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REALIZING A SUSTAINABLE ENERGY SYSTEM IN SWITZERLAND IN A GLOBAL CONTEXT

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Nomenclature / Abbreviations

CH_4 .... Methane
CO_2 .... Carbon Dioxide
°C .... Degree Celsius
N_2O .... Nitrous Oxide
AEEI .... Autonomous Energy Efficiency Improvements
BFE .... Swiss Federal Office of Energy
BFS .... Swiss Federal Office of Statistics
bio .... Biomass
bio(CCS) .... Biomass with CCS
bio-FT .... Biomass to synthetic fuel
bio-FT(CCS) .... Biomass to synthetic fuel with CCS
bio-H2 .... Biomass to Hydrogen
bio-H2(CCS) ... Biomass to Hydrogen with CCS
CANZ .... Canada, Australia and New Zealand
CCS .... Carbon capture and storage
CE .... Carbon equivalent
CER .... Ceramic fuel for FBR
CES .... Constant elasticity of substitution
CF .... Capacity factor
CFC .... Chlorofluorocarbon
CHF .... Swiss Franc
CHI .... China
coal-FT .... Coal to synthetic fuel
coal-H2 .... Coal to Hydrogen
coal-H2(CCS) .. Coal to Hydrogen with CCS
depU .... Depleted uranium
EAEEI .... AEEI rates for the electricity demand
EEFSU .... Eastern Europe and the Former Soviet Union
eff .... Efficiency
EFR .... European Fast Reactor
EJ .... Exa-joule
ele-H2 .... Water to Hydrogen using electrolysis
EPR .... European Pressurized Reactor
EREF .... Electricity reference demand

ETL .... Endogenous Technology Learning
EU .... European Union
EUP .... European Union region
FBR .... Fast breeder reactor
FOM .... Fixed operation and maintenance costs
FP .... Fission products
FSNF .... Spent fuel from FBR
FT .... Fischer-Tropsch
gas-FC .... Gas fuel cell
gas-H2 .... Gas to Hydrogen
gas-H2(CCS) ... Gas to Hydrogen with CCS
GDP .... Gross Domestic Product
GHG .... Greenhouse gas
GJ .... Giga-joule
GW .... Giga-watt
H_2 .... Hydrogen
heU .... High enriched uranium
HFC .... Hydrofluorocarbon
IAEA .... International Atomic Energy Agency
IAM .... Integrated Assessment Model
IEA .... International Energy Agency
IGCC .... Integrated Gasification Combined Cycle
IGCC(CCS) ..... Integrated Gasification Combined Cycle with CCS
IIASA .... International Institute for Applied Systems Analysis
IND .... India
IPCC .... Intergovernmental Panel on Climate Change
JPN .... Japan
kW .... Kilo-watt
LBD .... Learning-by-doing
LBS .... Learning-by-searching
leU .... Low enriched uranium
LLF .... Long-lived F-gases
LSNF .... Spent fuel from LWR
LWR .... Light water reactor
MEA .... Middle East
MERGE-ETL .... Model for Estimating the Regional and Global Effects of GHG reductions with Endogenous Technology Learning
MET .... Metallic fuel for FBR
MOX .... Mixed Oxide
Mtoe .... Mega-ton Oil Equivalent
MW .... Mega-watt
NAEEI .... AEEI rates for the non-electric energy demand
NGCC .... Natural Gas Combined Cycle
NGCC(CCS) .... Natural Gas Combined Cycle with carbon capture and storage (CCS)

NREF .... Non-electric energy reference demand
nuc-H2 .... Nuclear to Hydrogen
OECD .... Organisation for Economic Co-operation and Development
PC .... Pulverized coal
PC(CCS) .... Pulverized coal with CCS
PEC .... Primary energy carrier
PFC .... Prefluorocarbons
ppb .... Parts per Billion (volume)
ppm .... Parts per Million (volume)
ppt .... Part per trillion (volume)
Pu .... Plutonium
R&D .... Research and development
RCP .... Representative Concentration Pathway
repU .... Reprocessed uranium
rf .... Radiative forcing
ROW .... Rest of the World
RUS .... Russia
SEC .... Secondary energy carrier
SF_6 .... Sulfur Hexaflouride
SLF .... Short-lived F-gases
sth-H2 .... Solar thermal production of hydrogen
SWI .... Switzerland
SWU .... Separative work unit
TCM .... Trillion cubic meter
TPES .... Total Primary Energy Supply
tru .... Transuranics
UNFCC .... United Nations Framework Convention on Climate Change
UOX .... Uranium Oxide
ura .... Uranium
USA .... United States of America
USD2000 .... US Dollars (2000)
VOM .... Variable operation and maintenance costs
WEUR .... Western Europe
ZJ .... Zeta-joule

List of symbols

Subindexes

g	Greenhouse gas
r	Region
t	Period
trd	Tradeable good

y	Technology

Economic submodel

a	Productivity factor
b	Productivity factor
C	Consumption
d	Depreciation
E	Electricity
EC	Energy costs
ELF	Economic loss factor
EN	New electricity
g	Growth rate of output
I	Investment
K	Capital
KN	New capital
L	Labour
LN	New labour
mpc	Marginal productivity of capital
N	Non-electric energy
NN	New non-electric energy
u	Utility
w	Negishi weights
Y	Economic output
YN	New economic output
α	Elasticity of substitution between capital and labour
β	Elasticity of substitution between electricity and non-electric energy
γ	Elasticity of substitution between capital-labour and energy bundle (electricity and non-electric energy)
ρ	Social discount factor

Energy submodel

ag	Age of the technology
cap	Installed capacity
lf	Lifetime of a technology
PE	Electricity produced
X	Net exports

Nuclear cycle

e^F	Electricity produced by FBR
e^L	Electricity produced by LWR
k	Proportion of uranium and plutonium inputs to FBR
k_u	Ratio between uranium input and reprocessed uranium output in FBR
p^L	Plutonium produced by reprocessing LWR spent fuel
p_i^F	Plutonium used by FBR
p_o^F	Plutonium produced by reprocessing FBR spent fuel

u^F	Total uranium used by FBR
u_d^L	Depleted uranium (produced)
u_d^F	Depleted uranium (used by FBR)
u_e^L	Enriched uranium
u_o	Uranium ore
u_o^L	Uranium ore used by the LWR
u_o^F	Uranium ore used by the FBR
u_r^L	Reprocessed uranium from LWR spent fuel
u_{ri}^F	Reprocessed uranium used by FBR
u_{ro}^F	Reprocessed uranium from FBR spent fuel
ϵ	Ratio between enriched and depleted uranium

Endogenous technology learning

A	Learning constant calibrated with the initial cost and capacity
b	Learning-by-doing index
c	Learning-by-searching index
CC	Cumulative capacity
CRD	Cumulative research and development expenditures
l	Floor cost
inv	Investment costs

Climate submodel

A	Capacity fraction of atmospheric reservoirs
c	Atmospheric concentration
$catt$	Catastrophic temperature
hsk	Hockey-stick parameter
j	Atmospheric reservoirs
lg	Constant calibrating lag in the temperature increase
$nyper$	Number of years in a period
M	Magnitude of the impulse
S	climate sensitivity parameter
sul	Total sulfate emissions
T	Time constant for the absorption of the CO_2 by the ocean in each reservoir
x	Emission function
y	Atmospheric CO_2 response
y_δ	Atmospheric CO_2 response to an unitary impulse $\delta(t)$
τ	Mean lifetime of the gas
ΔAT	Actual temperature change
ΔF	Total radiative forcing
ΔF_{CFC}	Radiative forcing from CFCs
$\Delta F_{\mathrm{CH_4}}$	Radiative forcing from CH_4
$\Delta F_{\mathrm{CO_2}}$	Radiative forcing from CO_2
ΔF_{dir}	Direct radiative forcing from sulfate aerosols
ΔF_{indir}	Indirect radiative forcing from sulfate aerosols

ΔF_{N_2O}	Radiative forcing from N_2O
ΔQ	Change in heat flux absorbed by the ocean
ΔPT	Potential temperature change
ΔT	Temperature change
$\Delta T_{2\times CO_2}$	Equilibrium climate sensitivity

Abstract

A sustainable energy system requires the supply of today's energy demand while conserving the natural system for future generations. There is a dual relationship between sustainable development and energy: economic development implies higher energy consumption, but at the same time today's major source of greenhouse gas emissions is energy production and use. Therefore, a sustainable path where energy is supplied without compromising the global climate is needed to realize a sustainable energy system. This path has important challenges that include sufficiency, reliability, security and clean production. In Switzerland, the realization of such an energy system can be considerably influenced by global trends, comprising economic growth, resources availability, global and regional climate change mitigation policies and technology development. Thus, the aim of this dissertation is to improve understanding of how Swiss energy strategies can be affected by different global uncertainties and to determine robust technologies and policies to achieve a sustainable Swiss energy system.

Deciding the long-term strategies to realize this sustainable energy system constitutes an important challenge for policy makers, hence, analytical tools for energy analysis are important to provide insights for policy decisions. Thus, in this thesis, the future Swiss energy system was analyzed using the MERGE-ETL model. MERGE-ETL is a global integrated assessment model with a representation of the Swiss region. With this model an extensive scenario analysis of the different global uncertainties has been developed.

Four groups of scenarios were studied in this dissertation. First, global and regional policies for climate change mitigation are considerably uncertainty, since regional commitments and the actual reduction of greenhouse gas emissions can not be predicted. These different climate policies have implications on global technology development and global resource availability that affect the Swiss energy system. Thus, scenarios concerning different global and regional climate change mitigation targets were analyzed. Second, there are important uncertainties on technology development regarding future investment costs and the availability of particular technologies, such as carbon capture and storage, nuclear or hydrogen production. Hence, scenarios on technology costs; technology spillovers; and technology deployment were analyzed. Third, economic development, population growth and efficiency achievements are factors that influence future global energy consumption, and, as a consequence, global resource depletion and technology development. Accordingly, three scenarios on economic development and its consequences to the future Swiss energy system have been analyzed. Finally, resources play a key role in energy supply. However, estimation of resource availability has important uncertainties coming from the estimation of the abundance, the development of the technologies needed to extract the resources or the integration of renewable resources in the electricity generation. Thus, the last group of scenarios analyzes different estimations for fossil, nuclear and renewable-based resources.

The results of this analysis provide important insights for the realization of the sustainable Swiss energy system including robust energy and technology pathways and climate policies.

It was found that energy efficiency improvements are required to achieve stringent climate mitigation targets. Thus, a long-term 2000 W per capita society by 2080 with intermediate steps of 3500 W per capita by 2050 is found to be a robust pathway for the Swiss energy system. The realization of such an energy system requires efficiency improvements in buildings and end-use technologies, especially vehicles and large equipment such as industrial machines. In the same way, the transformation of the energy use, concerning the electrification of "non-electric" energy demands is found to be the second robust development for a sustainable Swiss energy system. This requires the use of electric vehicles or heat pumps for space heating.

Besides efficiency improvements and electrification, the robust Swiss technology pathway leads by the end of the century to renewable-based electricity system and biomass-based non-electric energy (for production of hydrogen or synthetic oil depending on the development of the technologies). Managing the intermittency of renewable supply technologies, especially in electricity generation, is an important challenge, which needs to be considered by Swiss policy-makers and utilities. Possible options for addressing this issue include the use of pumped-storage hydropower plants for back-up capacity or improved integration with the European grid. In the electricity sector, the transition to this renewable-based energy system would require the use of nuclear power, natural gas or biomass based technologies to meet the intermediate climate targets. In the non-electric energy sector, today's oil supply is replaced by gas in the middle of the century and biomass by 2070. The achievement of this shift from oil requires the definition of incentives to reduce or replace the use of gasoline, diesel and heating oil.

Carbon capture and storage showed to be an interesting alternative to the electricity production since it would help to reduce energy-related emissions. However, the availability of this technology is highly uncertain due to technology development and public acceptance.

Importantly, the analysis of the new Swiss nuclear policy of phasing out the current reactors at the end of their lifetimes showed important trade-offs with self-sufficiency, energy related CO_2-emissions reductions and energy security.

Finally, an important challenge for the Swiss energy system concerns energy security. In the transition periods, dependency on imported oil and natural gas could have important risks. Interruptible contracts and increased coordination with neighboring countries could increase Swiss energy security.

Keywords: sustainable energy system; climate change; mitigation; Swiss energy sector; energy efficiency; electrification; renewables; energy security

Riassunto

Un sistema energetico sostenibile deve poter mantenere l'attuale domanda energetica conservando allo stesso tempo l'ecosistema per le generazioni future. C'è una duplice relazione tra sviluppo sostenibile ed energia: da una parte lo sviluppo economico implica un più alto consumo energetico, dall'altra la principale fonte di emissione di gas serra consiste, oggigiorno, nella produzione e nell'uso dell'energia stessa. Per questo motivo, per realizzare un sistema energetico sostenibile, è necessario identificare un percorso in cui l'energia sia prodotta senza compromettere il clima del pianeta. Lungo questo percorso vanno affrontate importanti sfide che comprendono la quantità, l'affidabilità, la sicurezza e l'ecosostenibilità. In Svizzera la realizzazione di un tale sistema energetico può essere considerabilmente influenzata da variabili globali che comprendono lo sviluppo economico, la disponibilità di risorse, le strategie (globali e locali) di contenimento dei cambiamenti climatici e infine lo sviluppo tecnologico. Perciò gli scopi di questa tesi sono: migliorare la comprensione di come le strategie energetiche svizzere possano essere influenzate dalle incertezze su scala globale e determinare tecnologie e politiche affidabili per realizzare un sistema svizzero dell'energia.

Decidere le strategia a lungo termine per la realizzazione di tale sistema energetico sostenibile costituisce una sfida importante per il mondo politico e, per questo motivo, gli strumenti analitici per l'analisi energetica offrono un contributo importante alle decisioni politiche. In questa tesi è stato sviluppata un'analisi del futuro sistema energetico svizzero usando il modello MERGE-ETL. Il modello MERGE-ETL è un modello di valutazione integrato globale, con una rappresentazione della Svizzera come regione. Con questo modello è stata compiuta una estensiva analisi di multipli scenari di incertezze globale.

Quattro gruppi di scenari sono studiati in questo lavoro. Per prima cosa, le politiche regionali e globali per il contenimento dei cambiamenti climatici sono una variabile incerta, dato che gli impegni e le riduzioni effettive delle emissioni di gas serra non possono essere previste. Queste differenti politiche climatiche hanno implicazioni sullo sviluppo tecnologico globale e sulla generale disponibilità di risorse prime, elementi questi che influenzano il sistema energetico svizzero. Per questo sono stati analizzati diversi scenari corrispondenti alle diverse politiche di contenimento dei cambiamenti climatici. In secondo luogo ci sono considerevoli incertezze riguardo allo sviluppo delle tecnologie, in particolare rispetto al costo degli investimenti futuri e alla disponbilità futura di tecnologie specifiche come la cattura e l'intrappolamento dell'anidride carbonica, i nucleare e la produzione di idrogeno. Per cui sono stati analizzati scenari che tengono conto dei costi variabili, delle possibili ricadute tecnologiche e dei diversi livelli di applicazione delle tecnologie in questione. Come terzo punto, lo sviluppo economico, la crescita della popolazione e i fattori di efficienza energetica sono fattori che influenzano il consumo futuro di energie e di conseguenza il consumo globale di risorse e lo sviluppo tecnologi-

co. Per questo sono stati analizzati tre scenari di sviluppo economico, con diverse conseguenze sulle futuro sistema svizzero dell'energia. Infine, sebbene le risorse naturali giochino un ruolo fondamentale nell'approvvigionamento energetico, la stima della disponibilità delle riserve contiene notevoli incertezze nella valutazione della quantità delle materie stesse, dello sviluppo di tecnologie di estrazione e del grado possibile di integrazione delle fonti rinnovabile nella rete di generazione di energia elettrica. Per questo un ultimo gruppo di scenari tratta le differenti stime disponibili per le risorse, siano esse fossili, nucleari o rinnovabili.

I risultati dell'analisi forniscono indizi importanti per la realizzazione di un sistema energetico svizzero che includa allo stesso tempo un percorso energetico e tecnologico sicuro e una forte politica climatica.

Durante il corso di questo lavoro si è stabilito che miglioramenti dell'efficienza energetica sono indispensabili per realizzare una tale politica climatica. In particolare un percorso sicuro per una politica energetica svizzera è stato identificato nel raggiungimento di un obiettivo a lungo termine, ovvero una società da 2000W pro capita nel 2080, attraverso un passo intermedio, corrispondente a 3500W pro capita nel 2050. Il successo di un tale sistema energetico richiede miglioramenti di efficienza negli edifici e nelle tecnologie d'utenza finale, in particolar modo i veicoli e i grandi dispositivi come le macchine industriali. Similmente, si è identificato come secondo pilastro di questa politica energetica sostenibile la trasformazione delle modalità di consumo, ovvero l'elettrificazione delle richieste energetiche oggi non elettriche. Questo richiede la transizione a veicoli elettrici e l'uso di pompe di calore per il riscaldamento ambientale.

Oltre ai miglioramenti in termini di efficienza e alla elettrificazione, questo percorso di sviluppo tecnologico porta, entro la fine del secolo, verso un sistema di generazione di elettricità basato su fonti rinnovabili, con la domanda energetica non elettrica soddisfatta grazie alla biomassa (attraverso la produzione di idrogeno o di petrolio sintetico a seconda dello sviluppo delle rispettive tecnologie). Una sfida importante è rappresentata dalla gestione delle fluttuazioni di produzione tipiche delle energie rinnovabili, specialmente per quanto riguarda la generazione di elettricità. Questo aspetto deve essere considerato attentamente: possibili soluzione al problema includono l'uso di stazioni di pompaggio idroelettriche come capacità di riserva e una migliore integrazione con la rete elettrica europea. Nel settore elettrico, la transizione verso un futuro basato sulle energie rinnovabili richiederebbe l'uso di energia nucleare, gas naturale e biomassa per soddisfare gli obiettivi intermedi di politica climatica. Nel settore non elettrico, l'attuale uso di petrolio sarà sostituito dal gas naturale verso la metà del secolo e dalla biomassa entro il 2070. Il raggiungimento di questa transizione richiede la definizione di incentivi per ridurre o sostituire l'uso di benzina, carburante diesel e olio combustibile.

La cattura e il sequestro di anidride carbonica si è dimostrato una alternativa interessante per la produzione elettrica, poiche aiuterebbe a ridurre le emissioni dovute ala consumo di energia. In ogni caso, la disponibilità di questa tecnologia è altamente incerta per motivi legati allo sviluppo delle tecnologie stesse e alla consenso della pubblica opinione.

L'analisi della politica nucleare svizzera, che consiste nel non sostituire i reattori attuali alla fine della loro vita, ha mostrato importanti compromessi con le esigenze di autosufficienza e sicurezza energetica e con la riduzione delle emissioni di gas serra.

Infine, una sfida importante per il sistema energetico svizzero è costituito dalla sicurezza energetica: nei periodi di transizione la dipendenza da petrolio o gas naturale importato potrebbe comportare

rischi notevoli. Contratti interrompibili e una accresciuta coordinazione con gli stati vicini potrebbero aumentare la sicurezza dell'approvvigionamento energetico svizzero.

Keywords: sistema energetico sostenibile, cambiamenti climatici, settore energetico svizzero, efficienza energetica, elettrificazione, energie rinnovabili, sicurezza energetica

Chapter 1

Introduction

The term sustainability has different interpretations depending on the perspective from which it is studied. For ecologists it deals with preserving the structure and properties of ecosystems. Economists often define it as maintaining consumption (or utility) over generations (Perman et al., 2003). As a broad anthropocentric perspective it is often defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Graymorea et al., 2008). Following this last definition Swiss energy policy, guided by Article 89 of the Federal Constitution, aims to achieve a sustainable energy system, that is a "sufficient, reliable, diversified, cost-effective and environmentally-sound energy supply" (IEA, 2007c). Attaining this sustainable Swiss energy system, often associated with the vision of a 2000-Watt society, implies achieving economic growth, supplying the energy demand, while mitigating climate change (reducing CO_2 emissions) and guaranteeing energy independence and security. Realizing these objectives may be more difficult owing to the fact that from 2010 the long-term import contracts of electricity with France started expiring and the new Swiss nuclear policy aims to phase-out existing power plants at the end of their lifetimes and not to replace them (Swiss Federal Council, 2011).

Worldwide policy makers, seeking to realize sustainable energy systems, are facing the challenge of deciding on resource management; technology use and development; and the allocation of research and development (R&D) funding in order to support the most promising technologies. These decisions need to be made in the face of high levels of uncertainty regarding technology development, and long-term consequences of both climate change and changes in energy demand and consumption. Furthermore, even if optimal decisions can be taken from a domestic or regional perspective, there is a large uncertainty related to the effect of global economic trends or decisions taken in other regions or countries. Realizing a sustainable energy system in Switzerland, in particular, due to its size and shortage of natural resources is likely to be affected by global trends.

1.1 Scope of the Analysis

Given these global uncertainties, the overall objective of this dissertation is to improve understanding of how efforts to promote a sustainable Swiss energy system may affect, and be affected by global or regional influences; and to identify robust technology and policy options. Specifically we seek to assess technological options depending on different factors including climate change policy regimes, patterns of energy and resource trade, extraction and depletion; and trends in global economic and technological development.

This work seeks to give insight to Swiss policy makers in the realization of a sustainable energy system taking into account different alternatives of global developments.

1.2 Methodology

The future of the Swiss energy system under global uncertainty is studied using a scenario analysis of different uncertainties, quantified with a global model with explicit representation of Switzerland. The global model is MERGE-ETL. MERGE-ETL is a version of MERGE (Model for Estimating the Regional and Global Effects of greenhouse gas reductions), an integrated assessment model that represents the linkages between the economy, energy sector and climate (Manne et al., 1995). MERGE is an appropriate analytical framework to analyze global challenges affecting energy, economy and climate; and appropriate responses to them because it represents global energy and economic systems including such features as trade, resources, technology deployment, capital stocks and economic growth. Furthermore, MERGE-ETL (Magne et al., 2010) includes global endogenous technology learning (ETL) that enables the analysis of possible technological change that may improve the long-term competitiveness of technologies that are currently less mature.

In this thesis, improvements to the MERGE-ETL were implemented, including changes to the energy and climate representations, and a modification to the regional definition to better represent geopolitical groups and to distinguish Switzerland, which allows us to study the effects of global factors and policies on technology pathways for the Swiss region.

The different uncertainties analyzed in this PhD thesis comprise climate mitigation policies; technology developments including costs and availability of particular technologies of special relevance; availability of fossil fuels, uranium and renewable resources; economic development and nuclear policies. The scenario analysis allows the identification of a set of robust technologies and policies for the Swiss energy system.

1.3 Structure of the thesis

This thesis is organized in different chapters that discuss the implications for the Swiss energy system of different global uncertainties and an overall discussion concerning robust technologies and policies for Switzerland. In Chapter 2, the motivation for the development of this dissertation is presented. Chapter 3 describes the MERGE-ETL model, the reference scenario and the model calibration. The four submodels included in MERGE-ETL, namely: economic, energy, emissions and climate, and damage assessment are described; and the developments carried out during this PhD thesis, including changes to the energy and the climate submodels and the regional definition are presented. Chapter 3 also presents the main input assumptions used for the reference scenario including economic development, technology characteristics, resource assumptions, non-energy emissions baselines and the base year calibration.

The following five chapters analyze different global uncertainties and their implications for the global and Swiss energy systems. Chapter 4 presents the climate policy scenarios, which analyze the implications for the global and the Swiss energy systems of eight climate policy scenarios, including six cases with different stringency levels and two scenarios on carbon taxes. Technology development plays an important role in the future energy system and has considerably uncertainty, thus, Chapter 5 discusses the implication of different technology development scenarios on the Swiss energy system. These scenarios include different technology costs and availability of key technologies including carbon capture and storage, large-scale production of hydrogen with solar thermal processes and nuclear power. This last work was published in Marcucci and Turton (2012).

The nuclear accident in Fukushima, Japan, in March 2011 has increased worldwide the uncertainty regarding nuclear policy. Different policy responses may lead to different pathways of energy system development. In Switzerland, the federal cabinet decided in May 2011 to gradually decommission all Swiss nuclear power plants to reach a complete phase out by 2034 (Swiss Federal Council, 2011). Due to the importance and the question concerning electricity supply after this decision, an enhanced nuclear cycle that models the electricity production from light water and fast breeder reactors was developed in this thesis to analyze different global and Swiss nuclear policies and their consequences for the achievement of climate mitigation targets. This work is presented in Chapter 6.

Besides climate change and technology deployment, a sustainable Swiss energy system can be affected by global economic developments and resource availability, which are analyzed in Chapters 7 and 8, respectively.

Finally, Chapter 9 presents an overall discussion regarding robust technology options and energy and climate policies for Switzerland based on the different set of global scenarios developed in the previous chapters.

Chapter 2

A sustainable Swiss energy system

2.1 Sustainability: "The Earth is one but the world is not"

Sustainable development was defined by the World Comission on Environment and Development (WCED) (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Thus, sustainable development constitutes a framework in which development strategies are multidimensional decisions that embrace environmental, economical and social elements to guarantee today's consumption and the conservation of the natural system for future generations. Among the development strategies health, education and welfare, energy, food and water access are some of the most important goals (Intergovernmental Panel in Climate Change (IPCC), 2007a). Among these different goals, this dissertation is focused in the achievement of a sustainable energy system.

