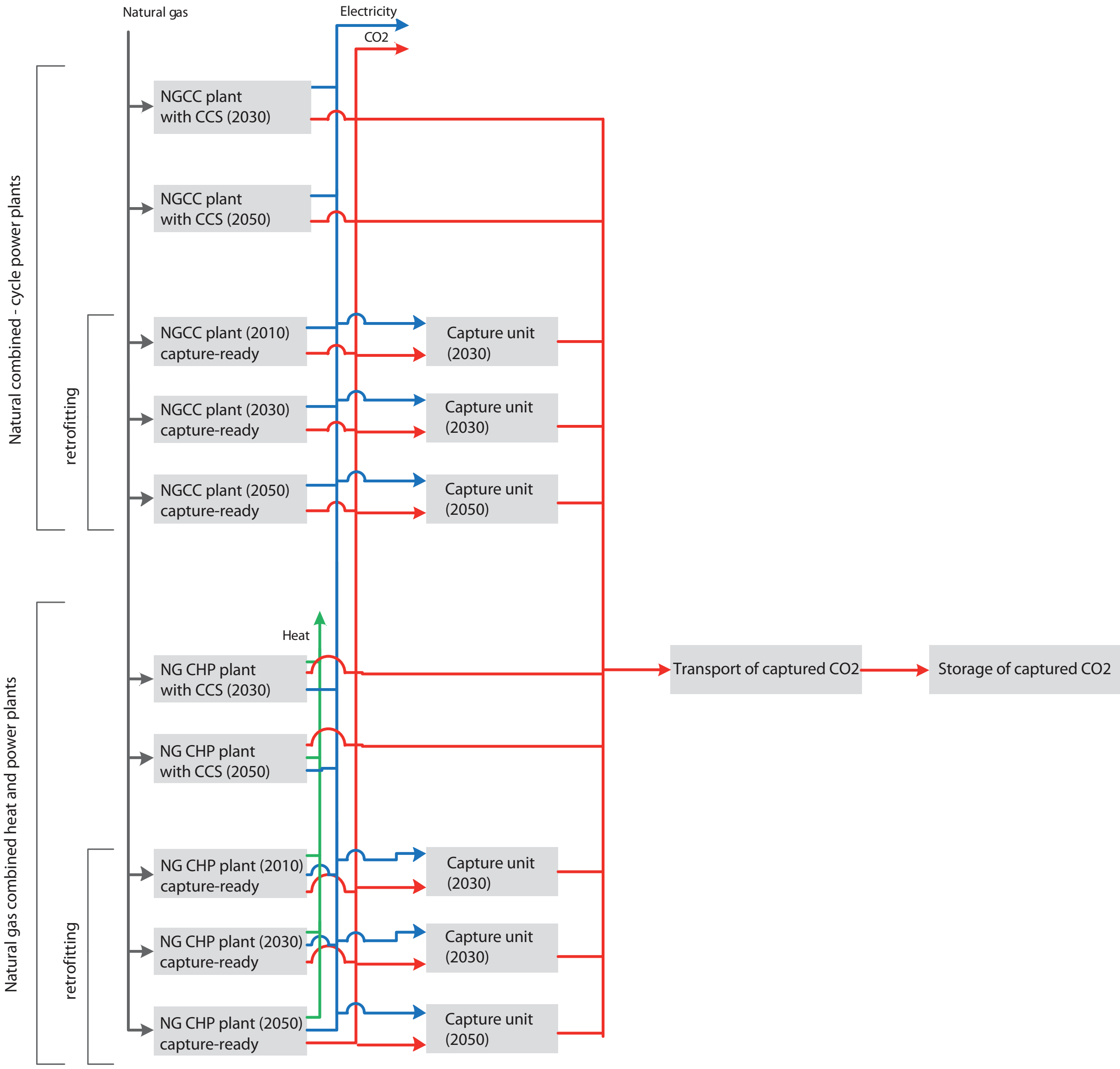


Figure 5.2: CCS module in Swiss MARKAL Model representing different CCS technologies including NGCC and centralized NGCHP technologies with CCS and CCS-ready powerplants and capture units with different vintages.

- CCS Retrofitting available (CCS-R): With this option, earlier-built *CCS-ready*[5] centralised NGCC and NGCHP technologies can be retrofitted by extending the power plant with capture units to a full CCS powerplant. While the capture technologies are not available before 2030, the CCS-ready powerplants can be installed before. As for the scenario described above, other CCS technologies than NGCC and NGCHP are not available in this scenario.

5.3.2 Stringency of CO_2 reduction target

In order to analyse the impact of different climate constraints on the role of CCS three stringency levels for CO_2 emission reductions are defined:

- No CO_2 reduction: Here, we assume that no climate policy is applied to the energy system.

- 60% CO_2 reduction (*60*): This target that is recommended by OcCC (2007) and SAAS (2009) assumes a 60% reduction of domestic CO_2 emissions in the year 2050 and is consistent with the reduction target used in chapter 4.

- 75% CO_2 reduction (*75*): Analogue to the 60% emission reduction target mentioned above, the 75% reduction target assumes a 75% reduction of domestic CO_2 emissions in the year 2050[6]. The 75% reduction target was chosen since an 80% reduction target (as recommended by OcCC (2012)) was not feasible based on the given scenario assumptions.

5.3.3 Fossil fuel price sensitivities

Following chapter 4, also in this chapter a sensitivity analysis on fossil fuel prices is conducted in order to analyse the potential impact of changes in international energy prices on the potential role of CCS technologies in the energy system given their likely reliance on imported natural gas. The four fossil fuels price sensitivities analysed are identical to the assumptions used for the analysis in chapter 4 (see Table 4.1) and are based on the global price scenarios of IEA (2012b):

- High fossil fuels prices (*EH*)

- Business as usual (BAU) fossil fuels prices (*EB*)

- Medium prices (*EM*)

- Low prices (*EL*)

[5]Here, it is assumed that a CCS-ready gas plant has slightly higher investment costs in order to account for the reservation of the additional space needed for possible future capture technologies.

[6]This more ambitious CO_2 reduction target was not feasible in the analysis presented in chapter 4 but is included here since it was expected that CCS-based low-carbon electricity could support the achievement of higher mitigation targets.

5.3.4 Support for new nuclear powerplants

Given the decision by the Federal Council to phase-out retired nuclear power plants (see chapter 2), the case where nuclear capacities are phased out after reaching the end of their assumed lifetimes is considered as the reference case for the analysis in this chapter. However, in order to illustrate the potential benefit of CCS technologies in a nuclear constrained energy system, also the case where nuclear can be replaced is analysed for comparison:

- Nuclear phase-out (*NuPhs*): In this case, it is assumed that existing nuclear powerplants are phased-out after they reach the end of their assumed lifetime of 50 years. The assumptions on residual nuclear capacities are consistent with the one used in chapter 4 and given in Figure 3.3.
- Nuclear replacement (*NuRep*): Nuclear power plants can be replaced when reaching the end of their lifetimes while total capacity cannot exceed current levels.

5.3.5 Scenario combinations

The uncertainties described above are combined and defined to scenarios. An overview on the scenario combinations analysed in this chapter is given in Table 5.2:

5.4 Role of CCS under climate and nuclear constraints

For better understanding some of the potential impacts of CCS technologies on the configuration of a carbon- and nuclear-constrained energy system, key insights from the analysis of a nuclear phase-out scenario with a 60% CO_2 emission reduction target (as analysed and discussed in chapter 4) are repeated in this section.

As in chapter 4, in a 60% CO_2 emission reduction target scenario with *business as usual* fossil fuel prices including a nuclear phase-out and no availability of CCS (*NuPhs_EB_60*), the energy system shifts away from both oil-based and nuclear primary energy carriers, while expanding the limited renewable resources (Figure 5.3), necessitating an increase in efficiency to meet energy service demands. At the time when nuclear power is being phased out and new renewables are not yet cost-effective (before 2025) the use of gas increases before decreasing towards the end of the time horizon when the climate target becomes more stringent. The additional gas is partially used for electricity generation in gas combined-cycle plants contributing to a slight increase in total electricity supply until the middle of the time horizon. After 2030 solar PV, wind and biomass combined heat and power technologies are becoming more and more attractive and compensate the phased-out nuclear capacities so that the existing electricity generation level can be maintained. At the end of the time horizon when the climate target is most stringent, centralized combined heat and power (CHP) gas plants are installed in order to further reduce emissions (Figure 5.4). Due to the climate target, the buildings sectors are decarbonized by the middle (residential sector) and by the end (services sector) of the time horizon (Figure 5.5). There are also reductions in CO_2 emissions in transport and industry. While end-use demand sectors show decreasing CO_2 emissions there is an increase in emissions in the power sector due the uptake of gas-based generation partly replacing

Table 5.2: Scenario combinations of the four sets of uncertainties related to availability of CCS technologies, climate policies, international fossil fuel prices, and support for new nuclear power plants.

	Energy price sensitivity	**Nu**clear **Ph**a**s**e-out	**Nu**clear **Rep**lacement
No clim. policy	**L**ow **M**edium **B**AU **H**igh	*NuPhs_EB*	*NuRep_EB*
Climate target (60% red.)	**L**ow **M**edium **B**AU **H**igh	*NuPhs_EL_60* *NuPhs_EM_60* *NuPhs_EB_60* *NuPhs_EH_60*	*NuRep_EB_60*
Climate target (60% red.) + CCS	**L**ow **M**edium **B**AU **H**igh	*NuPhs_EL_60_CCS* *NuPhs_EM_60_CCS* *NuPhs_EB_60_CCS* *NuPhs_EH_60_CCS*	*NuRep_EB_60_CCS*
Climate target (75% red.) + CCS	**L**ow **M**edium **B**AU **H**igh	*NuPhs_EB_75_CCS*	
Climate target (60% red.) + CCS retrofit.	**L**ow **M**edium **B**AU **H**igh	*NuPhs_EB_60_CCS-R*	

BAU: Business as usual

the nuclear capacity. In the residential sector, fossil fuel based heating technologies are replaced by electric heat pumps and district heat (Figure 5.6). This technological change coincides with the implementation of energy saving options (e.g. improved insulation of walls and windows). In the car sector we observe a shift from conventional gasoline and diesel cars to advanced natural gas, hydrogen, and electric propulsion systems (Figure 5.7), leading to higher efficiency and decreasing final energy consumption.

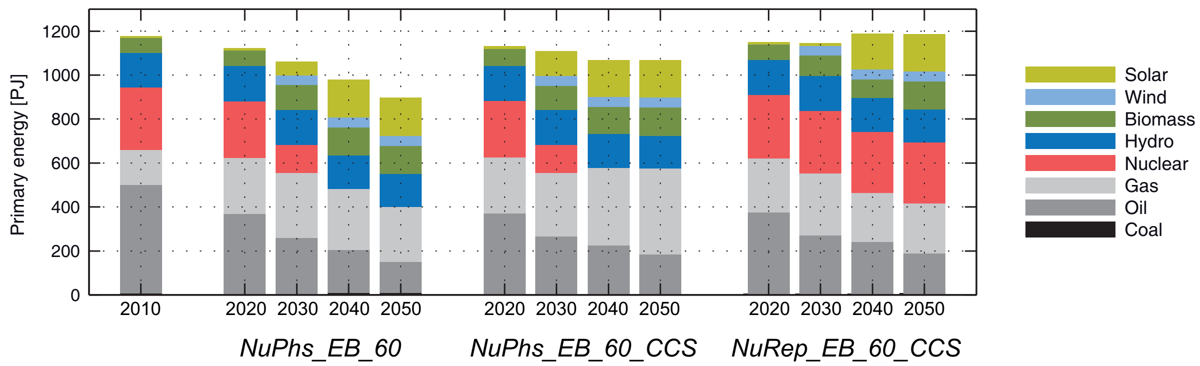


Figure 5.3: Primary energy supply for 60% CO_2 emission reduction scenarios w/ and w/o nuclear phase-out and w/ and w/o CCS

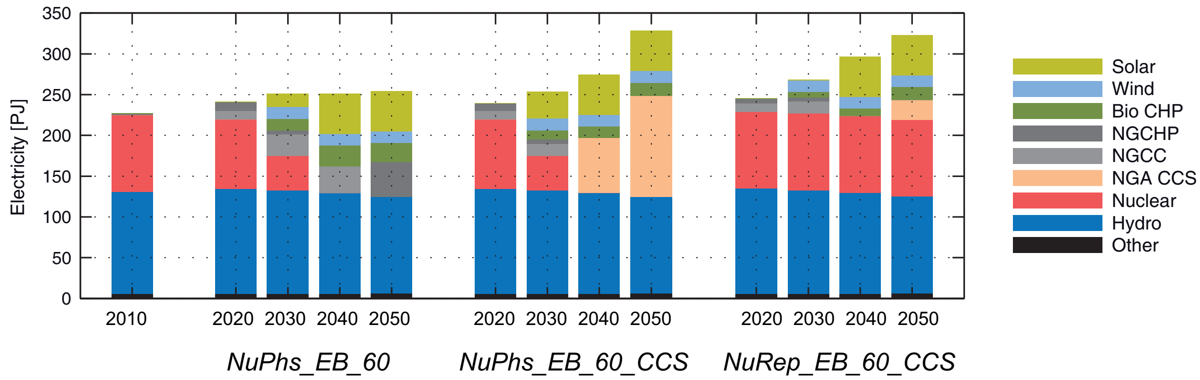


Figure 5.4: Electricity production for 60% CO_2 emission reduction scenarios w/ and w/o nuclear phase-out and w/ and w/o CCS

The availability of CCS (scenario *NuPhs_EB_60_CCS*), provides a relatively cheap and abundant low-carbon electricity source which contributes to increased electrification after 2030 compared to the *NuPhs_EB_60* scenario (Figure 5.4), reducing the need for some of the more costly energy-saving options. CCS also partially relieves the need to exploit some of the other (more expensive) low-carbon electricity sources such as biomass-based CHP plants. Other renewable electricity sources such as wind and solar PV are attractive before CCS becomes cost-effective. The increased availability of low-carbon electricity in the energy system allows the residential heating sector to install more electric heat pumps that partially replace district heat and reduce the need for some more costly energy saving measures (Figure 5.6). Given that the climate target stays unchanged, a decrease

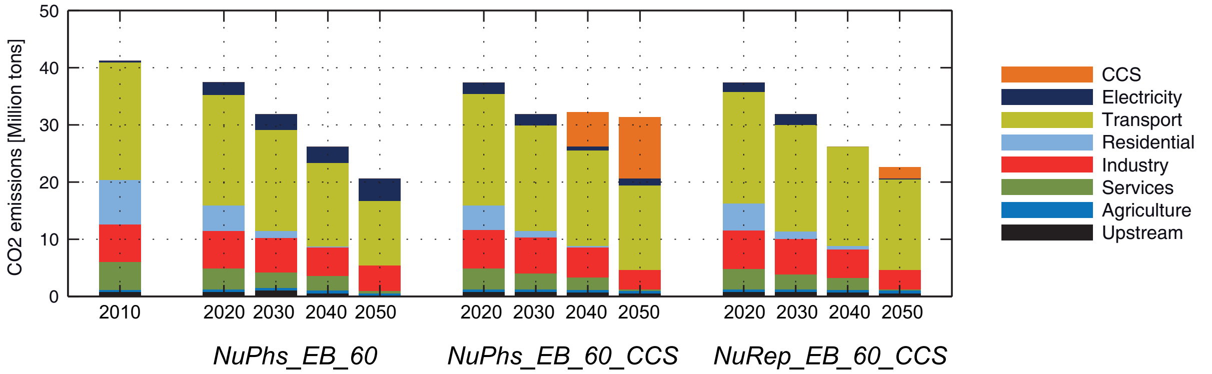


Figure 5.5: CO_2 emissions by sector for 60% CO_2 emission reduction scenarios w/ and w/o nuclear phase-out and w/ and w/o CCS

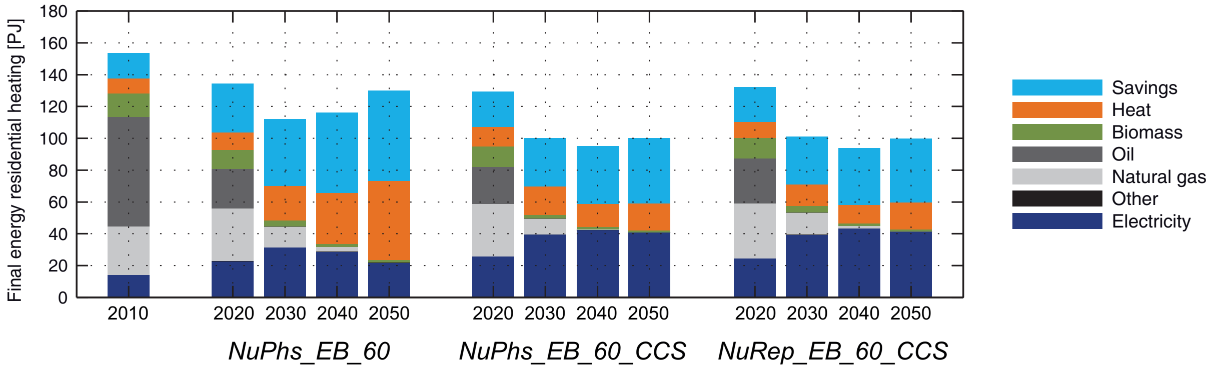


Figure 5.6: Final energy consumption in residential heating sector for 60% CO_2 emission reduction scenarios w/ and w/o nuclear phase-out and w/ and w/o CCS

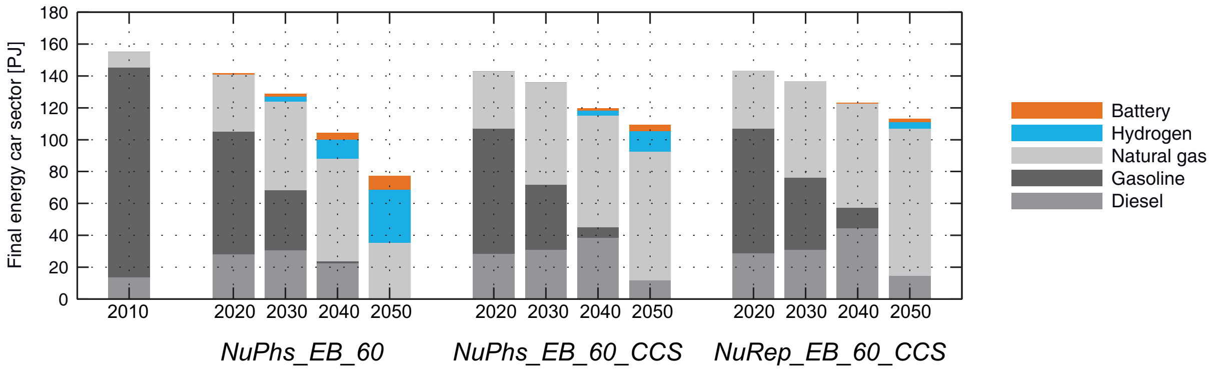


Figure 5.7: Final energy consumption in car sector for 60% CO_2 emission reduction scenarios w/ and w/o nuclear phase-out and w/ and w/o CCS

in emissions in the power sector in the *NuPhs_EB_60_CCS* scenario (compared to the *NuPhs_EB_60* scenario) allows for an increase in CO_2 emissions elsewhere in the energy system where carbon mitigation is more expensive for instance in the transport sector which appears to have higher abatement costs. Compared to the *NuPhs_EB_60* scenario, CO_2 emissions from transport in the *NuPhs_EB_60_CCS* scenario are slightly higher. The additional emissions come mainly from passenger cars where fossil-based car technologies (mainly gas and partly diesel and gasoline) are used instead of switching to more advanced (and expensive) low-carbon propulsion systems (i.e. hydrogen and battery electric)(Figure 5.7). These developments in the end-use sectors are reflected in an increase in primary energy consumption compared to the case without CCS (Figure 5.3).

By reducing the need for some expensive abatement options, the availability of CCS reduces total discounted energy system costs by around 3.2% for the time period between 2010 and 2050 compared to *NuPhs_EB_60_CCS*. While CCS is attractive at the end of the time horizon when climate mitigation targets become very stringent, it doesn't play a significant role in the middle of the time horizon when new renewable technologies such as wind and solar are more cost-effective and deployed up to assumed potentials (Figure 5.4).

In order to illustrate the role of CCS under a nuclear phase-out, also the case where nuclear capacities can be maintained at current levels is analysed for comparison. In such a scenario where nuclear capacities can be replaced and CCS is available (*NuRep_EB_-60_CCS*) the potential role of CCS is less significant. As can be seen in Figure 5.4 in the *NuRep_EB_60_CCS* scenario, there is only a small deployment of CCS in the last period of the time horizon when the climate policy target is most stringent, since nuclear power satisfies a large part of the demand for low-carbon electricity (Figure 5.4). Although CCS allows for a slightly higher level of electrification of the energy system (mainly taking place in the residential heating sector) there are no significant differences between the *NuRep_EB_60_CCS* scenario and the case where CCS is not available (*NuRep_EB_60*). This outcome is also reflected in energy system costs that only show a 0.03% reduction when CCS is available.

As mentioned in chapter 4, more stringent CO_2 emission reduction targets than the 60% reduction were tested with *SMM-W1*. For the nuclear phase-out scenario a 65% reduction could be achieved while the 70% target was not feasible under the given assumptions. The analysis of higher targets in the CCS scenario has shown that with the availability of CCS, a 75% reduction of domestic CO_2 emissions could be achieved for a nuclear phase-out scenario (NuPhs_EB_75_CCS). This reduction target could be achieved due to an increased deployment of CCS technologies supporting a further electrification of the energy system.

5.5 CCS Retrofitting option

As described in section 5.2, the CCS module in Swiss MARKAL also includes the possibility to retrofit earlier-built CCS-ready gas-combined cycle plants with CO_2 capture units. In order to explore the potential role of such a retrofitting option in the Swiss energy system we developed and analysed a scenario (including nuclear phase-out and climate target) where the capture unit is available after 2030 (*NuPhs_EB_60_CCS-R*) and compared it to the case without retrofitting option (*NuPhs_EB_60_CCS*). The results of this analysis show that retrofitting technologies could play a role during a transition period when there is need for new investments in generation capacity (to satisfy electricity demand) but CCS is not available or the climate target is not (yet) sufficiently stringent to make investments in more expensive NGCC plants with CCS attractive. Due to its perfect-foresight capabilities, the model is aware of the fact that the climate target will become more stringent and hence restrict the further use of NGCC plants without CCS. In such a case the economic lifetime of the plant would be shortened. The problem of such a stranded investment can be solved by investing in CCS-ready NGCC plants when CO_2 capturing is not yet needed, and retrofitting the plants when capturing becomes cost-effective. The use of the retrofitting option is illustrated in Figure 5.8 showing CO_2 emissions from NGCC plants for two scenarios with (right subfigure) and without (left subfigure) the retrofitting option, and a 60% emission reduction target. In this Figure, full areas mean CO_2 emissions that are not captured (and emitted to the atmosphere) whereas shaded areas mean captured emissions. In both scenarios NGCC technologies without CCS (grey bars) are used when the capture technologies are not mature or cost-effective. As soon as CCS becomes attractive in the non-retrofitting scenario (left subfigure) we see a large amount of CO_2 captured at NGCC plants with CCS (blue bars). In the scenario where retrofitting is available (right subfigure) we observe that the energy system invests in NGCC-CCS-ready plants in 2030 (red bars) but starts using them without capturing CO_2 (only positive emissions) and retrofits them when cost-effective in 2040. Before and in parallel to the retrofitting the energy system also uses CCS plants without retrofitting due to the higher cost-effectiveness of these technologies compared to the retrofitted plants[7]. However, the role of the retrofitting option could be significant in real world without perfect foresight, and if there is uncertainty about future climate targets.

The retrofitting option gives the energy system more flexibility related to the temporal decoupling of installations in generation on the one hand and in capture technologies on the other hand. While this gain in flexibility has consequences in technology choice the impact on total energy system costs is small (less than 0.01%).

5.6 Sensitivity analysis on fossil fuels prices

This section analyses how changes in fossil fuels prices could influence future technology and fuel choice in scenarios with a 60% CO_2 emission reduction target scenarios with (*NuPhs_E∗_60_CCS*) and without (*NuPhs_E∗_60*) availability of CCS. Special emphasis is given to the impact of changing energy prices on technology and fuel changes as well as on energy system costs under the abovementioned conditions.

5.6.1 60% emission reduction target (without CCS)

As mentioned in chapter 4, in a 60% emission reduction target scenario where CCS is not available, changes in fossil fuels prices seem to have only insignificant impacts on

[7]An additional cost is assumed for retrofitting due to separate installations of the powerplant and the capture unit.

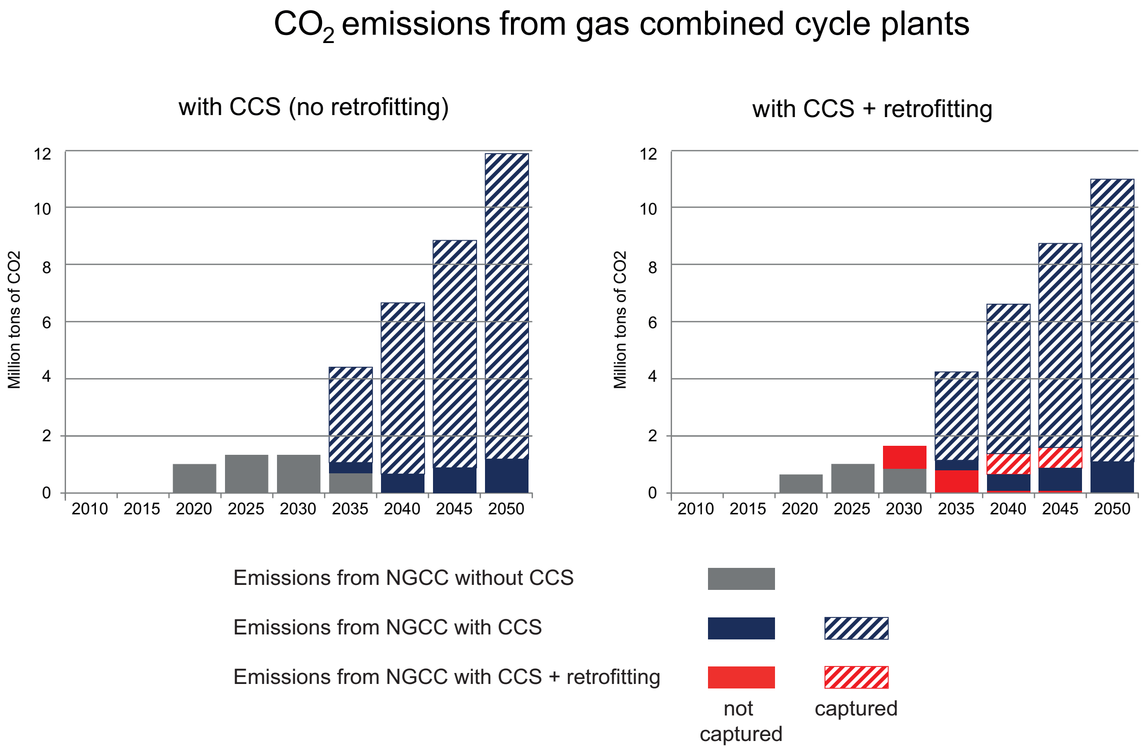


Figure 5.8: Comparison of CO_2 emissions from NGCC and NGCC + CCS with and without retrofitting option

technology and fuel choice in the different sectors of the energy system such as electricity generation, passenger cars, and residential heating sectors (see Figures 5.9, 5.10, and 5.11). Due to the stringent climate target (limiting the use of fossil fuels) many efficiency and fuel switching options are already taken so that the energy system's (limited) potential to further reduce the use of (expensive) fuels is exhausted. Since the energy system seems to be almost independent on changes in fossil fuels prices under a climate target the results of the additional sensitivity scenarios *NuPhs_EH_60*, *NuPhs_EM_60*, and *NuPhs_EL_60* closely correspond to the *NuPhs_EB_60* presented in this section.

While the energy system under a climate target seems to be insensitive to changes in energy prices the results could drastically change under absence of climate policies. In such a case, the use of fossil fuels is not limited and thus mainly driven by energy prices. An analysis looking at a case without emission reduction has shown that changes in energy prices have a significant impact on the configuration of the energy system in different sectors (e.g. on the attractiveness of new renewable electricity sources and on efficiency technologies in end-use demand sectors).

5.6.2 60% emission reduction target + CCS available

Unlike in the emission reduction target scenario without CCS described above, in the case where CCS is available changes in fossil fuels prices could have some impact on the configuration of the energy system. In the electricity sector, we observe that low fossil fuels prices reduce electricity generation cost of gas combined cycle plants with CCS. This leads to the result that CCS technologies become attractive earlier and reduce the energy system's need to deploy the still expensive solar PV technologies when alternative low-carbon electricity sources are not available (Figure 5.9). In the car sector, the decrease in fuel prices further reduces the need for expensive advanced car technologies (Figure 5.10). In contrast to the car sector, changes in fossil fuel prices don't seem to have a significant impact on the residential heating sector (Figure 5.11).

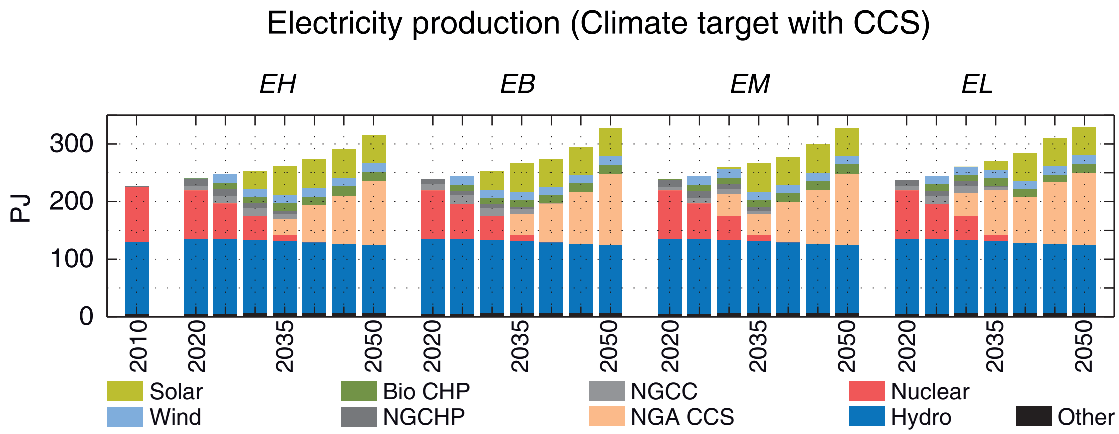


Figure 5.9: Fossil fuel price sensitivity analysis for four different price levels (prices are decreasing from left to right): Electricity production

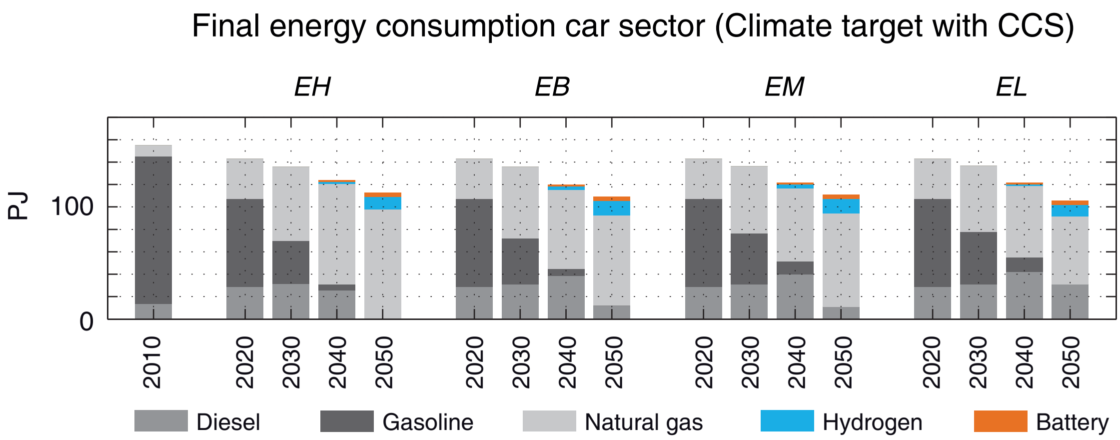


Figure 5.10: Fossil fuel price sensitivity analysis for four different price levels (prices are decreasing from left to right): Final energy consumption in car sector

5.6.3 Energy system costs

Figure 5.12 shows incremental total discounted energy system costs relative to the nuclear phase-out scenario with BAU fossil fuel price scenario without climate policy (*NuPhs_EB*) for all 12 scenarios analysed in this section. The bars represent relative differences in costs for the no climate target, climate target, and climate target + CCS cases and are grouped by fossil fuel price scenarios (*EH*, *EB*, *EM*, and *EL*).

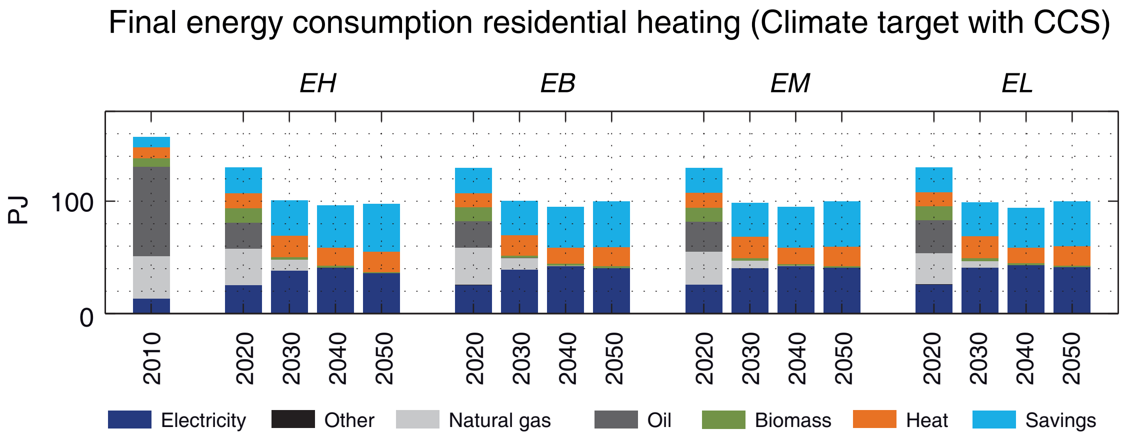


Figure 5.11: Fossil fuel price sensitivity analysis for four different price levels (prices are decreasing from left to right): Final energy consumption in residential heating sector

As one would expect the incremental costs decrease in line with fossil fuel prices (from left to right). When looking at the relative differences in each of the four fuel price scenarios we observe that additional costs of the climate target are between 4 and 7 percentage points, and when CCS is available these costs can be reduced by around 3 - 4 percentage points. A comparison of the four energy price scenarios shows that the additional costs from the no climate target scenario to the climate target scenarios are lower with the higher energy prices. In addition, the cost reductions provided by the availability of CCS in climate target scenarios are lower for higher energy prices. It seems that in high fossil fuel price scenarios without climate policy the high prices promote many efficiency measures to reduce the need for expensive (fossil) fuels. The reduction of fossil fuels consequently leads to a reduction in CO_2 emissions in the energy system. Due to the CO_2 abatement in the scenario without CO_2 emission reduction target, under high energy prices the efforts to reach the climate target are lower compared to the low energy price case where less CO_2 abatement is taking place. Due to the lower gas prices the electrification of the energy system based on electricity from CCS plants becomes more attractive and helps avoid the need of some of the more expensive efficiency measures. This leads to the outcome that the potential of CCS to reduce costs under climate constraints is slightly higher under low fossil fuel prices (Figure 5.12).

5.7 Discussion

The results presented in this chapter show that carbon capture and storage (CCS) technologies could play a significant role in supporting the realization of stringent mitigation targets under nuclear constraints by providing a relatively abundant source of low-carbon electricity. However, the timing and the extent of a possible future deployment of CCS seem to be dependent on various factors related to the availability of alternative low-carbon electricity sources (i.e. (domestic) potentials of new renewable energy or lifetimes of existing nuclear power plants), international developments (e.g. of fossil fuel prices), and (climate-) policy decisions. It is important to note that also in this analysis (as in all other analyses conducted in this work), we assume that Switzerland seeks to maintain the historical annual balance between electricity imports and exports, and the potential

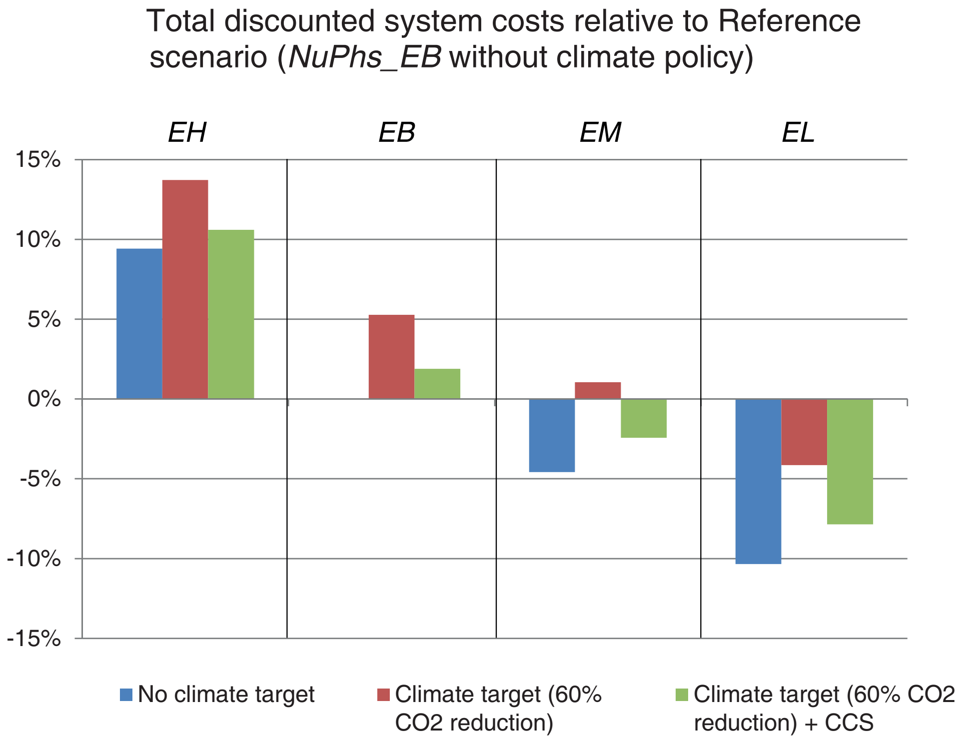


Figure 5.12: Comparison of additional total discounted system costs relative to the nuclear phase-out scenario with business as usual fossil fuel prices and no climate target (*NuPhs_EB* scenario) for different fossil fuel price levels (high, business as usual, medium, and low) in scenarios without climate target, with 60% CO_2 emissions reduction target, and with 60% CO_2 emissions reduction target with CCS.

role of CCS would likely be affected by an increased dependence on imported electricity.

The sensitivity analysis from section 5.6 shows that fossil fuel prices mainly influence the timing of the deployment of CCS rather than its long-term attractiveness. In contrast, the availability of alternative low-carbon electricity sources (e.g. due to a replacement of nuclear power) and the stringency of the climate target seem to have a significant impact on the penetration of CCS technologies (section 5.6). In a nuclear phase-out scenario under a stringent climate target CCS can support an extensive electrification of the energy system reducing the need for investments in some of the more costly efficiency technologies in the end-use sectors. For example, in the residential heating sector an increased electrification (with electricity used in heat pumps) reduces the need for some of the more expensive energy efficiency (e.g. insulation) measures. Whereas a possible deployment of CCS allows the power sector to extensively decarbonize, it relaxes the need to reduce emissions in other parts of the energy system where abatement costs may be higher (given that the climate target stays unchanged). While some expensive abatement options can be avoided due to the deployment of CCS there are other options that are needed and/or cost-effective regardless of the availability of CCS. These options including a broad set of energy efficiency measures in the end-use demand sectors as well as renewable energy sources, which thus represent important targets for policy support despite future uncertainty over the availability or acceptability of CCS. Realizing the potential of these abatement options will likely necessitate the implementation of regulatory and financial incentives to overcome potential market and information barriers.

As mentioned in chapter 1, there are limitations to the methodology applied that could change some of the results of this analysis. Due to the uncertainties related to the abatement costs the in end-use sectors, the role of CCS in the Swiss energy system could significantly change. For instance, although many end-use efficiency options are represented in SMM, there may be scope to achieve further reductions in energy demand (such as through behavioural change, or a more rapid deployment of efficient appliances and renovation of buildings; although both may come at a cost), to realize future energy demands levels in line with the New Energy Policy (NEP) and Politische Massnahmen (POM) scenario of the Swiss energy strategy (BFE, 2011d). In such a case, the renewable share (hydro, wind, solar, and biomass) in electricity generation in 2050 in our scenarios would largely satisfy electricity demands, reducing the potential role of CCS. Such issues can be explored with additional sensitivity analysis addressing those uncertainties.

Besides the economic aspects of CCS analysed in this chapter there are other major uncertainties related to geological and technical feasibility, public acceptance, and regulatory issues that have to be overcome for a successful deployment of CCS in Switzerland. To explore these uncertainties and overcome potential barriers strong efforts in different areas are needed. These include for example additional R&D related to technical and storage challenges, along with dissemination of information to the public to support an informed debate on social acceptance.

It is the first time that the potential role of CCS technologies in the future Swiss energy system has been analysed with the application of a technology-rich bottom-up cost-optimisation model of the entire energy system. The results of the analysis presented in this chapter contribute to the overall objective of this dissertation of how key uncertainties such as the availability of future low-carbon electricity sources could affect cost-optimal technology choice in the future energy system (see chapter 1). As the results show, a number of technology combinations could be identified that are robust independent on the availability of CCS technologies. These technology options comprise energy efficiency and climate change mitigation technologies in the end-use sectors including the building sectors and transport, and renewable electricity generation technologies such as wind and solar PV that become attractive in the second half of the time horizon.

Chapter 6

Calibration and structural extensions

6.1 Introduction

The Swiss MARKAL model version *SMM-W1* that is based on Schulz (2007) is fully calibrated to 2000 and 2005 statistics and includes a partial calibration of key sectors to 2009 as described in section 3.3.1. In order to increase the consistency of the model with recent statistics and other studies analysing scenarios of the future energy system, the entire model was recalibrated to statistical data from 2010. In addition, key end-use sectors of the model have also been restructured in order to facilitate the recalibration by increasing the consistency of the structure of the statistics and the structure of the model. Further, the restructuring of the model allowed to increase the level of technology detail in some of the end-use sectors. Both, the recalibration and the restructuring then results in model version *SMM-W2*. In the remainder of this chapter, the recalibration and restructuring of the end-use demand sectors is described and possible impacts of the structural adjustments on the scenario results are presented.

6.2 Recalibration and restructuring of end-use demands

For the calibration of the model the year 2010 was chosen since it perfectly fits to the 5-years time periods of *SMM*. An extensive literature research has shown that there exists a wide range of statistical sources related to the Swiss energy system. While many of those are consistent, there are also sources that are less consistent, partially related to methodological differences. The Swiss Overall Energy Statistics 2010 (BFE, 2011f) from the Swiss Federal Office of Energy (SFOE) was chosen as the main data source for this recalibration, since it is the most important statistical source covering the entire Swiss energy system. Since some of the statistical data in BFE (2011f) are only given on an aggregated level and for example do not include information on the final energy consumption by the different industrial branches or by end-uses, additional statistical sources focussing on specific parts of the energy system were used as a complement. Due to differences in scope, data sources, and methodologies, these additional statistical data sources do not exactly match BFE (2011f) in absolute terms. In such cases, the relative shares of these sources were applied to the absolute numbers in (BFE, 2011f).

When undertaking the recalibration, it came out that the structure in some parts of Reference Energy System (RES) of SMM (e.g. in the end-use demand sectors) was not consistent with the data available in the recent statistical sources. Some of these inconsistencies comprise the break down of energy consumption in industrial branches and the characterisation of energy service demands. Also, within the scope of a semester project looking at potential improvements of the industrial sector it was found by Hagspiel (2010) that the level of aggregation in some of the industrial branches is insufficient. In order to take benefit of the availability of detailed statistical data and to improve the representation of these sectors, restructuring key parts of the model turned out to be necessary.

In the remainder of this section, the restructuring and recalibration of the four main end-use demand sectors including transport, residential, services, and industrial sectors is described. As a starting point the final energy balance in all end-use sectors as reported by BFE (2011f) is used (see Table 6.1).

Table 6.1: Final energy consumption by energy carrier and end-use sectors in 2010 (PJ). The agriculture sector includes the statistical difference. (Source: BFE (2011f))

	Residential	Industry	Services	Transport	Agriculture	Total
Wood	20.74	9.67	6.95		0.73	38.09
Coal	0.4	6.02				6.42
Waste		10.03				10.03
Oil products	118.16	32.91	47.08	294.74	1.37	494.26
Gas	48.39	35.66	24.13	0.71	6.62	115.51
Other renewables	9.9	1.15	2.74	0.43	0.53	14.75
Electricity	67.02	69.37	63.84	11.39	3.61	215.23
Heat	6.91	6.3	4.05			17.26
Total	271.52	171.11	148.79	307.27	12.86	911.55

6.2.1 Transport sector

For the calibration of the transport sector, Switzerland's Greenhouse Gas Inventory 1990-2010 (BAFU, 2012b) was used for the breakdown of energy consumption into the different demand categories, since other sources including BFE (2011f) did not provide the level of detail required. For the calibration of the transport sector, the absolute numbers of BAFU (2012b) were used although there are differences to BFE (2011f). However, major parts of these differences seem to come from the fact that in BFE (2011f) the energy consumption of the Principality of Liechtenstein is included while it is not in BAFU (2012b). Another part of the difference can be explained with the effect of tank tourism due to slightly lower fuel price levels in Switzerland compared to neighbouring countries as described in BFE (2010b). The additional use of gasoline and diesel sold in Switzerland to tank tourists from neighbouring countries is given in BAFU (2012b) and has been subtracted from the total fuel consumption for this calibration, while the gross consumption of gasoline and diesel reported in BFE (2011f) is based on the foreign commerce statistics less accurately representing actual fuel use.

The calibration to BAFU (2012b) required adjustments in the definition of some of the energy service demand categories in *SMM-W1* since data were not available for all transport demands or additional data were available and allowed a further disaggregation of some of the existing categories. For example, in the truck demand category in *SMM-W1*, both Light Duty and Heavy Duty Vehicles (LDV and HDV respectively) were aggregated and have now been split into two categories in order to account for the differences in technological characterisation including differences in size, efficiency, and input fuels (i.e. gasoline and diesel for LDV and diesel only for HDV) of the two trucks types (BAFU, 2012b). Other demand categories in *SMM-W1* that have been adjusted include Buses (split into Coaches and Urban buses) and Rail transport. The latter has been splitted into freight, passenger, and construction in order to account for difference in input fuel type (i.e. electricity for passenger and freight, and diesel for construction). Further, due to a lack of data on international navigation this category was to added to the new category *Other* covering all transport demands that do not fall under one of the existing categories. The other categories not mentioned above are identical in *SMM-W1* and *SMM-W2*. Based on BAFU (2012b), a Table with final energy consumption by fuel type and end-use demand category has been constructed to be used for the calibration in *SMM-W2* (see Table 6.2).