There is a dual relationship between sustainable development and energy: economic development implies higher energy consumption, but at the same time today's major source of greenhouse gas emissions is energy production and use. Therefore, a sustainable path where energy is supplied without compromising the global climate is needed to realize a sustainable energy system. This path has important challenges that include sufficiency, reliability, security and clean production.

In Switzerland, the Federal Energy Policy seeks to achieve a sustainable energy system, guided by the Article 89 of the Federal Constitution, that is a "sufficient, reliable, diversified, cost-effective and environmentally-sound energy supply"(IEA, 2007c). The realization of this energy system implies achieving economic growth, while mitigating climate change (reducing CO_2 emissions) and guaranteeing energy independence and security. This dissertation analyses which are the robust technologies and policies for the achievement of this sustainable energy system under different global uncertainties that have important influence on, and are influenced by, the energy system, namely: economic development, climate change, resources availability and technology development.

2.2 Energy and economic development

Energy demand has grown historically as a response to industrialization and urbanization. Figure 2.1 presents the historical relationship between energy consumption and gross domestic product (GDP) per capita for selected countries. These historical trends show that increasing economic development implies higher energy per capita consumption.

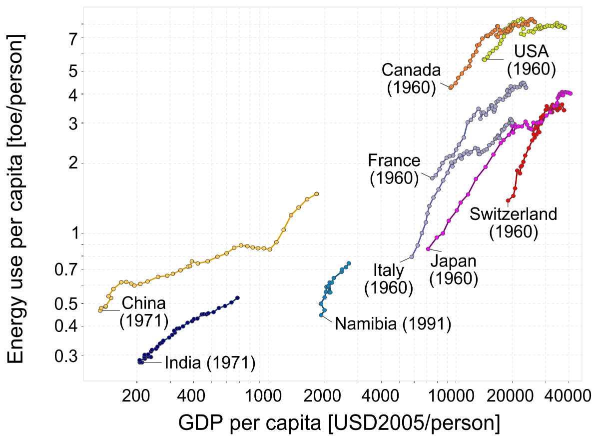
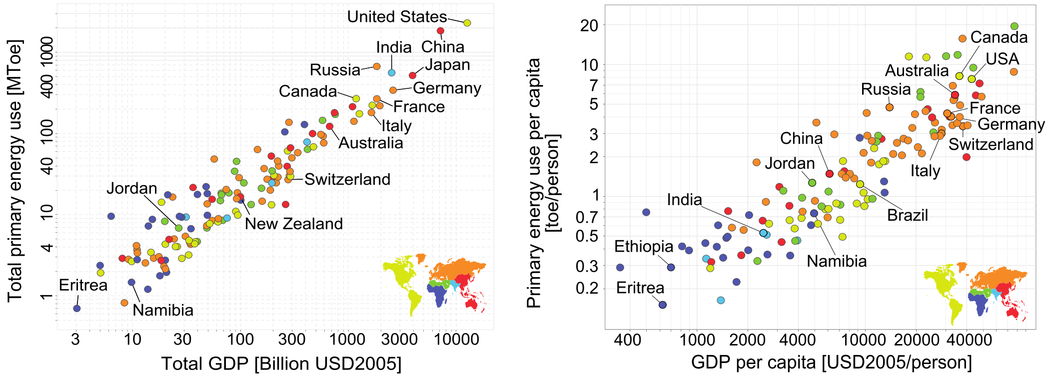


FIGURE 2.1: *Historical relationship between energy consumption and GDP. Source World Bank (2012), United Nations (2012) and Gapminder (2012) through* `www.gapminder.org`

Sustainable development does not require less economic growth, instead it aims to solve problems of poverty and underdevelopment (World Comission on Environment and Development (WCED), 1987). Figure 2.2 presents total and per capita energy and GDP levels for different countries in 2007. Total values show the clear dependency between economic output and energy requirements. However, the relationship between development levels and energy consumption can be better measured with the per capita values (as shown in Figure 2.2B). Figure 2.2B can be easily divided in world regions, with developed countries having around 10 times more energy consumption per capita than developing countries. In 2007, energy consumption per capita in Switzerland was 3.4 toe/person, in the United States 7.8; while in China it was 1.5, in India 0.53 and in Ethiopia 0.29. Thus, it is likely that global future energy demand will increase due to higher economic development levels, especially in today's developing countries. However, the difference between the consumption per capita in Switzerland and the United States indicates that other factors, such as efficiency of the energy systems, affect energy demand.

2.3 Climate change challenge

Climate change is one of the major challenges for achieving a sustainable energy system since the increase in temperature could cause irreversible and undesired changes to the environment. The atmospheric concentration of anthropogenic greenhouse gases (GHGs) has increased substantially since pre-industrial times. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most important greenhouse gases. Figure 2.3A shows the atmospheric CO_2 concentration over the last 10000 years, with a considerable increase after the industrial revolution. CO_2 emissions have grown historically at a yearly average rate of 1.7% since 1990 (Nakicenovic et al., 2006), producing an increase in the atmospheric concentration of carbon dioxide from a pre-industrial level of 280 ppm to 379 ppm in 2005, with an average increase of 1.9 ppm per year in the last decade (Intergovernmental Panel in Climate Change (IPCC), 2007b). Global CH_4 and N_2O concentrations have also increased from the pre-



(A) *Total* **(B)** *Per capita*

FIGURE 2.2: *2007 Relationship between energy consumption and GDP. Source World Bank (2012), United Nations (2012) and Gapminder (2012) through* `www.gapminder.org`

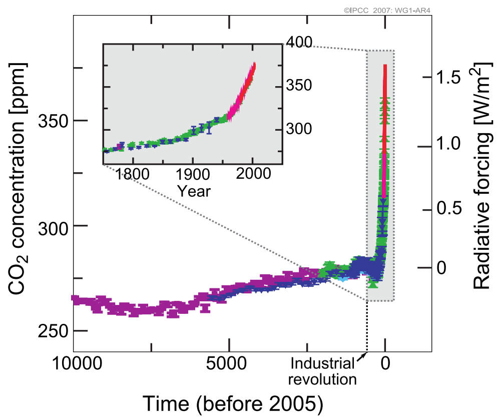
industrial levels (see Figures 2.3B and 2.3C). Methane concentration increased from a pre-industrial level of 715 to 1774 ppb in 2005 and N_2O concentration from 270 to 319 ppb in 2005 (Intergovernmental Panel in Climate Change (IPCC), 2007b).

Radiative forcing is the measure of change in global average net radiation in the atmosphere (Intergovernmental Panel in Climate Change (IPCC), 2001b). If the atmosphere is unperturbed, the incoming solar radiation would be balanced with the outgoing infrared radiation and the radiative forcing would be 0. However, greenhouse gases have the capacity to trap the outgoing infrared radiation, causing an increase in the radiative forcing and an increase in the temperate in the troposphere and the earth surface (Intergovernmental Panel in Climate Change (IPCC), 2001b). The right axis of the three plots in Figure 2.3 presents the historical increase in global radiative forcing caused by each gas. The radiative forcing due to increases in carbon dioxide, methane, and nitrous oxide is estimated to be between 2.07 and 2.53 W/m^2 (Intergovernmental Panel in Climate Change (IPCC), 2007b). This increase in radiative forcing has produced an increase in global mean temperature change from 1850-1899 to 2001-2005 between 0.57 and 0.95°C, as shown in Figure 2.4 (Intergovernmental Panel in Climate Change (IPCC), 2007b).

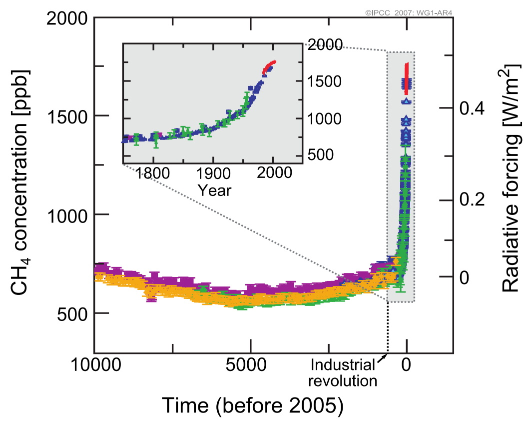
Figure 2.3 shows that CO_2 is the main contributor to the increase in radiative forcing. According to the IPCC (Intergovernmental Panel in Climate Change (IPCC), 2007b), the primary source of this increasing CO_2 concentration is use of fossil fuels and land cover changes. This increased use of fossil fuel is a result of different driving factors including economic development, population growth, resource use and technology development. The Kaya identity has been commonly used to describe the main driving forces of emissions (Nakicenovic et al., 2006), thus,

$$CO_2 = \underbrace{P}_{\text{Population}} \times \underbrace{\frac{GDP}{P}}_{\text{Economy}} \times \underbrace{\frac{E}{GDP}}_{\substack{\text{Economy/}\\ \text{technology}}} \times \underbrace{\frac{CO_2}{E}}_{\substack{\text{Technology/}\\ \text{resources}}}$$

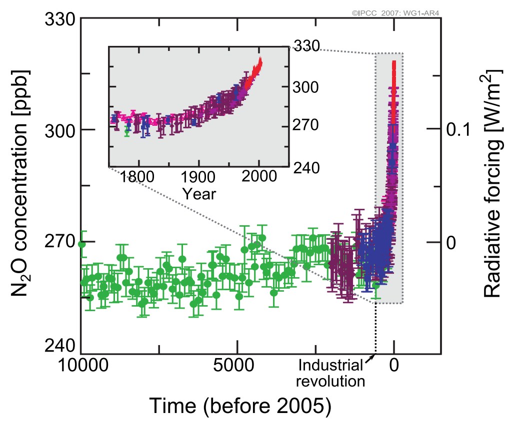
where P represents population, GDP gross domestic product and E energy consumption. Thus, the increase in CO_2 emissions can be explained by population growth; increase in per capita income (level



(A) *CO_2*



(B) *CH_4*



(C) *N_2O*

FIGURE 2.3: *Historical atmospheric GHG concentration from reconstructions with ice cores measurements (different colors represent different studies) and atmospheric samples (red lines). Source: Intergovernmental Panel in Climate Change (IPCC) (2007b, Fig. SPM.1)*

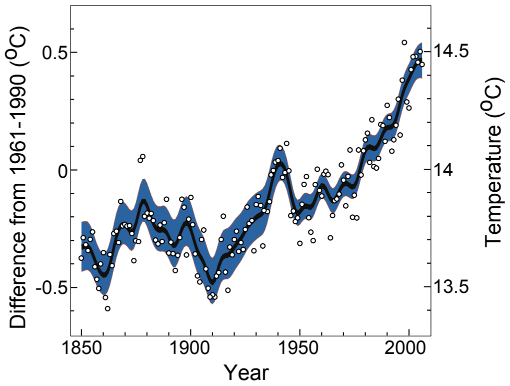
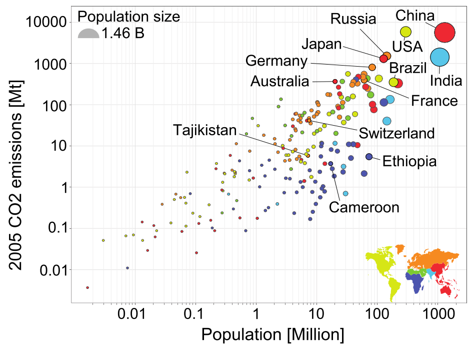
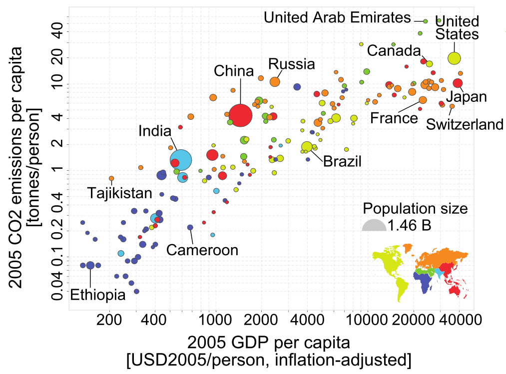


FIGURE 2.4: *Observed global surface temperature. Circles correspond to yearly values and the smoothed curve shows decadal average values. The shaded areas are the uncertainty intervals. Source: Intergovernmental Panel in Climate Change (IPCC) (2007b, Fig. SPM.3)*

of economic development); energy intensity, i.e. the amount of energy required to produce the economic output, which depends on economic and technology development; and the CO_2 emitted when producing the energy, which depends on technology and resource choices. Figure 2.5A presents the 2005 relationship between population and CO_2 energy emissions, showing an almost linear correlation between them, while Figure 2.5B presents the relationship between emissions and GDP per capita, showing how the increase in economic development produces an increase in emissions, that is partially compensated by energy efficiency. It is important to note, that these different driving forces are not independent, since, for example, higher economic growth could produce additional investments in efficiency of energy technologies, reducing the energy intensity.



(A) *Emissions and population*



(B) *Emissions and GDP*

FIGURE 2.5: *Emission trends. The size of the circles represents population size. Source: CDIAC (Carbon Dioxide Information Analysis Center) (2012), United Nations (2012) and Gapminder (2012) through* `www.gapminder.org`

Thus, the Kaya identity implies that population and economic growth might continue the trend of increasing GHG emissions. However, the future level of emissions and temperature change are uncertain. The Intergovernmental Panel in Climate Change (IPCC) (2007b) presented different scenarios estimating future emissions and temperature change. In these scenarios future temperature increase by 2100 is estimated in a range from 1.8 to 6°C from pre-industrial levels, an increase that is likely to produce undesirable changes to the environment. The high temperature increases correspond to the scenarios without climate policies, where high levels of emissions are observed. Thus, a sustainable energy system requires climate policies to reduce the increase in greenhouse gas emissions but with the important challenge of maintaining energy supply to assure economic development.

2.4 Technology development challenges

A sustainable energy system depends on technology change. Technologies constitute both a threat to and the possible solution for sustainable development since new and better technologies are required to achieve climate mitigation targets. Thus, both the rate at which technologies are deployed and which technologies are developed have considerable importance.

Technological change does not occur autonomously, it is motivated by the actions of different actors including the users, the developers and the inventors of the technologies (Intergovernmental Panel in Climate Change (IPCC), 2007a). The first step for technological change is the very unpredictable stage where the technologies are invented. After that, technologies are innovated, motivated by interest of users, developers, producers, among others. Nordhaus (1991) illustrates the technological change process with the case of illumination, showing that the costs of lighting have decreased approximately 1000-fold in the last 200 years. These potentials for technology learning and innovation may have an important role for the energy production, especially for less mature technologies.

Technology learning arises from three interacting factors: experience in the development of the technology; research and development (R&D) efforts and spillovers. The first one deals with the fact that increased experience in the production of the technology might improve the process. This is often called learning-by-doing and it is represented by means of learning curves that describe the investment costs as a function of experience. Figure 2.6 presents historical learning curves for 3 technologies: solar photovoltaic, wind, pulverized coal and gas turbines[1]. The curve shows how investment costs tend to decrease with the increase in global installed capacity which is a proxy for experience. The second factor is related to R&D efforts on a particular technology done by firms, governments, or other entities (Intergovernmental Panel in Climate Change (IPCC), 2007a). Finally, technology spillovers refer to the fact that companies or countries might benefit from the technology development done by other firms or countries.

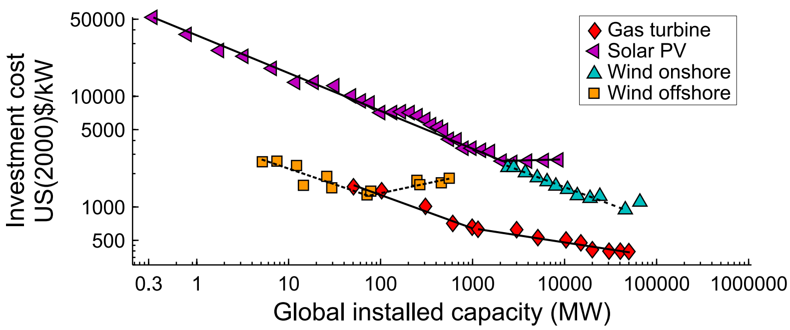


FIGURE 2.6: *Historic experiences curves. Based on Junginger et al. (2010, p. 252) and IIASA and WEC (1995, p. 168)*

[1]Increasing costs for wind turbines in the latest periods are related to higher material costs.

Technological change for sustainable development also implies the development of more efficient and climate friendly technologies. This could include the use of more efficient fossil technologies, renewable- and biomass-based alternatives, technologies with carbon capture and storage, hydrogen production options, and nuclear power.

The use of renewable technologies, including solar and wind-based electricity generation has increased substantially in the last decade because they bring a source of low-carbon electricity. Global solar-based electricity capacity reached 67.4 GW in 2011 (around 0.5% of the global electricity capacity), with the largest deployment being done in the EU, Japan and USA (EPIA, 2011; Intergovernmental Panel in Climate Change (IPCC), 2012). Wind-based electricity generation in 2009 reached a capacity able to supply 1.8% of the world electricity demand (Intergovernmental Panel in Climate Change (IPCC), 2012). However, some renewable technologies depend on intermittent sources and their deployment brings important challenges concerning the reliability of the electricity supply. The diversification of the renewable sources, including different types and locations; and the installation of large back-up capacity, such as gas-based power plants, might be needed to deal with these intermittency issues.

Technologies with carbon-capture and storage (CCS) constitute an interesting alternative for the production of electricity using fossil fuels and producing low CO_2 emissions. It is considered a key transition technology to achieve climate mitigation targets (IEA, 2008a). However, CCS is still in demonstration phase without commercial projects being developed yet. Capacity of storage, the development of the appropriate network and leakage problems constitute some of the challenges for the deployment of CCS technologies.

Nuclear power has also been considered an alternative to produce low-carbon electricity. However, issues concerning safety and unsolved questions regarding waste disposal are drawbacks for the development of this technology. Besides these issues, the nuclear accident in Fukushima in March 2011 has increased worldwide the uncertainty of nuclear development. Some countries, such as Germany and Switzerland have opted to phase out nuclear generation.

"Hydrogen is widely considered to be the transportation fuel of the future" (IEA, 2004) because it has the potential to address issues of energy security and climate change. The development of large-scale technologies to produce hydrogen and the appropriate network infrastructure for its transport constitute important challenges to be resolved.

Besides the technological constraints, the deployment of new technologies faces important challenges concerning policy support and public acceptance.

2.5 Energy security

Energy security is related to the availability of the resources and their distribution in the world. Energy production requires resources including fossil fuels, uranium or renewable sources. Global energy resources are located in few regions of the world. According to the World Energy Council (2007) conventional oil and gas reserves are mostly located in seven countries: Middle East, Venezuela, Kazakhstan, Libya, Nigeria, Algeria and Russia. While Canada, USA, Kazakhstan, Niger, China and Russia account for about 94% of total conventional uranium resources (Nuclear Energy Agency and the International

Atomic Energy Agency, 2010). The allocation of these resources in few regions can cause problems concerning energy security. Furthermore, there are risks associated with potential international conflicts and the stability issues in some of these countries.

As discussed in section 2.2 the economic development of emerging countries is likely to increase energy demand and, therefore, resource consumption. Thus, the uneven distribution of global resources and the potential risks associated to some of the countries that own the resources, plus the certain increase in resource consumption leading to depletion of the limited resources, constitute potential threads for a future sustainable energy system.

2.6 Swiss energy system and the challenges for sustainability

The total primary energy supply (TPES) in Switzerland was estimated to be around 26.95 Mtoe in 2009 (IEA, 2010b), following steady growth from 1971 as presented in Figure 2.7. Oil contributes considerably to the primary energy supply, used especially for transportation and heating. The use of natural gas has an increasing tendency, contributing to around 10% of the TPES in 2009. Electricity generation is almost CO_2 free, done mostly with hydropower (60%) and nuclear (40%) technologies. However, in May 2011, the Swiss federal cabinet decided to phase-out the current nuclear power plants at the end of their lifetimes and not to build new reactors (Swiss Federal Council, 2011), raising important questions concerning future electricity generation.

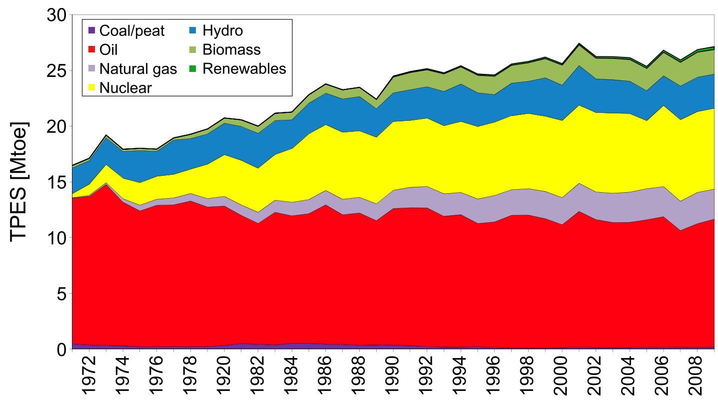


FIGURE 2.7: *Historical Swiss TPES. From IEA (2009)*

Swiss energy policy is guided by Article 89 of the Federal Constitution and its principles were confirmed on 21 February 2007. These principles include securing energy supply and mitigating climate change, with a focus on energy efficiency improvements and on deployment of renewable energy (IEA, 2007c). The Department of Environment, Transport, Energy and Communications (UVEK, 2008a,b), published two action plans with measures regarding energy efficiency and renewables, proposing a reduction in emissions of 20% by 2020 (compared to 1990 levels) and increasing the share of renewables in the TPES by 50%. Following the UVEK proposal of reducing greenhouse gas emissions, Switzerland imposed a CO_2 tax in 2008 of 8 CHF/ton, which was then increased in 2010 to CHF 36 per ton of CO_2(Swiss Federal Office of Environment (BAFU), 2009), which corresponds to 9 Rappen per liter of heating oil (according to Swiss Federal Office of Energy (BFE) (2012) the heating oil price was around 85 and 98 Rappen/liter in 2010 and 2011, respectively). In 2011, the Swiss parliament started discussing the new CO_2 regulation that will apply from 2013. According to the first proposal the CO_2 price could increase to 60 CHF/tonCO_2 by 2014 and up to 120 CHF/tonCO_2 in 2018 (Swiss Federal Office of Environment (BAFU), 2012a).

However, these policies are likely to be affected by all the global factors discussed in the previous sections, which constitute possible challenges for the Swiss energy system. First, global sustainable development is likely to imply larger energy demands in Switzerland, but especially in the developing countries. Thus, higher resource consumption from other world regions could be expected. Second, climate change is a global problem that requires global action; hence the energy policy principle of mitigating climate change can be affected by the different regional and global climate mitigation policies since they can affect technology development and resource availability and depletion. Third, the large dependency on global resource availability (in 2009, 15.64 of the 26.95 Mtoe were imported) implies important challenges for Switzerland in terms of energy security. Finally, technology development is a key aspect for the future energy system: the availability of certain technologies, such as carbon capture and storage or large-scale hydrogen production; and the efficiency improvements of demand-side technologies affect substantially energy production. Moreover, all these factors are interlinked. For example, larger energy demands can affect global climate change and resource availability; or resource availability can limit increases in energy demand.

One additional challenge for Switzerland is related to its decision system. Switzerland is a "democratic system with limited power of the government and high degree of federalism" (Bretschger and Brunnschweiler, 2010), which makes the decision processes relatively long and dependent on the public acceptance. Therefore, introduction of new policies and technologies can be considerably affected by public opinion.

2.6.1 Scenarios developed in this thesis

This dissertation investigates how uncertainties in global developments regarding climate change, economic development, population growth, resource availability and technological change affect the realization of a sustainable Swiss energy system using a scenario analysis on some of these global developments. Table 2.1 presents a summary of all the scenarios developed in this PhD thesis and short description of the analyzed parameter. For more detail please refer to the corresponding chapter.

TABLE 2.1: *Scenarios developed in this thesis*

Aspects analyzed	**Scenarios**	
	Description	**Name**
Climate change mitigation (Chapter 4)		
Scenarios analyzing global climate policies with different stringency based on radiative forcing (rf) targets	· rf target = 8.5 W/m^2	rf85
	· rf target = 6.0 W/m^2	rf60
	· rf target = 4.5 W/m^2	rf45
	· rf target = 3.5 W/m^2	rf35
	· rf target = 3.5 W/m^2	rf30
	· rf target = 2.6 W/m^2	rf26

TABLE 2.1: *Scenarios developed in this thesis (continued)*

Aspects analyzed	Scenarios Description	Name
Scenarios analyzing a global carbon tax and a first mover case for the EU and Switzerland	· Global carbon tax · EU and Switzerland first movers	globTax firstMov
Technology development (Chapter 5)		
Scenarios on future technology costs	· High investment costs · Low investment costs	High Low
Scenarios on learning spillovers	· No spillovers · Group spillovers · Regional spillovers	NoSpill GrSpill RgSpill
Scenarios on technology availability of carbon capture and storage and production of hydrogen with solar thermal processes	· Late development of CCS · No development of CCS · No production of hydrogen with solar thermal process	· LateCCS NoCCS NoSTH
Nuclear policies (Chapters 5 and 6)		
Scenarios on alternative nuclear policies with different support to development of nuclear globally and in Switzerland (Scenarios with CH in the name correspond to Swiss nuclear policies)	· 100% support to nuclear development · No development of FBRs · Non proliferation scenario · No development of nuclear · No development of nuclear in Switzerland · No development of LWRs in Switzerland	100%Nuc NoFBR NoProl NoNuc NoNucCH NoLWRCH
Economic development (Chapter 7)		
Scenarios on economic development representing different population growth, economic development and convergence between developing and developed regions	· Large population growth, slow economic development and low convergence · Low population growth, high economic development and high convergence	A2R B1
Resource availability (Chapter 8)		
Scenarios on availability of fossil fuels, uranium and renewable potentials	· Advanced renewable potentials, unconventional fossil fuels and uranium · Moderate renewable potentials, conventional fossil fuels and uranium · Moderate renewable potentials, unconventional fossil fuels and uranium	advUnc modCon modUnc

Chapter 3

Modeling framework: MERGE-ETL model

3.1 Introduction

To assess the effect of different global developments on the Swiss energy system it is necessary to use models that allow the analysis of the global energy system development including factors such as economic development, resource deployment, and climate and energy policies.

Therefore, in this thesis, a scenario analysis of global and regional technology preferences and availability, climate change mitigation policies, economic development and resource estimations, using a MERGE-ETL model with an explicit representation of the Swiss region was developed. MERGE (Model for Estimating the Regional and Global Effects of greenhouse gas reductions) is an integrated assessment model. It is consider to be an appropriate analytical framework to analyze global challenges affecting energy, economy and climate; and responses to them because it represents global energy and economic systems including such features as trade, resources, technology deployment, capital stocks and economic growth. Furthermore, MERGE-ETL includes global endogenous technology learning (ETL) that enables the analysis of possible technological change that may improve the long-term competitiveness of technologies that are currently less mature.

This chapter presents a description of MERGE-ETL including both the existing model and the developments carried out in the context of this thesis. The chapter is organized as follows: in the first section a brief description of the MERGE-ETL model is presented; and in the second to fourth sections the key scenario and model assumptions are described.

3.2 The MERGE-ETL model

MERGE (Model for Evaluating Regional and Global Effects of GHG reductions policies) is an integrated assessment model originally developed by Manne et al. (1995). It divides the world in geopolitical regions (see Section 3.3), each one represented by two coupled submodels describing the energy and economic sectors, respectively. MERGE acts as a global social planner with perfect foresight and determines the economic equilibrium in each region that maximizes global welfare, defined as a linear combination of the current and future regional welfares. Besides these regional energy-economic submodels, and linked to them, MERGE includes global submodels of greenhouse gas emissions and the climate to allow the analysis of the effectiveness and impacts of climate policies and the role of technologies to realize climate targets. Figure 3.1 presents a simplified diagram of the structure of the model showing the inputs (highlighted in red), outputs and linkages between submodels.

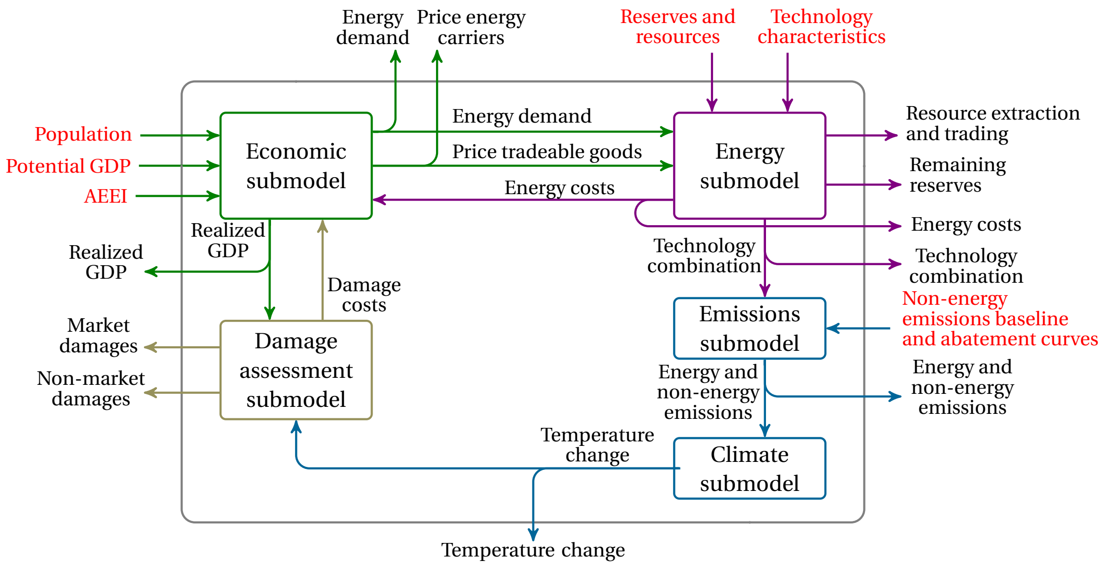


FIGURE 3.1: *MERGE-ETL model structure. Inputs to the model are highlighted in red, outputs are presented in black font coming from the different submodels.*

The economic submodel (see Section 3.2.1) is a top-down model that determines energy demand and prices as well as economic output (realized GDP) for each region. It is parametrized using exogenous inputs on population, potential GDP and autonomous energy efficiency improvements (AEEI); and the energy costs obtained from the energy submodel. The energy submodel (see Section 3.2.2) is a bottom-up description of the energy sector that includes endogenous technology learning (ETL) to account for the effect that the accumulation of experience and knowledge might have on the technology development (Manne and Barreto, 2004). The energy submodel determines the technology combination; resource extraction and trading; and research and development expenditures that maximize the global welfare and satisfy energy demands given by the economic submodel and climate objectives (Manne et al., 1995). The main exogenous inputs comprise detailed technology characteristics (costs, efficiencies, lifetimes and load factors) and resource restrictions. The combination of these two submodels adds a value to MERGE compared to bottom-up or top-down models, since energy demands and prices are determined endogenously and at the same time technological options can be analyzed in detail in MERGE's bottom-up energy sector submodel.

The emissions submodel (see Section 3.2.3) determines energy and non-energy related emissions based on the technology combination obtained by the energy submodel and a non-energy emissions baseline assumed exogenously. With these emissions, the climate submodel determines global mean temperature changes. The damage assessment submodel (see Section 3.2.3) determines market and non-market damages using the temperature change.

In the next subsections each of these submodels is described in more detail.

3.2.1 Economic submodel

The economic submodel is a general equilibrium model in which each region is viewed as a price taker subject to an intertemporal budget constraint and with the objective of maximizing global welfare. Supplies and demands are equilibrated every time period, through the prices of traded goods, which include energy commodities, an energy-intensive good and a numeraire good. The numeraire good represents the production of all goods but energy and it is assumed to be identical for all the regions (Manne et al., 1995).

Domestic supply and demand

The economic output for each region r in every period t ($Y_{r,t}$) is allocated among investment ($I_{r,t}$) used to built capital stock; consumption ($C_{r,t}$); and energy expenditures ($EC_{r,t}$) that represent the total costs of extracting the required resources and supplying electric and non-electric energy. Thus,

$$Y_{r,t} = I_{r,t} + C_{r,t} + EC_{r,t}. \tag{3.1}$$

The economic output in period t corresponds to the production done by new investments ($YN_{r,t}$) plus the production coming from earlier vintages ($Y_{r,t-1}$) depreciated with factor d (Manne, 1991). In this way the new output responds to current and future prices but the economy is "locked in to the technology choices made in earlier years" (Manne and Richels, 2004). Thus,

$$Y_{r,t} = YN_{r,t} + d \cdot Y_{r,t-1}. \tag{3.2}$$

The new output in each region is represented through a nested CES (constant elasticity of substitution) production function (Manne and Richels, 2004). Production of new economic output ($YN_{r,t}$), for each region r, in each period t, is determined by four inputs governed by transition equations similar to the one used for total output (Equation 3.2): new capital ($KN_{r,t}$), new labour ($LN_{r,t}$), new electricity ($EN_{r,t}$) and new non-electric energy ($NN_{r,t}$), thus, based on Manne and Richels (2004),

$$YN_{r,t} = \left[a\left(KN_{r,t}^{\alpha} LN_{r,t}^{1-\alpha}\right)^{\gamma} + b\left(EN_{r,t}^{\beta} NN_{r,t}^{1-\beta}\right)^{\gamma} \right]^{1/\gamma} \tag{3.3}$$

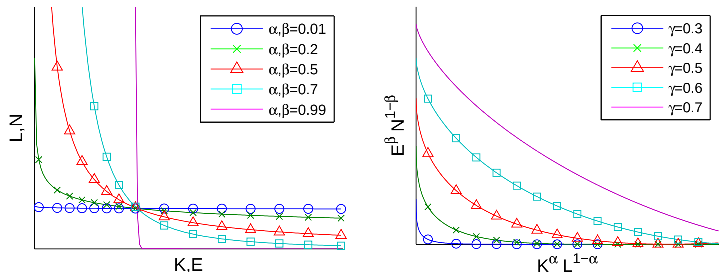
This production function implies three types of substitution:

- between capital and labour modeled with an unit elasticity of substitution and with α being the optimal value share between the inputs (Manne et al., 1995);
- interfuel substitution between electricity and non-electric energy. As with the capital-labour substitution, this substitution exhibits unit elasticity and β is the optimal value share between the inputs (Manne et al., 1995).

  Figure 3.2a shows the isoquant curves for these first two types of substitution. When the share (α, β) tends to 0 or 1 (L-shape curves) the inputs are poor substitutes. In the intermediate values of β (or α for the K-L bundle) the inputs are considered better substitutes. In the current version, the share for the capital-labour bundle, α, changes across regions and it is assumed to be around

0.3 and the share for the energy bundle, β, is 0.45 in all the regions (Kypreos, 2007). This means that capital and labour, and electricity and non-electric energy are substitutable to some extent.

- between the two pairs of inputs, capital-labour and electricity-non electric energy. This is modeled with a constant elasticity substitution (CES), where $\gamma = (\sigma-1)/\sigma$, σ being the constant elasticity of substitution. Thus, this formulation allows the substitution between the capital-labour ($K^{\alpha}L^{1-\alpha}$) and the energy ($E^{\beta}N^{1-\beta}$) bundles (Manne and Richels, 2004). Figure 3.2B presents the isoquant curves for the CES production function. When value σ tends to 0 the bundles are modeled as perfect compliments; and when it tends to 1 they are modeled as perfect substitutes. In MERGE-ETL, different values are assumed for different regions in the vicinity of 0.5 (Kypreos, 2007).



(A) *Isoquant curves K-L and N-E* **(B)** *CES isoquant curves*

FIGURE 3.2: *MERGE production function*

The parameters a and b in Equation 3.3 represent productivity factors, i.e. they account for changes in output not caused by changes in the quantity of inputs in the production function. These productivity factors are estimated from an exogenous scenario of 'potential' GDP growth and autonomous energy efficiency improvements (AEEIs). The potential (or reference) GDP pathway can be interpreted as representing productivity improvements, economic output and energy demand at constant energy prices. In MERGE this reference GDP does not exclusively determine the realized GDP due to the energy-economic interactions. A climate policy, for example, will produce an increase in energy costs, leading in turn to a substitution between the energy bundle and the capital-labour bundle in production, and some reduction in economic output (Manne et al., 1995). The AEEI parameter accounts for changes in energy consumption not driven by prices, e.g. increases in the efficiency of electrical appliances, or structural changes to either more or less energy-intensive types of industry, etc. For more details on the estimation of the reference scenario see Appendix A.1.

Intertemporal optimization

MERGE acts as a global social planner with perfect foresight where the objective function is the maximization of a global welfare that corresponds to the Negishi-weighted regional utility, thus,

$$\max \sum_{r} w_r u_r, \tag{3.4}$$

where w_r corresponds to the Negishi weight and u_r is the regional utility for the r-region. The utility is modeled as the natural logarithm of consumption. The logarithmic form of the regional utility function implies diminishing marginal utility to consumption (Manne et al., 1995); therefore, an additional dollar of consumption produces larger utility gains in poorer regions. The global utility is calculated using the utility of each region weighted by means of Negishi weights. The Negishi weights are used to equalize the marginal utility of consumption among regions, hence an additional dollar of consumption in any region has the same effect on the global welfare (Stanton, 2011). MERGE solves the maximizing problem iteratively, updating the Negishi weights in each iteration until a pareto-optimal equilibrium is found (Kypreos, 2005; Stanton, 2011). It is important to note that the use of Negishi weights in the definition of global welfare leaves aside the income redistribution problem, "preventing large flows of capital between regions" (Stanton, 2011), so the climatic change problem is analyzed independently from the underdevelopment problem.

Furthermore, MERGE is a perfect foresight model in which total regional utility is calculated as an intertemporal discounted utility, thus,

$$u_r = \sum_t \frac{1}{\left(1+\rho_{r,t}\right)^t} \ln\left(C_{r,t} \cdot ELF_{r,t}\right)$$

where $C_{r,t}$ and $\rho_{r,t}$ are the consumption and the social discount factor of region r in period t, respectively. Notice that in this case the utility is measured as the logarithm of the consumption adjusted by the $ELF_{r,t}$ parameter, which represents an economic loss factor due to the impact of climate change (see Section 3.2.3).

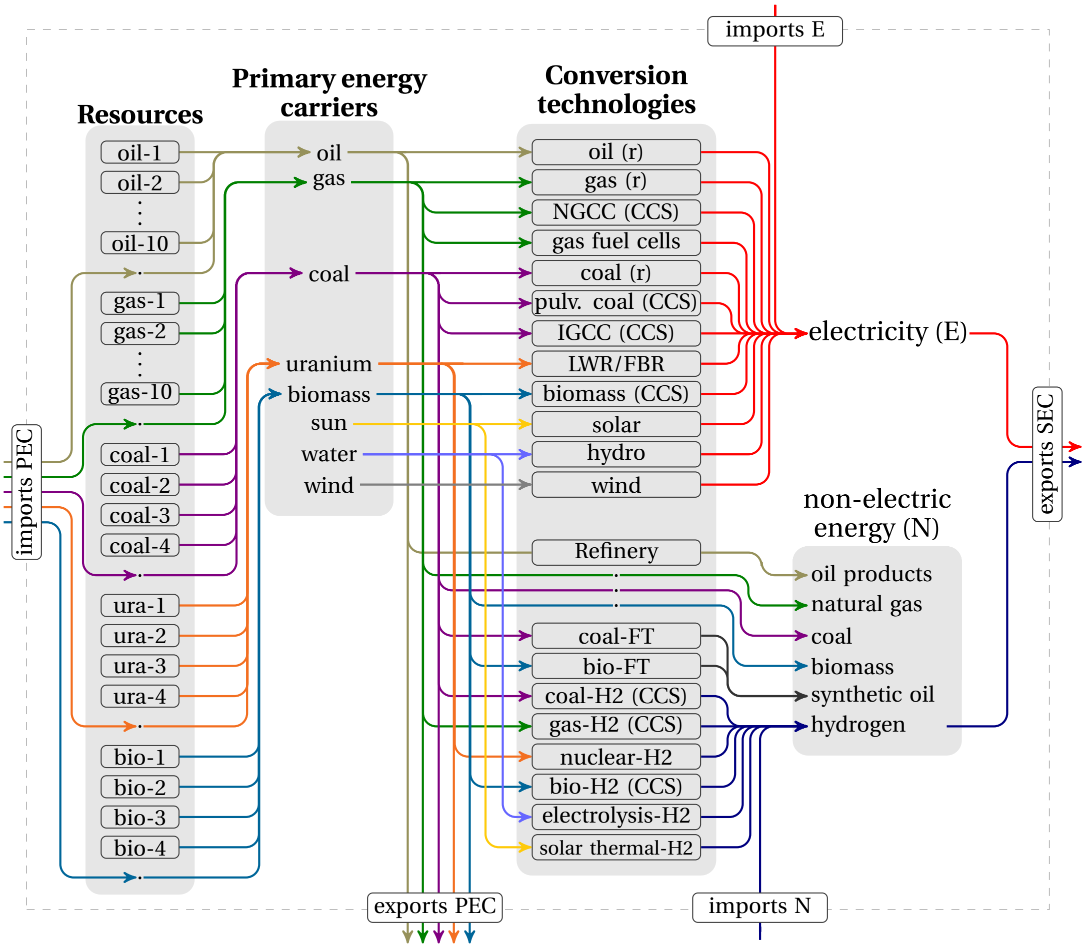
For a logarithmic utility function, the solution of the social planner maximizing problem (Equation 3.4) gives the following "optimal steady-state growth path" (Manne et al., 1995) (See Appendix A.2 for a proof of this optimal growth path),

$$mpc_{r,t} = g_{r,t} + \rho_{r,t}$$

where $\rho_{r,t}$ is the social discount factor and represents the discounting of the utility of different generations; $mpc_{r,t}$ is the marginal productivity of capital that corresponds to the discount rate of goods and services; and $g_{r,t}$ is the annual growth rate of output. Therefore, the potential GDP scenario implies a certain choice between consumption by current generations and investment in the present to support consumption in the future.

3.2.2 Energy submodel

The energy submodel determines the optimal combination of conversion technologies to supply electric and non-electric energy to the rest of the economy, i.e. E and N in Equation 3.3, subject to restrictions on resource availability and depletion. In MERGE-ETL, the energy sector in each region is represented by a reference energy system like that shown in Figure 3.3. In the first step, primary energy carriers (PEC) are either extracted from resources in the region or imported from another region. The extraction technologies cover oil, gas, coal, uranium and biomass. The primary energy carriers are then exported to other regions or processed by the conversion technologies to produce secondary energy carriers (SEC); that is, electricity and non-electric energy carriers. Non-electric energy carriers



PEC=Primary energy carrier SEC=Secondary energy carrier
(r)=remaining (CCS)=technology with and without carbon capture and storage

FIGURE 3.3: *Reference Energy System. The colors represent each primary and secondary energy carrier. See Tables 3.1 and 3.2 for a description of each technology presented in this diagram.*

comprise oil products, natural gas, coal, biomass, synthetic oil and hydrogen.

Energy technologies in MERGE are described in a relatively simplified way, including representative conversion technologies and the demand of electricity and non-electric energy rather than detailed end-use technologies. Bottom-up models such as MARKAL or TIMES (see for example Gül (2008), Reiter (2010), Weidmann et al. (2009), Ramachandran (2011)) include a more detailed technology description but have the drawback that energy demands are assumed exogenously. The level of detail in MERGE gives a good overview of the energy sector and its interaction and impacts with and in the global economy. Therefore, the results obtained with these two type of models are complementary.

Resource extraction technologies

The natural resources (primary energy carriers) included in MERGE-ETL comprise oil, gas, coal, uranium and biomass; and additional *free* primary energy carriers including wind, water and sun. The resources are extracted from different resource categories with different costs of extraction (e.g. coal-1, coal-2, ...). Total proven reserves and undiscovered resources of exhaustible energy carriers, i.e. oil, coal, gas and uranium, are given exogenously to the model. Proven reserves are depleted by extraction of resources and augmented by the 'discovery' of the undiscovered resources. The rate of resource discovery is related to the remaining undiscovered resources in any time period (Manne et al., 1995).

Energy and electricity trading

MERGE-ETL models inter-regional trading (with a trading cost) of primary energy carriers (as shown in Figure 3.3); the numeraire good[1]; emission permits; and energy intensive products, such as steel and cement (Manne and Richels, 2004). Additionally, for this work, trading of electricity between regions has been included to better represent the geographic location of Switzerland and its access to the European network. This is of particular relevance for the analysis of the future Swiss energy system since Switzerland is integrated into the European electricity grid and future options to supply Swiss electricity demand can include a larger share of imports from neighboring countries.

In every period, the net exports (X) of each tradeable good *trd* are balanced, thus,

$$\sum_r X_{r,t,trd} = 0,$$

where $X_{r,t,trd}$ corresponds to the exports minus imports of the region r, in the period t, for tradeable good *trd*. Each of these balance equations has a price associated (shadow price of the restriction) that corresponds to the trading price of the tradeable good (Manne and Richels, 2004).

The economic output allocated to the production of net exports of the numeraire good is represented by adding a term to Equation 3.1, thus,

$$Y_{r,t} = I_{r,t} + C_{r,t} + EC_{r,t} + X_{r,t,nmr}. \tag{3.5}$$

[1] The numeraire good represents the production of all goods but energy and it is assumed to be identical for all the regions (Manne et al., 1995).

Conversion technologies

Conversion technologies transform primary energy carriers to either electricity or non-electric final energy carriers. Various characteristics of each conversion technology are represented in the model, such as efficiency, load factor, investment cost, and operation and maintenance expenditures. These determine the levelized cost of each energy carrier, along with fuel consumption and emissions. Future characteristics (and hence costs) of conversion technologies are highly uncertain. Chapter 5 discusses the assumptions done in this work for these parameters and Section 3.5.3 presents the values used in the reference scenario.

TABLE 3.1: *Electricity technologies*

Name	Description
Oil based technologies	
oil(r)	Oil existing technology
Natural gas based technologies	
gas(r)	Gas existing technology
NGCC	Natural Gas Combined Cycle
NGCC(CCS)	Natural Gas Combined Cycle with carbon capture and storage (CCS)
gas-FC	Gas fuel cell
Coal based technologies	
coal(r)	Coal existing technology
PC	Pulverized coal
PC(CCS)	Pulverized coal with CCS
IGCC	Integrated Gasification Combined Cycle
IGCC(CCS)	Integrated Gasification Combined Cycle with CCS
Nuclear technologies	
LWR	Light water reactor
FBR	Fast breeder reactor
Renewable technologies	
bio	Biomass
bio(CCS)	Biomass with CCS
Solar	Solar photovoltaic and concentration
Hydro	Hydropower generation
Wind	Wind-based electricity generation

Electric technologies (see Table 3.1) consist of technologies for the generation of electricity from oil, coal, gas, uranium and renewable energy carriers:

- Oil-fired power plants (oil-r) represent the current oil power plants, whose use has declined in recent years but which are still important in some regions such as the Middle East (accounting in 2005 for 38% of the total electricity generation); some OECD countries such as Mexico, Portugal, Italy and Greece, where it accounted in 2005 for 29, 19, 16 and 15.5%, respectively ; and Africa and Latin America where the share in 2005 was around 10% (IEA, 2007a).

- Natural gas-based power plants include the current natural gas-fired power plants (gas-r), which correspond to both gas turbines and combined cycle technologies. Natural gas combined cycle plants (NGCC) and gas fuel cells (gas-FC) are the new natural gas-based power plants represented in MERGE.

- Coal-based power plants include current coal-fired power plants (coal-r) that combust pulverized coal and operate at less than supercritical conditions (IEA, 2010c). They represent an important technology in the current world electricity generation, especially in China and India (IEA, 2007a). New pulverized coal technologies (PC) represented in the model include plants operating at both supercritical and ultrasupercritical conditions. Integrated gasification combined cycle (IGCC) plants are another option to generate electricity with a combined cycle using gasified coal.

- Technologies with carbon capture are included as an alternative for reducing greenhouse gas emissions. Pre- and post-combustion capture options are comprised in MERGE-ETL. The post-combustion capture process is used in PC(CCS) and NGCC(CCS) where the CO_2 is captured from the flue gases produced in the fuel combustion. Pre-combustion capture is used in technologies that include the production of synthesis gas, such as IGCC(CCS).

- Nuclear technologies included in MERGE comprise light water and fast breeder reactors. Section 3.2.2 presents a description of the nuclear fuel cycle included in MERGE and Chapter 6 presents the enhanced fuel cycle developed in this thesis.

- Biomass is one of the more diverse renewable energy sources, it can be obtained from many different feedstocks such as forest or agriculture residues, energy crops, municipal waste, among others (Intergovernmental Panel in Climate Change (IPCC), 2012) and it can be use directly or through a gasification process to produce electricity with (bio(CCS)) and without (bio) pre-combustion capture of CO_2.

- Solar technologies use the energy coming from the sun to produce electricity using photovoltaic (PV) panels or solar concentrators.

- Hydropower (hydro) is a mature technology widely used worldwide, accounting for around 20% of the global electricity production in 2005. Hydropower technologies include run-of-river and dam power plants.

- Wind technologies represent wind turbines installed both onshore and offshore.

Non-electric energy conversion technologies (see Table 3.2) embrace oil refining, direct use of natural gas, coal and biomass, and synthetic fuel and hydrogen production:

- Refinery: Petroleum products such as diesel, gasoline and jet fuel are the most used fuels for transportation today. Oil is also used for heating purposes. In MERGE these different oil products and uses are modeled as one final energy carrier produced by the refinery from oil.

- Coal and natural gas are modeled as energy carriers to supply non-electric energy. Currently, natural gas is used for different purposes including heating, transportation, cooking, and others.

- Biomass technologies include a broad set of alternatives for heat production, cooking or biofuels (biodiesel or ethanol) (Intergovernmental Panel in Climate Change (IPCC), 2012) for transportation. They are modeled in MERGE as biomass used directly.

TABLE 3.2: *Non-electric energy production technologies*

Name	Description
Oil products	
Refinery	Oil refinery
Energy carriers used directly	
Natural gas	
Coal	
Biomass	
Synthetic fuel production through Fischer-Tropsch process	
coal-FT	Coal to synthetic fuel (Fischer-Tropsch)
bio-FT	Biomass to synthetic fuel (Fischer-Tropsch)
bio-FT(CCS)	Biomass to synthetic fuel (Fischer-Tropsch) with CCS
Hydrogen production technologies	
coal-H2	Coal to Hydrogen
coal-H2(CCS)	Coal to Hydrogen with CCS
gas-H2	Gas to Hydrogen
gas-H2(CCS)	Gas to Hydrogen with CCS
nuc-H2	Nuclear to Hydrogen
bio-H2	Biomass to Hydrogen
bio-H2(CCS)	Biomass to Hydrogen with CCS
ele-H2	Water to Hydrogen using electrolysis
sth-H2	Solar thermal to Hydrogen

- Synthetic fuels: Hydrocarbon synthetic fuels are an alternative to oil products for transportation. They are produced using a Fischer-Tropsch (FT) process from coal (coal-FT), natural gas or biomass (bio-FT) (IEA, 2004). Partial carbon capture in synthetic fuel production (bio-FT(CCS)) is possible because the synthesis gas produced in the gasification process has a high concentration of CO_2 (Yamashita and Barreto, 2005). It uses a pre-combustion CO_2 process as the one described above for IGCC.