Table 6.2: Final energy consumption by energy carrier and energy service demand in the transport sector in Switzerland in the year 2010 (PJ). Source: BAFU (2012b).

	Gasoline	Diesel	Kerosene	Gas	Electricity	Total
Passenger cars	111.9	38.4		0.5		150.8
Light duty vehicles	3.8	8.8				12.5
Heavy duty vehicles		24.6				24.6
Coaches		1.3				1.3
Urban buses	0.9	2.8		0.1		3.8
Two wheelers	3.2					3.2
Construction rail		0.5				0.5
Passenger rail					9.8	9.8
Freight rail					1.6	1.6
Domestic navigation	0.6	1.0				1.6
Domestic aviation			3.3			3.3
International aviation			58.1			58.1
Others	2.0	12.1				14.1
Total	122.5	89.4	61.4	0.6	11.4	285.3

The car sector in *SMM-W2* has been extended with detailed car technology data for gasoline, diesel, natural gas, hydrogen, and battery electric car technologies based on data from Densing et al. (2012). Table A.1 gives an overview on key car technology parameters used in *SMM-W2*.

6.2.2 Industrial sector

The recalibration of the industrial sector is primarily based on BFE (2011f) for total energy consumption by fuel type, on BFE (2011b) for energy consumption by branches, and on BFE (2011a) for the breakdown in consumption by energy service demands. As mentioned above, not all sources are consistent due to differences in boundary definitions or methodologies. Hence, for the calibration absolute numbers were adopted from BFE (2011f) while relative shares on breakdowns on branch and service demand levels are taken from the BFE (2011a) and BFE (2011b). In the context of this recalibration, the industrial sector has also been restructured based on the availability of data, the characteristics of the single branches, and the representation of energy services demands. The following sections first describe the restructuring and then the recalibration of the industrial sector in *SMM-W2*.

Restructuring

The industrial sector has been restructured in terms of branches and end-use demands. For the restructuring of the branches the goal was to group the 12 branches reported in BFE (2011a) (i.e. Food, Textile, Pulp and Paper, Chemicals, Cement, other non-ferrous minerals, Metals, non-ferrous Metals, Metal tools, Machinery, Other industries, and Construction) (Table 6.3) to six[1] branch groups that were considered to have some similarities in terms of total energy consumption, the shares of energy consumption by energy services (i.e. space heating, process heat, machine drive, lighting and information and communication (I&C), and other services), the type of technologies and processes used in the branch, the growth rate and the energy intensity of the branches. The shares of energy consumption by energy services in a respective branch has been analysed based on Muggli and Baumgartner (1996) with adjustments to account for structural changes in the Swiss industrial sector in the past 20 years (see Figure 6.1).

Table 6.3: Industrial branches in *SMM-W1*, statistics, and *SMM-W2*

SMM-W1	*Statistics*	*SMM-W2*
Chemicals	Chemicals	Chemicals
Non-metals	Cement	Cement, other minerals
	other minerals	
Iron and steel	Ferrous metals	Basic metals
Non-ferrous metals	Non-ferrous metals	
Pulp and paper	Pulp and paper	Food, Textile, Pulp and paper
other industries	Food	
	Textil	
	Metal tools	Metal tools, machinery, other industries
	Machinery	
	other industries	
	Construction	Construction

The first branch group adopted in the restructuring consists of food, textile, and pulp and paper since they have similar shares of energy consumption by services (Figure 6.1). This

[1]The different branches were aggregated into six branch group as a trade-off between keeping the model simple and reducing the number of branch groups but still account for the different characters of the respective branches.

allocation also makes sense when looking at the energy intensities of the three branches indicating that all of them belong to the less energy intensive branches compared to other industries including basic metals and minerals (Figure 6.2). The Chemical industry stays as an own group due to its size (accounting for more than 20% of the total industrial energy consumption) and the fact that this branch is expected to grow quite strongly by 150% until 2050 compared to the other branches that only grow by less than 40% (BFE, 2012a). The next group includes cement and other non-metallic minerals since those two branches are unique due to their high need for process heat (more than 80% of energy consumption is used for process heat in these branches) (Figure 6.1). The next group includes ferrous and non-ferrous basic metals that are grouped together due to their relatively high energy intensity (Figure 6.2). The branches metal tools, machinery, and other industries comprise the next group due to their similar energy consumption by services shares (space heating is around 50% of total final energy consumption in these branches). The last branch that is rather small but can only hardly be grouped with one of the other branches is construction. This industry is very different to all other branches due to its relatively high demand share for other services (probably fuels for construction machines) (Figure 6.1).

Besides the restructuring of the branches, also the energy service demands have been restructured. In *SMM-W1* the industrial demands covered services including process heat, steam, electro chemicals, machine drive, and other consumption, but missed important services such as space heating, hot water, AC and ventilation, Entertainment, I&C, and on-site mobility. For the restructuring of the industrial sector in *SMM-W2*, the energy service demand categories as given in statistics (BFE, 2011b) have been adopted. This includes the integration of processes and machine drive, space heating, hot water, AC and ventilation, entertainment and I&C, and on-site mobility while steam is now integrated in process heat. The technologies for these extended energy service demands have been adopted from the services sector from *SMM-W2*. Table 6.4 gives an overview on the energy services in *SMM-W1* and *SMM-W2*.

Table 6.4: Industrial energy services in *SMM-W1* and *SMM-W2*

SMM-W1	*SMM-W2*
Steam Process heat	Process heat (incl. steam)
Machine drive Electrochemical	Machine drive and other processes
Other consumption	Information and communication Lighting Space heating Hot water Cooling, ventilation On-site mobility

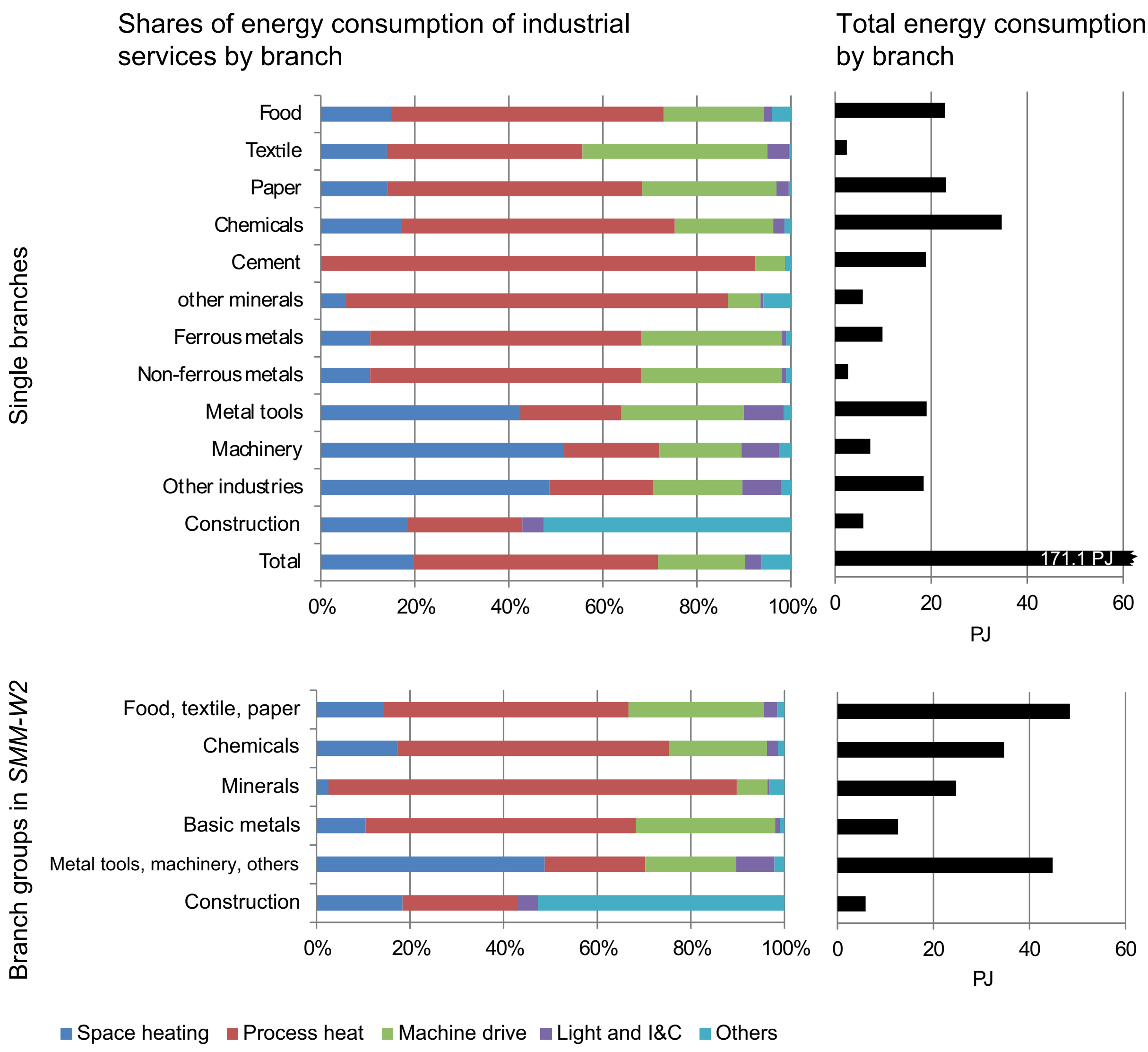


Figure 6.1: Shares of energy consumption by industrial services and branches in Switzerland in the year 2010. (Sources: BFE (2011f); Muggli and Baumgartner (1996), own assumptions)

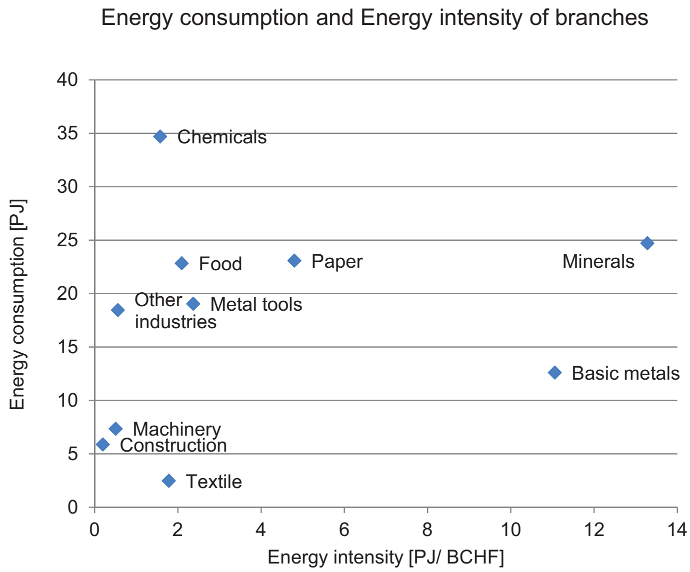


Figure 6.2: Energy consumption and energy intensity for different industrial branches in Switzerland in the year 2010. Sources: BFE (2011b,f, 2012a), and own assumptions.

From a modelling perspective, the structure of the energy service demand processes have been changed. While in *SMM-W1* there was only one demand per branch consuming a mixture of different services such as process heat and machine drive, in *SMM-W2* the energy service demands per branch are now modelled as single demand categories. This adjustment allows for a better control and maintenance of end-use demand technologies to make sure that model does not produce unrealistic results.

Another structural change that has been made to the industrial sectors is related to industrial cogeneration technologies. Cogeneration plays today an important role in the industrial sector today (4.6% of total industrial electricity consumption and 64% of low-temperature heat (used for space heating, hot water and partially process heat) is own-produced mainly with industrial combined heat and power (CHP) technologies. In order to account for the importance of industrial cogeneration each industrial branch group in *SMM-W2* has been extended with cogeneration module, each representing a set of different CHP technologies. The cogeneration modules are modelled separately from the industrial branch group in order to achieve well defined boundaries. Figure 6.3 shows the boundaries of an industrial branch group without cogeneration (orange), the industrial cogeneration module (blue), and the entire industrial branch including cogeneration (black).

Calibration

As discussed, the industrial sector is calibrated to Swiss overall energy statistics (BFE, 2011f). In this statistical source, the industrial cogeneration sector is not allocated to the industrial sector but rather to the conversion sector. For the calibration of the industrial cogeneration sector the statistics on thermal electricity generation (BFE, 2011g) was used complementarily to BFE (2011f). Based on these sources, a Table with energy consumption by fuel type for the entire industrial sector including the cogeneration sec-

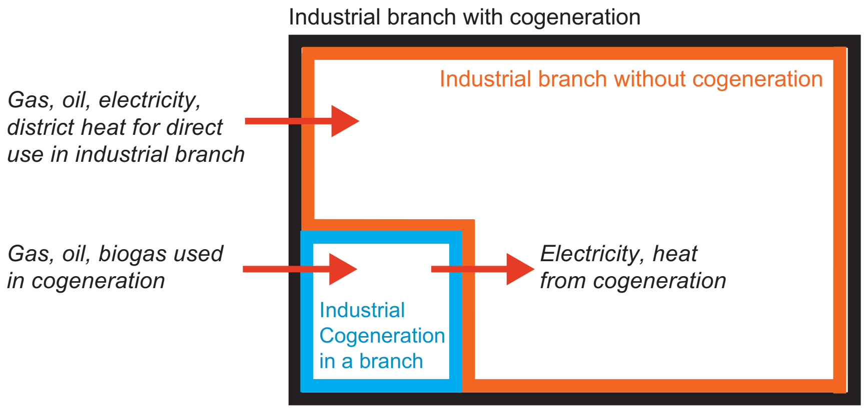


Figure 6.3: Boundaries of industrial branch and cogeneration module as applied for all six branches

tor was constructed (Table 6.5). The values of the final energy consumption by fuels of the industrial sector without cogeneration are consistent with BFE (2011f) except for heat. Based on a personal communication from the Swiss Federal Office of Energy (BFE, 2012b), the heat use from large industrial CHPs is not included in their statistics and thus had to be added to the heat consumption of the industrial sector without cogeneration in the scope of this work. Further, the break-down in the consumption of oil products into light heating oil and heavy/medium heating fuel is adopted from the NAMEA Swiss input/output table (BFE, 2011c) since it is not available in BFE (2011f). Further, the industrial cogeneration sector is calibrated to the statistics of thermal electricity generation (BFE, 2011g) with own assumptions on the allocation of statistical data of CHP generation to the different industrial branches.

Table 6.5: Energy use in the industrial sector incl. industrial cogeneration in the year 2010. Positive values represent consumption, negative values generation of energy (PJ). Sources: BFE (2011f,g)

	Ind. sector incl. cogen	Industrial cogeneration	Ind. sector w/o cogen
Light oil	26.81	0.06	26.76
Heavy oil	6.66	0.00	6.66
Natural gas	45.03	9.37	35.66
Coal	6.02	0.00	6.02
Wastes	14.52	4.49	10.03
Wood	11.44	1.77	9.67
Biogas	0.53	0.53	0.00
Other renewables	1.15	0.00	1.15
Electricity	66.19	-3.18	69.37
Heat	5.72	-10.08	15.80

In a next step, the energy consumption by energy carrier (Table 6.5) was allocated to the six branch groups as given in Table 6.3. Within each branch group, the energy use by fuel type has been allocated to the different services in a way that they are consistent with BFE (2011a,b,g) and Muggli and Baumgartner (1996). The allocation of energy carriers to industrial services in each branch group is presented in Tables 6.6, 6.7, 6.8, 6.9, 6.10, and 6.11.

Table 6.6: Final energy consumption by energy carrier and energy service in the Basic metals industrial branch in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Space heating	Hot water	Process heat	Lighting	AC, ventilation	I&C	Machine drive	Mobility domestic	Total
Light oil	0.11	0.03					0.10	0.30	0.5
Heavy oil			0.14						0.1
Natural gas	1.00	0.10	2.80				0.05		4.0
Coal			0.45						0.5
Wastes									0.0
Wood									0.0
Renewables	0.12	0.02							0.1
Electricity	0.03		2.16	0.15	0.03	0.01	3.13	0.01	5.5
Heat									0.0
Total	1.3	0.2	5.6	0.2	0.0	0.0	3.3	0.3	10.7

Table 6.7: Final energy consumption by energy carrier and energy service in the Chemicals industrial branch in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Space heating	Hot water	Process heat	Lighting	AC, ventilation	I&C	Machine drive	Mobility domestic	Total
Light oil	1.19	0.10	0.90				0.10	0.35	2.6
Heavy oil			0.19						0.2
Natural gas	1.00	0.10	7.90				0.05		9.1
Coal									0.0
Wastes			3.74						3.7
Wood			0.03						0.0
Renewables	0.12	0.02							0.1
Electricity	0.03		4.70	0.84	0.15	0.12	7.53	0.01	13.4
Heat	1.80	0.50							2.3
Total	4.1	0.7	17.5	0.8	0.1	0.1	7.7	0.4	31.5

6.2.3 Services sector

Structure

Similar to the transport and industrial sectors, the services sector has been revised and restructured according to the availability of statistical data. As for *SMM-W1*, also for *SMM-W2* the different commercial branches are aggregated in one sector assuming that

Table 6.8: Final energy consumption by energy carrier and energy service in the Cement and Other minerals industrial branch in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Space heating	Hot water	Process heat	Lighting	AC, ventilation	I&C	Machine drive	Mobility domestic	Total
Light oil	0.10	0.03	1.70				0.10	0.30	2.2
Heavy oil			4.60				0.10		4.7
Natural gas	0.20	0.10	1.90				0.05		2.3
Coal			5.58						5.6
Wastes			4.97						5.0
Wood	0.07		0.64						0.7
Renewables	0.12	0.02							0.1
Electricity	0.03		2.50	0.18	0.03	0.01	1.82	0.01	4.6
Heat									0.0
Total	0.5	0.2	21.9	0.2	0.0	0.0	2.1	0.3	25.2

Table 6.9: Final energy consumption by energy carrier and energy service in the Construction industrial branch in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Space heating	Hot water	Process heat	Lighting	AC, ventilation	I&C	Machine drive	Mobility domestic	Total
Light oil	0.93	0.10	2.30				0.15	0.35	3.8
Heavy oil									0.0
Natural gas	0.22	0.02	0.30				0.05		0.6
Coal									0.0
Wastes									0.0
Wood			0.06						0.1
Renewables	0.12	0.02							0.1
Electricity	0.03		0.83	0.51	0.09	0.16	0.80	0.01	2.4
Heat									0.0
Total	1.3	0.1	3.5	0.5	0.1	0.2	1.0	0.4	7.1

Table 6.10: Final energy consumption by energy carrier and energy service in the Food, Textile, and Pulp and Paper industrial branch in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Space heating	Hot water	Process heat	Lighting	AC, ventilation	I&C	Machine drive	Mobility domestic	Total
Light oil	1.57	0.31	4.00				0.20	0.70	6.8
Heavy oil			0.72				0.11		0.8
Natural gas	0.45	0.40	12.44				0.50		13.8
Coal									0.0
Wastes			1.24						1.2
Wood	0.26		2.41						2.7
Renewables	0.24	0.05							0.3
Electricity	0.06		5.70	0.99	0.17	0.07	10.86	0.02	17.9
Heat	2.26	1.17							3.4
Total	4.8	1.9	26.5	1.0	0.2	0.1	11.7	0.7	46.9

Table 6.11: Final energy consumption by energy carrier and energy service in the Machinery, Metal tools, and Others industrial branch in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Space heating	Hot water	Process heat	Lighting	AC, ventilation	I&C	Machine drive	Mobility domestic	Total
Light oil	5.70	0.40	3.65				0.30	0.60	10.7
Heavy oil	0.15	0.02	0.13				0.10	0.00	0.4
Natural gas	2.75	0.43	2.70				0.15		6.0
Coal									0.0
Wastes			0.08						0.1
Wood	2.00		4.21						6.2
Renewables	0.24	0.05							0.3
Electricity	0.06		7.76	3.13	0.54	0.33	13.76	0.02	25.6
Heat	0.40	0.17							0.6
Total	11.3	1.1	18.5	3.1	0.5	0.3	14.3	0.6	49.8

the energy service demands in these branches are similar enough to be combined. In future work, these branches could be broken down in order to account for differences between branches and gain insight into developments of a respective branch. The restructured energy service demand categories (from *SMM-W1* to *SMM-W2*) are given in Table 6.12. Some of end-uses in *SMM-W2* have been adopted from *SMM-W1* (e.g. hot water, space heating, and lighting). Others, such as the demand for cooking has been integrated into the process heat category in *SMM-W2*.

Table 6.12: Energy service demand categories in the services sector of *SMM-W1* and *SMM-W2*

SMM-W1	*SMM-W2*
Cooling	Air conditioning, ventilation
Cooking	Process heat
Space heating	Space heating
Hot water	Hot water
Lighting	Lighting
Office equipment	Information and communication
Refrigeration	Machine drive
Others	Others

Calibration

For the calibration, the energy carriers consumed in the commercial sector (as presented in Table 6.1) have been allocated to the 8 commercial energy service demands (Table 6.12) in line with BFE (2011f) for total energy consumption by fuel and with BFE (2011a) for the shares of energy consumed by service demands.

Table 6.13: Calibration of final energy consumption by energy carrier and energy service in the services sector in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,b,c,f,g), and own assumptions.

	Wood	Light oil	Gas	Electricity	Heat	Solar heat	Ambient heat	Total
Heating	6.62	39.19	21.94	5.22	4.65	0.28	1.21	79.10
Hot water	0.33	7.89	2.19	0.87	0.40	0.01	0.06	11.76
Process heat				2.99				2.99
Lighting				14.78				14.78
AC, ventilation				16.71				16.71
I&C				3.96				3.96
Machine drive				16.42				16.42
Other				2.90				2.90
Total	6.95	47.08	24.13	63.84	5.05	0.29	1.27	148.62

6.2.4 Residential sector

Restructuring

For the residential sector, the same energy service demand categories have been used as introduced in Schulz (2007), but some adjustments have been made regarding the allocation of demands in some categories. For example, the demand category Residential space Cooling (RC1) now only includes the cooling of the buildings and not any more the ventilation demand that is moved to the category Residential Electric Appliances (REA). One of the main reasons for this change is the expected strong penetration of air conditioning modules until 2050 (BFE, 2012a) and the differences in drivers and technology characteristics of the two demands. For example, the air conditioning demand includes technologies that are based on electric heat pumps or natural gas, which are not appropriate for the representation of ventilation technologies. The category REA includes all electric building appliances including ventilation, heating supporting appliances, cooking appliances, information and communication (I&C), and entertainment technologies. All other demand categories include the same end-use demands as in Schulz (2007). Table 6.14 gives an overview on all energy service demand categories of the residential sector in *SMM-W2*.

Table 6.14: Energy service demand categories in the residential sector. SFH: Single-family house, MFH: Multi-family house.

Acronyms	Demand description
RC1	Space cooling (no ventilation)
RCD	Clothes drying
RCW	Clothes washing
RDW	Dish washing
RH1	Space heating SFH old buildings (built before the year 2000)
RH2	Space heating SFH new buildings (built after the year 2000)
RH3	Space heating MFH old buildings (built before the year 2000)
RH4	Space heating MFH new buildings (built after the year 2000)
RHW	Hot water
RK1	Cooking (except cooking appliances)
RL1	Lighting
REA	Other electric appliances, I&C, entertainment, cooking appliances, ventilation
RRF	Refrigeration, freezing

Calibration

The residential sector in *SMM-W2* is calibrated to the Swiss Overall Energy Statistics (BFE, 2011f) and the Statistics of energy consumption by end-uses (BFE, 2011a). Similar to other end-use demand sectors, also in the residential sector there are some inconsistencies in terms of absolute values between BFE (2011f) and BFE (2011a). Hence, the model was calibrated in a way that the absolute values match the data from BFE (2011f), and the relative shares of fuels by demand are consistent with BFE (2011a). Table 6.15 shows the calibrated final energy consumption by end-use demand categories (columns) and fuel type (rows). The very right column shows the totals of each fuel type and matches BFE

(2011f). The cells without entries indicate a value of zero.

Table 6.15: Calibration of final energy consumption by fuel and end-use demands in the residential sector in Switzerland in the year 2010 (PJ). Sources: BFE (2011a,f), and own assumptions.

	RC1	RCD	RCW	RDW	RH1	RH2	RH3	RH4	RHW	RK1	RL1	REA	RRF	Total
Light oil					43.8	6.7	48.4	5.6	13.7					118.2
Gas					17.6	2.7	19.5	2.3	6.0	0.4				48.4
Electricity	0.1	1.9	1.9	1.8	7.2	0.3	8.1	0.2	8.4	5.1	5.7	19.2	7.2	67.0
Wood					8.2	1.3	9.0	1.0	1.1	0.1				20.7
Coal					0.2		0.2							0.4
District heat					2.6	0.4	2.9	0.3	0.6					6.9
Ambient heat					3.5	0.5	3.9	0.5	0.6					9.0
Solar energy					0.1	0.02	0.1	0.02	0.6					0.9
Total	0.1	1.9	1.9	1.8	83.3	11.9	92.1	9.9	31.0	5.6	5.7	19.2	7.2	271.5

Whereas the demand for Cooling (RC1), Clothes Washing (RCW), Clothes Drying (RCD), Dish Washing (RDW), Lighting (RL1), REA, and Refrigeration and Freezing (RRF) depend only on electricity, space Heating (RH1-RH4), Hot Water (RHW), and cooking (RK1) also depend on other fuels. The allocation of energy carriers to energy service demands is based on BFE (2011a) including relations between fuels and energy service demands. In some cases, also a break-down into different technologies consuming the same fuel was necessary. The break-down of final energy consumption of resistance heaters and heat pumps used for space heating and hot water production has also been adopted from BFE (2011a). In the lighting demand category, the break-down into incandescent, compact fluorescent, fluorescent, and halogen lamps has been updated based on Grieder and Huser (2008). While the previous break-down in Schulz (2007) was based on final energy consumption, the break-down now is based on energy service demand proportional to the relative shares of lighted floor area for each technology.

For the calibration of the heating demand in 2010, the categories with old buildings built before the year 2000 (RH1, RH3) were directly adopted from Schulz (2007) since it is assumed that the 2010 projection for specific heating demand (SHD) has not significantly changed in these categories and is still 384 MJ/m^2 for RH1 and 364 MJ/m^2 for RH3 as given in Schulz (2007). Similar to the SHD, it also assumed that the Energy Reference Floor Area (ERFA) for RH1 and RH3 did not significantly change and could be adopted from Schulz (2007) (i.e. 186 million m^2 for RH1 and 220 million m^2 for RH3). This leads to a total annual heating demand in 2010 of 72 PJ for RH1 and of 80 PJ for RH3. For the new buildings categories RH2 and RH4 different assumptions had to be taken. While the SHDs used in Schulz (2007) (i.e. 258 MJ/m^2 for RH2 and 231 MJ/m^2 for RH4) are assumed to not have significantly changed for 2010, the assumptions for ERFA in the new buildings category had to be adjusted. Due to the updated projection on total ERFA in the residential building sector of 486.7 million m^2 (BFE, 2012a) the ERFA for RH2 and RH4 had to be adjusted in order the total ERFA of all four categories is consistent with BFE (2012a) and the ratio between RH2 and RH4 is consistent with Schulz (2007). With the new values for ERFA for RH2 (i.e. 41 million m^2) and RH4 (i.e. 39 million m^2) the new total heating demands are 11 PJ (RH2) and 9 PJ (RH4).

The total final energy consumption in residential space heating has been adopted from

BFE (2011a) and allocated to the four categories RH1, RH2, RH3, and RH4. Basically, each fuel has been allocated close to the shares of total heating demand by category since it is assumed that each space heating technology type is installed in each category. Only for electric resistance heaters and coal based heating systems it is assumed that these technologies are not installed anymore in new buildings.

Each residential space heating demand has energy saving measures (ESM) representing different types of insulations of the building envelope that reduces the heating demand in the demand category when they are installed. Since the energy saving technologies available in SMM can be installed from 2005, assumptions had to be made about the level of energy saving technologies installed in the years 2005 and 2010. The assumed reductions are needed for the calibration of the space heating technologies. The total RH demand is reduced by 7.6 PJ, which is consistent with the difference between average SHD in 2010 over all four categories in SMM (352 MJ/m^2) and the average SHD for 2010 (338 MJ/m^2) as reported in BFE (2012a). The reduction of 7.6 PJ is then allocated to the four demand categories proportional to their ERFA shares. Then, the efficiencies of the heating technologies had to be recalibrated (reduced by 4%) in order final energy and heating demand match.

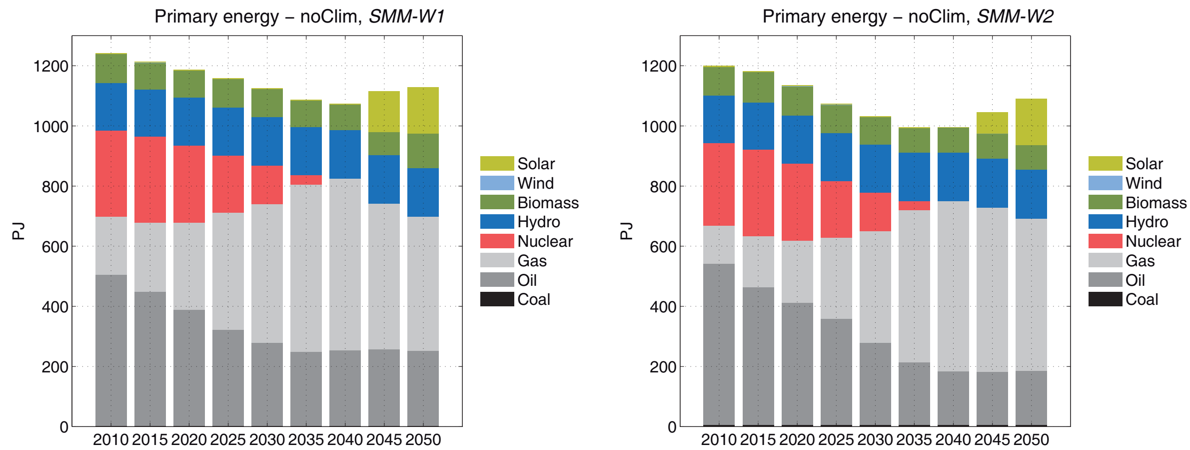
For the calibration of the energy saving options it is assumed that each demand category has one existing saving technology with a constant residual capacity, meaning that this capacity is available over the entire time horizon. These existing technologies represent the energy saving technologies that were assumed to be installed in each residential heating category in the years 2005 and 2010.

6.3 Impact of model structure adjustments on scenario results

To illustrate some of the impacts of the adjustments in the model structure on the scenario results as described before, a set of scenarios with and without a 60% CO_2 emission reduction target under a nuclear phase-out are compared for primary and final energy consumption for the original (*SMM-W1*) and the adjusted (*SMM-W2*) model structure. Further, the changes in the restructured passenger car and industrial sectors are presented for *SMM-W2* compared to *SMM-W1*.

6.3.1 Primary and final energy consumption

In the absence of a climate target, primary energy consumption shows a similar pattern for *SMM-W1* and for *SMM-W2* (i.e. a decline in total primary energy consumption, a partial shift from oil and nuclear to gas, and an uptake of solar at the end of the time horizon) (Figures 6.4(a) and 6.4(b)). Due to the calibration to 2010 historical data conducted in *SMM-W2*, primary energy consumption is slightly lower in *SMM-W2* compared to *SMM-W1*. Further, *SMM-W2* shows an increased shift from oil to gas in the second half of the time horizon compared to *SMM-W1*. Similar to the case without climate policy, also under a CO_2 emission reduction target of 60% in 2050, similar results could be



(a) Original model structure (*SMM-W1*) (b) Adjusted model structure (*SMM-W2*)

Figure 6.4: Primary energy consumption, nuclear phase-out without climate target: *SMM-W1* and *SMM-W2*

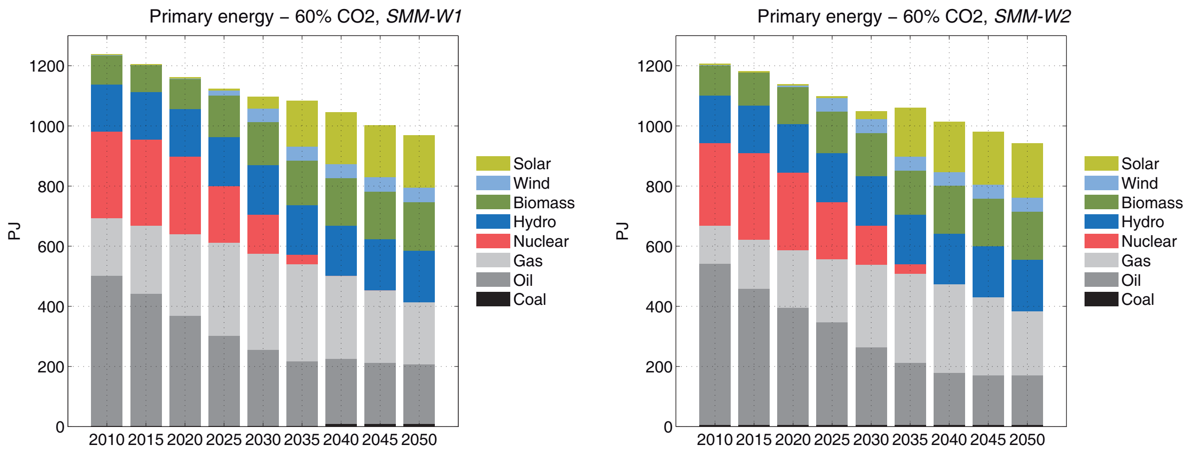
found for primary energy consumption for *SMM-W2* and *SMM-W1* (i.e. an accelerated penetration of renewable energy carriers such as solar, wind, and biomass replacing fossil fuels) (Figures 6.5(a) and 6.5(b)). The shift from oil to gas in *SMM-W2* compared to *SMM-W1* that was seen in the absence of a climate target can also be observed under a climate constraint.

As for primary energy consumption, also in the level of final energy similar results are seen for *SMM-W2* and *SMM-W1*. However, after a decline in total final energy consumption mainly driven by a reduction in fossil fuels in the building sector, the consumption again increases due to an increase in industrial cogeneration and structural differences in demand categories and demand-driver relationships in the industrial sector. Final energy consumption in the residential sector is slightly higher in 2010 for *SMM-W2* compared to *SMM-W1* due to the calibration, while in 2050 the levels are similar. This implies a stronger reduction in residential final energy consumption in *SMM-W2* compared to *SMM-W1* partially related to the reduction in residential specific space heating demand caused by the temperature increase due to climate change, an effect that is not included in *SMM-W1*.

6.3.2 Passenger car sector

As mentioned before, the passenger car sector in Swiss MARKAL has been restructured and updated based on data from Densing et al. (2012) and Gül (2008). These changes in structure and data assumptions have a significant impact on the model results as shown in the remainder of this subsection.

In the absence of a climate target, the higher use of gas (and lower use of oil) in the energy system in *SMM-W2* as mentioned above, is partially related to the higher deployment of gas-based passenger cars replacing gasoline and diesel in *SMM-W2* compared to *SMM-W1*, where diesel cars are more attractive (Figures 6.6(a) and 6.6(b)). The attractiveness



(a) Original model structure (*SMM-W1*) (b) Adjusted model structure (*SMM-W2*)

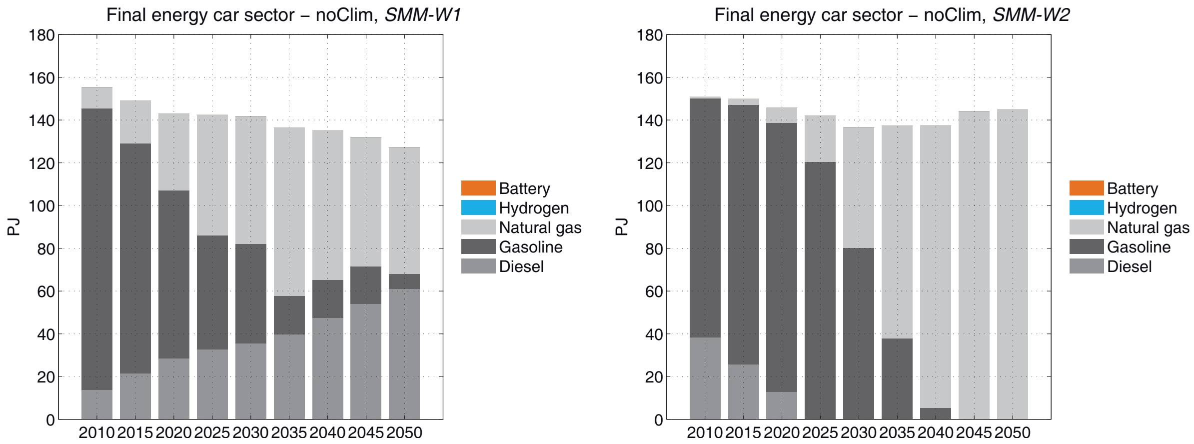
Figure 6.5: Primary energy consumption, nuclear phase-out with 60% CO_2 emission target: *SMM-W1* and *SMM-W2*

of gas cars in *SMM-W2* is mainly driven by the lower assumptions on investment costs of these technologies compared to *SMM-W1*. In *SMM-W1*, the deployment of diesel cars is limited by a growth constraint representing a maximum annual growth in the incremental invested capacity of a technology, while in *SMM-W2* the penetration of natural gas cars is limited by an upper bound on the share of gas cars in the car fleet in the first half of the time horizon based on the assumption that building a nation-wide gas fuelling infrastructure would require a certain amount of time. Another difference between *SMM-W1* and *SMM-W2* is related to the development of total final energy consumption in the passenger car sector. While in *SMM-W1* a significant decline can be seen, in *SMM-W2*, the reduction in final energy consumption is lower and slightly increasing at the end of the time horizon. This result can be explained with more pessimistic assumptions on efficiency improvements of the car technologies over time for *SMM-W2* compared to *SMM-W1*.

Under a climate constraint, for both *SMM-W1* and *SMM-W2* a shift from gas cars to battery electric and hydrogen cars can be seen at the end of the time horizon. However, the penetration of these alternative technologies is significantly higher in *SMM-W2* compared to *SMM-W1* due to the lower assumptions on investment costs for battery electric and hydrogen technologies in *SMM-W2*. The lower total final energy consumption in the passenger car sector in *SMM-W2* compared to *SMM-W1* is a result of mainly two factors, the higher efficiency of battery electric and hydrogen based drivetrains compared to internal combustion engines and the higher deployment of hybrid car technologies in *SMM-W2* compared to *SMM-W1*.

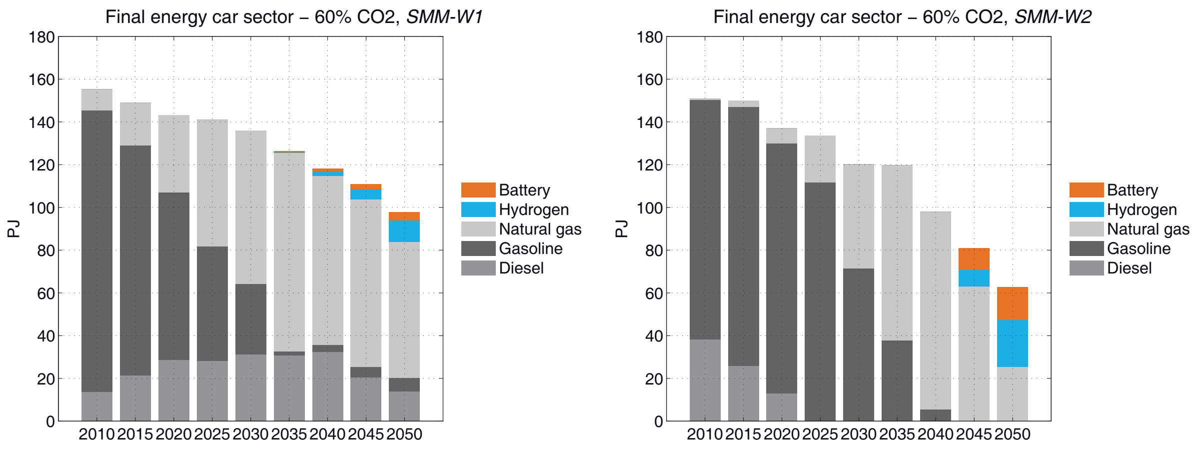
6.3.3 Industrial sector

As introduced in section 6.2.2, a major structural change including a reorganisation of energy service demand categories and branches has been conducted for the industrial sector in Swiss MARKAL. Such a change has an impact on the scenario results in the industrial sector. Under a nuclear phase-out without climate target, significant differences can be seen for *SMM-W1* and *SMM-W2*. As Figures 6.8(a) and 6.8(b) show, total industrial



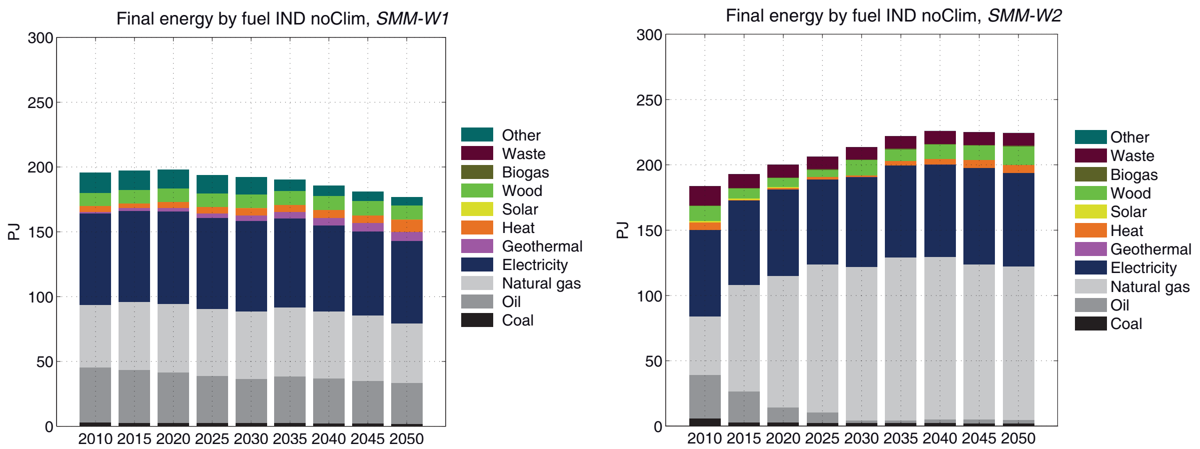
(a) Original model structure (*SMM-W1*) (b) Adjusted model structure (*SMM-W2*)

Figure 6.6: Final energy consumption passenger car sector, nuclear phase-out without climate target: SMM-W1 vs. SMM-W2



(a) Original model structure (*SMM-W1*) (b) Adjusted model structure (*SMM-W2*)

Figure 6.7: Final energy consumption passenger car sector, nuclear phase-out with 60% CO_2 emission target: *SMM-W1* and *SMM-W2*

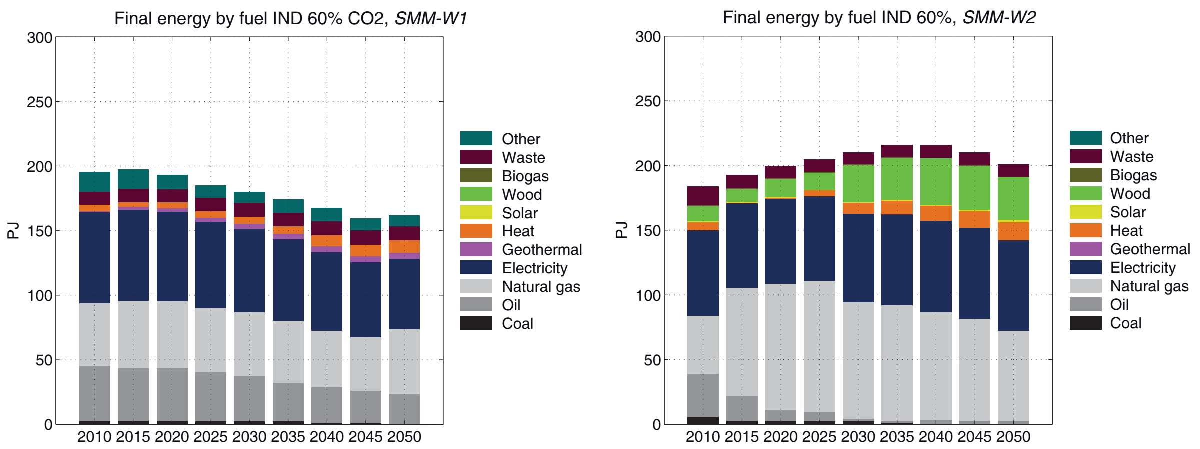


(a) Original model structure (*SMM-W1*)　　(b) Adjusted model structure (*SMM-W2*)

Figure 6.8: Final energy consumption in the industrial sector, nuclear phase-out without climate target

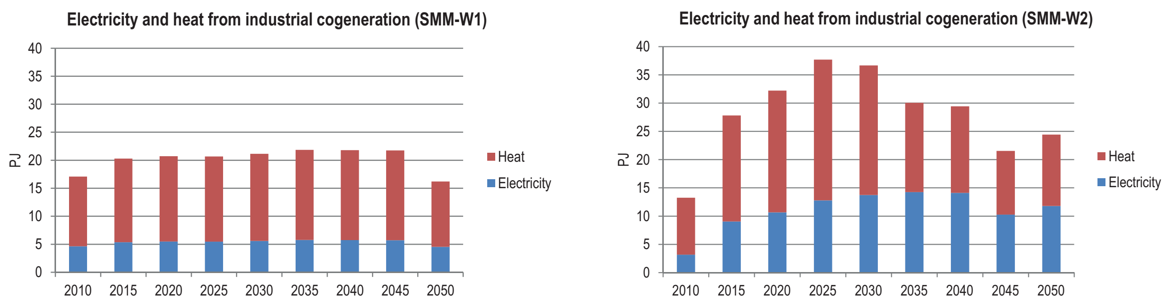
final energy consumption decreases for *SMM-W1* over the time horizon while it increases for *SMM-W2*. This result seems to be unexpected, given the fact that key drivers are equal for *SMM-W1* and *SMM-W2*. However, the result can be explained by differences in the elasticities between drivers and demands and different categories of energy service demands (e.g. in *SMM-W2*, industrial space heating and hot water demand is explicitly modelled, whereas these demands are allocated to the *other consumption* category in *SMM-W1*). The increase in total final energy consumption in the industrial sector of *SMM-W2* is mainly driven by an increase in the production output of the pulp and paper and the chemical industries, while in *SMM-W1* the increase in outpout has a lower impact on final energy consumption due to the abovementioned reasons related to the structural changes. Under a 60% CO_2 emission reduction target, both *SMM-W1* and *SMM-W2* show reductions in total industrial final energy consumption mainly due to a reduction in fossil fuels (Figures 6.9(a) and 6.9(b)). For *SMM-W2*, a shift from gas to wood used in the industrial cogeneration sectors can be observed.