- Hydrogen production: MERGE-ETL includes hydrogen production from gas, coal, biomass, electrolysis and thermochemical nuclear and solar processes:

  – Hydrogen from natural gas (gas-H2) using steam reforming.
  – Production of hydrogen from coal (coal-H2) is based on a water shift reaction of the syngas produced from coal gasification (Hawkins and Joffe, 2005).
  – Hydrogen from biomass (bio-H2) can be produced using gasification and pyrolysis followed by a reforming process (Hawkins and Joffe, 2005).
  – Electrolysis (ele-H2) allows the use of electricity to produce hydrogen by splitting water into hydrogen and oxygen (Gül, 2008).
  – The thermochemical production of hydrogen from nuclear energy (nuc-H2) consists on a sulphur-iodine cycle where the water is split and hydrogen is thermally produced (Nuclear Energy Agency, 2006b).
  – Solar-thermal hydrogen (sth-H2) is produced through a hydrolysis process that converts water into hydrogen and oxygen using zinc as catalyst (IEA, 2011b).

MERGE-ETL includes the possibility of carbon capture for hydrogen production from gas (gas-H2(CCS)), coal (coal-H2(CCS)) and biomass (bio-H2(CCS)) which requires an additional capture unit usually added after the water shifting reaction (Hawkins and Joffe, 2005).

Technology deployment and retirement

Technology deployment is limited by different physical, institutional, regulatory and even social aspects, e.g. time needed to build the technologies, rate at which people can be trained to build new technologies, rate at which renewable technologies can be integrated into the grid, availability of supplies (steel, concrete, wires, etc.), time to accomplish regulatory aspects or to gain social acceptance, etc. These limits in the rate of technology deployment are modeled in MERGE by means of maximum expansion rates for both electric and non-electric energy conversion technologies. Furthermore, each technology has an upper limit upon its share of the total energy production (Manne et al., 1995). This is highly relevant for the contribution of renewable technologies to electricity production. These technologies are intermittent sources, i.e. sun intensity or wind speed can not be controlled and, therefore, the amount of electricity produced can vary randomly with the weather. MERGE does not explicitly include stochastic renewable technologies featuring in-built backup. However, expansion is controlled by the maximum share in the electricity mix, limiting generation from stochastic sources.

The retirement of energy technologies occurs when the technologies reach the end their lifetimes[2]; however, neither the original MERGE developed by Manne and Richels (2004) nor the MERGE-ETL model MERGE-ETL (Kypreos, 2007) included explicitly considerations about installed capacity nor vintages of technologies. In these versions of MERGE, technology retirement is modeled through a constraint on the decline of the electricity produced by the technology. This approach does not keep a good tracking of technology vintages and allows their early retirement. For this thesis, the retirement of power plants is modeled assuming that they have to be operated for their entire lifetimes. For this a new capacity equation has been included, thus,

$$\begin{aligned} cap_{r,t+1,y}^{ag+1} &= cap_{r,t,y}^{ag} \quad \forall ag \in [0, \mathrm{lf}_y) \\ \sum_{i \in ag} cap_{r,t,y}^{ag} &= PE_{r,t,y} \end{aligned}$$

where $cap_{r,t,y}^{ag}$ and $PE_{r,t,y}$ are the installed capacity and electricity produced with the y-technology in region r and period t with age ag; and lf is the lifetime of the technology.

Nuclear cycle

Nuclear generation contributes an important share to current global electricity generation and it has a considerable potential to provide low-carbon electricity. However, the conversion from natural uranium to electricity is more complicated than the conversion process with fossil fuels. To represent this, MERGE-ETL includes a simplified model of the nuclear fuel cycle (see Figure 3.4)[3]. This nuclear cycle includes two types of reactors, a light water and a fast breeder, and models the flows of the different

[2]The lifetime of a conversion technology is considered as the total time period in which the technology can function before it must be replaced.

[3]Chapter 6 presents an enhanced nuclear cycle developed in this thesis.

types of uranium, plutonium and wastes. It is based on Chakravorty et al. (2009).

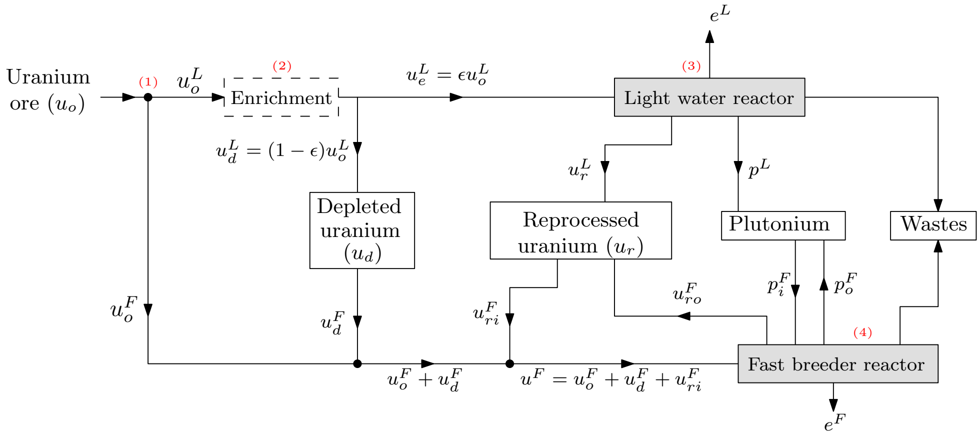


FIGURE 3.4: *Nuclear Cycle*

(1) The cycle starts with the uranium ore coming from the uranium resources (ura-1 to ura-4 or imports). Uranium ore (u_o) can be used in the LWR (u_o^L) or the FBR (u_o^F).

(2) The uranium going to the LWR is enriched, producing enriched uranium (u_e^L) and depleted uranium (u_d^L) with a ratio ϵ.

(3) The Light Water Reactor (LWR) uses enriched uranium, producing energy (e^L), reprocessed uranium (u_r^L), plutonium (p^L) and wastes. The light water reactor is modeled based on the European Pressurized Reactor (EPR), with the input-output relationship presented in Figure 3.5.

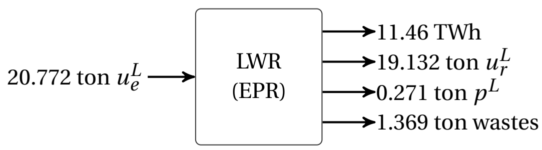


FIGURE 3.5: *Inputs and outputs of the LWR*

Assuming that the quantity of mass converted to energy is negligible; the mass in the reactor is balanced to estimate the amount of enriched uranium needed by the reactor, thus,

$$u_e^L = u_r^L + p^L + \text{wastes}$$

(4) The Fast Breeder Reactor (FBR) uses a combination of uranium from uranium ore (u_o^F), depleted uranium from the enrichment process (u_d^F), and reprocessed uranium (u_{ri}^F). These different types of uranium are assumed to be substitutes, thus: $u^F = u_o^F + u_{ri}^F + u_d^F$. Besides uranium, the FBR uses plutonium (p_i^F). The uranium and plutonium inputs are assumed to be used in a fixed proportion, $\frac{u^F}{p_i^F} = k$. The FBR produces energy (e^F), reprocessed uranium (u_{ro}^F), plutonium (p_o^F) and wastes. The ratio between uranium input and reprocessed uranium output is assumed to be a fixed proportion, $\frac{u^F}{u_{ro}^F} = k_u$. The Fast Breeder Reactor is modeled based on the European Fast Reactor (EFR), with the input-output relationship presented in Figure 3.6.

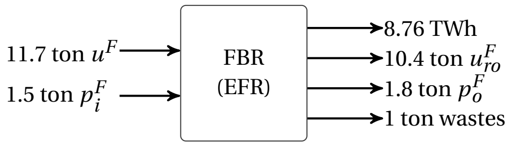


FIGURE 3.6: *Inputs and outputs of the FBR*

Endogenous technology learning

As presented in Section 2.4 technology learning is the process by which the technical and economical performance of technologies improves with the increase in production experience and with technological improvements achieved in the research and development of the technology (Junginger et al., 2010). It is an important determinant for the development of the future energy system since it captures the possibility for those technologies with high investment costs today to achieve long-term competitiveness.

This phenomenon is modeled in MERGE-ETL by means of a two-factor learning curve that describes the reduction in investment costs as a function of experience and knowledge. This was originally proposed by Kypreos (2000) and Manne and Barreto (2004) and further developed by Barreto and Kypreos (2004); Kypreos (2005); Kypreos and Bahn (2003).

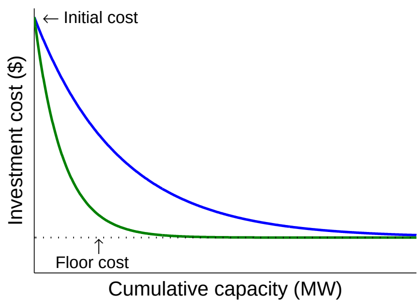


FIGURE 3.7: *Endogenous technology learning*

The first learning factor, often called "learning-by-doing" (LBD), models the possibility of achieving declining investment costs with the accumulation of experience on the production of a technology. The accumulation of experience is assumed to be reflected by the cumulative installations of a technology, and therefore, as shown in Figure 3.7, the learning curve describes investment cost as a function of the cumulative capacity (Magne et al., 2010). For this factor, the investment cost for the y-technology declines with the installed capacity until it reaches a floor cost, thus,

$$inv_y = \begin{cases} A_y \cdot CC_y^{-b_y} & \text{if } inv_y \geq l_y, \\ l_y & \text{otherwise,} \end{cases}$$

where A_y is a constant calibrated with the initial cost and capacity; CC_y is the cumulative capacity; b_y is the learning index, which reflects the effectiveness of the learning process for the y-technology; and l_y is the floor cost of the y-technology. The two different learning curves presented in Figure 3.7 illustrate an example of two technologies with the same initial investment cost, the same floor cost but different learning indices.

The second learning factor accounts for the accumulation of knowledge through research and development, so called "learning-by-searching" (LBS). Consequently, due to the learning processes, investment costs are assumed to decline with both cumulative capacity deployment and cumulative research and development expenditures (*CRD*), thus,

$$inv_y = \begin{cases} A_y \cdot CC_y^{-b_y} CRD_y^{-c_y} & \text{if } inv_y \geq l_y, \\ l_y & \text{otherwise,} \end{cases} \tag{3.6}$$

where c_y is the learning-by-searching index. Cumulative R&D expenditures and cumulative capacity are estimated endogenously for each region.

In MERGE-ETL, technology learning is assumed to occur as a collective evolutionary process, following the paradigm of technology clusters described in Seebregts et al. (2000). This approach, implemented in MERGE-ETL by Magne et al. (2010), is based on the idea that a number of key components (e.g. gasifier, gas turbines, carbon capture technologies, etc.) are often used across different technologies. Thus, the learning process for the y-technology benefits the other technologies that share key components with y.

Accordingly, the two factor learning represented in Equation 3.6 is applied at the level of key components. The key components included in MERGE-ETL and their relationships with the conversion technologies are presented in Table 3.3.

TABLE 3.3: *Key learning components of the conversion technologies*

		Gasifier	Gas turbine	Biomass balance of plant	Advanced coal	Coal balance of plant	Stationary fuel cell	Carbon capture			New nuclear		Wind	Solar	
								Pre combustion	Post combustion	H_2 prod.	Power prod.	H_2 prod.		PV power	Thermal H_2 prod.
Electricity	oil(r)														
	gas(r)		x												
	NGCC		x												
	NGCC(CCS)		x						x						
	gas-FC						x								
	coal(r)														
	PC				x										
	PC(CCS)				x				x						
	IGCC	x	x			x									
	IGCC(CCS)	x	x			x		x							
	LWR														
	FBR										x				
	bio	x	x	x											
	bio(CCS)	x	x	x				x							
	solar													x	
	hydro														
	wind												x		
Non-electric energy	coal-FT	x			x										
	bio-FT	x		x											
	bio-FT(CCS)	x		x				x							
	coal-H2	x													
	coal-H2(CCS)	x								x					
	gas-H2														
	gas-H2(CCS)									x					
	nuc-H2											x			
	bio-H2	x		x											
	bio-H2(CCS)	x		x						x					
	ele-H2														
	sth-H2														x

3.2.3 Emissions, climate and damage assessment submodels

In addition to the economic and energy submodels, MERGE includes submodels on emissions and climate. The emissions submodel estimates energy and non-energy related emissions of the three main greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O); and other greenhouse gases: short-lived (SLF) and long-lived F-gases (LLF). Short-lived F-gases correspond to the hydrofluorocarbon (HFCs) with a lifetime of less than 100 years. LLF includes HFCs with lifetimes greater than 100 years, SF_6 and prefluorocarbons (PFCs).

Energy-related emissions are calculated based on energy production and the emission factors of each technology. Non-energy-related emissions and emissions of SLF and LLF gases are estimated using an exogenous baseline and abatement curves for different world regions.

The climate submodel estimates the temperature change produced by the atmospheric concentration of greenhouse gases. Besides the warming effect of the GHGs, MERGE includes the cooling effect of sulfur aerosols, modeled with an exogenous baseline that depends on the climate scenario.

Emissions and abatement

Energy-related CO_2 emissions are estimated using emission coefficients for both current and future technologies. These coefficients are estimated using the efficiency of each technology and the carbon content the used energy carrier. Table 3.11 presents the values used in this thesis. Additionally, MERGE includes fugitive methane emissions related to the extraction, transport and distribution of the energy carriers. For this work, we calculated regional emission coefficients based on the 2000 and 2005 methane emission inventories (European Commission, Joint Research Centre (JRC) / Netherlands Environmental Assessment Agency (PBL), 2009) and regional resource extraction from the International Energy Agency (IEA) energy balances (IEA, 2002, 2003, 2007a,b).

Non-energy emissions are specified with an exogenous baseline (see Section 3.5.4 for the baseline assumed in the reference scenario in this thesis). The model allows the abatement of these emissions using abatement cost curves (also given exogenously, based on Manne and Richels (2004)).

Climate submodel

The climate submodel represents carbon and non-CO_2 gases cycles to estimate atmospheric concentration of GHGs, and then calculates the radiative forcing and global temperature change. There are a number of uncertainties about these processes (van Vuuren et al., 2011b) that are not the focus of this thesis. Therefore, this section presents in detail the climate submodel, assumed to have fixed physical constants and presents an additional comparison with other integrated assessment models.

The carbon cycle in MERGE is based on the atmospheric CO_2 impulse-response estimated by Maier-Reimer and Hasselman (1987), who used a coupled atmosphere-ocean model, to estimate the atmospheric CO_2 response $y(t)$, for an arbitrary emission function $x(t)$ as,

$$y(t) = \int_0^{\tau} (A_0 + \sum_{j=1}^{4} A_j e^{-(t-\tau)/T_j}) x(\tau) d\tau \tag{3.7}$$

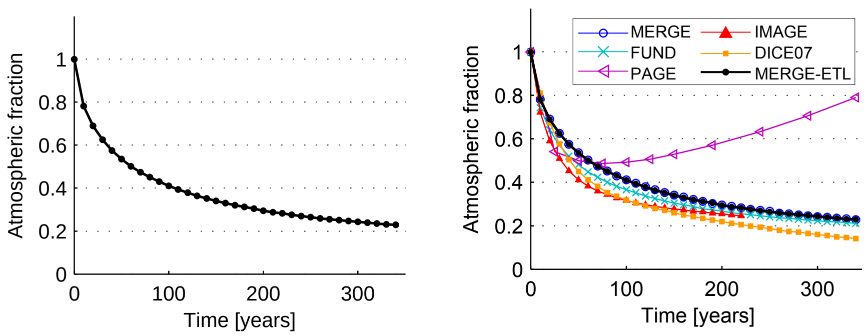
where A_0 represents the emitted CO_2 that remains in the atmosphere after many thousand of years. Maier-Reimer and Hasselman (1987) estimated A_0 around 0.15, consistent with more recent studies that estimate this fraction to 19±4% (Solomon et al., 2010). The other 4 terms (indexed with j) can be interpreted as independent atmospheric reservoirs, with A_j capacity fraction and T_j being the time constant for the absorption of the CO_2 by the ocean[4]. Using equation 3.7, the atmospheric CO_2 response $y_\delta(t)$ to an unitary impulse $\delta(t)$ is given by,

$$y_\delta(t) = A_0 + \sum_{j=1}^{4} A_j e^{-t/T_j}.$$

Therefore, the CO_2 concentration in each time period corresponds to the sum of the impulse responses during the period plus the remaining carbon in each reservoir. Maier-Reimer and Hasselman (1987) estimated the atmospheric CO_2 response for three impulse emissions that correspond to a 1.25x, 2x and 4x increase in the CO_2 concentration. The parameters A_j and T_j used in MERGE-ETL correspond to the 2x fit (Maier-Reimer and Hasselman, 1987):

	Reservoir				
	0	1	2	3	4
A_j	0.142	0.241	0.323	0.206	0.088
T_j [years]	∞	313.8	79.8	18.8	1.7

Figure 3.8A presents the unitary impulse response of the carbon cycle in MERGE-ETL. After 100 years 40% of the emitted CO_2 remains in the atmosphere and after 300 years the atmospheric fraction is reduced to around 20%. When comparing with other integrated assessment models[5] (see Figure 3.8B) and other climate models[6]presented in van Vuuren et al. (2011b), MERGE-ETL has a relatively slow decay in the first 200 years but an overall picture consistent with the behavior of all the models.



(A) *MERGE-ETL*

(B) *Comparison with other IAMs. Modified from van Vuuren et al. (2011b)*

FIGURE 3.8: *Impulse response carbon cycle. Compared to DICE99 (Nordhaus, 1999), DICE07 (Nordhaus, 2008), FUND 2.8 (Tol, 2006), IMAGE (Bowman et al., 2006), MAGICC (Wigley), MERGE (Manne and Richels, 2004) and PAGE2002 (Hope, 2006).*

The behavior in the atmosphere of the other greenhouse gases is modeled using a single reservoir

[4]The CO_2 absorption is modeled as an exponential decay, therefore, T_j represents the time that takes the CO_2 in the reservoir to decline to 63.2% of the initial value.

[5]DICE99 (Nordhaus, 1999), DICE07 (Nordhaus, 2008), FUND 2.8 (Tol, 2006), IMAGE (Bowman et al., 2006), MAGICC (Wigley), MERGE (Manne and Richels, 2004) and PAGE2002 (Hope, 2006)

[6]BERN 2.5 with carbon cycle feedbacks, which is a reduced-complexity climate model with a detailed carbon cycle (Plattner et al., 2008)

representation, based on Intergovernmental Panel in Climate Change (IPCC) (1997, App. 1), thus, for the gas g,

$$\frac{dc_g(t)}{dt} + \frac{1}{\tau_g} c_g(t) = x_g(t), \tag{3.8}$$

where $c_g(t)$ represents the concentration, $x_g(t)$ is an arbitrary emission function and τ_g is the mean lifetime of each gas [7].

The atmospheric concentration for the other greenhouse gases is calculated using the impulse response in Equation 3.8, thus,

$$c_g(t) = Me^{-t/\tau_g}$$

where M is the magnitude of the impulse. As in the CO_2 emissions case, the atmospheric concentration in each period is calculated as the sum of the impulse responses during the period plus the remaining concentration of the gas in the atmosphere.

Temperature increase

Global temperature increase is estimated by determining the impact of changes to the concentration of greenhouse gases (calculated as presented in the previous section) on the earth's radiative forcing balance. According to the IPCC's Fourth Assessment Report (Intergovernmental Panel in Climate Change (IPCC), 2007b) the main contributors to changes in radiative forcing are long-lived greenhouse gases (CO_2, CH_4, N_2O, halocarbons); ozone; surface albedo and aerosols. The previous version of MERGE-ETL (Kypreos, 2007) includes the main GHGs, i.e. CO_2, CH_4, N_2O, SF_6, HFC134 and the cooling effect from sulfate aerosols. In this thesis, other hydrofluorocarbons, prefluorocarbons, and two main chlorofluorocarbons: CFC-11 and CFC-12 were also included.

For the greenhouse gases, the change in radiative forcing is calculated using the simplified expressions presented in Table 3.4 based on the IPCC Third Assessment Report (Intergovernmental Panel in Climate Change (IPCC), 2001b, Table 6.2). These expressions depend on the current concentration of each greenhouse gas: CO_2 [ppm], CH_4 [ppb], N_2O [ppb], SLF [ppb] and LLF [ppb]; and the pre-industrial concentration indicated with the subindex *o*. The concentrations of CO_2, CH_4, N_2O, SLF and LLF are estimated endogenously in the model. For the chlorofluorocarbons, we assume that their effect on the world radiative forcing does not change among scenarios because they are regulated under the Montreal Protocol, thus their production ended in 1996 and 2010 for developed and developing regions, respectively (Fahey and Hegglin, 2011).

Besides the warming effect of the major greenhouse gases, MERGE includes the cooling effect of the sulfate aerosols, both direct and indirect forcing, given by Intergovernmental Panel in Climate Change (IPCC) (1997, app. 2),

[7] The atmospheric lifetime of a species measures the time required to restore equilibrium after a change (increase or decrease) in its atmospheric concentration (Intergovernmental Panel in Climate Change (IPCC), 2001b). Based on Intergovernmental Panel in Climate Change (IPCC) (2001b) τ_{CH_4} =12 years; τ_{N_2O} = 114 y; τ_{SLF} = 13.8 y; and τ_{LLF} = 3200 y.

TABLE 3.4: *Radiative forcing for each greenhouse gas. Based on Intergovernmental Panel in Climate Change (IPCC) (2001b, p. 358)*

Gas	Change in net flux [W/m^2]
CO_2	$5.35 \ln\left(\frac{CO_2}{CO_{2o}}\right)$
CH_4	$0.036\left(CH_4^{0.5} - CH_{4o}^{0.5}\right) - f(CH_4, N_2O)^* - f(CH_{4o}, N_2O)$
N_2O	$0.12\left(N_2O^{0.5} - N_2O_o^{0.5}\right) - f(CH_{4o}, N_2O) - f(CH_{4o}, N_2O_o)$
SLF†	$0.15\ (SLF - SLF_o)$
LLF‡	$0.52\ (LLF - LLF_o)$
CFC-11	$0.25\ (\text{CFC-11} - \text{CFC-11}_o)$
CFC-12	$0.32\ (\text{CFC-12} - \text{CFC-12}_o)$

$^* f(CH_4, N_2O) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}\,(CH_4 \cdot N_2O)^{0.75} + 5.31 \times 10^{-15} CH_4\,(CH_4 \cdot N_2O)^{1.52}\right]$

†Corresponds to the HFC-134a value

‡Corresponds to the SF_6 value

$$\Delta F_{dir} = \frac{\text{sul} - \text{sul}_{nat}}{\text{sul}_{1990} - \text{sul}_{nat}} \Delta F_{dir,1990}$$
$$\Delta F_{indir} = \frac{\log(\text{sul}/\text{Sul}_{nat})}{\log(\text{sul}_{1990}/\text{sul}_{nat})} \Delta F_{indir,1990}$$

where ΔF_{dir} and ΔF_{indir} are the direct and indirect radiative forcings measured in W/m^2; sul is total sulfate emissions (natural + fossil fuel burning) in TgS; $\text{sul}_{1990} = 69 + \text{sul}_{nat}$ TgS; $\text{sul}_{nat} = 42$ TgS; $\Delta F_{dir,1990} = -0.3$ W/m^2; and $\Delta F_{indir,1990} = -0.8$ W/m^2.

The aggregate effect (ΔF) corresponds to the sum of the radiative forcing of each GHG, thus

$$\Delta F = \Delta F_{CO_2} + \Delta F_{CH_4} + \Delta F_{N_2O} + \Delta F_{CFC} + \Delta F_{S,dir} + \Delta F_{S,indir}.$$

The temperature change is calculated using a simple global energy balance model, $\Delta Q = \Delta F - \frac{1}{S}\Delta T$, where the change in heat flux absorbed by the ocean (ΔQ) is produced by the difference between radiative forcing (ΔF) and the outgoing long wave radiation ($\frac{1}{S}\Delta T$) (Knutti and Hegerl, 2008). ΔT is the temperature change and S is the climate sensitivity parameter measured in Km^2/W. For a constant radiative forcing the system reaches an equilibrium where the change in heat uptake is zero ($\Delta Q = 0$), thus,

$$\Delta T = S \Delta F$$

The equilibrium climate sensitivity ($\Delta T_{2\times CO_2}$) is the global average temperature change produced by a doubling in the CO_2 concentration (Knutti and Hegerl, 2008), $\Delta T_{2\times CO_2} = S \cdot 5.35 \ln(2)$ (see Table 3.4).

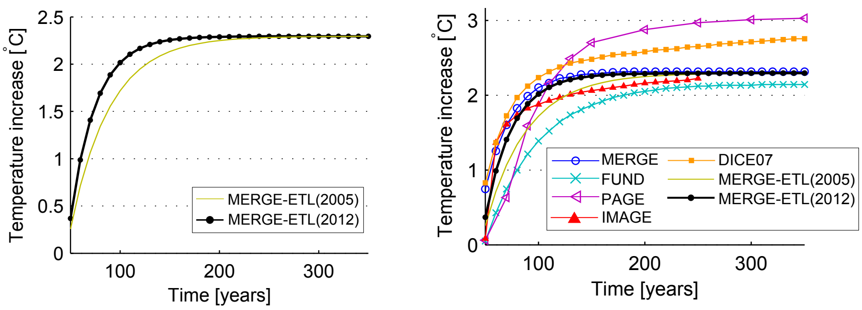
For this thesis, we define the climate sensitivity $\Delta T_{2\times CO_2}$= 2.3°C, consistent with the ranges presented in Knutti and Hegerl (2008) and Intergovernmental Panel in Climate Change (IPCC) (2007b), thus $S = \Delta T_{2\times CO_2}/5.35\ln(2)$. The potential temperature change (ΔPT), defined as the long-run temperature that will occur if forcing level is kept constant indefinitely, is calculated as,

$$\Delta PT = \frac{\Delta T_{2\times CO_2}}{5.35\ln(2)}\Delta F. \tag{3.9}$$

This potential temperature change corresponds to the system equilibrium where the heat uptake by the ocean is negligible. Therefore, the actual temperature increase is delayed from the potential temperature change, since the oceans take a long tome to warm up, thus based on Kypreos (2008),

$$\Delta AT_{t+1} = (1-lg)^{nyper_t}\,\Delta AT_t + \left[1-(1-lg)^{nyper_t}\right]\frac{\Delta PT_{t+1}+\Delta PT_t}{2}$$

where ΔAT_t represents the actual temperature change in the period t compared to the base year; $nyper_t$ represents the number of years of the period t; and $(1-lg)$ represents the yearly decay of the actual temperature increase with lg being a constant. For this thesis this constant was calibrated to reduce the lag between the potential and the actual temperature increase. Figure 3.9A presents the actual temperature increase resulting by a doubling in CO_2 concentration (modeled by a step in radiative forcing of 3.7 m^2/W) for the previous version of MERGE-ETL (Kypreos, 2005) and the version developed in this thesis. Comparing with the response of other IAMs (see Figure 3.9B) the new calibrated MERGE-ETL has a delay in the actual temperature change closer to most of the other models.



(A) *MERGE-ETL*

(B) *Comparison with other IAMs. Modified from van Vuuren et al. (2011b)*

FIGURE 3.9: *Temperature change produced by a doubling in CO_2 concentration*

Two additional experiments were developed to analyze the response of the climate submodel and then compared to the response of other IAMs presented in van Vuuren et al. (2011b). These experiments considered high and low CO_2 emissions scenarios, corresponding to the IPCC's A2 scenario (Nakicenovic, 2000) and a 450ppm CO_2e scenario, respectively. Figure 3.10 presents the temperature change for the two experiments. The behavior of the new calibrated climate submodel in MERGE-ETL in both experiments is comparable to the other IAM's and the climate models shown in van Vuuren et al. (2011b).

Damages

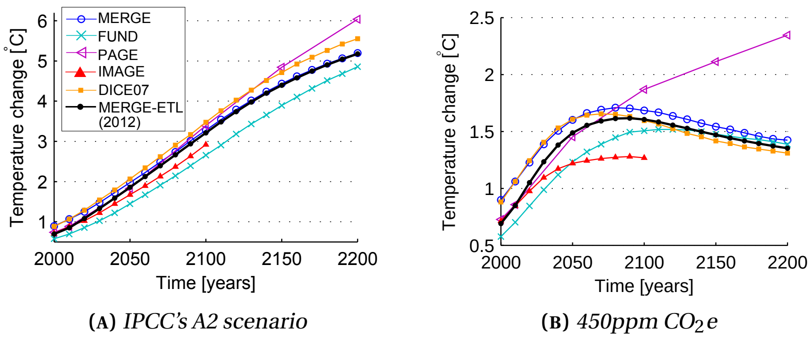


FIGURE 3.10: *Climate submodel response. Modified from van Vuuren et al. (2011b)*

Manne and Richels (2004) included the assessment of market and non-market damages of climate change in MERGE. The market damages are estimated assuming that a rise in temperature of 2.5°C would lead to GDP losses of 0.25% in the high income nations and 0.5% in the low-income ones (Manne and Richels, 2004). At higher or lower temperatures than 2.5°C the losses are estimated proportionally to the temperature increase. Market damages are subtracted from the economic output (Y_t) shown in Equation 3.1. For non-market damages, the expected losses are assumed to increase quadratically with the temperature increase. This was modeled by Manne and Richels (2004) using an "economic loss factor" (*ELF*), that is given by:

$$1 - ELF_t = \left(1 - \left(\frac{\Delta AT_t}{catt}\right)^2\right)^{hsk}$$

where *catt* is the catastrophic temperature and *hsk* is the hockey-stick parameter. The catastrophic temperature is the temperature after which the economic output of the region will be 0. The catastrophic temperature parameter is specified such that 5.5°C warming corresponds to a loss in GDP of 10% when *hsk*=1. The hockey-stick parameter determines how sensitive the losses are to a change in the actual temperature, e.g. if *hsk*=1, the loss is quadratic with ΔAT (Manne and Richels, 2004). In MERGE-ETL the hockey-stick parameter changes among regions and periods. Figure 3.11 presents the economic loss factor (*ELF*) for the different possible values of *hsk*. Less developed regions have lower *hsk*.

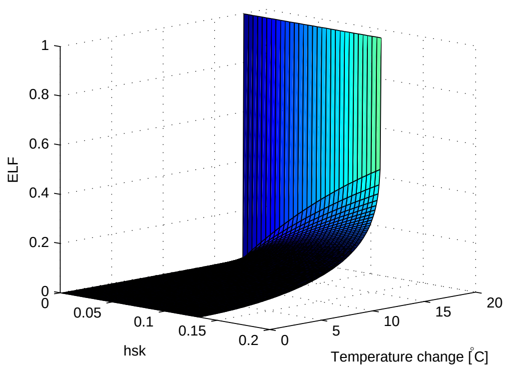


FIGURE 3.11: *Economic loss factor*

The shape of the damage function is highly uncertain. Different models use linear, cubic or exponential forms, which lead to different policy recommendations (Intergovernmental Panel in Climate Change (IPCC), 2001a, p. 944). For instance, DICE-2007 (Nordhaus, 2008) uses an exponential damage function that produces a 7% lost in the global output when the mean temperature is increased by 5°C. PAGE-2002 (Hope, 2006; Stern, 2006) also uses an exponential function, but its exponent varies in the range [1,3] with a most likely value of 1.3.

Damage assessment is commonly used in cost-benefit analyses to determine optimal climate mitigation targets. However, the analysis done in this thesis, rather than determining optimal emissions targets, is focused on analyzing the impact of given climate policies on the energy system. For this reason, this PhD does not include the estimation of damages.

3.3 Region definition

To analyze the impacts of global uncertainties for the Swiss energy system we have updated the region definition of the model. The previous definition of the regions (Kypreos, 2005), shown in Figure 3.12, included 9 world regions: United States (USA); Western Europe (WEUR); Eastern Europe and the Former Soviet Union (EEFSU); Mexico and Middle East; China; Japan; India; Canada, Australia and New Zealand (CANZ); and Rest of the World (ROW).

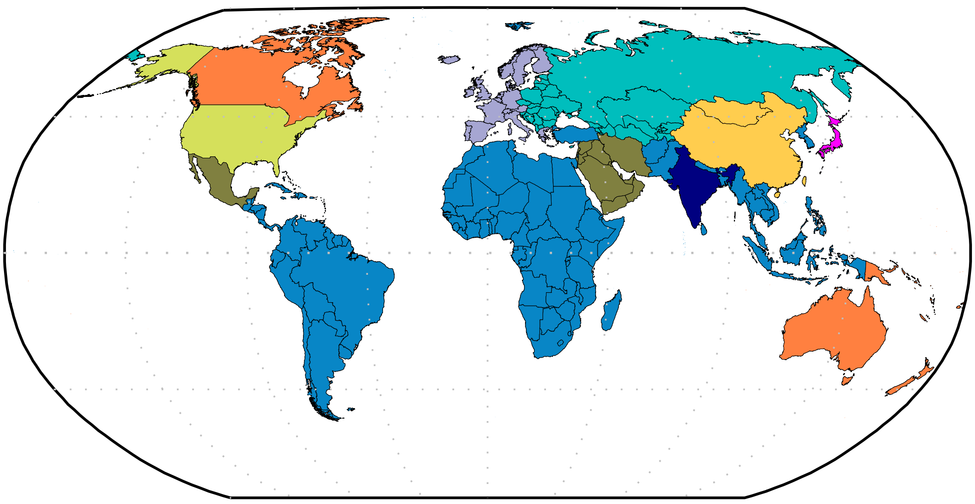


FIGURE 3.12: *Previous regions definition*

An explicit Swiss region has been added, along with additional changes to better reflect important political-economic groupings:

- WEUR and EEFSU: reorganized into European Union[8] (EU), Switzerland and Russia. The countries that belonged to the Former Soviet (except Russia and the Baltic states) are now included in the Rest of the World region.

[8]The European Union region includes some countries that are not part of the European Union: Andorra, Faroe Islands, Gibraltar, Holy See, Iceland, Liechtenstein, Monaco, Norway, San Marino, Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia and Montenegro.

- Mexico and Middle East: reorganized to create a Middle East region, with Mexico moved to ROW.

With these changes the new regional definition (see Figure 3.13) includes 10 regions: European Union (EUP); Switzerland (SWI); Russia (RUS); Middle East (MEA); India (IND); China (CHI); Japan (JPN); Canada, Australia and New Zealand (CANZ), United States (USA); and the Rest of the World (ROW).

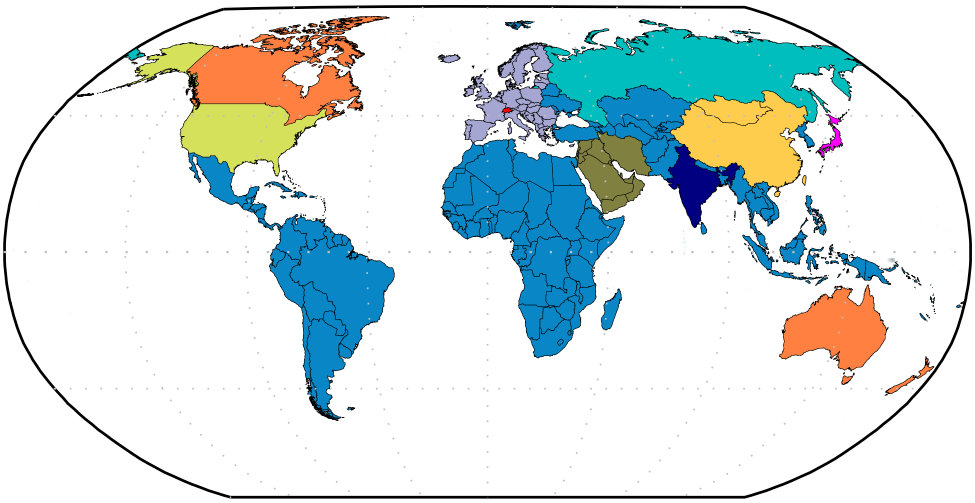


FIGURE 3.13: *New regions definition*

3.4 Time horizon and calibration years

The projection period corresponds to the years 2010 to 2100 in steps of 10 years. All the scenarios are calibrated in the years 2000 and 2005 concerning the following variables:

- Population: The base years are calibrated to United Nations statistics (United Nations. Population Division, 2009) and Swiss statistics (Swiss Federal Statistical Office - BFS, 2010a).

- GDP: The base years are calibrated to World Economic Outlook (International Monetary Fund, 2009) and Swiss Statistics (Swiss Federal Statistical Office - BFS, 2010b).

- Primary energy carrier and electricity consumption: The values are based on the IEA energy balances (IEA, 2002, 2003, 2007a,b) and uranium from Nuclear Energy Agency (2006a); Nuclear Energy Agency and the International Atomic Energy Agency (2008).

- International trade: The trade values for coal, oil, gas and electricity are based on the IEA energy balances (IEA, 2002, 2003, 2007a,b).

- Atmospheric stock of greenhouse gases: The values for the calibration years, 2000 and 2005, are estimated from the IPCC's Third and Fourth Assessment Reports (Intergovernmental Panel in Climate Change (IPCC), 2001b, 2007b), respectively, and correspond to:

Gas	2000	2005
CO_2 [ppm]	368.7	379
CH_4 [ppb]	1751	1774
N_2O [ppb]	315	319
SLF [ppt]	21.7	43
LLF [ppt]	26.3	25.4

- Energy-related GHG emissions: Are based on the EDGAR 4.0 database (European Commission, Joint Research Centre (JRC) / Netherlands Environmental Assessment Agency (PBL), 2009). The global 2000 value corresponds to 6.17 billion tons of carbon equivalent (CE) and the value for 2005 is 7.09 billion tons CE . For Switzerland, the values are 11.54 and 12.27 millions tons CE for 2000 and 2005, respectively.
- Sulfate emissions are based on the EDGAR 4.0 database, the values are 114.8 and 124.2 Mton SO_2 in 2000 and 2005, respectively.
- Potential temperature change: We use 2005 as the base year. According to the Intergovernmental Panel in Climate Change (IPCC) (2007b, p. 204) the total radiative forcing by 2005 is 1.84 [-1.06,+0.98] W/m^2 and the observed climate change from 1850 to 2005 is 0.76±0.19 °C (Intergovernmental Panel in Climate Change (IPCC), 2007b, p. 237).
- Research and development expenditures: The research and development expenditures include both governmental and business related expenditures. They are based on the Techpol database developed in the context of the Cascade Mints (2003) project and European Comission (2006).

3.5 Global energy system: Reference scenario

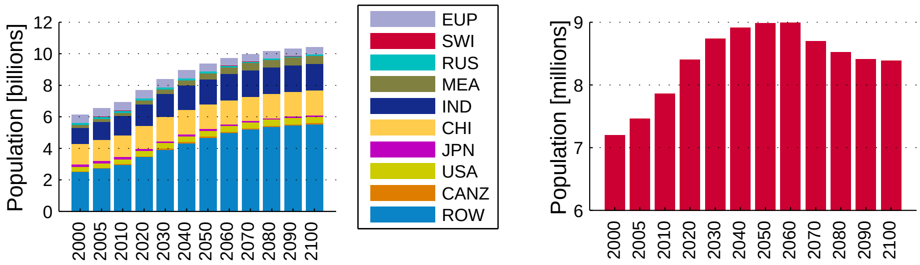
The reference scenario of the global energy system is based on elements of the B2 scenario from the IPCC's Special Report on Emissions Scenarios (Nakicenovic, 2000). However, it is not the intention to replicate the B2 scenario. B2 describes a world with increasing global population, and intermediate economic growth and technological development, and these key drivers from B2 are used here.

3.5.1 Economic development

Economic development is one of the major uncertainties that affect the future energy system. Economic and population growth imply additional energy demand. In the reference scenario in this thesis the global energy system is modeled with an intermediate economic and population growth scenario.

Population growth

In the IIASA B2 scenario (Nakicenovic, 2000) population follows a medium growth path, with a "strong convergence in fertility levels toward replacement levels, ultimately yielding a stabilization of world population levels" (Riahi et al., 2007). The global population is assumed to be 8.95 Billion by 2050 and 10.4 Billion by 2100 (see Figure 3.14A). Although global population stabilizes to around 10 Billion people after 2070, this global picture hides some important regional differences. For instance, China and Eastern Europe continue to have low fertility rates or further declines in fertility, which lead to a declining population in the second half of the century. Globally, this is offset with high population growth in the ROW region, mainly Africa, driven by high fertility and reduced mortality rates (Lutz et al., 2008).



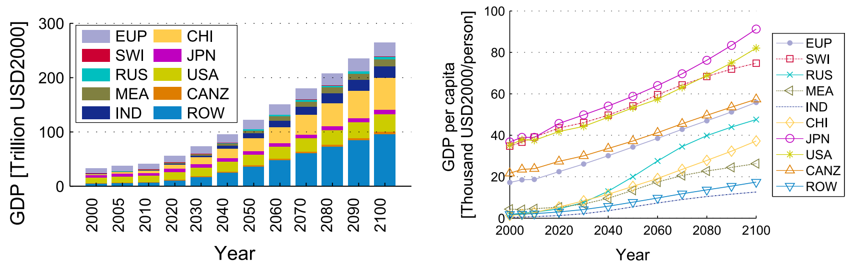
(A) *World* **(B)** *Switzerland*

FIGURE 3.14: *Reference scenario: Population*

In Switzerland, the population is estimated until 2050 based on the medium growth scenario from the BFS (2010). It uses a medium fertility scenario with around 1.5 births per woman and an average childbearing age of 31.5; a slight increase in life expectancy from 84 to 90 years for women and 80 to 86 for men; and a decrease in net migration from 98000 people per year in 2008 to 22500 in 2030 and constant afterwards. After 2050, Swiss population is estimated using the IIASA B2 scenario, which assumes decreasing fertility rates. Based on the BFS assumption, the net migration is kept constant after 2050. With these assumptions Swiss population rises from 7.2 million in 2000, reaches 9 million by 2050 and then declines to 8.4 million by the end of the projection period (see Figure 3.14B).

Economic growth

The economic growth, represented by GDP growth, is a key factor affecting energy demand. As an input to the model we apply a potential (or reference) GDP pathway representing productivity improvements and economic output at constant energy prices. However in MERGE, due the energy-economic interactions, this reference GDP does not exclusively determine the realized GDP. A climate policy, for example, will lead to an increase in energy costs which will reduce the economic output (Manne et al., 1995). Potential (or reference) GDP is based on the IIASA B2 scenario (IIASA, 2009) and the projections from the Federal Department of Finance for Switzerland until 2050 (EFD, 2008). The IIASA B2 scenario is a medium growth scenario. It assumes that growth in per capita productivity is higher in low-income regions; and that in lagging regions (e.g., Africa) the economic catch-up is delayed (Riahi et al., 2007). With this projection, global potential GDP grows by a factor of 3.74 (up to 89.7 trillion USD2000) between 2000 and 2050. In Figure 3.15 we present the potential GDP and potential GDP per capita for the 10 regions. Notice that economies in transition, such as China and ROW, are responsible for most of the global economic growth. Potential GDP per capita in China is assumed to grow by a factor of 20 from 2005 to 2100; while in EU29 it increases just by a factor of 2.8 in the same period. Switzerland has a yearly growth rate of potential GDP of 0.7% for the period 2020 to 2050, slowing to an average of 0.4% after 2050.



(A) *GDP* (B) *GDP per capita*

FIGURE 3.15: *Reference Scenario: Potential GDP*

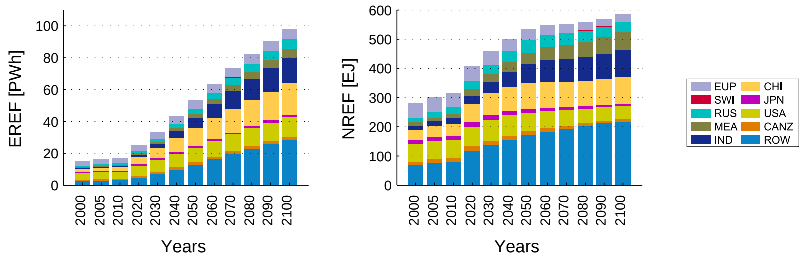
In the year 2000, the regions can be divided in three groups, according to the GDP per capita: (1) Japan, USA and Switzerland with an average GDP per capita of USD2000 35 thousand; (2) CANZ and EUP, which GDP per capita is around USD 20 thousand; and (3) Russia, Middle East, India, China and ROW with an average GDP per capita of USD2000 2 thousand, but with a considerable difference between Middle East and India, which GDP per capita are USD2000 4.4 and 0.44 thousand, respectively. The first group of regions continues being the group with higher GDP per capita during the entire projection period. The variation in the third group increases considerably and by 2100 two countries (Russia and China) join the group of the middle GDP per capita. India has the lowest GDP per capita during the whole period.

Autonomous energy efficiency improvement (AEEI)

As described in section 3.2.1 this variable reflects non-price driven changes in the economy-wide energy intensity. In previous versions of MERGE (Kypreos, 2007; Manne et al., 1995), the AEEI is assumed to be the same for both electricity and non-electric energy demand. Nevertheless, non-economic driven efficiency improvements for electricity and non-electric demand are not necessarily equivalent. For instance, better insulated buildings generally reduce non-electric energy demand more than electricity demand.

The rate of AEEI for the reference scenario in this thesis is estimated from the IIASA B2 scenario (IIASA, 2009) projections for final electricity and non-electric energy consumption and GDP. AEEI rates for the non-electric energy demand (NAEEI) are generally higher than those for electricity (EAEEI). In this reference scenario EAAEIs vary in the range 0 to 1.5%, with the exception of developing regions - China in particular - where the higher values in the first two periods reflect the fast growth in the economy and the rapid turn-over of capital stock, leading to efficiency improvements. NAEEI has values between 0 and 3%. Until 2050 the group of less-developed regions, i.e. India, China, Middle East, Russia and ROW are those with higher NAEEI. After 2050 all the regions have a similar NAEEI, in the range between 1 and 2%, and with a decrease mainly for India and Middle East in the late periods, which can be related to a slower growth in GDP per capita (see Figure 3.15).

This scenario of electric and non-electric AEEI affects the reference electricity and non-electric demand (as shown in Appendix A.1). Figure 3.16 shows the resulting electricity and non-electric energy reference demand, EREF and NREF, respectively. Consistently with the behaviour of the AEEIs the reference electricity demand increases approximately 5-fold from 2000 to 2100, while the non-electric energy increases just by a factor of 2 in the same period. The total final energy demand for this reference scenario corresponds to 725 and 1056 EJ in 2050 and 2100, respectively.



(A) *EREF* (B) *NREF*

FIGURE 3.16: *Reference electricity and non-electric energy demands*

3.5.2 Natural resources

The availability of natural resources and the cost at which they can be extracted is one main driver of the global energy system. The estimates used in this thesis for the reference scenario correspond to conventional resources.

Fossil fuels

Table 3.5 presents the proven reserves and undiscovered resources estimates for fossil fuels used in the reference scenario. It should be noted that these estimates are not based on the IIASA B2 scenario but on recent resources estimates. Proven reserves for oil, gas and coal correspond to the Proved Recoverable Reserves of the 2001 and 2007 Surveys of Energy Resources from the World Energy Council (2001, 2007); Undiscovered resources of oil, gas and coal are based on the conventional resources presented by the German Federal Institute for Geosciences and Natural Resources (BGR) (2008).

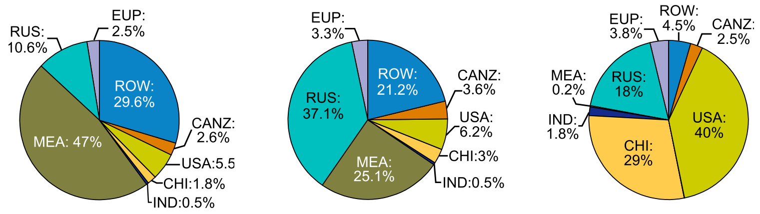
TABLE 3.5: *Fossil fuels resources estimates. Based on German Federal Institute for Geosciences and Natural Resources (BGR) (2008); World Energy Council (2001, 2007)*

Energy carrier	Extraction costs [USD 2000/GJ]	Proven reserves by 2005 [EJ]	Undiscovered resources by 2005 [EJ]	Total EJ
Oil	3 to 5.25 (10 cost categories)	6640	3760	10400
Gas	2 to 4.25 (10 cost categories)	6693	9046	15739
Coal	1.6 to 5.5 (4 cost categories)	21883	449625	471508

Oil and gas reserves are mostly located in three regions: Middle East, rest of the world (mainly in Venezuela, Kazakhstan, Libya, Nigeria and Algeria) and Russia (see Figures 3.17A and 3.17B), while coal is mostly located in USA, China and Russia (see Figure 3.17C).

Uranium

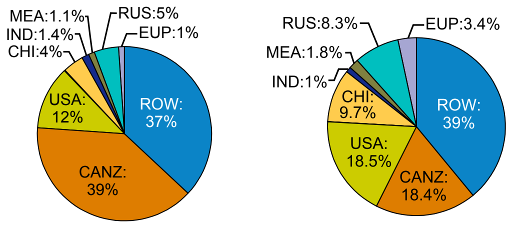
Proven reserves of Uranium are based on the Reasonably Assured Resources (RAR) from the 2009 Red Book (Nuclear Energy Agency and the International Atomic Energy Agency, 2010) with a global esti-



(A) *Oil* (B) *Gas* (C) *Coal*

FIGURE 3.17: *Fossil fuels: Proven reserves + Undiscovered Resources*

mate of 2002.25 EJ. Undiscovered resources of Uranium are estimated as Inferred Resources + Prognosticated Resources + Speculative Resources from the 2009 Red Book (Nuclear Energy Agency and the International Atomic Energy Agency, 2010) with a global estimate of 6351.2 EJ. The four cost categories of uranium presented in the Red Book are included in the model, that is <40, <80, <130 and <160 USD/kg. Figure 3.18 presents the distribution of the uranium resources in the world. Canada, US and the ROW (mainly in Kazakhstan and Niger) account for 88% of the global RAR; and these three regions plus China and Russia have about 94% of total resources.