The industrial cogeneration sector as part of the industrial sector, has been revised, restructured, and extended with additional technology options including gas, wood, and biogas combined heat and power (CHP) technologies. In order to account for technological and cost improvements for the CHP technologies, different vintages have been included. Additionally, in *SMM-W1*, the share of electricity from industrial cogeneration in total industrial electricity consumption is limited. This constraint has been removed and replaced by limitations on the use of low temperature heat from industrial cogeneration in this sector. A comparison of electricity and heat production from industrial cogeneration between *SMM-W1* and *SMM-W2* shows that in the restructured industrial sector, cogeneration plays a more important role, which is illustrated in Figures 6.10(a) and 6.10(b) showing a higher production of electricity and heat from cogeneration for *SMM-W2* compared to *SMM-W1*. The higher deployment of industrial CHP technologies in *SMM-W2* is partially reflected by the higher total industrial final energy consumption for the restructured model version.



(a) Original model structure (*SMM-W1*) (b) Adjusted model structure (*SMM-W2*)

Figure 6.9: Final energy consumption in the industrial sector, nuclear phase-out with 60% CO_2 reduction target



(a) Original model structure (*SMM-W1*) (b) Adjusted model structure (*SMM-W2*)

Figure 6.10: Electricity and heat output from industrial cogeneration, nuclear phase-out without climate target

6.4 Summary and discussion

This chapter presents the calibration of the entire Swiss MARKAL model to 2010 statistics, a restructuring of key end-use demand sectors, and a comparison of scenario results from the original model structure (*SMM-W1*) and the restructured model version (*SMM-W2*) for nuclear phase-out scenarios without climate policy and with a 60% CO_2 emission reduction target in 2050. It has been shown that the structural changes conducted particularly in the passenger car and industrial sectors have an impact on technology choice and final energy consumption in these sectors. This implies that assumptions on technology characteristics are crucial to scenario results. Particularly, changes in efficiencies, costs, and other important technology parameters could significantly change the technology combinations as well as the level of energy consumption. Beside the technology assumptions, also user-defined constraints that are applied to avoid unrealistic deployments of new technologies are crucial and need to be carefully chosen. The structural changes in the industrial sector allow for a better representation of important energy service demand technologies in space heating, lighting and other demand categories that were not included in the model before. Further, the extended cogeneration sector allows for a better analysis of the role of industrial cogeneration technologies.

Chapter 7

Alternative socio-economic developments

7.1 Introduction

Future developments of economic and population growth are likely to have an impact on energy consumption in and the configuration of the future energy system. Projections of future key socio-economic factors such as population and GDP are naturally subject to significant uncertainty. This uncertainty is partially reflected by the fact that projections can be significantly different depending on the source and the publication date of a respective projection. As mentioned in chapter 3, the energy service demands used for the scenario analysis presented in chapters 4, 5, and 6 are based on projections from BFS (2001)) and SECO (2004). More recent projections from BFS (2010) and BFE (2012a) show a 16 percentage points (pp) higher GDP and a 17 pp higher population growth in 2050 compared to BFS (2001)) and SECO (2004) (see figure 7.1).

In order to investigate the impact of uncertainty related to future socio-economic developments on the configuration of the future energy system, a scenario with alternative energy service demand growth based on recent projections for key demand drivers including GDP, population, and energy reference floor area was developed and analysed in the remainder of this chapter.

7.2 Development of alternative end-use demands

The development of alternative end-use demands between 2010 and 2050 in *SMM-W2* has been derived based on recent projections for a set of scenario driving forces including GDP, population, energy reference floor area, lighted floor area, heating degree days, cooling degree days, and behavioural changes (BFS, 2010; BFE, 2012a) (see Table 7.1). While some demand categories are assumed to be driven by only one significant driver, others depend on two or more drivers[1]. For this analysis, all end-use demands are assumed to

[1] An example for a demand with more than one driver is residential space cooling, where the drivers are the energy reference floor area (ERFA) in the residential sector, the share of the ERFA that will be equipped with air conditioning devices, and the area-specific cooling demand depending on the annual number cooling degree days. The growth of the product of these factors is assumed to be the proportional driver for the space cooling demand.

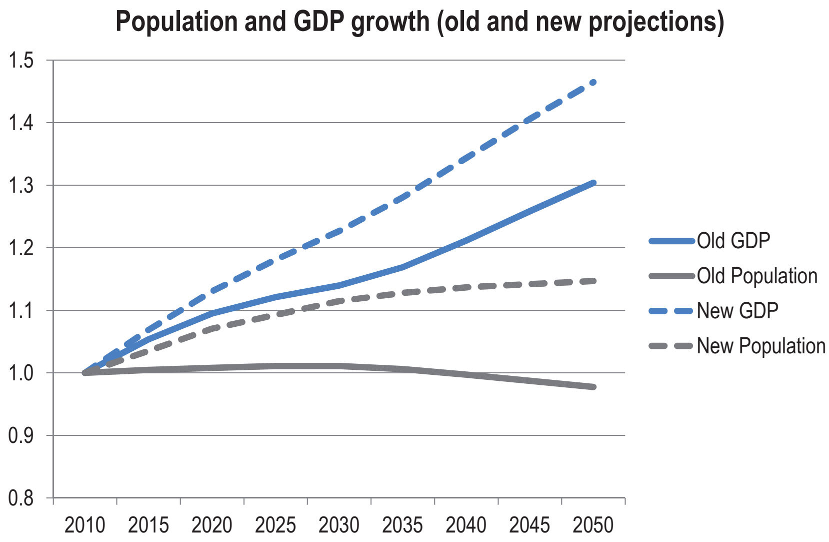


Figure 7.1: Alternative projections for GDP and population growth. Sources: BFS (2001), SECO (2004), BFS (2010), and BFE (2012a).

be proportional to the respective demand driver, meaning that the elasticity of a given demand with respect to the relevant driver is one. An elasticity of one has been chosen as a simplification of the driver-demand relationships and is based on historical relationships for some demand categories showing elasticities close to one. However, in many cases, the elasticities are likely to be different from one and possibly change relative to the growth of the driver. For example, the per capita demand for a luxury service such as holiday air transport is dependent on income. However, the elasticity between income and holiday air transport likely changes for different levels of income. When income becomes very low and falls below a certain level, the demand for holiday air transport is strongly reduced to almost zero (elasticity = 0), and when income increases above a certain level the demand for holiday air transport does not further increase due to other constraints (e.g. time limitations).

Table 7.1: Selected demand drivers used for the development of alternative demands. Sources: BFS (2010); BFE (2012a)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Residential floor area [Million m2]	487	524	561	587	614	631	645	655	666
Lighted floor area [Million m2]	475	511.5	548	574.5	601	618	631	641	651
Population [Million]	7.880	8.159	8.437	8.611	8.784	8.887	8.958	8.998	9.038
GDP (Total) [Billion CHF2010]	547	584	618	646	671	700	734	769	801
GDP (Industry) [Billion CHF2010]	138	144	150	157	163	171	180	189	198

The remainder of this section presents the identification of suitable drivers for the respective demands and the development of future demand projections in the four main end-use sectors including transport, residential, commercial, and industrial sectors in *SMM-W2*. Additionally, the rationale for each demand-driver relationship is described. Further, the updated growth rates for each end-use demand in comparison with their key drivers are presented.

7.2.1 Residential sector

For the residential end-use demands a set of suitable drivers has been identified and allocated to the respective demand as presented in Table 7.2. Based on these drivers, the demand growth between 2010 and 2050 has been calculated as shown in Figure 7.2.

Table 7.2: Residential demands and drivers with ERFA: Energy Reference Floor Area, SHD: Specific Heating Demand, clim.corr_heating: Climate correction factor for heating demand, per_capita_reduction: Reduction in per capita cooking demand due to behavioural change. Sources: BFS (2010); BFE (2012a).

Acronyms	Demand description	Driver
RC1	Space cooling	∝ cooled ERFA * specific cooling demand
RCD	Clothes drying	∝ #clothes dryers/#washing machines
RCW	Clothes washing	∝ population growth
RDW	Dish washing	∝ #dishwashers
RH1	Space heating SFH old buildings	∝ ERFA_RH1 * SHD_RH1 * climcorr_heating
RH2	Space heating SFH new buildings	∝ ERFA_RH2 * SHD_RH2 * climcorr_heating
RH3	Space heating MFH old buildings	∝ ERFA_RH3 * SHD_RH3 * climcorr_heating
RH4	Space heating SFH new buildings	∝ ERFA_RH4 * SHD_RH4 * climcorr_heating
RHW	Hot water	∝ population growth * climcorr_hot_water
RK1	Cooking	∝ population growth * per_capita_reduction
RL1	Lighting	∝ lighted floor area
REA	Other electric appliances	∝ various drivers (#devices, POP, ERFA,...)
RRF	Refrigeration, freezing	∝ #refrigerators+#freezers

Residential cooling (RC1)

Following BFE (2012a), residential cooling is expected to be the strongest growing energy service demand in this sector. It is assumed that the cooling demand is the product of the cooled floor area and the floor-area-specific cooling demand (of the cooled floor area). Due to an assumed annual average temperature increase (caused by climate change) of 1.84 °C until 2050 (BFE, 2012a), the floor-area-specific cooling demand is expected to grow, since households with air conditioning are expected to use their cooling devices more intensively when ambient temperatures rise. While the increase in floor-area-specific cooling demand is about 114% the increase in cooled floor area (due to an increase in the number of households installing air conditioning technologies) is 3545%. This results in an increase of residential cooling demand by a factor of around 78.

Residential clothes washing (RCW)

Based on the rather flat development of the number of washing machines per household in the last 10 years as presented in BFE (2012a), it is assumed that clothes washing demand is saturated today. Additionally, it is assumed that the load of washing machines in operation will not significantly change and is more or less independent of possible

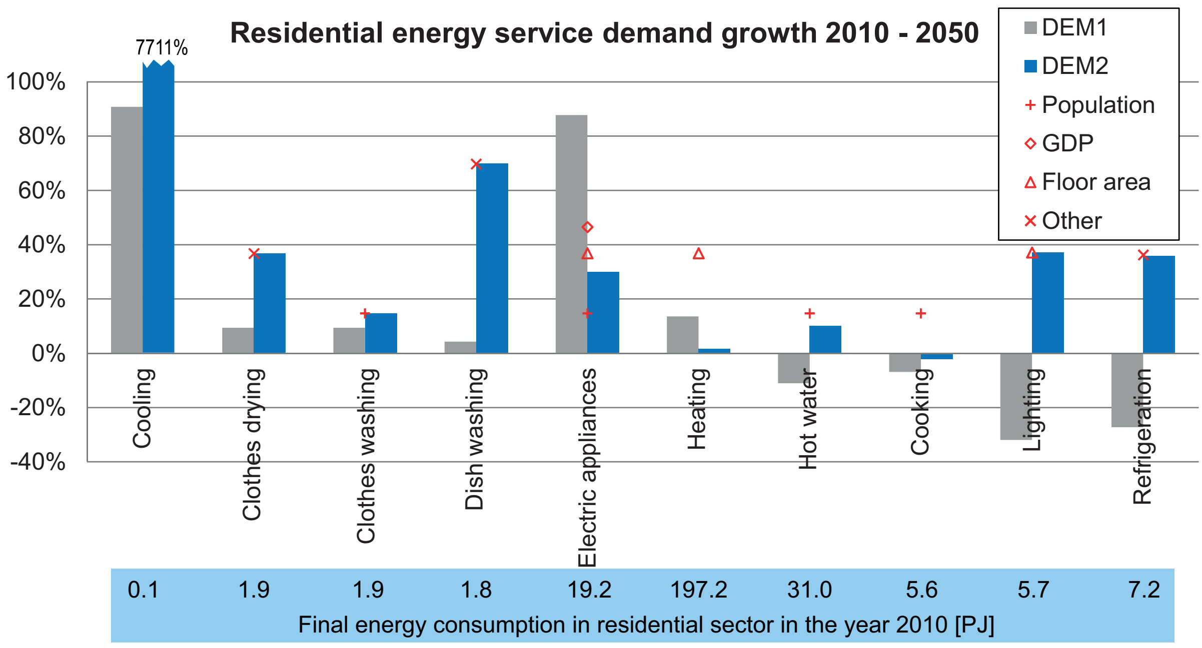


Figure 7.2: Demand growth and drivers in the residential sector. Sources: BFE (2011a,f) and own assumptions.

structural changes in number of people per household or per washing machine. Hence, the per capita demand for clothes washing is expected to stay constant until the middle of the century.

Residential clothes drying (RCD)

As the 40% increase in the number of clothes dryers per household during the last decade (BFE, 2012a) implies, this demand does not seem to be saturated. For the future projection of the demand for clothes drying this demand is linked to the assumed saturated demand for clothes washing. It is then assumed that the demand for clothes drying grows proportionately with the ratio of the number of clothes drying machine relative to the number of washing machines. In doing so, possible structural changes (e.g. related to the number of people using the same clothes drier) can be excluded. As for the washing machines, it is also assumed that the load of clothes drier use stays unchanged.

Residential dish washing (RDW)

The dish washing demand is assumed to be proportional to the number of dishwashers in operation in each year as reported in BFE (2012a). Another assumption is that the load of dish washers in operation doesn't significantly change until the end of the time horizon.

Residential other electric appliances (REA)

The demand category other electric appliances covers different energy service demands including electric building appliances, I&C, entertainment, cooking appliances, and ventilation technologies. Due to the variety of these technologies also the drivers are different.

While heating supporting appliances and ventilators are more linked to ERFA, entertainment, I&C, and cooking appliances more rather depend on population and other factors such as income. For simplification, for entertainment and I&C we adopt the projections of all devices in operation by BFE (2012a). For cooking appliances we assume a 10% increase in per capita use of cooking appliances to account for the shift from the use of conventional ovens to an increased use of cooking appliances such as small ovens, baking machines, and others. For more building related appliances such as ventilation and heating supporting appliances it is assumed that the demand is proportional to the total residential ERFA.

Residential space heating (RH1, RH2, RH3, and RH4)

For the projection of the space heating demand in the four categories we assume that mainly four factors are significant: specific heating demand per energy reference floor area, energy reference floor area, demolition rate, and climate change. For the ERFA for old buildings (RH1 and RH3) we adopt the projections from Schulz (2007) with the assumptions that the demolition rates between 2010 and 2050 and therefore the ERFA projections are still valid. For ERFA projections of the new buildings (RH2 and RH4) adjustments had to be made to account for the changes in total ERFA projection as reported in BFE (2012a). For the breakdown of new buildings into SFH and MFH the shares described by Schulz (2007) have been adopted.

For the projections of specific heating demand (SHD) we adopt the assumptions for SHD for the four categories RH1-RH4 used in Schulz (2007). As reported in BFE (2012a), the expected temperature increase due to climate change has an influence on the heating demand in the Swiss energy system. Following BFE (2012a), the temperature increase causes a 15% reduction in specific space heating demand in 2050. As in BFE (2012a), we assume a linear reduction between 0% in 2010 and 15% in 2050 in specific space heating demand. This assumption requires an adjustment of the formulas to calculate the demands in the four residential space heating categories RH1, RH2, RH3, and RH4 as presented in Schulz (2007). Specifically, this means that in both formulas for old and new buildings a climate correction factor *climcorr* has to be added to account for the reduction in heating demand. The adjusted formula for RH1 and RH3 is:

$$DMD_t = SHD_t \cdot ERFA_t \cdot climcorr_t \tag{7.1}$$

For RH2 and RH4 the adjusted formula is:

$$DMD_t = (SHD_t \cdot (ERFA_t - ERFA_{t-1}) + DMD_{t-1}) \cdot climcorr_t \tag{7.2}$$

DMD_t: Total annual heating demand in a respective heating demand category in a time period
SHD_t: Specific heating demand in a time period
$ERFA_t$: Energy reference floor area in a time period
$climcorr_t$: Climate correction factor in a time period
t: Time period in SMM

The climate change related reductions in residential space heating demands also require an adjustment of the benefits of the energy saving technologies. These energy saving measures for space heating which were introduced by Schulz (2007), are based on marginal cost curves and are modelled so that they have investment costs in $ per PJ of capacity and a maximum capacity or potential that can be installed in each year. The potential in each step of the cost curve depends on the ERFA of the respective building category, the renovation rate, the specific demand for useful energy, and the reduced benefits from this measure caused by the temperature increase due to climate change. It is assumed that the projections of the renovation rates and the specific heating demands did not change and can be adopted from Schulz (2007). Due to the temperature increase from climate change, the heating demand saving reduction of energy saving measures is decreased proportionately to the reduction in heating demand as reported in BFE (2012a). Since the energy saving potential is dependent on the time period, the climate correction factor had to be applied to the capacity factor in order to decrease the efficiency of an energy saving installation in a particular year. For example, when an insulation measure is installed in the year 2010, the amount of energy that can be saved with this measure in 2050 is only 85% from the amount that can be saved in 2010.

Residential hot water (RHW)

The hot water demand is assumed to be proportional to population growth assuming that other factors (e.g. higher water use for cleaning larger floor area per capita and income effects) are negligible. While the per capita demand for hot water is assumed to stay constant, the energy demand to heat the water is assumed to change due to temperature increase from the climate change effect. According to BFE (2012a), the reduction in heating energy use in 2050 is 4%. For this analysis, we assume a linear decrease from 0% in 2010 to 4% in 2050 in heating energy use per capita. This means that the hot water demand is multiplied with a climate correction factor similar to the space heating demand. Based on these assumptions, the heating demand for hot water increases by 10% from 2010 to 2050 (Figure 7.2). For comparison, the old demand decreased by 10% partly due to the decrease in population (see section 3.2).

Residential cooking (RK1)

The residential cooking demand is assumed to be driven by population growth and behavioural changes (e.g. a shift from own cooking to externally cooked meals in restaurants or precooked dishes, convenience food etc...). For the quantification of the per capita cooking demand the projection of the per capita cooking energy consumption growth was calculated based on BFE (2012a) leading to a reduction of around 13% energy consumption. We assume then that 50% of this reduction is related to behavioural changes and 50% from efficiency improvements in the cooking technologies. From there, the per capita end-use demand is multiplied with population growth for the calculation of the total cooking demand. The new cooking demand increases by 7% compared to the old demand that increased by less than 3% (Figure 7.2).

Residential lighting (RL1)

The demand for residential lighting is assumed to grow proportionately with the lighted floor area projected in BFE (2012a). We also assume that the estimate of lighted floor area accounts for possible demand reduction technologies such as roof windows and other technologies that bring day light into the buildings. Hence, the lighted floor area only includes floor area that has to be artificially lighted with lamps. Based on these assumptions, the lighting demand increases by 37% compared to the reduction of 27% in the old demand projections applied in *SMM-W1*.

Residential refrigeration and freezing (RRF)

Future projections for refrigeration and freezing demands are assumed to be driven mainly by the number of fridges and freezers operated as projected in BFE (2012a). We assume that the projections for number of fridges and freezers in operation are based on driving factors such population growth, income or structural changes (e.g. changes in number of people per household), so no additional assumptions was needed for the projection of this demand.

7.2.2 Services sector

The 8 end-use demands of the services sector (i.e. air conditioning and ventilation (CC1), heating (CH1), hot water (CHW), lighting (CLA), I&C (COE), Other (COT), process heat (CPH), propulsion and processes (CPP)) are assumed to be mainly driven by two factors, the energy reference floor area (ERFA) and the economic output (GDP) of this sector. While building-related services such as CC1, CH1, CHW, and CLA are expected to depend on ERFA, services that are more related to economic output of the sector (i.e. COE, COT, CPH, and CPP) are linked to GDP growth in the services sector. Similar to the residential sector, for heating, hot water, and cooling a climate correction factor[2] has been applied in order to account for changes in demands due to climate change. For hot water, it is assumed, that there is an increase in area specific hot water demand due to an increased demand for hot water (e.g. driven by increased use of wellness appliances in hotels and others) (BFE, 2012a). For the calculation of the demand for office equipment, the final energy consumption projection from BFE (2012a) has been applied converted to energy service demand based on own assumptions on efficiency improvements of upto 50% in 2050. Table 7.3 shows the allocation of drivers to end-use demands in the services sector and Figure 7.3 shows the changes in end-use demands between 2010 and 2050 for *SMM-W2* in comparison to *SMM-W1*.

7.2.3 Industrial sector

Similar to the services sector, also in the industrial sector ERFA and GDP are assumed to be the key drivers for energy services. Again, the building-related services heating, hot water, lighting, and air conditioning and ventilation are linked to ERFA growth, and the services that are more related to the economic output are linked to industrial GDP. As mentioned earlier, the industrial sector is divided into 6 branch groups which each include all services described above. In order to account for the differences in future growth of these branches, the GDP and ERFA breakdown by branch has been used to estimate demand in each branch group. Table 7.4 shows the allocation of drivers to services in a branch and Figure 7.4 shows the growth of end-use demands in each industrial branch

[2]The climate correction factor for hot water and space heating demand corresponds to the values in the residential sector. For cooling, only the influence of the cooling degree days, but not from the increase in cooled floor area is applied for the calculation of the demand growth.

Table 7.3: Commercial energy service demands and drivers. Source: BFE (2012a).

Acronyms	Demand description	Driver
CC1	AC, ventilation	∝Floor area, climcorr
CH1	Space heating	∝Floor area, climcorr
CHW	Hot water	∝Floor area, climcorr, increase in specific hot water demand
CLA	Lighting	∝Floor area
COE	I&C	∝Projection for final energy consumption, own assumptions for efficiency improvements
COT	Other	∝GDP_COM
CPH	Process heat	∝GDP_COM
CPP	Propulsion, processes	∝GDP_COM

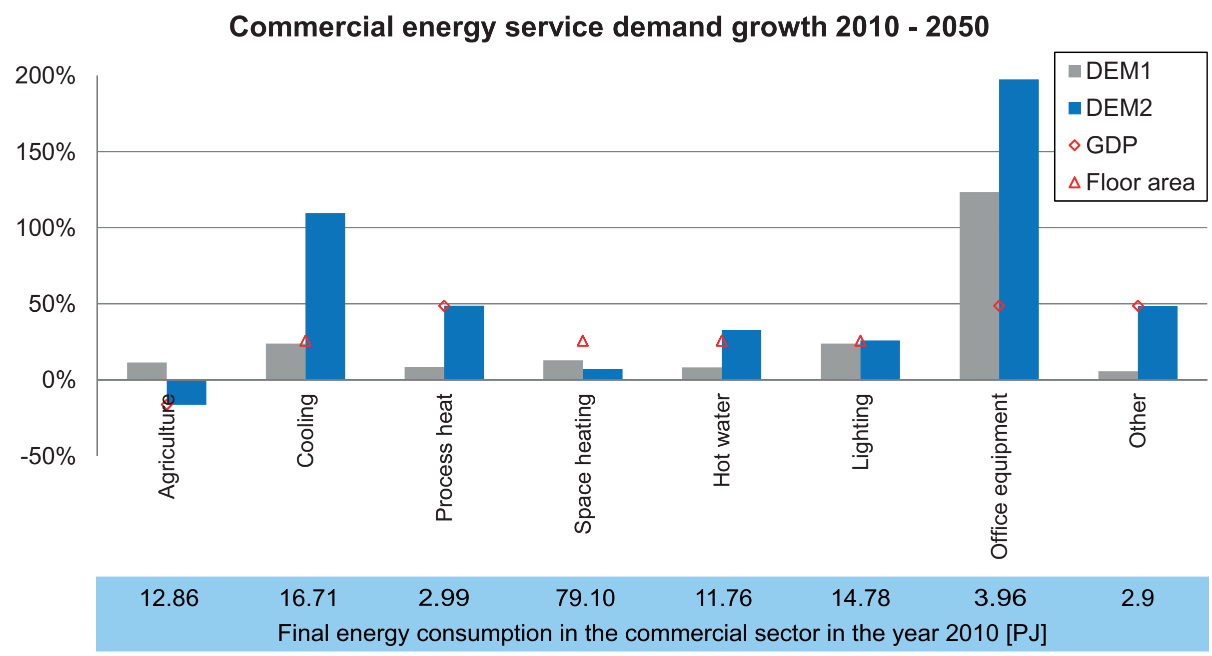


Figure 7.3: Demand growth and drivers in the commercial sector. Sources: BFE (2011a,b,c,f,g) and own assumptions.

group. For comparison, the old demand growth rates from *SMM-W1* are presented as well.