(A) *Proven reserves* (B) *Total*

FIGURE 3.18: *Uranium resources*

Biomass

Biomass is one of the more diverse renewable energy sources. It can be used directly to produce electricity or heat; but it can also be transformed into liquids, bio-gas or hydrogen to supply other non-electric demands, such as transportation. For all the regions, except Switzerland, the biomass potential is based on the *Prospects for Hydrogen and Fuel Cells* (IEA, 2005b). It is a medium projection scenario with a long-term global potential of 185.4 EJ/a. For Switzerland, Oettli et al. (2004) published in 2004 two scenarios for the Ecological potential of biomass, with potential by 2040 of 104.8 and 126.5 PJ for the pessimistic and optimistic scenarios, respectively. The Energie Trialog Schweiz (2009) presents a potential by 2035 of 130 PJ and assumes that after that year no additional biomass for electricity, heat or fuel production will be available, and therefore the biomass potential will not increase further; and the SATW (2007) estimates 33 TWh (119 PJ) by 2070. For the baseline we use the potential estimated in Oettli et al. (2004) until 2040 and a constant potential from 2050 of 130 PJ based on the Energie Trialog estimates (Energie Trialog Schweiz, 2009). Table 3.6 presents the estimated potential by region.

The distribution among the cost categories (2, 4, 7 and 10 US$/GJ) is based on Ragettli (2007). These

TABLE 3.6: *Regional biomass potentials by 2050 [EJ/a]. Based on IEA (2005b) and SATW (2007)*

	EUP	SWI	RUS	MEA	IND	CHI	JPN	USA	CANZ	ROW	World
Wood residues	3.14	0.07	9.41	3.55	5.58	9.58	0.52	6.95	5.71	58.78	103.29
Corn grains	0.86	0.00	0.81	0.39	1.29	1.14	0.04	1.41	0.57	3.71	10.22
Sugar cane/sugar beet	0.00	0.00	0.00	0.00	3.05	2.22	0.01	0.16	0.52	17.15	23.09
Stover	4.92	0.029	7.85	1.23	3.05	2.93	0.23	7.26	4.14	15.33	46.97
Waste	1.12	0.027	0.27	0.03	0.07	0.25	0.12	1.57	0.58	1.04	5.07
Total	10.04	0.127	18.34	5.20	13.04	16.13	0.91	17.34	11.51	96.00	188.64

costs include the cost of truck transport from the place of harvest to the processing location (estimated to be a distance of 50 km).

Small and large scale hydropower

The hydropower potentials for the reference scenario are based on realistic development from the World Energy Council (2007) Survey of Energy Resources. For Switzerland, the Energie Trialog (Energie Trialog Schweiz, 2009) estimates a potential for 2035 of 34.8 TWh/a and by 2050 of 33.3 TWh/a. The reduction in 2050 is due to the regulation of residual flows[9] and the impact of climate change. Following Laufer et al. (2004) we use a hydropower potential including the adjustment to residual flows but not the impact of climate change. In this scenario the potential increases to 37.4 TWh/a in 2035 due to efficiency improvements and potential development of small scale hydropower sites. This increase stops in 2035 where the regulation of residual water decreases the potential. Due to the 10-year resolution of the model the peak occurs by 2040. After 2050 we assume the hydropower potential is exhausted and stays constant at 37 TWh/a.

TABLE 3.7: *Regional hydropower potentials by 2050 [TWh/a]. Based on World Energy Council (2007) and Laufer et al. (2004)*

	EUP	SWI	RUS	MEA	IND	CHI	JPN	USA	CANZ	ROW	World
Hydropower	627	37	479	51	220	927	92	364	503	1952	5252

Wind and solar technologies

The potential in the reference scenario corresponds to an advanced technology scenario where the maximum share of each renewable-based technology is limited to a share of 25% of the regional electricity or non-electric energy production. In Switzerland, the renewable based technology potentials correspond to:

- The wind technical potential in Switzerland is limited by the number of good sites and, in addition, the acceptance of the population and concerns about landscape protection. Different

[9] Residual water flow refers to the water that remains in a watercourse downstream of a withdrawal site such as a hydropower plant (Swiss Federal Office for the Environment - BAFU, 2010). The Water Protection Act determines the requirements for appropriate residual flow levels. When a withdraw takes place the minimum residual water flow must be: 50, 130, 280, 900, 2500 and 10000 l/s, corresponding to a rate of flow up to 60, 160, 500, 2500, 10000 and 60000 1/s, respectively. New water withdrawals (since 1992) and existing withdrawals for which concessions have to be renewed must comply with this requirement. Many of the Swiss hydropower plants were built in the years 1955-1970. Therefore, the residual water regulations affect the hydropower potential in the years 2035-2050 - when the existing licenses must be renewed (Piot, 2006).

studies estimate different potentials in the range from 2 to 4 TWh in 2050 (see Table 3.8).

TABLE 3.8: *Wind potential in Switzerland*

Study	Potential and assumptions
Stromperspectiven 2020 (AXPO, 2005)	0.45 TWh by 2020 and 4.2 TWh after 2050
PSI (Hirschberg et al., 2005)	1.15 TWh in wind parks and 2.85 TWh in single installations by 2050
Road Map Renewable Energies in Switzerland (SATW, 2007)	1.2 TWh produced by wind parks and 2.8 TWh produced by individual installations in 2050. The potential is limited to the sites where the wind speed is greater than 4.5 m/s but does not include social acceptance considerations
Energy Strategy 2050 (Energie Trialog Schweiz, 2009)	1.5 TWh by 2035 and 2-3 TWh in 2050. Assuming social acceptance and willingness to invest

The wind potential in Switzerland for the reference scenario in this thesis assumes a considerable potential growth until 2035, reaching around 1.5 TWh; and an exhaustion of the potential after 2035 and, therefore, an slower increase from 2035 to to 2050, reaching 2.5 TWh. This scenario is based on the Energie-Strategie from the Energie Trialog Schweiz (2009). After 2050 we assume an increase in the potential to a maximum of 4 TWh by 2100, a value that corresponds to the maximum estimated potentials for both wind parks and individual installations in SATW (2007) and Hirschberg et al. (2005).

- Solar photovoltaic: Table 3.9 presents the estimated solar PV potential of different studies in Switzerland.

TABLE 3.9: *Solar PV potential in Switzerland*

Study	Potential and assumptions
Stromperspectiven 2020 (AXPO, 2005)	0.4 TWh by 2020 and 5.3 TWh after 2050
PSI (Hirschberg et al., 2005)	Technical potential of 11GW by 2050 (9.4-13.7 TWh)
Road Map Renewable Energies in Switzerland (SATW, 2007)	Three scenarios of installed potential by 2050: – Limits on available roofing surface and adequate orientation to the sun: 14 GW (13.3 TWh) – Current technologies for capacity control and network remain constant: 2 GW (1.9 TWh) – New backup technologies: 6 GW (5.7 TWh)
Energy Strategy 2050 (Energie Trialog Schweiz, 2009)	1.5 TWh by 2035 and 8-12 TWh in 2050. Assuming existence of policies supporting deployment of SPV

The reference scenario used in this thesis is an optimistic scenario with a limitation on available roofing surface but excluding restrictions due to integration into the existing network, assuming that this limitation can be overcome in the long term. Therefore, based on Hirschberg et al. (2005) the potential installed capacity by 2050 is approx. 11 GW, corresponding to a potential electricity production of 10 TWh. This value is consistent with the potentials estimated in Energie Trialog Schweiz (2009) and Weidmann et al. (2009). After 2050 we assume the potential remains constant.

- Solar thermal to hydrogen: The SATW (2007) presents a potential for heating with solar thermal of 4.4 TWh by 2070. As a maximum potential for solar thermal hydrogen production we assume that 30% of this heat is suitable for hydrogen production. This corresponds to a potential by 2070 of 4.75 PJ.

3.5.3 Technology characteristics

A key feature of MERGE-ETL is that it combines an economic model with a representation of the energy system, including a detailed description of technology characteristics. Table 3.10 lists the set of technologies in the model and their initial and floor (in parenthesis) levelized costs for the reference scenario based on the detailed technology characteristics described in Appendix B.2. As mentioned in Section 3.2.2, MERGE-ETL represents different resources categories with different extraction costs. The estimates in Table 3.10 are based on the cheapest resource category so the actual costs, endogenous to the model, will vary. These levelized costs are calculated with a discount rate of 5%.

TABLE 3.10: *Conversion technologies levelized costs*

Electricity technologies		Non-electric technologies	
Technology	**cents$/kWh**	**Technology**	**$/GJ/a**
NGCC	2.60 (2.46)	coal-FT	10.42 (9.39)
NGCC(CCS)	3.68 (3.32)	bio-FT	13.78 (12.24)
gas-FC	9.91 (8.66)	bio-FT(CCS)	16.02 (13.96)
PC	3.53 (3.26)	coal-H2	11.14 (10.62)
PC(CCS)	4.93 (4.51)	coal-H2(CCS)	11.90 (11.12)
IGCC	3.60 (3.29)	gas-H2	9.42 (9.42)
IGCC(CCS)	4.8 (4.33)	gas-H2(CCS)	10.02 (9.82)
LWR*	3.11 (3.11)	nuc-H2	7.32 (6.03)
FBR†	3.92 (2.85)	bio-H2	13.14 (11.59)
bio	5.41 (4.87)	bio-H2(CCS)	13.87 (12.06)
bio(CCS)	6.84 (6.13)	ele-H2	6.70 (6.70)
solar	16.6 (5.38)	sth-H2	39.47 (19.96)
hydro	3.3 (3.3)		
wind	6.65 (5.58)		

*The costs for nuclear technologies are based on the unit costs of the nuclear cycle presented in Table 3.12.

†We assume that all the uranium used in the FBR is natural uranium; that the plutonium produced in the LWR is stored indefinitely; and that the plutonium produced in the FBR is completely used by the reactor.

For some of the technologies, these levelized costs change with technology learning. Table 3.10 shows the initial investment costs and the floor costs in parenthesis. The impact of technology learning depends on the deployment of the key components. For most of the technologies the key components represent 45% to 60% of the initial investment cost, except for wind and solar technologies where the key component accounts for 100% of the initial investment cost. Carbon capture, fuel cells and solar components have a learning rate of 10%; while wind, gasifiers and gas turbines have a learning rate of 5%. As mentioned in Section 3.2.2, all the learning components have a floor cost, which corresponds to 20% to 50% of the initial investment cost.

CO_2-emissions coefficients

Table 3.11 presents the CO_2-emissions coefficients used in this thesis for current and future technologies.

TABLE 3.11: *CO_2-emissions coefficients for current and future energy technologies*

Electricity technologies			Non-electric technologies		
Technology	**g CE/kWh**	**Reference**	**Technology**	**g CE/MJ**	**Reference**
oil(r)	206	IPCC 2006*	Refinery	20	IPCC 2006
gas(r)	172	IPCC 2006	Natural Gas	15.3	IPCC 2006
NGCC	108	IPCC 2006 and Sims et al. (2003)	Coal	26.6	IPCC 2006
NGCC(CCS)	17	Sims et al. (2003)	Biomass	0	
gas-FC	128	IPCC 2006	coal-FT	50.3	IPCC 2006
coal(r)	274	IPCC 2006	bio-FT	0	
PC	259	IPCC 2006	bio-FT(CCS)	-27.3	Gielen and Unander (2005)
PC(CCS)	53	Sims et al. (2003)	**Hydrogen technologies** †		
IGCC	239	IPCC 2006	coal-H2	44.3	IPCC 2006
IGCC(CCS)	46	Sims et al. (2003)	coal-H2(CCS)	3.26	Yamashita and Barreto (2003)
LWR	0		gas-H2	20.4	IPCC 2006
FBR	0		gas-H2(CCS)	6.6	Yamashita and Barreto (2003)
bio	0		nuc-H2	0	
bio (CCS)	-200	Rhodes and Keith (2005)	bio-H2	0	
solar	0		bio-H2(CCS)	-23.5	Cascade Mints (2003)
hydro	0		ele-H2	0	
wind	0		sth-H2	0	

* Intergovernmental Panel in Climate Change (IPCC) (2006)

† Wietschel et al. (2006) propose a well-to-tank CO_2 emission factor for hydrogen production that includes the emissions from the electricity used in the compression process of 19.8 g/kWh compress gaseous H_2. In this thesis we assumed a zero emission factor for the compression process due to the fact that hydrogen technologies would be most likely used in a climate mitigation scenarios where the electricity is produced mainly with carbon free technologies.

Nuclear cycle costs

The unit costs of the nuclear cycle are based on Chakravorty et al. (2009) and are presented in Table 3.12. Fabrication and reprocessing of the fuel account for the largest part of the costs, which are highly dependent on the type of reactor.

Storage potentials

Technologies with carbon capture and storage can play an important role in the achievement of stringent climate policy, as transition technologies to a renewable and hydrogen economy or as definitive solutions using resources that are relatively abundant, such as coal. One restriction on the deployment of CCS technologies is the CO_2 storage potential. In the reference scenario, carbon storage potentials

TABLE 3.12: *Nuclear fuel cycle cost data. All costs are in \$/kg except costs for Plutonium storage where they are \$/kg per year. Based on Chakravorty et al. (2009)*

Cost	LWR	FBR
Conversion	5	
Separation + enrichment	80	-
Fuel fabrication	250	2500
Fuel reprocessing	700	2000
Depleted uranium storage	3.5	-
Reprocessed uranium storage	60	
Plutonium storage	1500	
Waste disposal	400	100

were estimated based on the work of Ecofys (Hendriks et al., 2004). Table 3.13 presents the regional carbon storage potential. This potential accounts for different types of storages reservoirs including remaining and depleted oil fields onshore and offshore, remaining and depleted gas fields onshore and offshore, "unmineable coal layers to which enhanced coal bed methane recovery can be applied (ECBM)" and aquifers (Hendriks et al., 2004).

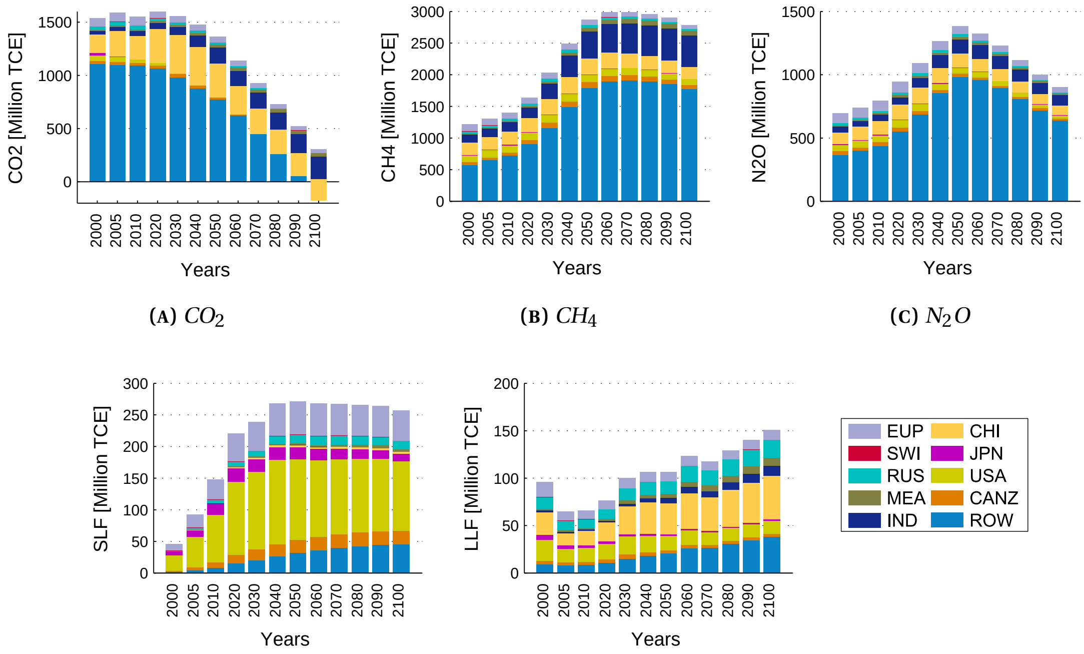
TABLE 3.13: *Carbon storage potential [$GtCO_2$]. Based on Hendriks et al. (2004)*

	EUP	SWI	RUS	MEA	IND	CHI	JPN	USA	CANZ	ROW	World
Potential [$GtCO_2$]	86	0.8	365.8	449.2	44.2	189.7	2	78.2	102.1	342.5	1660.5

The different deposit types have different storage costs, in this thesis the cost were estimated from Hendriks et al. (2004) and vary from 1.2 USD2000/tCO_2 in remaining oil field onshore in the EU to 33.8 USD2000/tCO_2 in a ECBM in Russia.

3.5.4 Non-energy emissions

As mentioned in Section 3.2.3, MERGE also accounts for non-energy GHG emissions based on an exogenous baseline and abatement cost curves. The baseline emissions for the GHGs included in MERGE, namely: CO_2, CH_4, CO_2, SLF and LLF, are calibrated for the base years (2000 and 2005) to the EDGAR database (European Commission, Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL), 2009) and projected using the growth rates for the same set of emissions from the IIASA B2 scenario (IIASA, 2009). Figure 3.19 shows the baseline of the different GHGs.



(A) CO_2 (B) CH_4 (C) N_2O

(D) *SLF* (E) *LLF*

FIGURE 3.19: *Baseline non-energy related emissions. These emissions are an exogenous input for the emissions and climate submodel described in Section 3.2.3*

Chapter 4

Climate change mitigation

4.1 Introduction

One important challenge for global long-term sustainability is climate change. According to the Intergovernmental Panel in Climate Change (IPCC) (2007b) greenhouse gas emissions need to be stabilized to avoid undesirable temperate changes. Since the environment is a public good, markets fail to control pollution (Perman et al., 2003), thus climate policies are required to realize the stabilization of GHG emissions.

The Kyoto protocol (United Nations Framework Convention on Climate Change, 1998) was the first international agreement concerning climate change. It envisaged that "Annex I" countries[1] reduce their greenhouse gas emissions by an average of 5.2% for the period 2008-2012 (compared to 1990 levels). However, the United States did not ratified the protocol, Canada renounced in 2011, many of the countries that ratified it are far to meet the target (European Environment Agency, 2010) and many developing countries do not have a commitment. Thus, despite the establishment of the Kyoto Protocol, anthropogenic greenhouse gas emissions have shown an increasing tendency.

In 2007, the European Comission (2007) and, later in 2009, the Copenhagen accord (United Nations Climate Change Conference, 2009) established that global warming most be limited to no more than 2°C above the pre-industrial levels. According to the European Comission (2007), the 2°C "will limit the impacts of climate change and the likelihood of massive and irreversible disruptions of the global ecosystem". Although the target of a temperature increase of 2°C seems to be the guiding principle for different countries (European Comission, 2007; Meinshausen et al., 2009), this goal has to be translated into emission targets or technology policies. The European Comission (2007) establishes that this objective will require global emissions to peak within the next 10-15 years and then be cut by at least 50% of 1990 levels by 2050. However, there is some uncertainty regarding the effects on temperature from emissions (Meinshausen et al., 2009), due to uncertainties in the carbon cycle, e.g. how much time does CO_2 remain in the atmosphere; radiative forcing estimation and the contribution of other greenhouse gases; and climate responses, e.g. Knutti and Hegerl (2008) show that the climate sensitivity can vary in a range from 2.1 to 4.4 °C. An alternative climate policy target has been proposed by Meinshausen et al. (2009), they determined a probabilistic relationship between emissions

[1]According to the UNFCC, Annex I countries are industrialized countries including all the OECD countries and economies in transition

and temperature, and established that limiting cumulative CO_2 emissions from 2000 to 2050 to a maximum of 1440 $GtCO_2$ yields a 50% probability that the global temperature increase will remain below the 2°C. The Fourth Assessment Report from the Intergovernmental Panel in Climate Change (IPCC) (2007b) links temperature increase, CO_2 concentration, GHG concentration and radiative forcing targets, estimating that a temperature increase from 2.0 to 2.4°C requires an atmospheric CO_2 concentration around 350-400ppm, and translates into a radiative forcing target of 2.0-2.4 W/m^2.

However, the question of which climate policies will be established by the different governments remains highly uncertain. The Copenhagen Accord determined a global temperature increase goal of 2°C without setting a target in emissions. Many developing countries, responsible for an important part of the global CO_2 emissions[2], do not have commitments to reduce them. Thus, the uncertainty concerning the participation in global mitigating efforts and the levels of commitment is analyzed in this chapter with different scenarios on climate change mitigation with alternative stringency targets. This helps identifying technology pathways needed to achieve climate mitigation and the consequences of the different policy regimes for the sustainable Swiss energy system. Importantly, this analysis excludes additional climate factors such as air pollution and focuses on climate change mitigation. This chapter is organized as follows: In the first two sections two scenarios without climate policy intervention are presented, these scenarios are used as a reference global energy system for comparison against different scenarios. In the third and fourth section the climate mitigation scenarios are presented and the results for the global and Swiss energy systems under climate stabilization pathways are described. Finally, conclusions and the consequences for the Swiss region are presented.

4.2 Baseline scenario

The baseline scenario considers the development of the global energy system without any climate or technology policy. It corresponds to the optimal global system from an economic point of view, where MERGE-ETL estimates the optimal energy production that maximizes the global social welfare (as presented in Section 3.2.1). The scenario drivers described in Section 3.5 were applied in MERGE-ETL to quantify the economic, energy technology and emissions implications of the baseline scenario.

Figure 4.1 presents the total primary energy supply for the baseline scenario. Coal is the most used energy carrier from 2030 since coal-based conversion technologies are the least expensive alternatives, and coal has the lowest extraction cost and the highest proven reserves. This is driven by the fact that no climate policy is imposed in this scenario. Oil and gas are also used but the amount of reserves assumed in this baseline is limited, and these resources are depleted over the time horizon (with oil production peaking in 2020).

Figure 4.2 presents global and Swiss electricity production. Global demand increases considerably from 18.2 in 2005 to 108.6 TWh by 2100, driven primarily by the emerging economies (with demand decreasing for some of the slower growing regions, such as EUP, Switzerland, Russia, Japan, USA and CANZ). In terms of production, coal-based technologies are the dominant alternatives, with pulverized coal (PC) replacing existing technologies in the first half of the century and integrated gasification combined cycle (IGCC) being deployed from 2050 and representing 93% of the global electricity pro-

[2]China accounted for 21% of the global anthropogenic CO_2 emissions in 2008 (European Commission, Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL), 2009)

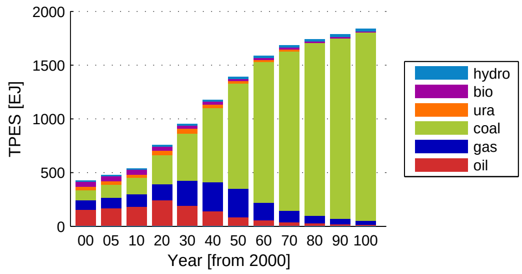
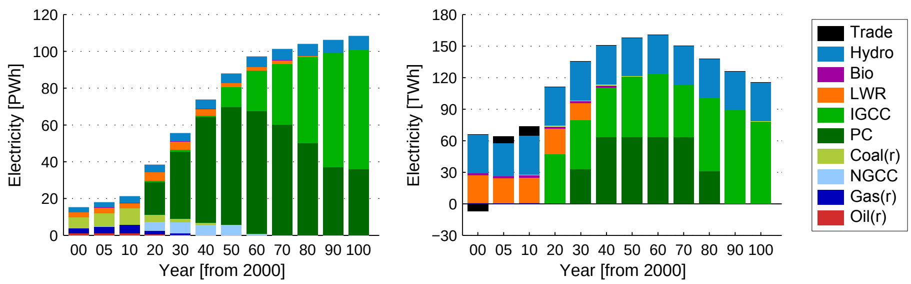


FIGURE 4.1: *Baseline scenario: Global total primary energy supply*

duction by 2100. Technology learning plays a role in making IGCC an attractive technology in the second half of the century. Nuclear technologies (note that the fast breeder reactor is not considered in this scenario) have a small share in the electricity production since coal technologies are a cheaper alternative. Natural gas combined cycle is used as a transition technology from 2020 to 2050 in those regions with high gas resources, i.e. Russia, Middle East and the ROW. Swiss electricity production, reaches a peak in 2060 of 160 TWh and decreases to 115 TWh by the end of the century. As in the other regions, in Switzerland electricity is produced mainly with coal technologies with a share of 68% in 2100. Historically Swiss electricity generation has been based mainly on hydropower and nuclear power. Additionally, the Swiss Federal Office of Energy (BFE, 2007) published four scenarios for the future Swiss energy system with different technology alternatives including nuclear, hydropower, NGCC, decentralized heat and power and renewable-based plants. In none of the scenarios coal is considered an alternative for electricity production. Therefore, a reference scenario (presented below) is developed to model a more likely future Swiss energy system, including an additional restriction on the technology options for Switzerland, to exclude coal-based electricity technologies.



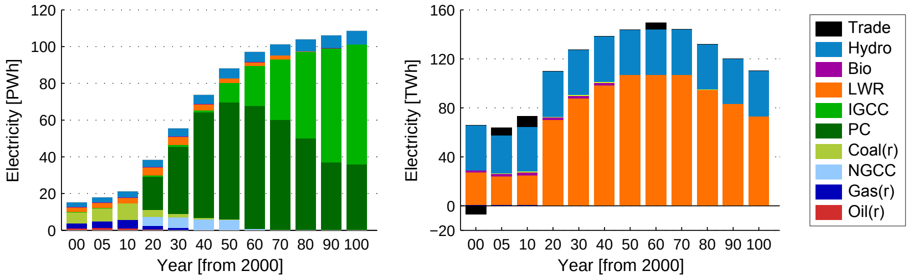
(A) *Global* **(B)** *Switzlerland*

FIGURE 4.2: *Baseline scenario: Electricity production*

4.3 Reference scenario

In the baseline scenario described above, electricity production in Switzerland is based primarily on coal technologies. However, as discussed above this in unlikely considering historical developments and current energy policies (BFE, 2007). Therefore, this reference scenario excludes coal-based technologies (IGCC and PC) from the electricity technology alternatives for Switzerland.

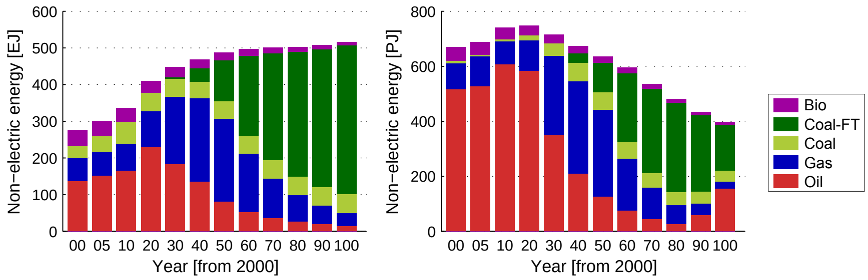
4.3.1 Energy production



(A) *Global* (B) *Switzerland*

FIGURE 4.3: *Reference scenario: Electricity production*

Global electricity production (see Figure 4.3A) remains relatively unchanged compared to the baseline scenario presented in Figure 4.2A, using mainly coal-based technologies, including PC and IGCC. Electricity production in Switzerland in the reference scenario is presented in Figure 4.3B. When coal-based technologies are not available electricity production is dominated throughout the scenario timeframe by nuclear and hydropower, as it is currently the case. Additionally, Swiss electricity demand is slightly reduced compared to the baseline, from 160 to 150 TWh in 2060 and from 115 to 110 TWh in 2100 due to slightly higher electricity costs. Wind and solar generation remain uncompetitive. There is also bilateral electricity trade with the European Union (a negative value in Figure 4.3B indicates exports to the EU and a positive value indicates imports). In 2010 and 2060 Switzerland imports 8.8 and 5.5 TWh from the EU, respectively[3].



(A) *Global* (B) *Switzerland*

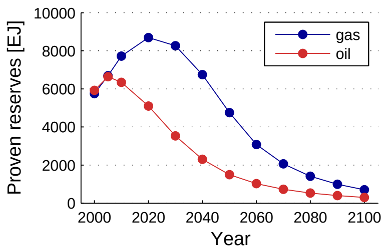
FIGURE 4.4: *Reference scenario: Non-electric energy production*

For the non-electric energy supply (see Figure 4.4A), as oil and gas reserves are depleted as shown in Figure 4.5A, synthetic oil production from coal (coal to liquids) starts playing an important role and becomes a major source of fuel by 2100. The global demand of non-electric energy increases over the projection period, although at a much slower rate than electricity demand. This is due to assumed autonomous efficiency improvements presented in Section 3.5.1 and the larger relative change in price of the non-electric energy compared to the electricity, because of the depletion of cheap oil and gas.

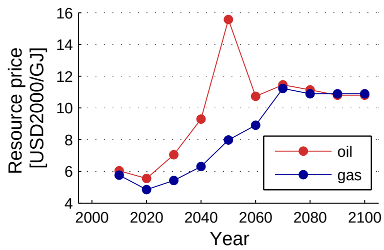
[3]Note that the period 2010 is not calibrated to the actual energy statistics, hence the values here correspond to the optimal solution rather than the historical data.

The electricity price in 2100 decreases in the different regions by 17-82% (compared to the price in 2010), while the price of non-electric energy increases by 62-89%. The growth in global non-electric demand is driven by developing regions, predominantly China, India, the Middle East and the Rest of the World, while most of the other regions have declining demand, due to the assumed population growth and efficiency improvements.

Figure 4.4B presents non-electric energy production for the reference scenario in Switzerland. It shows a reduction in demand from 748 PJ in 2020 to around 398 PJ by 2100. This decline is driven partly by the decreasing population (after 2050) and efficiency improvements; but it is accelerated by increasing international prices of non-electric energy carriers, particularly oil, which leads to additional efficiency and substitution by electricity. Although electricity production is also declining, the substitution of non-electric energy by electricity is reflected in the increasing relative share of electricity in the energy bundle. Furthermore, the depletion of oil and gas resources shown in Figure 4.5A, primarily by countries other than Switzerland, leads to a substitution of oil by gas in the first half of the century and after 2050 with coal-to-liquids[4]. After 2090, Switzerland increases the use of oil in the non-electric sector because global natural gas depletion makes it slightly more expensive than oil in 2090 and 2100 (see Figure 4.5B).



(A) *Global resources*



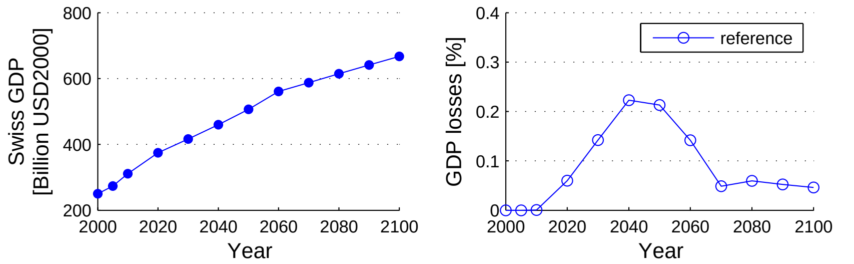
(B) *Price*

FIGURE 4.5: *Reference scenario: Oil and gas resources*

4.3.2 Realized GDP

In the first half of the century developing regions, i.e. China and India, Russia, Middle East and the ROW are the regions with the highest economic growth, e.g. in China, GDP in 2050 is 15 times the GDP in 2005. The other regions have moderate economic growth. In the second half of the century, the economic growth of the less-developed regions slows down and all the regions experience a moderate growth, i.e. regional GDP in 2100 is around 1.5 to 2.5 times the GDP in 2050. Realized GDP for the Swiss region (see Figure 4.6) increases moderately from USD2000 273 Billions in 2005 to USD2000 667 Billions in 2100. Furthermore, Figure 4.6B shows that the restriction in the use of coal results in some GDP losses for the Swiss region. The losses are higher in the periods in which the electricity generated with coal-based power plants in the baseline scenario was larger, that is from 2040 to 2060.

[4] Note that no restrictions on the contribution of synthetic oil produced from coal are included in this reference scenario.



(A) *GDP* (B) *GDP losses compared to the baseline*

FIGURE 4.6: *Reference scenario: Swiss realized GDP and GDP losses compared to baseline*

4.3.3 Emissions

In the reference scenario the energy-related CO_2 emissions increase to 174 billion tons CO_2 by 2100 and the atmospheric CO_2 concentration level reaches 1296 ppm. In the same way the atmospheric concentration of methane increases to 3811 ppb (from 1774 in 2005). This considerable increase in the energy-related emissions is due to large use of coal in the electricity and non-electric energy production. The high level of atmospheric GHG concentration, slightly compensated by the cooling effect of sulfates, leads to an increase in the radiative forcing of 9.7 W/m^2 from pre-industrial levels to 2100. The improved climate submodel, presented in Section 3.2.3, allows the estimation of the potential and temperature increases. The potential temperature increase from 2000 to 2100 is 5.8°C, however the heat uptake by the ocean is likely to reduce this increase, producing an actual global temperature increase of 4.9°C from 2000 to 2100, corresponding to approximately 5.5°C from pre-industrial levels.

Energy-related emissions in Switzerland in the reference scenario (see Figure 4.7) come mainly from the non-electric energy production since electricity is generated with low-carbon technologies (nuclear and hydro). Swiss energy emissions peak in 2070, where the largest amount of synthetic fuel from coal is produced, and decreases afterwards when coal-FT is partly replaced with oil products.

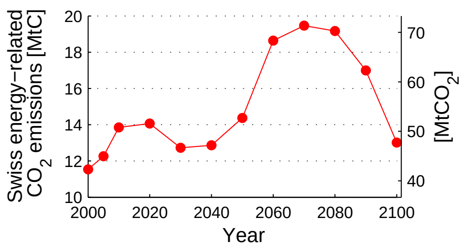


FIGURE 4.7: *Reference scenario: Energy related CO_2 emissions in Switzerland*

4.4 Climate stabilization pathways

Different scenarios have been analyzed in the literature for climate stabilization. Table 4.1 summarizes different scenarios presented in the Fourth Assessment Report from the Intergovernmental Panel in Climate Change (IPCC) (2007b). This table shows the link between radiative forcing, CO_2 concentration in the atmosphere, CO_2-equivalent concentration and temperature increase.

TABLE 4.1: *Summary of CO_2 stabilization scenarios by 2100. Based on Intergovernmental Panel in Climate Change (IPCC) (2007b)*

Radiative forcing [W/m^2]	CO_2 concentration [ppm]	CO_2-equivalent concentration [ppm]	Global mean temperature increase* [°C]
2.5-3.0	350-400	445-490	2.0-2.4
3.0-3.5	400-440	490-535	2.4-2.8
3.5-4.0	440-485	535-590	2.8-3.2
4.0-5.0	485-570	590-710	3.2-4.0
5.0-6.0	570-660	710-855	4.0-4.9
6.0-7.5	660-790	855-1130	4.9-6.1

* Using "best estimate climate sensitivity"

In this thesis, the different climate change scenarios are defined using radiative forcing (rf) targets. These targets can be translated to CO_2 concentration or temperature increase using the climate submodel of MERGE-ETL. The advantage of using radiative forcing targets is that they give the model the flexibility to decide the optimal emission pathways, which brings important insights for policy makers concerning emissions targets and technology deployment. Temperature targets have also this flexibility but they depend on the chosen climate sensitivity that includes an additional element of uncertainty to the analysis (Knutti and Hegerl, 2008). Table 4.2 presents the different long-term radiative forcing targets analyzed in this thesis. These pathways include those proposed in the Representative Concentration Pathways (RCPs)(van Vuuren et al., 2011a) and some additional scenarios based on the Intergovernmental Panel in Climate Change (IPCC) (2007b). The RCPs are four pathways developed by the climate modeling community for long and near-term analyses. In all scenarios MERGE-ETL determines the optimal technology combination from a global social planer perspective that maximizes global welfare; that is, it determines "when", "where" and "how" abatement is undertaken to achieve the global target.

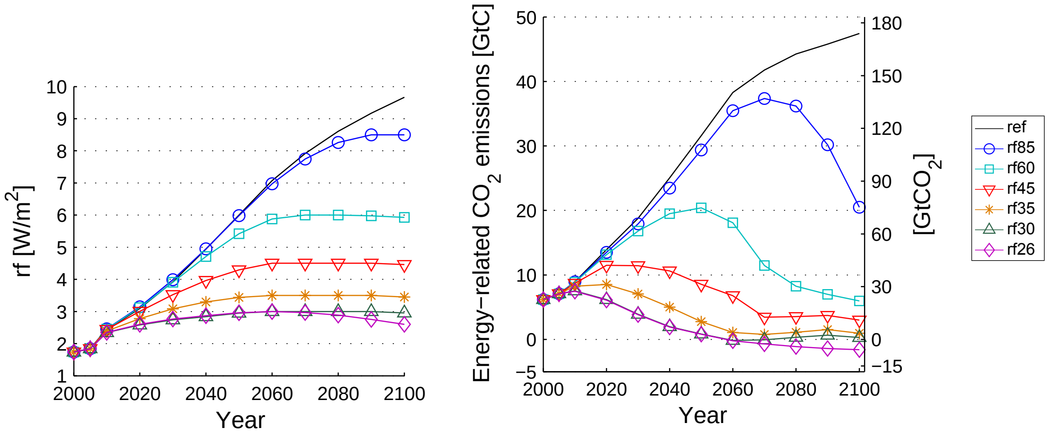
TABLE 4.2: *Climate stabilization scenarios*

Name	rf26	rf30	rf35	rf45	rf60	rf85
Radiative forcing target by 2100 [W/m^2]	2.6	3.0	3.5	4.5	6.0	8.5

4.4.1 Global energy system under climate stabilization pathways

The long term radiative forcing stabilization targets presented in Table 4.2 represent different global policy alternatives and imply different radiative forcing and emissions pathways as shown in Figure 4.8A. The most stringent scenario has an overshoot in radiative forcing up to 3 W/m^2 in 2060 and just in the last two periods the radiative forcing decreases reaching 2.6 W/m^2 by 2100. The other pathways reach the target by 2100 without an overshoot.

Figure 4.8B presents the energy-related emission for each scenario. The more stringent the radiative forcing target, the earlier the peak in energy-related emissions occurs (see Table 4.3). The rf60 scenario has a peak in emissions by 2050 of 74.8 $GtCO_2$, while the most stringent scenario has a peak in 2010. Besides the earlier action needed in the stringent pathways, the longer-term emissions trajectory also



(A) *Radiative forcing*　　(B) *CO_2 energy-related emissions*

FIGURE 4.8: *Climate scenario: Radiative forcing and CO_2 emissions*

exhibits substantial differences. By 2050, energy-related emissions in the scenarios rf26, rf30 and rf35 are lower than the 2000 level. Table 4.3 presents the change in 2050 emissions as a percentage of emission in 2000. It shows that after 2050 the most stringent scenario requires negative emissions, while scenarios rf30 and rf35 reach almost zero energy-related emissions after 2070. Negative emissions can be achieved by the deployment of biomass technologies with carbon-capture and storage.

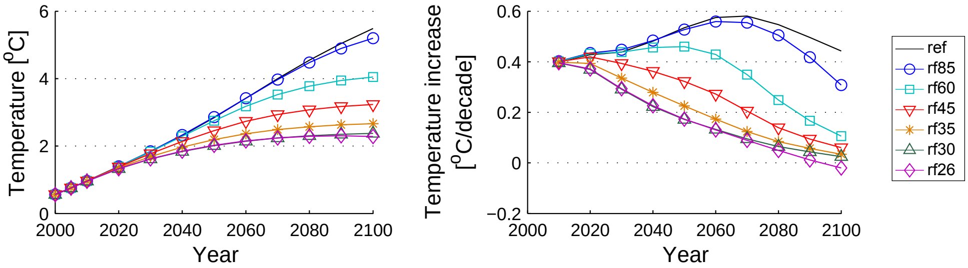
TABLE 4.3: *Climate scenarios: Energy-related emissions*

		rf26	rf30	rf35	rf45	rf60	rf85
Maximum emissions	Year	2010	2010	2020	2020	2050	2070
	Emissions [$GtCO_2$]	27.4	27.6	31.3	42.1	74.8	137
Change in 2050 emissions [% 2000 emissions]		-87.1	-86. 6	-55.3	38.6	230.6	376.2

The temperature changes obtained in the model with these radiative forcing targets are presented in Figure 4.9A. Scenarios rf26, rf30 and rf35 reach a global mean temperature change close to 2.3 and 2.7°C relative to pre-industrial levels (around 1.8 to 2.2°C over 1990 levels), slightly above the temperature target of the Copenhagen Accord (United Nations Climate Change Conference, 2009) of 2°C above pre-industrial levels. The other scenarios lead to mean temperature increases between 3 and 5.2°C, changes that are likely to have important consequences for human health, food and water supply, sea level rise and industry (van Vuuren et al., 2011c). The new calibration of the climate submodel developed in this thesis, brings a more accurate calculation of the temperature increase due to the different emission pathways. Figure 4.9B presents the temperature increase per decade for the different long term radiative forcing targets.

Global demand reductions

The emission pathways presented above have different effects on the energy system. The first consequence (as seen also in Section 4.5) is the reduction in both electricity and non-electric energy demand. Compared to the reference scenario (see Table 4.4) both electricity and non-electric energy



(A) *Temperature* **(B)** *Temperature increase*

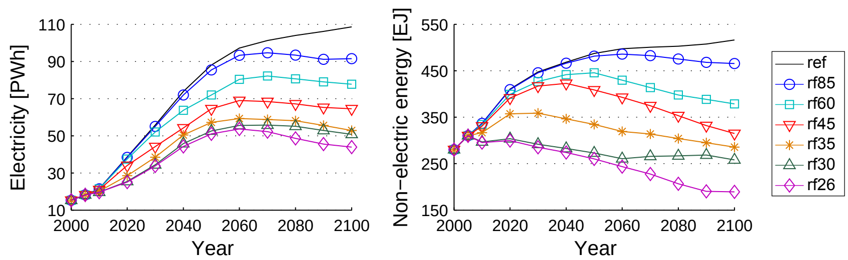
FIGURE 4.9: *Climate scenario: Temperature change*

demand are reduced considerably. These reductions imply important efficiency achievements and produce lower economic outputs.

TABLE 4.4: *Climate scenarios: Demand reductions compared to reference scenario*

		rf26	rf30	rf35	rf45	rf60	rf85
Electricity	2050 [%]	42.1	40.3	35	26.7	18.3	3
	2100 [%]	59.6	53.2	51.3	40.5	28.4	15.8
Non-electric energy	2050 [%]	46.6	44	31.3	16.2	8.6	1.2
	2100 [%]	63.4	50	44.7	39	26.7	9.8

Moreover, in the stringent climate stabilization pathways non-electric energy is substituted with electricity, due to higher availability of low-carbon technologies in the electricity sector. Figure 4.10 presents the global electricity and non-electric energy demand in the climate scenarios. In all scenarios, electricity demand continues to grow over the projection period while non-electric energy demands in the most stringent scenarios decrease to levels lower than the 2000 value. For instance, in rf26 and rf30 non-electric energy demand declines to below 2000 levels from 2040. This electrification of the non-electric energy sector will most likely imply the deployment of electric vehicles or heat pumps for heating[5].



(A) *Electricity* **(B)** *Non-electric energy*

FIGURE 4.10: *Climate scenarios: Global energy demand*

[5]MERGE-ETL does not model final energy demand, see Weidmann et al. (2009) and Gül (2008) for more detailed models of the end-use technologies in Switzerland and globally, respectively

Technology pathways

Besides the reduction in energy demand, the climate stabilization pathways require changes in the technology deployment to supply the demand. Figure 4.11 compares the technology breakdown of global electricity production in selected periods across the scenarios. The increase in the stringency of the climate stabilization target produces a transformation in the electricity production from coal based technologies to renewables, nuclear and gas with carbon capture.

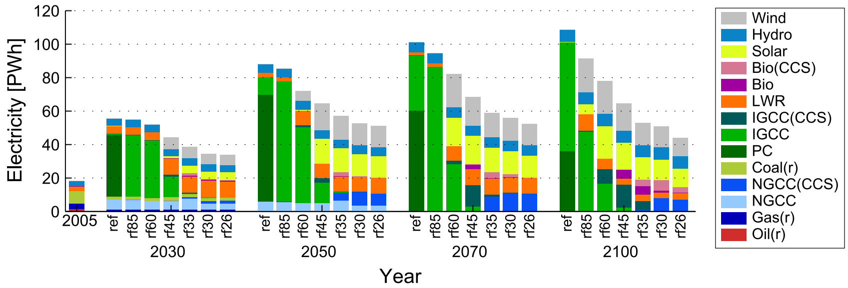
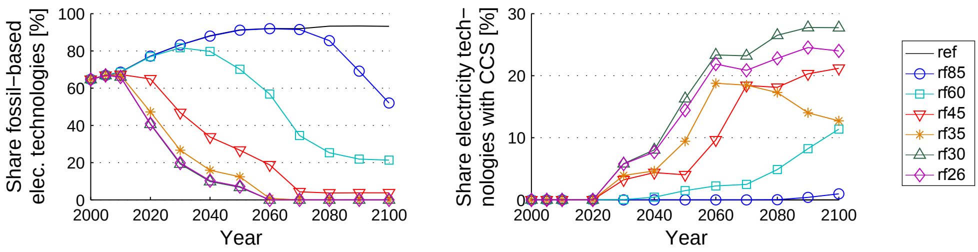


FIGURE 4.11: *Climate scenarios: Technology mix in global electricity production*

Fossil-based electricity generation is reduced with the increase in the stringency of the radiative forcing target. Figure 4.12A shows the share of fossil-based technologies (without CCS) in all the climate mitigation scenarios. The share of electricity produced from fossil fuels in 2100 is reduced from 93% in the reference scenario to 0% in rf26. Coal technologies (Integrated gasification combined cycle (IGCC) and pulverized coal (PC) without CCS) are not deployed in the most stringent scenarios (rf26 and rf30), while IGCC continues being an attractive option in the less stringent ones (rf85 and rf60). In all the scenarios, the natural gas combined cycle (NGCC) is used as a transition technology from 2020 to 2050. Carbon capture and storage becomes an important alternative to supply electricity demand when climate targets are imposed. Figure 4.12B presents the share of carbon capture technologies across all the scenarios. While in the reference and rf85 scenarios CCS technologies are not deployed, in the other scenarios carbon capture technologies, based on coal or natural gas, account for a considerable share of electricity generation after 2030, reaching 10 to 30% by 2100. The deployment of carbon capture technologies is limited by the availability of storage (see Table 3.13). When comparing the most stringent scenarios the total CCS in the electricity sector is less in rf26 than in rf30 because the storage capacity is used for the stored carbon coming from the non-electric sector (see Figure 4.16A). Trading of captured CO_2 among regions for storage purposes is not modeled in this thesis.

In all climate stabilization scenarios, except rf85, independently of the target, renewable technologies (wind, solar, hydro and biomass) are deployed to their maximum potential by the end of the projection period. The main difference across the scenarios is the time in which they are introduced. Figure 4.13 shows the share of renewable-based technologies (including biomass) in the different scenarios. In the reference scenario the only renewable technology deployed is hydropower and it represents 6.8% of the global electricity generation in 2100; whereas for the radiative forcing target pathways renewable technologies reach a share of 60 to 80%. Wind technology starts being largely deployed from 2020 in all world regions in all scenarios with a target lower or equal than 4.5 W/m^2, while the solar technology is deployed slightly later.

Nuclear power plays an important role in achieving the climate stabilization target but its deployment



(A) *Fossil-based technologies* **(B)** *Technologies with CCS*

FIGURE 4.12: *Climate scenarios: Share of fossil-based technologies in electricity generation*

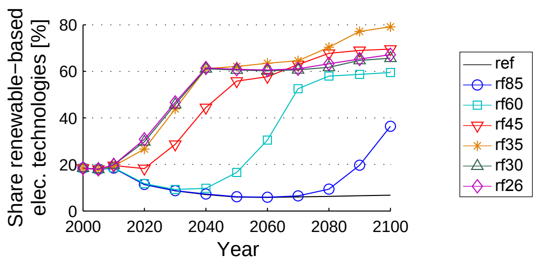
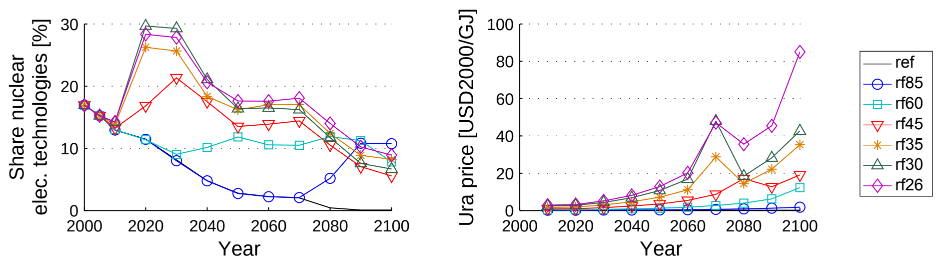


FIGURE 4.13: *Climate scenarios: Share of renewable-based technologies in electricity generation*

is reduced after 2070 due to high uranium prices (see Figure 4.14) coming from the global depletion of uranium resources. One technology option that has the potential to overcome this depletion is the Fast Breeder Reactor, which can use depleted and reprocessed uranium as well as plutonium besides natural uranium. The potential role of such a technology, assuming it is publicly acceptable, is discussed in Chapter 6.



(A) *Share in electricity generation* **(B)** *Uranium price*

FIGURE 4.14: *Climate scenarios: Share of nuclear technologies in electricity generation and uranium price*

In the production of non-electric energy (see Figure 4.15), the increasing stringency of the radiative forcing targets leads to a shift from synthetic fuel from coal to hydrogen, gas and oil products. Hydrogen is produced mainly with coal gasification (coal-H2) with carbon capture and sequestration (CCS), biomass gasification and solar-thermal thermochemical processes (sth-H2). Coal-H2 is used due to its low cost and the possibility of CO_2 sequestration; and sth-H2 becomes an attractive technology for climate change mitigation due to global technology learning. The deployed hydrogen technologies in the climate stabilization scenarios imply the production of hydrogen in mid- or large-scale facilities and its distribution to the consumers using a hydrogen infrastructure.