Table 7.4: Industrial energy service demands and drivers. The $*$ is a place holder for the six industrial branches Basic metals (IBMT), Chemicals (ICHM), Cement and other minerals (ICMN), Construction (ICNS), Food, textile, and pulp and paper(IFTP), and Machinery and other industries (IMMO).

Acronyms	Demand description	Driver
$*$A	AC, ventilation	$\propto$ ERFA$_*$, climcorr
$*$W	Hot water	$\propto$ ERFA$_*$, climcorr
$*$I	I&C	$\propto$ GDP$_*$ growth
$*$L	Lighting	$\propto$ ERFA$_*$
$*$M	Machine drive	$\propto$ GDP$_*$ growth
$*$O	Mobility	$\propto$ GDP$_*$ growth
$*$P	Process heat	$\propto$ GDP$_*$ growth
$*$H	Space heat	$\propto$ ERFA$_*$, climcorr

7.2.4 Transport sector

The end-use demands of the transport sector has been updated base on projections for traffic capacity growth from BFE (2012a) for a set of different demand categories (see Table 7.5). For demand categories where no projections were available such as international air transport, navigation, and other transport GDP was used as driver.

Table 7.5: Transport energy service demands and drivers

Acronyms	Demand description	Driver
TRC	Passenger cars	$\propto$ Projection on traffic capacity growth
TRL	Light duty vehicles	$\propto$ Projection on traffic capacity growth
TRH	Heavy duty vehicle	$\propto$ Projection on traffic capacity growth
TRBC	Coaches	$\propto$ Projection on traffic capacity growth
TRBU	Urban buses	$\propto$ Projection on traffic capacity growth
TRW	Two wheelers	$\propto$ Projection on traffic capacity growth
TTR	Rail Construction	$\propto$ Projection on traffic capacity growth
TTP	Rail Passenger	$\propto$ Projection on traffic capacity growth
TTF	Rail Freight	$\propto$ Projection on traffic capacity growth
TWD	Navigation	$\propto$ GDP growth
TAD	Dom. Aviation	$\propto$ Projection on final energy consumption
TAI	Int. Aviation	$\propto$ GDP growth
TOO	Others	$\propto$ GDP growth

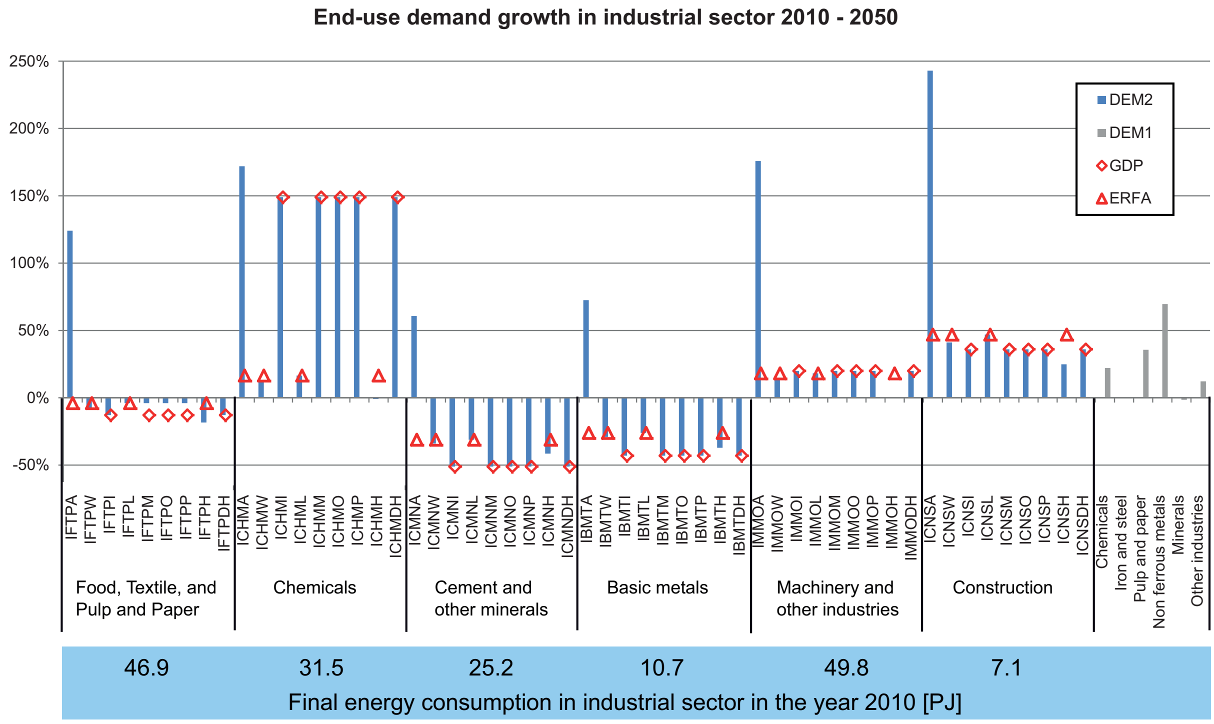


Figure 7.4: Demand growth and drivers in the industrial sector. The last characters in the x-axis label represent the different industrial services: AC and ventilation (A), Hot water (W), I&C (I), Lighting (L), Machine drive (M), Mobility (O), Process heat (P), Space heating (H), Other non specified heat use (DH). Sources: BFE (2011a,b,c,f,g) and own assumptions.

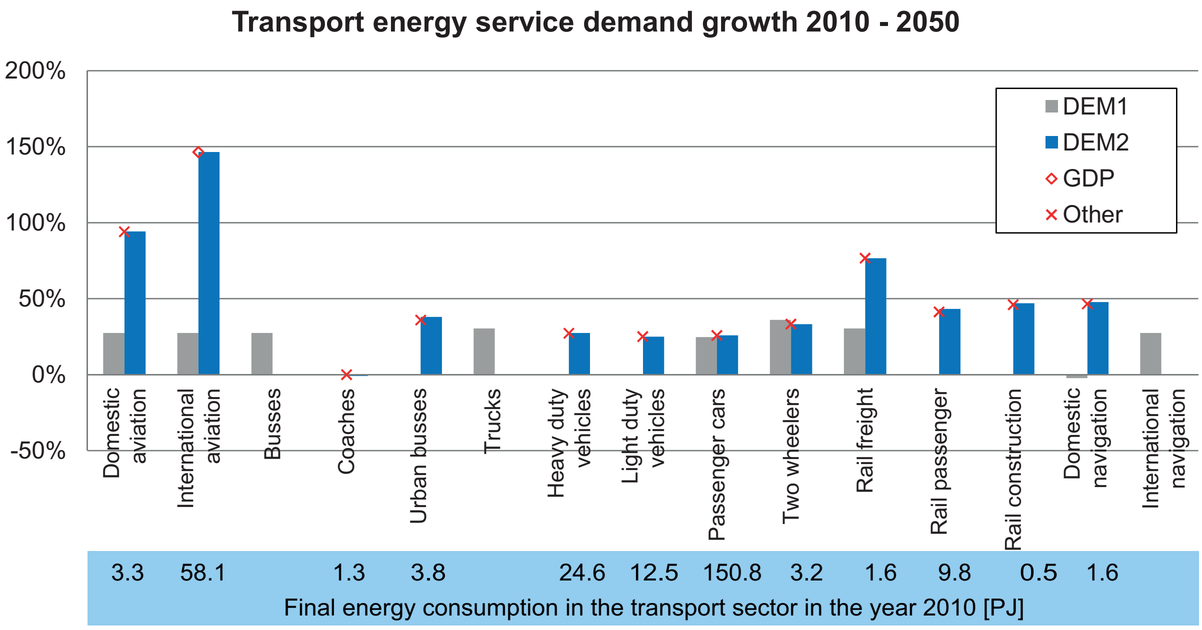


Figure 7.5: Demand growth and drivers in the transport sector. Sources: BAFU (2012b) and own assumptions.

7.3 Impact of alternative end-use demands on the configuration of the energy system

To investigate some of the impacts of the uncertainty related to alternative end-use demands presented in the previous section, a set of scenarios with and without climate policy under a nuclear phase-out are compared for old and new energy service demands. This set of scenarios is defined as follows:

- *DEM1_noClim*: This scenario includes old end-use demands and assumes a nuclear phase-out (existing nuclear power plants are not replaced after reaching the end of their 50 year lifetime). Further, no climate policy is applied in this scenario.

- *DEM1_50%*: In this scenario, the same assumptions as for *DEM1_noClim* are used but a 50%[3] CO_2 emission reduction target has to be met in the year 2050.

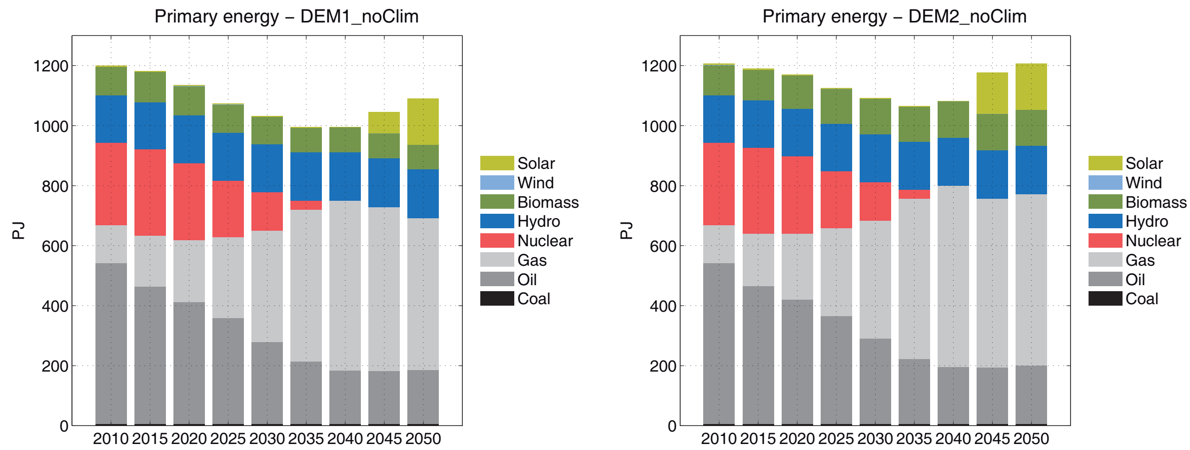
- *DEM2_noClim*: This scenario is based on the same assumptions as *DEM1_noClim* but includes the new end-use demands.

- *DEM2_50%*: This scenario is based on the same assumptions as *DEM1_noClim* but includes the new end-use demands.

These scenarios are analysed and compared for different parts of the energy system. The results from this analysis are presented below.

In many cases, the new demands are higher compared to the old ones due to higher GDP and population growth. This general increase in end-use demands results in a slightly higher primary energy consumption (mainly due to an increase in oil and gas) in a nuclear phase-out scenario without climate policy (see Figures 7.6(a) and 7.6(b)). The higher energy use for the new demand scenario is also reflected by an increase in final energy consumption that is driven by an increase in electricity consumption and in the use of fossil final energy carriers (Figures 7.7(a) and 7.7(b)). The sectoral break down shows that final energy consumption increases in the commercial, industrial, and transport sectors when demands are higher. Unlike these sectors, the residential sector shows a similar level of final energy consumption for both demand scenarios. This result can be explained by the fact that the new demands include a demand reduction for space heating due to a temperature increase caused by climate change. Since in the residential sector space heating accounts for a relatively large share of total final energy consumption in this sector (i.e. 73% in 2010 (BFE, 2011a)), the demand reduction due to climate change compensates the increase in final energy consumption of other residential demand categories. In order to satisfy the higher need for electricity in a scenario with higher demands as mentioned above, a higher deployment of NGCC and NGCHP technologies and an earlier uptake of solar PV modules is needed compared to the old demand scenario (see Figures 7.8(a) and 7.8(b)).

[3]The 50% CO_2 emissions reduction target was chosen for consistency reasons since higher targets including a 60% and 55% reduction target are not feasible for the new demands with the given set of basic scenario assumptions (including the limitations on domestic potentials for low-carbon energy sources) presented in chapter 3.



(a) Old demands (*DEM1_noClim*) (b) New demands (*DEM2_noClim*)

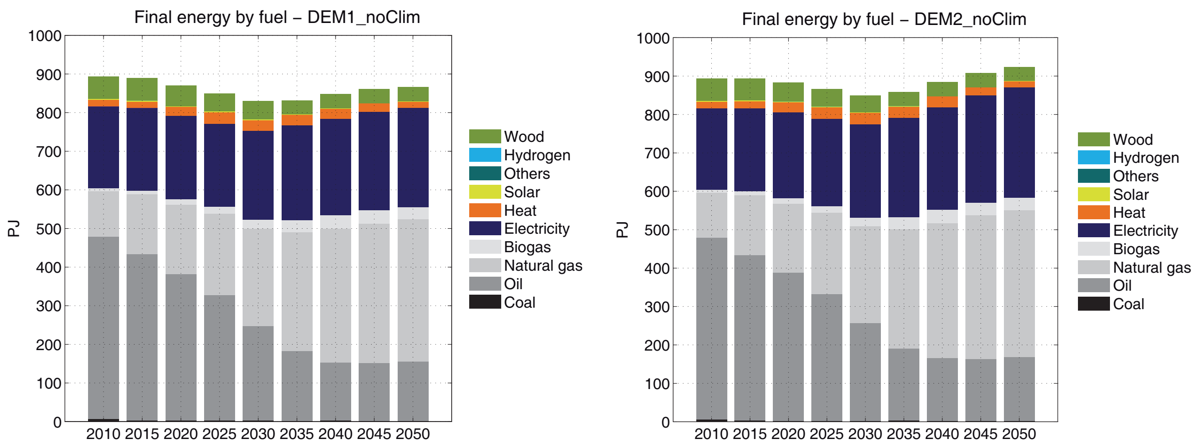
Figure 7.6: Primary energy consumption, nuclear phase-out without climate target: *DEM1_noClim* and *DEM2_noClim* scenarios.

Similar to the case without climate constraint (*DEM2_noClim*), also under a 50% CO_2 reduction target (*DEM2_50%*), higher end-use demands lead to an increase in electricity production. Given that low-carbon electricity from renewable sources is limited in the energy system (due to limited domestic potentials), the increased electricity production needs to be realised with an additional deployment of fossil-based electricity generation technologies increasing the level of CO_2 emissions in the electricity sector (see Figures 7.9(a) and 7.9(b)). The higher use of fossil fuels in the electricity sector needs to be compensated by a decrease in the direct use of fossil fuels in some of the end-use sectors, particularly transport (where hydrogen cars replace gas cars) and in the services sector (where fossil-based heating systems are replaced by district heat).

7.3.1 Car sector

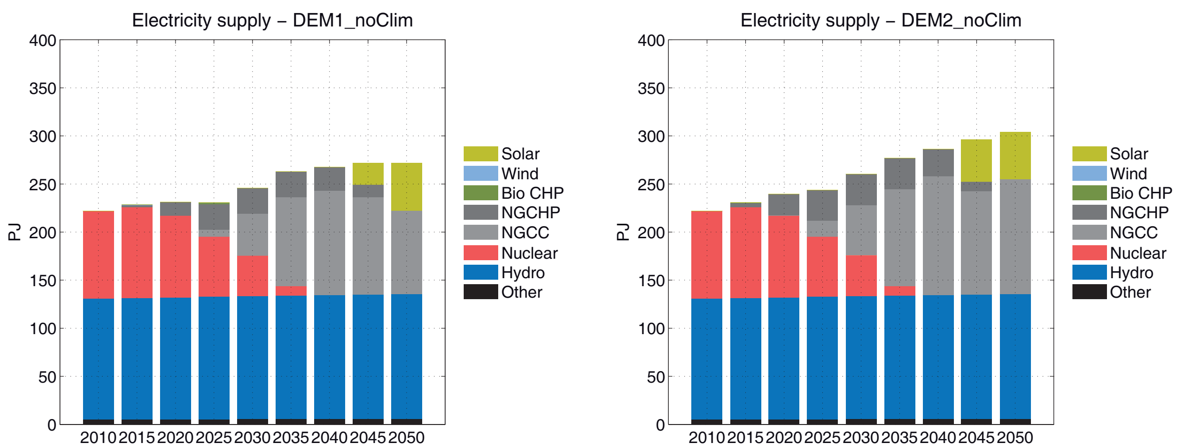
As presented in Figure 7.5, the car demand shows a similar growth and similar technology combinations for the old and new demand scenarios and therefore do not require a further discussion here. However, technological changes in the car sector and insights from the truck sector for scenarios without climate policy and with a 50% CO_2 reduction target for the new demands are analysed in the remainder of this section.

Similar to the results presented in chapter 6, in the *DEM2_noClim* scenario, the car sector shows a strong penetration of gas cars replacing diesel and gasoline cars after 2030 (Figure 7.10(a)). When diesel and gasoline cars reach the end of their 15 year lifetime by 2030, conventional natural gas cars are deployed at a large scale. This shift from oil-based fuels to natural gas is mainly driven by the lower assumptions on the gas price relative to the oil price. The penetration of natural gas cars is limited in the first half of the time horizon (i.e. by an upper bound on the share of gas cars in the car fleet to account for the time needed to build a new gas fuelling infrastructure). Gasoline hybrid cars are assumed to be relatively expensive at the start of the time horizon, so conventional gasoline cars continue to be deployed, but gasoline hybrids become cost-effective. In the *DEM2_noClim* scenario, no battery and hydrogen cars and only a few hybrids are seen



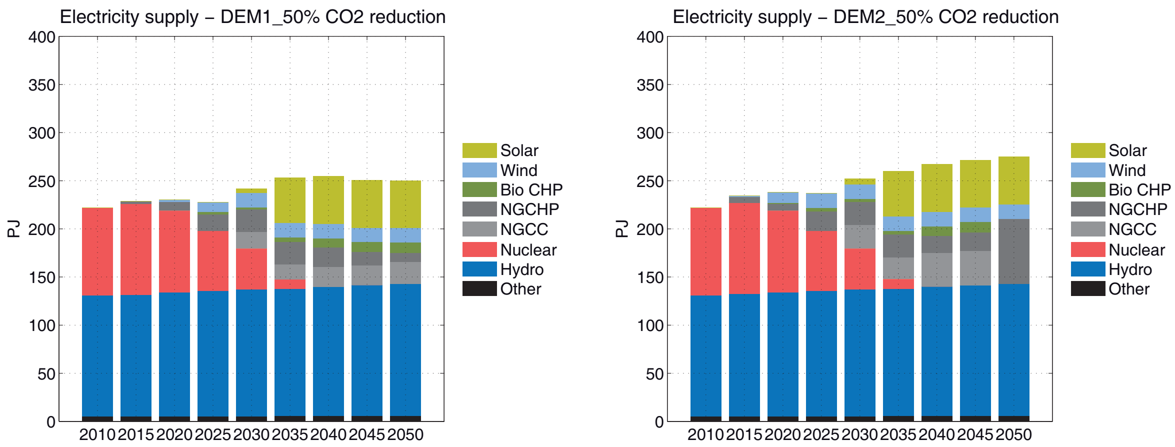
(a) Old demands (*DEM1_noClim*) (b) New demands (*DEM2_noClim*)

Figure 7.7: Final energy consumption by energy carrier, nuclear phase-out without climate target: *DEM1_noClim* and *DEM2_noClim* scenarios.



(a) Old demands (*DEM1_noClim*) (b) New demands (*DEM2_noClim*)

Figure 7.8: Electricity production, nuclear phase-out without climate target: *DEM1_noClim* and *DEM2_noClim* scenarios.



(a) Old demands (*DEM1_Clim*) (b) New demands (*DEM2_Clim*)

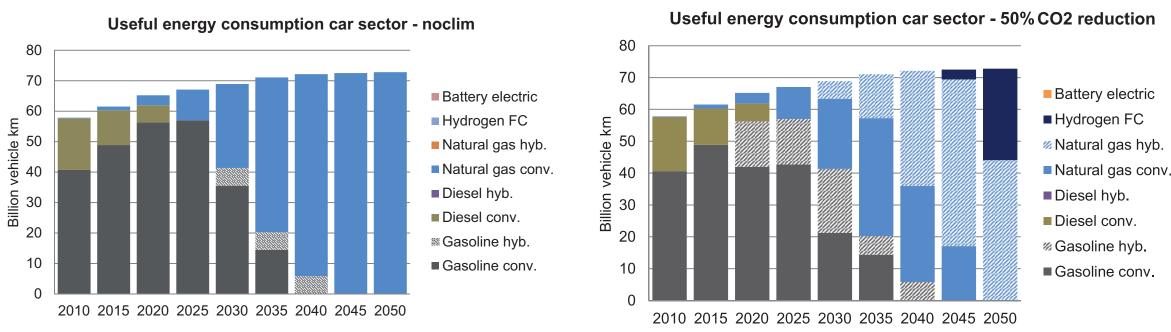
Figure 7.9: Electricity production, nuclear phase-out with 50% CO_2 emission target: *DEM1_50%* and *DEM2_50%* scenarios.

over the entire time horizon. This changes under a CO_2 reduction target (*DEM2_50%*), when significant amounts of gasoline hybrids and later natural gas hybrids and hydrogen fuel cell cars are used (Figure 7.10(b)). However, before these hybrid technologies become attractive, for both natural gas and gasoline some conventional car technologies are deployed. At the end of the time horizon when the CO_2 reduction target becomes most stringent, the car sector is decarbonized by a deployment of hydrogen fuel cell cars. The high efficiency of the hybrid technologies and hydrogen fuel cell cars leads to a strong reduction in final energy consumption in the car sector in 2050 by around 60% compared to the *DEM2_noClim* scenario.

While the car sector shows significant responses when energy system faces climate constraints, the transport sector as a whole is relatively inflexible partially due to the large share of fuels used in international air transport that are not included in the climate target. The truck sector is today mainly diesel-based, since this is the only fuel option assumed for heavy duty vehicles (HDV). For light duty vehicles (LDV) a shift from gasoline and diesel to natural gas can be observed in the last periods of the time horizon when the climate target becomes most stringent.

7.3.2 Industrial sector

The differences in industrial end-use demands have an impact on final energy consumption in this sector. In a nuclear phase-out scenario without climate policy, the alternative demand projections (*DEM2_noClim*) show an increase in total industrial final energy consumption compared to the old demand scenario (*DEM1_noClim*). This increase is mainly caused by an increase in final energy consumption in the chemical industry (driven by a strong increase in GDP in this branch) for *DEM2_noClim* compared to *DEM1_noClim*. The strong increase in final energy consumption in the chemical industry also compensates the decreases in other branches such as the branch group including food, pulp & paper, and textile, and the cement industry, both showing a significant decline in final energy consumption. Other branch groups such as the basic metal, construction, and machinery



(a) No climate policy (*DEM2_noClim*   (b) 50% CO_2 reduction (*DEM2_50%*

Figure 7.10: Useful energy consumption in the car sector. *DEM2_noClim*) and *DEM2_50%* scenarios.)

and others industries have either only a small share in total final energy or show only small increases in final energy consumption.

When looking at final energy consumption by energy carrier, an increase in gas and electricity can be seen while oil significantly declines due to higher prices for oil compared to gas. However, this shift from oil to gas is limited in branches where less substitution options from oil to gas are assumed (e.g. in construction). The strong increase in final energy consumption in the chemical industry goes along with an increase in electricity consumption in this sector. This electricity is produced by cogeneration units in the chemical industry.

Under a 50% CO_2 emission reduction target, emissions are reduced also in the industrial sector for both the old (*DEM1_50%*) and the new (*DEM2_50%*) demands. Climate mitigation in the industrial sector is realised by a shift from gas to wood used in industrial cogeneration units in branches which are typically suited to process wood (e.g. wood and pulp and paper industries). In addition, CO_2 emissions are also reduced by electrification and efficiency improvements in the industrial sector.

7.4 Summary and discussion

This chapter presents the development of an alternative demand scenario based on recent projections of socio-economic parameters including GDP and population growth. For the development of the new demands scenarios, appropriate drivers were allocated to the different energy service demands. For the relationship between the growth of demands and drivers, an elasticity of 1 was chosen as a simplification. However, in reality, the growth of the demand and the driver is likely not proportional. Hence, a revision of the particular driver-demand relationships could further improve the demand projections and therefore be an area for future work.

A comparison of the old and new energy service demand scenarios showed that higher population and economic growth can lead to higher energy service demands and increased energy consumption in total. Further, the result have shown that the 60% CO_2 emission reduction target was not feasible with the higher demand assumptions. Given the limitations on domestic potentials for renewable energy sources, higher demands can make climate change mitigation more challenging and expensive and can therefore have a significant impact on the realisation of a sustainable energy system as described in chapter 1. Further, the assumptions introduced at the beginning of this chapter, that socio-economic developments could have an impact on the configuration of the energy system could be confirmed by the results of this analysis. However, these results could change if important basic scenario assumptions change. Particularly, assumptions on domestic renewables or annual net electricity import levels could significantly change the impact of alternative demands on the configuration of the future energy system. Despite the increase in energy demands due to the higher population and economic growth assumptions, some of the overall findings (e.g. the trend to electrify key parts of the energy system) do not change for the range of uncertainty analysed in this work.

The results of the scenario analysis of SMM with the new demands presented above (namely scenarios DEM2_noClim and DEM2_50%) were compared to the set of scenarios from the Energieperspektiven 2050 report (EP) (BFE, 2012a) as introduced in chapter 2. The EP scenarios were chosen for comparison with the SMM results since both analyses are at large parts based on similar assumptions for key socio-economic parameters such as GDP and population (see Figure 7.1). The results comparison presented in the remainder of this chapter comprises final energy consumption by energy carrier and electricity production for different scenarios. For final energy consumption, the SMM scenarios DEM2_noClim and DEM2_50% are compared to the three EP scenarios WWB (Weiter Wie Bisher), POM (POlitische Massnahmen), and NEP (Neue EnergiePolitik)[4] introduced in BFE (2012a). For electricity production, the two SMM scenarios are compared to eight combinations of the scenarios WWB, NEP, and POM with three electricity supply variants C, C&E, and E[5] representing different levels of support for investments in gas-combined cycle plants and renewable electricity technologies presented in BFE (2012a).

As Figure 7.11 shows, the total electricity generation levels for the eight EP scenario combinations and the two SMM scenarios are in the range between 65.1 TWh (NEP scenarios) and 84.5 TWh (DEM2_noClim scenario). As expected and similar to the results presented in chapter 4, total electricity production is lower in scenarios with more stringent climate constraints or applied energy saving / CO_2 emission reduction measures (i.e. POM, NEP, and DEM2_50%) compared to less stringent scenarios (i.e. WWB and DEM_noClim). The reason for the lower electricity production levels in the more stringent scenarios is related to the restricted use of fossil fuels (particularly gas) in the energy system (due to climate constraints or included mitigation/energy saving measures) and the limited domestic renewable electricity sources. Figure 7.11 further shows that the

[4]The WWB scenario represents a business-as-usual scenario assuming a continuation of the current Swiss energy policy. The goal-oriented NEP scenario seeks at analysing which measures would be needed to achieve given goals (amongst others, a reduction in domestic CO_2 emissions to 1 to 1.5 tonnes of CO_2 per capita). Further, the POM scenario is measures-oriented in order to analyse which goals can be achieved with a given set of measures for energy saving and CO_2 emission reduction (BFE, 2012a).

[5]In all three variants C, C&E, and E investments in new nuclear power plants are banned. Instead, nuclear capacities are replaced by mainly gas-combined cycle (NGCC) plants in variant C, by mainly renewable technologies in variant E, and with both NGCC and renewables in variant C&E (BFE, 2012a).

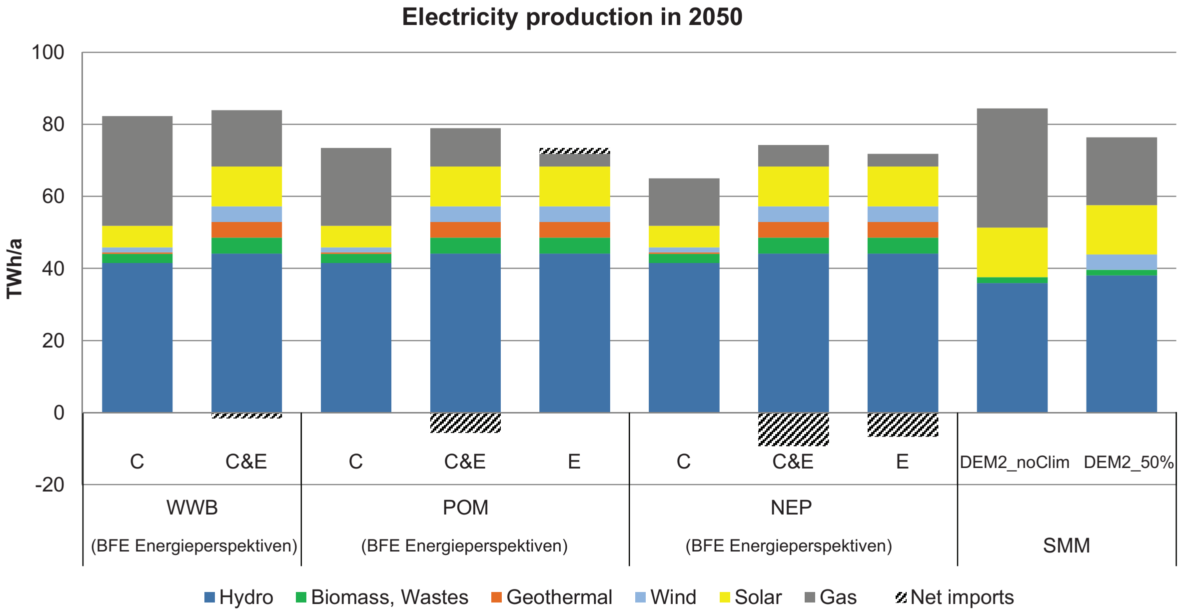


Figure 7.11: Comparison of electricity production for WWB, POM, and NEP scenarios of the Energieperspektiven 2050 (BFE, 2012a) and and two Swiss MARKAL scenarios with updated demands without climate target (DEM2_noClim) and with 50% CO_2 emission reduction target (DEM2_50%).

total electricity production levels are similar between EP and SMM for the less stringent scenarios (i.e. WWB and DEM2_noClim) and the more stringent scenarios (i.e. POM, NEP, and DEM2_50%). However, there are partially significant differences in the absolute shares of the different electricity generation technologies. In particular, the assumptions on the implementable potentials for renewable sources such as solar PV and hydro are different across the scenarios analysed. While in both SMM scenarios the full (technical) solar PV potential of 13.7 TWh is cost-effective and used, in the BFE scenario the (expected) potentials are only 11.1 TWh for the electricity supply variants E and C&E (both assuming intensified supporting measures for renewable technologies) and 5.9 TWh for the electricity supply variant C (assuming the maintenance of the current supporting policies for renewables). Unlike solar PV, the (expected) potentials for hydro are higher in all electricity supply variants of the EP (41.6 TWh and 44.5 TWh) compared to the (technical) potentials in the SMM scenarios (36.1 and 38.1 TWh). Further, in the EP scenarios with supply variant C, a slight contribution from wind of 1.4 TWh can be seen, whereas in the DEM2_noClim scenario this technology option is not attractive at all. For the more stringent EP scenarios with electricity supply variants E and C&E, the wind potentials are almost same as in the SMM scenario DEM2_50% (i.e. 4.26 and 4.2 TWh). One reason for the slightly lower use of gas-based electricity production in NEP scenario with electricity supply variant C compared to the DEM2_50% scenario could be the more stringent CO_2 emission reduction target to at most 1.5 tonnes of CO_2 per capita (or a reduction in total domestic CO_2 emissions of approx. 67% relative to the 1990 level) compared to the DEM2_50% scenario with 50% reduction. As can also be seen in Figure 7.11, the level of biomass-based electricity production is higher for the EP electricity supply variants (significantly for E and C&E) compared to the SMM scenar-

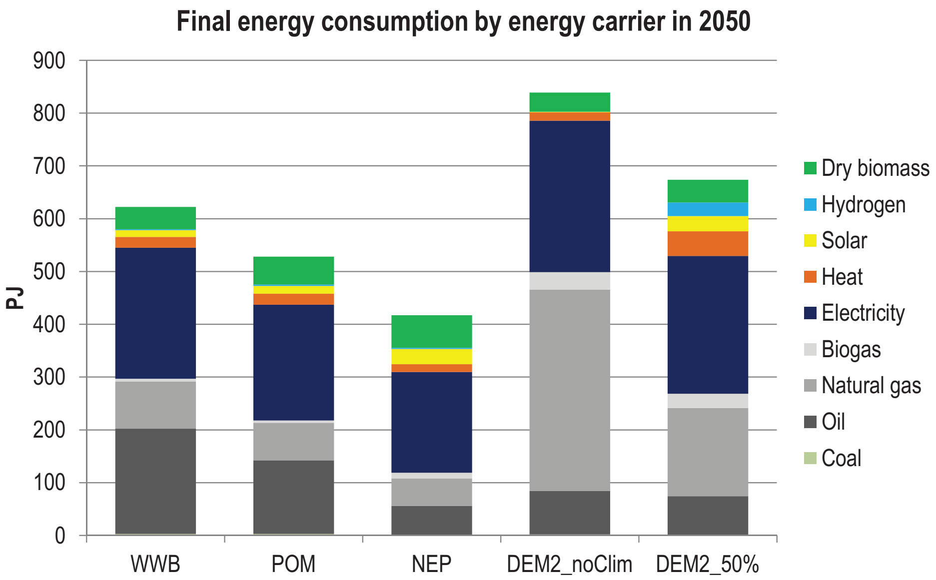


Figure 7.12: Comparison of final energy consumption (without international air transport) by energy carrier for WWB, POM, and NEP scenarios of the Energieperspektiven 2050 (BFE, 2012a) and two Swiss MARKAL scenarios with updated demands without climate target (DEM2_noClim) and with 50% CO_2 emission reduction target (DEM2_50%).

ios. The lower use of biomass in the electricity sector in SMM is a result of the model's cost-optimisation and the more cost-effective use of biomass in other parts of the energy system than the electricity sector (e.g. for hydrogen production or in the end-use demand sectors) rather than of limitations on the domestic biomass potential. Further differences between the EP scenario combinations and the SMM scenarios comprise the contribution from geothermal electricity in all three EP electricity supply variants (i.e. between 0.42 TWh and 4.39 TWh) whereas this technology option is not cost-effective in the SMM scenarios analysed in this study. In addition, Figure 7.11 shows that in the EP supply variants E and C&E unbalanced annual electricity imports and exports (leading to positive/negative net imports) occur, whereas for all SMM scenarios analysed in this work, electricity imports and exports are assumed to stay balanced over the year as introduced in section 3.2.2.

Similar to electricity production, also total final energy consumption is lower when the stringency of a scenario increases (see Figure 7.12, showing final energy consumption by energy carrier in 2050). As mentioned earlier in this chapter, for the SMM scenarios, a 50% CO_2 emission reduction target (DEM2_50%) reduces final energy consumption compared to a scenario without climate target (DEM2_noClim). Similar findings can be observed for the EP scenarios, where the POM and the NEP include more ambitious climate change mitigation and energy efficiency targets and measures compared to the WWB scenario.

Despite these similarities, significant differences exist in terms of total final energy consumption and the absolute shares of energy carriers between the EP and SMM scenarios. As can be seen in Figure 7.12, total final energy consumption is significantly higher in the two SMM scenarios compared to the three EP scenarios. This difference is mainly caused by a higher use of natural gas in commercial building, industrial, and transport sectors in the SMM scenarios compared to the EP scenarios. Part of the reason for the lower use of gas in the EP scenarios is the fact that these scenarios have more optimistic assumptions on the availability of energy saving options efficiency technologies supporting ambitious reductions in energy consumption compared to the SMM scenarios. There, the energy saving potentials in the commercial building sector might be underestimated.

In the transport sector, the NEP scenario shows only about 33 PJ of oil-based fuel consumption but significant shares of electricity and biofuels in 2050, while in the DEM2_50% scenario oil plays a larger role with 64 PJ (excluding air transport). Additionally, biofuels are not attractive in DEM2_50% since based on SMM's cross-sectoral optimisation capabilities, biomass seems to be preferably used somewhere else in the energy system (e.g. for hydrogen production and in industrial cogeneration). One of the reasons for the higher use of oil in the transport sector in DEM2_50% compared to NEP is related to differences in the availability of technologies in the two sets of scenarios (e.g. in SMM, the truck sector includes mainly oil-based technologies while in the EP scenarios also alternative technology options (including electric trucks) are available).

As described above, key reasons for some of the differences between the results from the SMM and EP scenarios are related to differences in the availability and characteristics of advanced technology options to reduce both energy consumption and CO_2 emissions. In this regard, the SMM scenarios tend to be less optimistic than some of the more ambitious EP scenarios that partially show significant reductions in the use of fossil fuels and electricity likely requiring substantial structural changes in infrastructure and technological improvements in the future. While in SMM, measures to support energy saving and climate change mitigation are not explicitly modelled, the EP scenarios comprise relevant instruments and measures in line with current and future energy policy. Therefore, the integration of important current and future instruments and measures could support the achievement of more ambitious energy consumption and climate mitigation levels in the energy system in the SMM scenarios and could be an area for future work.

The potentials for hydro-based electricity production expected in the EP scenarios seem to be on a rather high level compared to other studies (e.g. see Figure 2.4) and the SMM scenarios presented in this work and could be challenging to fully exploit. Further, geothermal-based electricity generation also plays an important role with up to 4.39 TWh per year in the EP scenarios. However, given the high uncertainty related to the future availability of this technology option, the analysis of scenarios where geothermal electricity technologies play no role (as in DEM2_noClim and DEM2_50%) could be worthwhile to consider as well.

The scenarios presented in the EP study show three possible future electricity supply variants (i.e. C, C&E, and E) in combination with three energy policy scenarios (i.e. WWB, POM, and NEP). The resulting eight scenario combinations illustrate how the future Swiss energy system could evolve depending on future (policy) decisions. However, despite their variety, the presented scenarios including the comprising technology combinations and the allocation of resources in the energy system must not necessarily be cost-optimal from an entire energy system's perspective. For example, the EP supply variants assume a fixed expected (and used) potential for biomass for electricity generation. However, depending on the particular scenario, the biomass could possibly also be used more cost-effectively in other parts of the energy system (e.g. for the production of hydrogen or synthetic natural gas (SNG)). Besides the allocation of the limited energy resources also the allocation of CO_2 emissions to the different sectors in the energy system can be critical regarding total system costs. In this regard, the application of a technology-rich bottom-up cost-optimisation model covering the entire energy system (such as the Swiss MARKAL model used in this thesis) would allow analysing cost-optimal configurations and cross-sectoral trade-offs of the future energy system. Such analyses could provide further insights complementing the scenarios of the EP report.

Chapter 8

Conclusions and outlook

The overall objective of this dissertation was to improve the understanding of how a more sustainable Swiss energy system[1] can be realised and to analyse the impact of key uncertainties on technology choice. In doing so, robust technology combinations that could support the realisation of the transformation towards a more sustainable energy system were identified. Within this PhD, a wide set of scenarios reflecting uncertainties related to climate change mitigation targets, availability of carbon capture and storage technologies, energy prices sensitivities, and alternative economic and population growth were developed, quantified, and analysed in chapters 4, 5, 6, and 7 using the Swiss MARKAL energy system model. This set of scenarios analysed represents a number of uncertainties, including:

- Future electricity supply options (chapter 4): The accident in Fukushima in the year 2011 had an influence on the Swiss nuclear policy and resulted in a decision of the Federal Council to phase-out nuclear power by not replacing the existing nuclear capacities when they reach the end of their lifetimes. However, there is significant uncertainty related to the questions of how long the lifetime of the existing nuclear power plants will be and if the ban on investments into new nuclear technologies also includes possible break-through technological improvements, such as inherently safe reactor designs. Further, the decision on phasing out nuclear power could theoretically be reversed. Assuming that nuclear power will be phased-out within the next decades, alternative electricity generation technologies will be required to meet future electricity demands. While new renewable electricity sources will likely not be able to compensate the retired nuclear capacities due to their limited domestic potentials, centralised gas combined cycle and combined heat and power plants are discussed as an option for future electricity supply. However, fossil-based electricity generation on a large scale has the disadvantage of significant amounts of CO_2 emissions that could make meeting climate targets more challenging. Further, these technologies rely on imported fuels and could increase challenges related to energy security. In order to account for the high uncertainty related to future electricity supply options, three scenarios with different levels of nuclear support (i.e. nuclear phase-out, nuclear replacement, and nuclear extension) and a scenario that assumes

[1] In the scope of this thesis, key aspects of a sustainable energy system including CO_2 emissions, energy security, and economics are analysed. However, other aspects related to sustainability such as social impacts, ecosystem damages and others are not adressed in this analysis (see section 8.4).

a nuclear phase-out and a restriction on investment in centralised gas-base electricity generation technologies were analysed in chapter 4.

- Climate mitigation targets (chapter 4): Reducing anthropogenic CO_2 emissions is a key measure for climate change mitigation. As an Annex I country of the UNFCCC, Switzerland has committed to reduce domestic CO_2 emissions by 20% relative to the 1990 level in 2020. While this reduction target is part of the current Swiss CO_2 law, official longer-term CO_2 reduction targets until the middle of the century and beyond currently have not been defined for Switzerland. However, there are recommendations by the Advisory Body on Climate Change (OcCC) (OcCC, 2007, 2012) and the Swiss Academies of Arts and Sciences (SAAS, 2009) which include CO_2 reduction targets of 60% and 80% by the year 2050. However, despite the need for ambitious long-term CO_2 reduction targets, the level of future climate mitigation action in Switzerland is highly uncertain. In order to account for this uncertainty, scenarios with different CO_2 emissions reduction targets including 60% reduction have been analysed in chapter chapter 4.

- Availability of carbon capture and storage technologies: In order to meet ambitious climate mitigation targets as mentioned above, the availability of future low-carbon electricity options is likely to be crucial. One potential source for low-carbon electricity could be the deployment of gas-power plants with carbon capture and storage (CCS) allowing to capture the CO_2 emissions at the source and store them underground in order to avoid emissions into the atmosphere. While CCS could be an interesting option supporting the realisation of a future low-carbon energy system, it is still highly uncertain if this technology option will be available on a large scale in the future. Many important issues related to public acceptance, technical and geological feasibility, and cost will have to be resolved before. In order to account for the uncertainty related to the future availability of CCS technologies, a set of scenarios representing different CCS technology options including gas combined-cycle plants with CCS, combined heat and power plants with CCS, and CCS retrofitting technologies has been developed and analysed in chapter 5.

- Socioeconomic development: The development of key socioeconomic factors such economic and population growth can have a significant impact on the development of future energy service demands that again drive the energy consumption in the future energy system. Hence, the highly uncertain development of socioeconomic factors such as GDP and population are likely to have a significant impact on the configuration of the future Swiss energy system and can be challenging for the realisation of the transformation towards a sustainable configuration. In order to account for the uncertainty related to future developments of population and economic growth an scenario based on alternative projections for GDP and population growth has been developed and analysed in chapter 7.

Beside the scenario developments, also methodological developments have been conducted in the scope of this thesis, including:

- Extensions of electricity and car technologies: The technologies in the passenger car and electricity sector, have been revised and extended based on more recent data sources.

- Development and implementation of a carbon capture and storage (CCS) module in the Swiss MARKAL model (SMM): In order to analyse the potential role of CCS technologies in the future energy system a wide set of CCS technologies has been implemented in SMM. The CCS module include different CCS technologies including natural gas combined cycle plants, centralised combined heat and power plants (both for different vintages), capture units to retrofit earlier-built gas power plants (and therefore decouple investments into the power plant and the capture technology), and transport and storage technologies.

- In order to better represent the characteristics of the Swiss energy system and increase the level of technology detail in important parts of the energy system, key end-use sectors such as the industrial sector including industrial cogeneration have been restructured as described in chapter 6.

- Implementation of climate change effects. Effects from rising temperatures due to climate change on future heating, hot water, and cooling demands have been integrated in the model. In doing so, the energy saving potentials of building insulation measures was also adjusted.

- Calibration to 2010 statistics. The entire model including end-use demand and electricity sectors has been calibrated to 2010 statistics.

The remainder of this chapter presents robust technology combinations that have been identified based on the scenario analysis and gives policy implications. Further conclusion are drawn and an outlook to future research is given.

8.1 Future electricity supply options

Across all scenarios, existing hydro-electric power plants continue to be used up to the installed capacity. In addition, new hydro capacities are attractive depending on the availability of cost-effective alternative electricity options and the stringency of the climate constraint. Nuclear powerplants are cost-effective across all scenarios and are built and used up to the assumed scenario limitations on capacity. When the assumed capacity limitations of nuclear power plants are exploited, natural gas combined cycle plants are the next preferred option. However, this technology option is replaced by solar PV when gas prices become high in the middle of the century or when a CO_2 reduction target limits the use of fossil-base electricity generation. Wind-based electricity only becomes attractive under a climate constraints or if centralised fossil-based electricity generation is not available. If the energy system faces a nuclear phase-out and at the same time has to meet an ambitious CO_2 reduction target of 60% by 2050, wood incineration combined heat and power technologies are used at large scale in the last decade. A sensitivity analysis on fossil fuel prices has shown that high prices generally promote an earlier uptake of new renewable electricity sources at the expense of fossil-based generation. However, there are variations across the different electricity supply options.

Nuclear and hydro are the only technologies that are robust across all scenarios. Further, with some of the limitations mentioned above, also solar PV can be considered as a robust technology option for the last decade of the observation period. In cases where nuclear power can not be extended and a 60% CO_2 reduction target is applied, wind can also be seen as a robust technology option. The electricity production costs of the existing nuclear power plants don't include potential additional investment costs for safety upgrades particularly for the older plants (i.e. Beznau and Mühleberg) as required by the Swiss Federal Nuclear Safety Inspectorate (ENSI, 2013). However, the effect of these measures on electricity production costs would be rather limited and is unlikely to affect the attractiveness of the existing nuclear plants given that the plants can be operated over their entire originally foreseen lifetimes. In this regard, a potentially shortened life time of the existing nuclear plants could significantly reduce their cost-effectiveness. The assumed cost of (from today's perspective hypothetical) future nuclear plants in this analysis could increase depending on possible more demanding required levels of seismic protection potentially leading to increased capital costs and hence decrease the cost-effectiveness of these technologies. For hydro, the analysis shows that the less expensive options (i.e. mainly small hydro plants) are cost-effective and therefore should be exploited in the suitable locations without major conflicts with nature protection. For the cost-effectiveness of the more expensive hydro technologies (that are only attractive under stringent climate mitigation targets), future (international) electricity spot prices at peak times will be crucial when exporting electricity to neighbouring countries.[2] However, installations in large pump storage hydro plants could make sense if the share of intermittent renewables will increase in the future. Then, additional storage capacities will likely be required. In most scenarios analysed, solar PV technologies become attractive in the second half of the time horizon, however their future attractiveness will be dependent on the development of international gas prices, the decline in solar PV technology costs, and the stringency of future climate policies. Due to their decentralised character, a large scale deployment of solar PV technologies will also require significant extensions of the electric grid. The costs of these infrastructural investments are not included in this analysis and could possibly reduce the cost-effectiveness of these technologies in the energy system. In addition, the abovementioned intermittency issues of solar PV will need to be resolved (e.g. by additional investments in storage capacities) and could possibly further increase the overall costs related to solar PV. Hence, a large scale deployment of solar PV (and other intermittent renewable electricity sources such as wind) will require an integrated assessment of the technologies and the relevant infrastrucural needs related to this technology option.

As the results from this analysis show, new renewable electricity sources such as wind and solar are likely to contribute to a cost-effective realisation of the transformation of the energy system towards a low-carbon configuration which is less dependent on imported fossil fuels and more sustainable. Though, the deployment of these renewable sources would also generate intermittency issues that have to be resolved. One way of overcoming this challenge could be the installation of additional pumped storage capacities. However, these investments would have to be carefully planned since with the increasing solar PV capacities also in neighbouring countries the gains from electricity trade at peak times could be reduced changing the return on investment situation of the pumped hydro plants.

The cost-effectiveness and relative attractiveness of the different electricity production technologies (but also of all other technologies in the energy system) applied in this

[2]Recent developments show a decrease in electricity prices at peak times partially related to the increased capacity of solar PV installed in Germany.

analysis can significantly depend on the discount rate applied. As mentioned in section 3.2.2, in this work, a social discount rate of 3% is used in order to reflect a society's valuation of future costs compared to present cost. Such a social discount rate is typically lower than an individual (market) discount rate and reflects the valuation of future and present costs for the society as a whole rather than for individual persons or companies. Some of the reasons for the different levels of the social and the individual discount rates are related to the different risks and preferences faced by a society and individual persons or companies on the market. Due to their lower levels a social discount rate is more favourable for capital-intensive technologies such as nuclear and solar PV than an individual discount rate.

8.2 Carbon capture and storage

Carbon capture and storage (CCS) is widely discussed as an interesting low-carbon electricity option. The analysis on CCS conducted in chapter 5 shows that CCS could play a significant role in supporting the realization of stringent CO_2 mitigation targets under a nuclear phase-out. With the higher levels of electrification supported by natural gas combined cycle plants with CCS, the energy system can avoid some of the more expensive climate change mitigation measures (e.g. the uptake of electric heat pumps reduces the need for more expensive insulation measures) resulting in a reduction of energy system costs. While in nuclear phase-out scenarios without CCS only a 65% reduction of domestic CO_2 emissions could be achieved, with CCS higher targets of 75% reduction were feasible. This reduction is realised with an increased electrification of some of the end-use sectors. If CCS electricity technologies replace conventional NGCC technologies in the electricity sector, the reduction in CO_2 emissions in the electricity sector also relaxes the need for CO_2 mitigation in other parts of the energy system that includes less cost-effective mitigation options.

The need for CCS significantly depends on the availability of other large scale low-carbon electricity sources, such as nuclear and future levels of electricity imports. While in scenarios where nuclear power can be replaced or extended CCS plays no or only a minor role, it significantly contributes to the electrification of the energy system under a nuclear phase-out where low-carbon electricity is scarce. The need for electrification is high enough so that CCS is a robust technology independent on changes in fossil fuel prices. However, depending on the fuel price level the timing of the uptake of CCS technologies can slightly change.

While CCS is an attractive option to support the realisation of a low-carbon energy system, CCS in combination with gas-based electricity generation technologies is likely to increase the dependence on energy imports and the challenges related to energy security. Unlike other low-carbon electricity technologies existing today, CCS technologies are far from being a mature technology. Many issues related to public acceptance, technical and geological feasibility and open questions related to legal aspects and technology cost have be resolved before CCS can be a realistic option for Switzerland. Resolving some of these issues (e.g. identifying suitable storage locations) can require substantial amounts of time and therefore should be addressed early enough.

8.3 End-use demand technologies

End-use demand technologies, being the actual consumers of energy, play an important role in the energy system. Given their nature of providing different energy services across all main end-use demand sectors, the end-use demand technologies can be very diverse and show significant differences in energy efficiency. This can be seen even for technologies providing the same energy service such as heat pumps and electric resistance heaters which have significantly different electric efficiencies.

In order to achieve the goals related to the transformation of the energy system towards a more sustainable configuration, energy efficiency technologies are critical. As the analysis conducted in this dissertation showed, there are many efficiency technologies in the residential sector including heat pumps and energy saving measures such as insulation of building envelopes that are cost-effective across a wide set of scenarios and could contribute to the achievement of the abovementioned transformation of the energy system. However, although many of these technology options are cost-effective today, they are not deployed and imply the existence of barriers. These barriers can be diverse and are often related to high upfront investment costs, the long times of returns of the investments, split incentives[3], or insufficient knowledge. In order to overcome these barriers, a good mixture of incentives (e.g. supported by subsidies or emissions of credits at low discount rates) or reasonable regulatory frameworks are required. Regulations could be suited where costs have a lower impact on investment decisions, which is partially the case for electric appliances in households where for example the energy efficiency level of a television is less important for the buyer (given the current low electricity prices) than other factors such as the size of the screen. Incentive systems could be better suited where costs are likely to have a higher impact on purchase decisions (e.g. for the heating system in residential and commercial buildings, where the saved costs for not used fossil fuels (during the technology's lifetime) are higher than the additional (investment) costs of the more efficient heating system).

8.4 Conclusions

From the scenario analysis conducted in this PhD a number of conclusions related to the realisation of the transformation towards a more sustainable Swiss energy system can be drawn.

Given the uncertainty related to future climate policies, climate constraints can have a significant impact on the future energy system. In order to meet stringent CO_2 emission reduction targets, an increase in energy efficiency across all end-use sectors of the energy system will likely be required. In addition, energy saving measures in the buildings sectors (i.e. residential, services, and industrial sectors) are needed to reduce energy consumption in these sectors. An increased electrification could support the decarbonisation of the building sectors and reduce the need for more costly mitigation options in other parts of the energy system. In doing so, the costs of the energy system could be significantly

[3] Split incentives can occur in a residential building when the landlord invests in an efficiency measure but the tenant (and not the landlord) benefits from the saved energy due to the improved efficiency.

reduced on one hand and allow for more ambitious mitigation targets on the other hand. Under stringent climate constraints, such electrification will likely require a deployment of low-carbon electricity sources such as renewable energy from wind, solar, and biomass. As the results from the scenario analysis conducted in this work show, the full potential of the domestic renewable sources will likely need to be exploited in order to meet the climate targets. However, intermittency issues related to solar and wind will have to be resolved (e.g. by extending the capacities for electricity storage) in order to guarantee meeting future electricity demands at all times in the year.

As the CCS scenarios in this analysis showed, CCS technologies could be an interesting additional source for low-carbon electricity. However, based on the assumptions on technology costs and fuel prices, this technology option should be used complementary to the new renewables rather than as a substitute. Whether CCS could be an attractive source for future low-carbon electricity is highly uncertain due to issues related to public acceptance, and technical and geological feasibility which would have to be resolved first. Although CCS is a potential source for low-carbon electricity, it would lead to a continued reliance on fossil fuels that could have consequences for the security of the energy supply.

Uncertainties in future projections for economic and population growth can have a significant impact on the development of future energy service demands and energy consumption. Given the limitations on domestic renewable potentials and the assumption on balanced annual electricity imports and exports and no availability of alternative low-carbon electricity sources, increasing energy demands could make the achievement of ambitious climate targets more challenging and also more expensive. However, there also positive aspects related to higher economic growth. For example fixed costs, particularly of investments that are less dependent on population growth (partially electric grid infrastructure), can be paid more easily with higher GDP (economy of scale). Given the result that future GDP and population growth could have an impact on the costs and the feasibility of future climate change mitigation targets, a reduction of fossil fuels in the energy system could reduce the potential negative impacts of the uncertainty related to socioeconomic developments.

As mentioned at the beginning of chapter 1, this work focuses on some key aspects of a sustainable future energy system including CO_2 emissions, energy system costs, and security of supply that are in line with Swiss energy policy (see BSE (1999)). However, there are other important criteria of the term sustainability such as health effects, ecosystem damages, land-use, resource consumption and depletion, social impacts (e.g. poverty), accidental risks, public acceptance, further economic aspects besides energy system costs (see UNWCED (United Nations World Commission on Environment and Development) (1987)), that could not be analysed within the scope of this study. Considering these additional aspects of sustainability would be essential for the overall assessment of a sustainable energy system. Further, the trade-off between factors that increase sustainability (e.g. reductions in CO_2 emissions, improvements in supply security) and others that reduce sustainability (e.g. increase in energy system costs) would allow proving the actual sustainability gains that could be realised in the scenarios presented in this thesis. The use of technologies with CCS is a good example to illustrate such trade-offs and the diverse implications of technologies on sustainability. On the one hand, CCS technologies allow for a reduction in CO_2 emissions in the atmosphere leading to a gain in sustainability. On the other hand, the additional costs of the technology, the increased gas imports, and possible issues with public acceptance (due to unclear long-term risks) can reduce the gain in sustainability. One way of achieving a broader assessment of a sustainable energy system is the combination of Life-cycle assessment (LCA) and energy economic modelling as introduced by Volkart et al. (2013) and currently further developed within another PhD project in collaboration between the Energy Economics and the Technology Assessment groups of the Laboratory for Energy System Analysis at the Paul Scherrer Institute.

8.5 Outlook to future work

Within the scope of this dissertation, a set of scenarios has been analysed illustrating possible strategies towards the realisation of a more sustainable future Swiss energy system. However, given the limitations on time, there are still some areas that could not have been analysed as intensively as the ones presented in this thesis. These areas open opportunities for further research that would complement this analysis conducted in this work. Some of these areas have been identified and are described in the remainder of this section. The areas for future work are related to the modelling framework and the scenarios developments.

8.5.1 Modelling framework

As mentioned in chapter 3, the Swiss MARKAL model has an annual time resolution of six time periods representing summer, winter, and intermediate and day and night. With this relatively rough time resolution, the demand load curves for electricity and the availability of intermittent renewable sources such as solar PV and wind cannot be accurately represented. With this simplified representation of electricity supply and demand curves, the capacity need for electricity generation in the energy system is possibly underestimated and the attractiveness of intermittent sources overestimated in SMM.

For the accurate analysis of hourly demand and supply fluctuations another modelling framework such as the TIMES model would be more appropriate and could give additional insights into the analysis and would also allow to account for some intermittency issues related to the deployment of new renewable sources. A first analysis using a soft-coupled Swiss MARKAL model and a TIMES electricity model has been conducted by Weidmann et al. (2012a) and illustrated the benefits of both the energy system and the electricity sector approaches providing insights into cross-sectoral implications of future energy policies and technology choices and the dynamics of a hourly electricity load and supply curve. As Weidmann et al. (2012a) also showed, a further step could be the integration of both approaches into one TIMES model representing the entire Swiss energy system enable more insights into system-wide effects. Such a TIMES model is currently being developed for Switzerland by colleagues in the Energy Economics Group at PSI.

An important part of an energy system are energy-related grids for electricity, gas, hydrogen, and district heat. In the Swiss MARKAL model, these grids are not modelled in detail although transmission losses in the grid are accounted. However, important factors such as capacity limits are not represented. The representation of grids in the model or possibly with another analytical framework would add substantial value to this analysis by integrating infrastructure costs of the grid to the total energy system costs and by identifying potential bottlenecks and capacity limits of the energy flows in the energy system.

While parts of SMM have been revised and updated in terms of technology data (including technology parameters such as efficiency, costs, lifetime, and availability), there are areas where a revision of technologies would improve the consistency with actual technologies given the fact that many technologies are likely to have significantly developed or emerged since the last revision. Key areas for such a revision could be the wide range of different electric appliances and energy saving measures in the building sectors.

The current version of SMM represents the Swiss energy system as a single region without connections to the neighbouring countries. In order to better represent the electricity trade between Switzerland and other countries and analyse cross-regional effects, SMM could be extended by additional regions.

While the residential sector in the current version of SMM shows a detailed representation of energy efficiency technologies and energy saving measures, other sectors including the commercial buildings sector could be improved and extended in this regards. In addition, in the industrial sector, energy efficiency options could be extended for some of the industrial processes.

8.5.2 Further scenario analysis

Although, a wide set of scenarios has been developed and analysed within this dissertation, there are many areas of uncertainty that could be represented in additional scenarios and analysed using the Swiss MARKAL model. One possibility could be the development of policy scenarios that include taxes on energy commodities and emissions since they are currently not represented in SMM. In doing so, the effect of taxes on the cost-effectiveness of technology options could be analysed.

In Schulz (2007) the concept of the 2000 Watt per capita society has been discussed and intermediate steps (i.e. a 3500 Watt target by 2050) towards this long-term goal have been presented. In the meantime, the 2000 Watt concept has been complemented by the concept of the 1 ton of CO_2 per capita society being a long-term goal for the year 2100 (Boulouchos et al., 2008). Similar to the concept of the 2000 Watt society, also for the 1 ton of CO_2 society an intermediate target of 2 tons of CO_2 by the year 2050 has been identified. The analysis of these two complementary concepts could be interesting since they are partially heading in a similar direction (i.e. by reducing the dependence of fossil fuels). Particularly, it is not clear to which extent the two concepts supports each other (e.g. how can per capita primary energy consumption be reduced by meeting a per capita CO_2 reduction target?). A CO_2 emissions per capita target can be translated into a cap on total CO_2 emissions in the energy system, which has been analysed within the scope of this thesis. Further constraints with a cap on primary energy consumption could lead to changes in technology and fuel choice and further promote energy efficiency technologies.

Within the scope of this dissertation alternative demand scenarios have been developed based on most recent projections of socioeconomic parameters[4]. While the choice of drivers for each of the energy service demands was relatively straight forward, the elasticities representing the relationships between growths of drivers and demands are more difficult to project. In the current model version, for all demands an elasticity of one has been applied. This simplified assumption likely needs to be revised and refined which would be another area for future work.

As the results of this analysis imply, the assumptions on the development of future key technology parameters such as efficiencies and costs is crucial and can have an impact on the attractiveness of future technologies in SMM. However, there are differences in the level of uncertainty related to these parameters across the different technologies. While some technologies are not yet mature and future developments are more uncertain (e.g. solar PV technologies, hydrogen and battery electric cars), there is a wide range of other technologies that are more mature and future developments are more certain. Despite the uncertainty related to future developments of some of the technologies, the findings based on the analysis conducted within this thesis are widely robust. However, one way of addressing the uncertainty of the development of some of the technologies is the application of a sensitivity analysis (e.g. to illuminate the impact of cost on technology choice in the energy system).

As mentioned at the beginning of this chapter, in this thesis selected aspects of a sustainable energy system were analysed (i.e. CO_2 emissions, economic indicators, and energy security). However, a sustainable energy system includes important additional aspects related to impacts on health, ecosystem damages, and social issues. Complementing the analysis conducted within this PhD with additional aspects related to sustainability could be another area for future work. A first analysis conducted by Volkart et al. (2013) analysed and compared sustainability indicators for a set of three scenarios of the future energy system that have first been quantified and analysed with the Swiss MARKAL energy system model. Volkart et al. (2013) could show that substantial difference between the three scenario could be found in terms of fossil fuel consumption and human health damages amongst others. However, this analysis could be extended by analysing additional scenarios and indicators.

[4]There is a range of other socioeconmic scenarios from different sources including the Swiss Federal Statistical Office, the State Secretariat for Economic Affairs (SECO), and different consultancies looking at a broad set of projections of indicators of future socioeconomic developments. Many of these projections are updated in regular intervals.

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Appendix A

Technology data

A.1 Car technologies characteristics in *SMM-W2*

In Table A.1, the car technology characterstics as used in model version *SMM-W2* are presented.

Table A.1: Car technology data used in model version *SMM-W2*

Car technology	INVCOST [CHF_{2010}/ kv-km/y]	FIXOM [CHF_{2010}/ kv-km/y]	EFF [bv-km/y]
Gasoline conventional 2010	1616	69	0.33
Gasoline conventional 2020	1621	69	0.34
Gasoline conventional 2030	1626	69	0.35
Gasoline conventional advanced 2010	1629	69	0.44
Gasoline conventional advanced 2020	1661	71	0.47
Gasoline conventional advanced 2030	1692	72	0.50
Gasoline hybrid 2010	1981	84	0.54
Gasoline hybrid 2020	1942	83	0.68
Gasoline hybrid 2030	1903	81	0.91
Gasoline hybrid 2040	1864	79	0.91
Gasoline hybrid 2050	1825	78	0.91
Diesel conventional 2010	1787	76	0.37
Diesel conventional 2020	1792	76	0.38
Diesel conventional 2030	1797	76	0.38
Diesel conventional advanced 2010	1800	76	0.47
Diesel conventional advanced 2020	1800	76	0.51
Diesel conventional advanced 2030	1800	76	0.58
Diesel hybrid 2010	2089	89	0.57
Diesel hybrid 2020	2050	87	0.73
Diesel hybrid 2030	2011	85	0.99
Diesel hybrid 2040	1972	84	0.99
Diesel hybrid 2050	1933	82	0.99
Natural gas conventional 2010	1710	73	0.45
Natural gas conventional 2020	1719	73	0.47
Natural gas conventional 2030	1728	73	0.50
Natural gas hybrid 2010	2008	85	0.60
Natural gas hybrid 2020	1969	84	0.73
Natural gas hybrid 2030	1930	82	0.93
Natural gas hybrid 2040	1891	80	0.93
Natural gas hybrid 2050	1852	79	0.93
Battery electric 2010	2906	123	1.41
Battery electric 2020	2672	114	1.48
Battery electric 2030	2438	104	1.55
Battery electric 2040	2204	94	1.55
Battery electric 2050	1970	84	1.55
Hydrogen Fuel Cell 2010	2836	121	1.00
Hydrogen Fuel Cell 2020	2641	112	1.06
Hydrogen Fuel Cell 2030	2352	100	1.13
Hydrogen Fuel Cell 2040	2139	91	1.13
Hydrogen Fuel Cell 2050	2006	85	1.13
Hydrogen ICE 2010	2170	92	0.56
Hydrogen ICE 2020	2131	91	0.70
Hydrogen ICE 2030	2092	89	0.92
Hydrogen ICE 2040	2053	87	0.92
Hydrogen ICE 2050	2014	86	0.92

INVCOST: Investment cost
FIXOM: Fixed O&M cost
EFF: Efficiency
kv-km/y: thousand vehicle kilometers per year
bv-km/y: billion vehicle kilometers per year

Appendix B

Figures

B.1 Carbon Capture and Storage

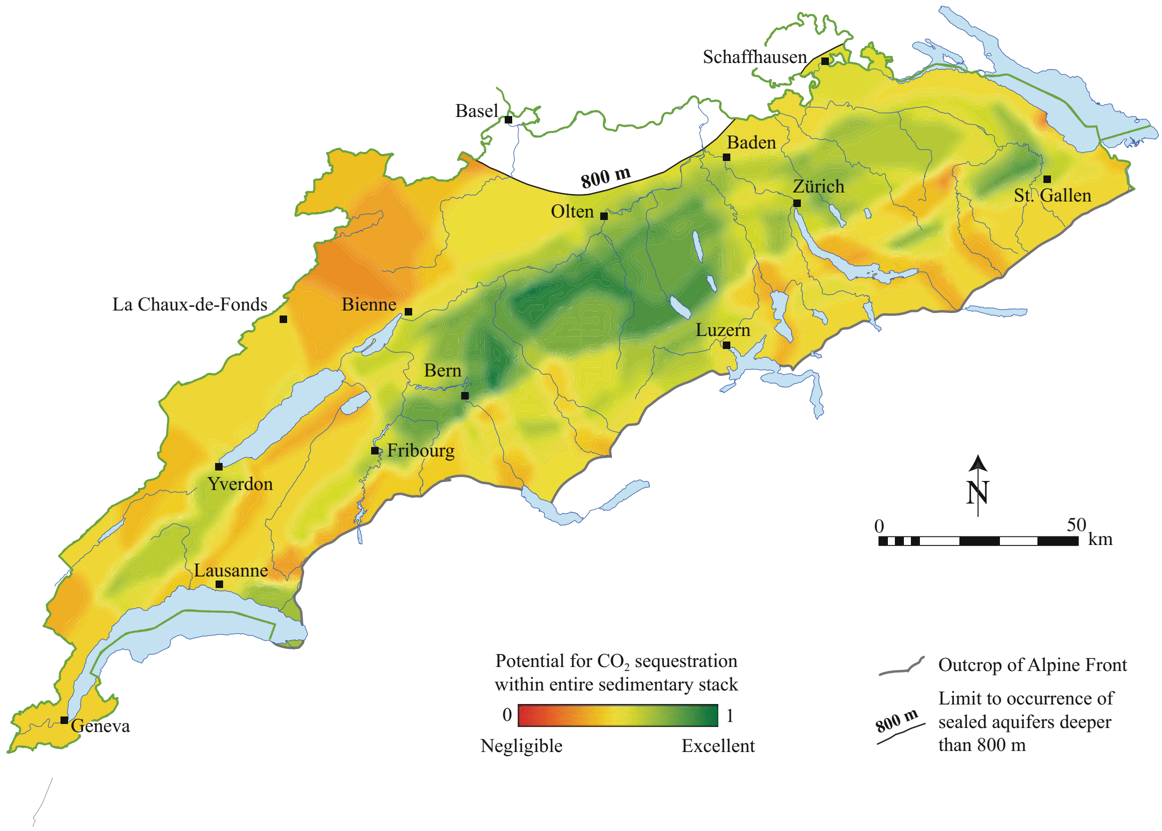

Figure B.1: Map showing areas in Switzerland where potentials for CO_2 storage within deep saline aquifers have been identified (green areas mean higher and red areas mean lower potentials). As found by Chevalier et al. (2010), the total theoretical (unproven) storage capacity in areas with potentials above 0.6 is approximately 2680 million tonnes of CO_2 (Figure adopted from Chevalier et al. (2010) and courtesy of Larryn Diamond).