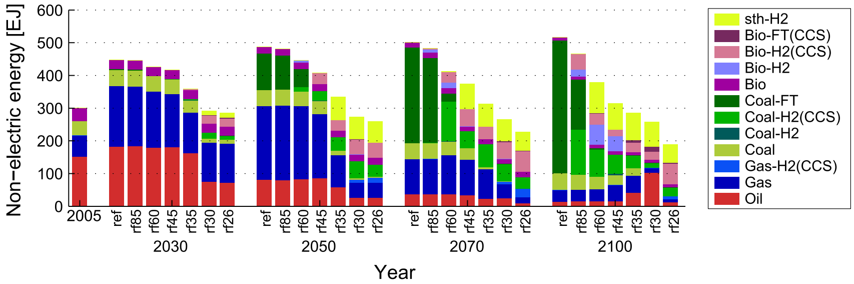
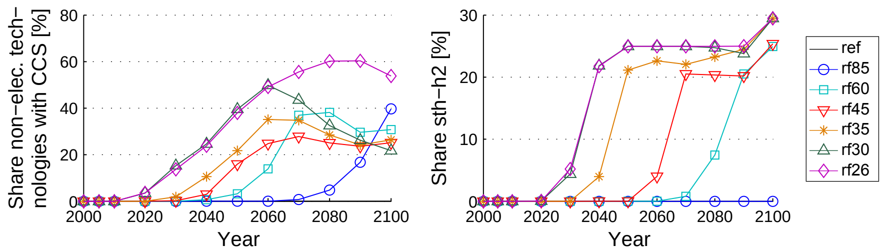


FIGURE 4.15: *Climate scenarios: Technology mix in global non-electric energy production*

As in the electricity sector, carbon capture and storage technologies have an important role in the production of non-electric energy, especially in the production of hydrogen. Figure 4.16B shows the share of technologies with CCS in the non-electric energy sector. The share in the two most stringent scenarios has an important difference, being higher in rf26 due to the additional need of reducing emissions in rf26 by the end of the century, which requires the use of biomass technologies with carbon capture. Finally, Figure 4.16B shows how the importance of solar thermal production of hydrogen increases substantially with the stringency of the long-term target. It becomes one of the most deployed technologies to supply the non-electric energy demand by the end of the century in almost all scenarios.

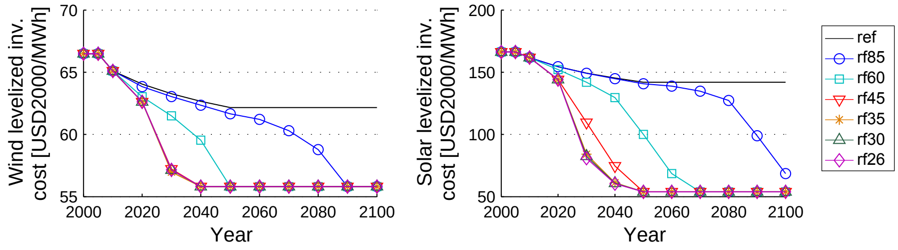


(A) *Technologies with CCS* (B) *Solar thermal hydrogen*

FIGURE 4.16: *Climate scenarios: Share of technologies in non-electric energy production*

Global technology leaning

One important feature of the MERGE-ETL model (described in Section 3.2.2) is the possibility of accounting for improvements to the technologies. Figure 4.17 presents the levelized investment cost for the wind and solar technologies in the different climate scenarios. These two technologies have a large learning potential and both of them reach the floor investment costs in all scenarios with stringent or relatively stringent long term targets. Neither solar nor wind are deployed in the reference scenario and have a small contribution in the rf85 scenario. For this reason, their levelized investment costs remain high in these two cases. The slight decrease in the reference scenario is due to some research and development efforts done in some world regions and in rf85 is due to only learning-by-searching until 2050 and both learning-by-doing and learning-by-searching in the second half of the century.

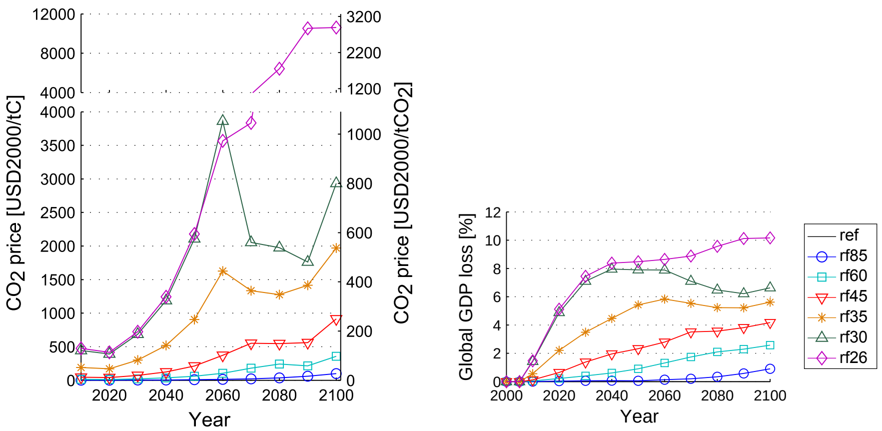


(A) *Wind* (B) *Solar*

FIGURE 4.17: *Climate scenarios: Levelized costs of wind and solar technologies*

Carbon price and economic impact

Figure 4.18 presents the carbon price[6] and the GDP loss for the climate scenarios. The carbon price in MERGE-ETL corresponds to the shadow price of the emissions constrain, and represents the cost of an additional unit of CO_2. The rf26 scenario has a considerably higher carbon price than the other scenarios at the end of the projection period, reaching around 3000 USD/tCO_2. This is because the higher stringency implies larger energy demand reductions late in the century together with the depletion of the cheaper energy carriers, especially uranium. Carbon price in the rf30 and rf26 scenarios are similar until 2050. This is due to the overshoot in the first periods to 3 W/m^2 in the rf26 scenario, which implies that the energy systems in both scenarios are almost identical in the first periods. The rf35 has a rapidly increase in the carbon price from 2030, reaching around 400 USD/tCO_2 in 2060. This increase comes from investment in expensive technologies, such as solar PV, wind, biomass and NGCC(CCS). The other three scenarios (rf45, rf6 and rf85) have relatively low carbon price, that reach 249.6, 97.7 and 27.3 USD/tCO_2 in 2100, respectively.



(A) *CO_2 price* (B) *GDP loss*

FIGURE 4.18: *Climate scenarios: Carbon price and global GDP loss*

The GDP losses have a behavior similar to the carbon price, with very high losses for the rf26 scenario, reaching around 10% by 2100. The less stringent scenarios rf85, rf60 and rf45 show an increasing tendency in the GDP losses, reflecting the increasing need in changes to the energy system towards a low-CO_2 production. However, the scenarios rf35 and rf30 have decreasing losses from 2060, showing

[6]Note that the y-axis in this plot is divided in 2 different scales to allow the comparison among the different scenarios

that more stringent scenarios require earlier action. In these analyses we have not included the savings due to avoided damages for the estimation of the realized GDP.

As shown in Figure 4.18, the increase in emissions abatement implies higher economic cost. However, it is possible that the emissions abatement obtained with the most stringent stabilization targets is not optimal and adaptation strategies become an interesting option. To analyze the efficiency of the different climate targets we use the abatement curve in Figure 4.19, which compares cumulative abatement until 2100 with the economic costs (calculated as cumulative GDP losses by 2100). The curve shows a reduced efficiency of the policies when the target is more stringent than 3.5 W/m^2, since the marginal abatement costs are considerably higher, consistent with the carbon prices shown in Figure 4.18. Comparing scenarios rf26 and rf30 the increase in CO_2 abatement is almost zero while the GDP losses increase by around 400 Trillion USD2000.

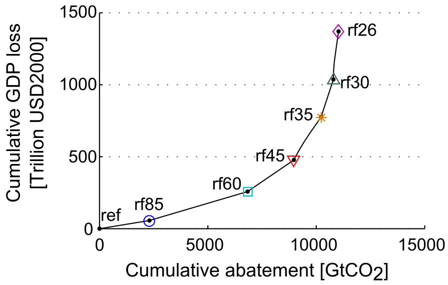


FIGURE 4.19: *Climate scenarios: Cumulative abatement curve*

4.4.2 Swiss region under global stabilization pathways

The different global radiative forcing targets imply different pathways for energy system development and energy-related emissions in Switzerland. Figure 4.20 shows the emissions pathways for each global radiative forcing target. The climate stabilization scenarios reach a CO_2 emissions level by 2100 between 0 and 10.8 $MtCO_2$. The OcCC (2007) proposed a domestic target for Switzerland of reducing greenhouse gas emissions by 60% in 2050 (compared to 1990 levels), approximately 17.6 $MtCO_2$[7]. Swiss emissions are 24.8 and 0 $MtCO_2$ in the scenarios rf45 and rf35, respectively. Therefore, the Swiss emissions target proposal is consistent with a global target between 3.5 and 4.5 W/m^2.

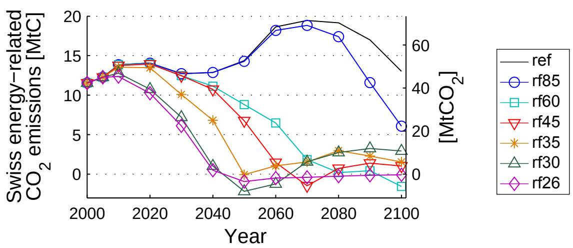
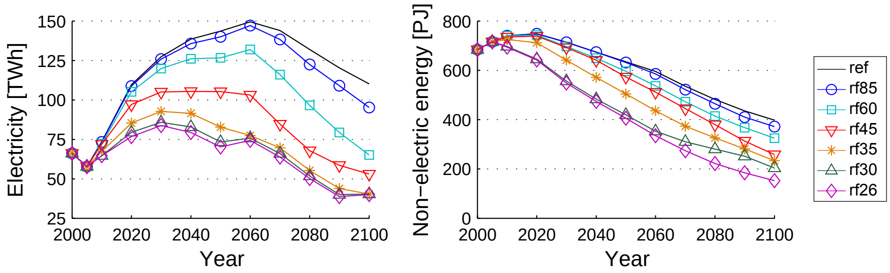


FIGURE 4.20: *Climate scenarios: Energy-related CO_2 emissions in Switzerland*

[7] In 1990, energy related CO_2 emissions were 44.043 $MtCO_2$ (Swiss Federal Office of Environment (BAFU), 2012b)

In the Swiss region, the climate stabilization pathways, as in the global case, need efficiency improvements on the demand side, reflected in the reduction of energy demand (see Figure 4.22). Although both electricity and non-electric demands are reduced when imposing the climate targets, in Switzerland, as in the rest of the world, non-electric energy is replaced with electricity.



(A) *Electricity* (B) *Non-electric energy*

FIGURE 4.21: *Climate scenarios: Energy demands in Switzerland*

Regarding the technology breakdown, electricity in Switzerland is produced in all scenarios mainly with nuclear power and renewable-based technologies, which are deployed to their maximum potentials after 2050. The stringent climate targets imply the depletion of uranium resources due to the larger use of nuclear generation in other world regions, such as India, China and the USA, which increases uranium prices and, hence, nuclear power is not used in the Swiss region in the last periods. NGCC(CCS) is used as a transition technology from 2040 to 2060 in the 2 most stringent scenarios. In rf35, rf30 and rf26 Switzerland exports around 10.7 TWh to the EU in 2090 and 2100 due to the relatively high potential of renewable resources in Switzerland.

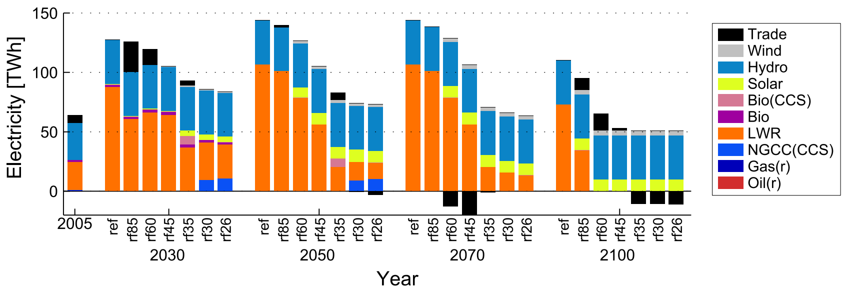


FIGURE 4.22: *Climate scenarios: Electricity generation in Switzerland*

Regarding non-electric energy production, coal-FT used in the reference scenario is replaced by hydrogen technologies, mainly biomass gasification with and without carbon capture; and, in some periods, imports of hydrogen from the EU. These results show that a hydrogen economy is an alternative solution to supply non-electric energy demand, especially for the transportation sector. However, a hydrogen economy requires considerable efforts for the development of the appropriate infrastructure for the distribution of the hydrogen (not modeled in MERGE-ETL).

The energy demand reductions and the development of a renewable and hydrogen economy have impacts on the Swiss economic output. Figure 4.24 shows the GDP losses for the climate stabilization scenarios compared to the reference scenario. The losses vary from 2 to 4% by 2100 but the three most

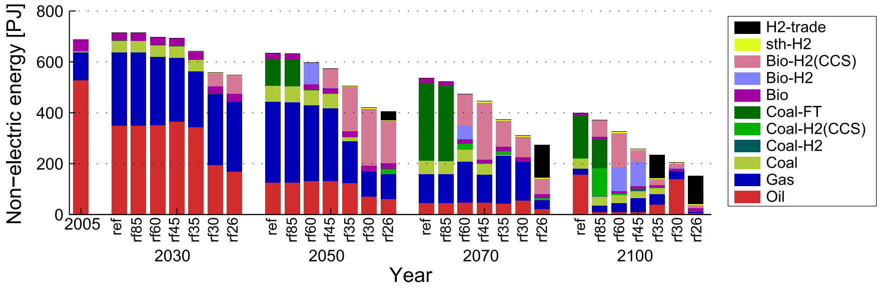


FIGURE 4.23: *Climate scenarios: Non-electric energy production in Switzerland*

stringent scenarios have a higher peak in economic losses by 2060 (and rf26 in 2070) of 5.8, 7.8 and 8.9% for rf35, rf30 and rf26, respectively, due to lower uranium availability compared to the reference scenario and the larger deployment of hydrogen technologies. GDP losses in Switzerland are always lower than global losses because the electricity sector in Switzerland was already decarbonized in the reference scenario.

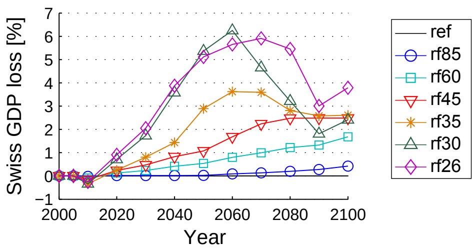


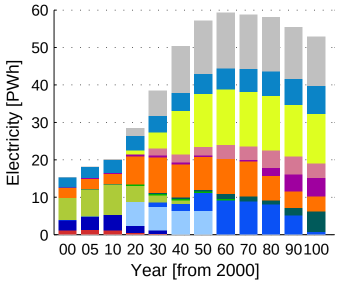
FIGURE 4.24: *Climate scenarios: Swiss GDP losses*

4.5 Reference climate stabilization scenario

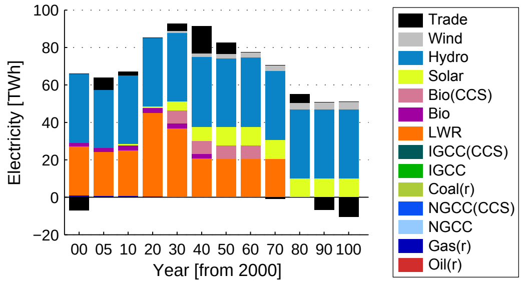
According to the EU climate policy (European Comission, 2007), emissions should peak in the next 10 years and reach a level in 2050 of half the level in 1990. As shown in Figure 4.8B, the scenario with a radiative forcing limit of 3.5 W/m^2, has a peak in emissions by 2020 of 31.3 $GtCO_2$ and reaches a level of emissions in 2050 of 10.1 $GtCO_2$. Since, the peak in emissions occurs in 2020 and the global energy-related emission by 2050 corresponds to approximately 49% the global energy-related emissions in 1990 (20.5 $GtCO_2$ according to European Commission, Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL) (2009)) this case is a good representation of the European objectives translated to a global scale. Thus, the rf35 scenario was chosen as the reference climate stabilization scenario in this thesis[8]. This reference climate scenario represents a middle stringency target that leads to an increase in global temperature of around 2.66°C using the climate sensitivity of 2.3°C. A more stringent scenario aiming to achieve the EU climate target of a maximum temperature increase of 2°C (European Comission, 2007) would imply radical changes to the energy system with high economic costs that might not be realizable.

[8]The scenarios presented in the following chapters use this radiative forcing target as the climate policy target.

Figure 4.25 presents global and Swiss electricity production in the reference climate stabilization scenario. As described in the previous section, the achievement of the radiative forcing target implies a considerable deployment of renewable and nuclear technologies; and natural gas generation with and without carbon capture (NGCC and NGCC(CCS), respectively) is used as a transition technology. Nuclear generation represents around 16% of the total electricity generation by 2050 and 8% by 2100. This decrease in the share of nuclear generation is related to the global depletion of natural uranium. Renewable based technologies represent 60% and 64% of the global electricity generation by 2050 and 2100, respectively.



(A) *Global*



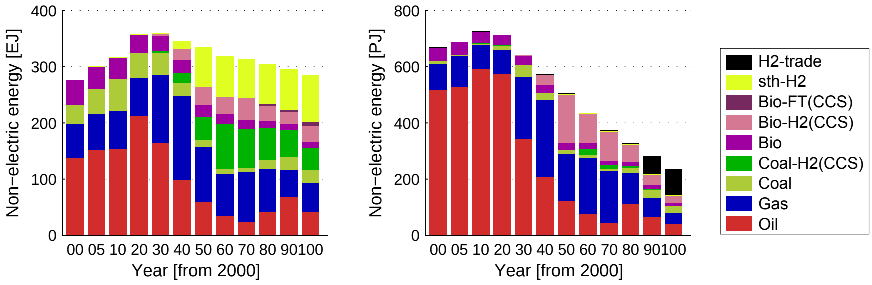
(B) *Switzerland*

FIGURE 4.25: *Reference stabilization scenario: Electricity production*

Although electricity generation in Switzerland in the reference scenario was already decarbonized (see Figure 4.3B) the global target has important consequences in Switzerland. Particularly, higher prices of uranium, coming from depletion and demand in other world regions, such as India, China and the USA, lead to lower development of nuclear generation, implying a reduction in the Swiss electricity demand of 42 and 64% by 2050 and 2100, respectively; and the incorporation of biomass with CCS, solar and wind in the electricity mix after 2030.

Regarding the non-electric energy production (see Figure 4.26) this scenario has an important contribution from hydrogen produced from biomass, solar thermal processes and coal gasification. Global and Swiss non-electric energy demand are reduced compared to the reference scenario by 31% (20% in Switzerland) and 45% (42% in Switzerland) in 2050 and 2100, respectively, thus non-electric energy demand by 2100 is approximately equal to the demand in 2000. In the last two periods, imports of hydrogen from the EU to Switzerland constitute an important share of Swiss non-electric energy supply. This is driven by depletion of global oil and gas resources and the global learning of the solar-thermal hydrogen technology.

As shown in Figure 4.18, the reference climate scenario (rf35) has an initial (2010-2020) carbon price of 50 USD/tCO_2, which increases rapidly reaching around 400 USD/tCO_2in 2060. This increase comes from investment in expensive technologies, such as solar PV, wind, biomass and NGCC(CCS), which are deployed on a large scale after 2030. The reference climate scenario has GDP losses that increase by around 1 percentage point per decade until 2060 and then remain relatively constant until the end of the projection period.



(A) *Global* (B) *Switzerland*

FIGURE 4.26: *Reference stabilization scenario: Electricity production*

4.6 Carbon taxes

A climate policy that results from the different radiative forcing target scenarios is a carbon tax. A global carbon tax, as a representative global climate mitigation measure that can encompass different instruments, such as carbon trading, regional emissions caps, etc. is analyzed in this section. The carbon tax is based on the carbon price from the reference climate scenario (see Figure 4.27). By 2020, the carbon tax has a value of 50 USD2000/tCO_2; which increases substantially to 450 USD2000/tCO_2 in 2060 and it is assumed to remain constant from that year. However, as a policy closer to the reality of the climate mitigation debate, a case in which just Switzerland and the EU apply this tax from 2010 and the rest of the regions imposed it with a delay of 30 years is also analyzed (1stMove in Figure 4.27).

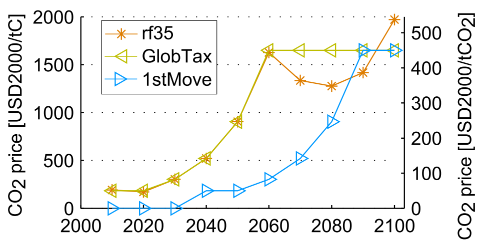
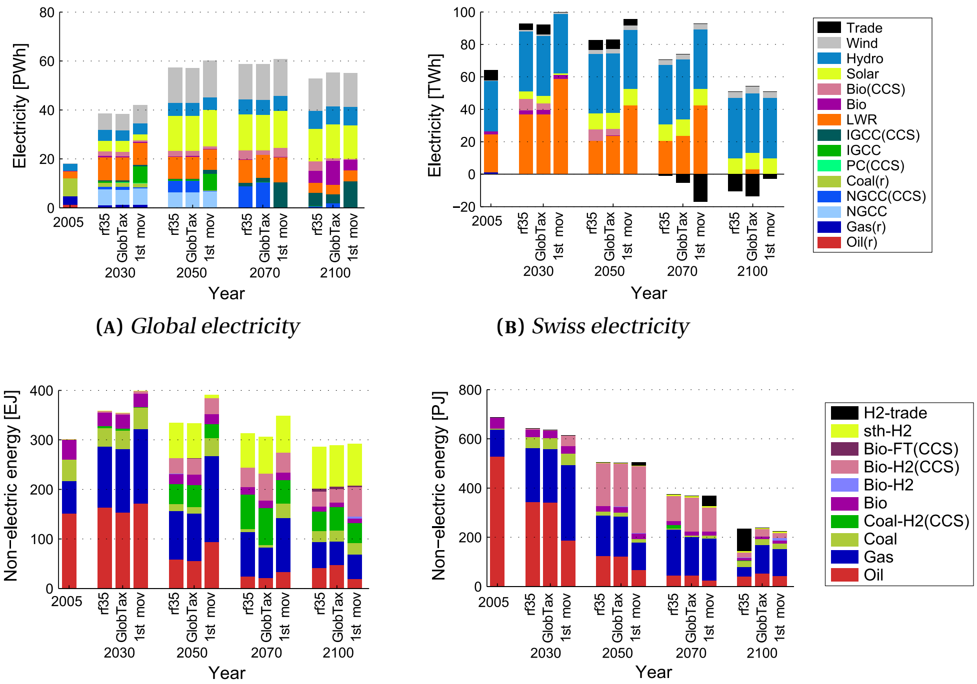


FIGURE 4.27: *Climate scenarios: carbon tax scenarios*

The consequences to the energy production of the tax scenarios are presented in Figure 4.28. The global tax case is almost identical to the reference climate scenario, since the carbon tax corresponds to the obtained carbon price, showing that this stringent climate policy would require a considerably high carbon tax of 450 USD2000/tCO_2 in the second half of the century. This carbon tax would incentive the deployment of renewable-based technologies to produce electricity and hydrogen to supply the non-electric energy sector. The first move scenario shows that the initial absence (until 2030) of a climate policy in the world regions different than EU and Switzerland results in a substantial increase in the use of coal-based technologies in the electricity sector and oil and gas for non-electric energy supply. This has an important effect for Switzerland, since additional uranium resources in the first 30 years allow a larger deployment of nuclear-based electricity, showing some first mover advantage.

Finally, these climate policies have economic implications. Figure 4.29 presents the global and Swiss cumulative abatement curves. The global tax scenario has relatively high GDP losses and abatement

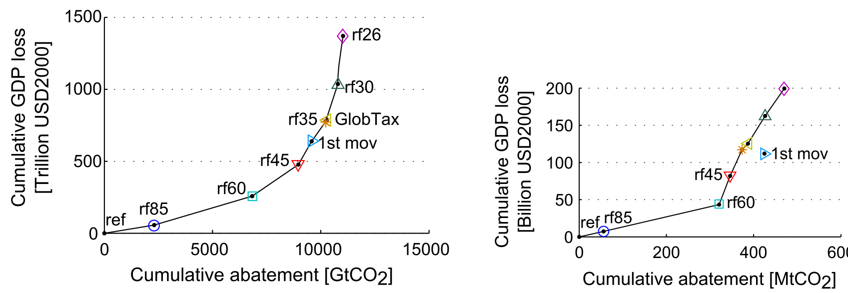


(A) *Global electricity* (B) *Swiss electricity*

(C) *Global non-electric energy* (D) *Swiss non-electric energy*

FIGURE 4.28: *Carbon tax scenarios: Energy production*

levels compared to the reference climate scenario since the tax is higher than the carbon price in rf35 after 2060. On the other hand, the first move scenario has lower global GDP losses and abatement, showing the decrease in the efficiency of this policy when it is not applied on a global level. For Switzerland, this scenario implies additional abatement without increasing the GDP losses, showing again the first move advantage mentioned above.



(A) *Global* (B) *Swiss*

FIGURE 4.29: *Carbon tax scenarios: Cumulative abatement curves*

4.7 Discussion

4.7.1 Reference scenario

The reference scenario illustrates a mechanism by which options for the Swiss energy system are affected by global factors, including the available oil and gas resources, and the rates of energy demand growth in other regions (which is driven in turn by economic growth and technological developments). Schulz (2007) and Weidmann et al. (2009), as part of the Energie Trialog Schweiz, analyzed previously a baseline (and other) scenarios of the Swiss energy system. They used a Swiss MARKAL model in their analysis. MARKAL is a bottom-up model with a highly detailed description of the energy sector and end-use demands. However, compared to MERGE, the linkages between economic activity and energy demand are not modeled explicitly; that is, energy prices and service demands are exogenous. In addition, Swiss MARKAL is a domestic model and does not account endogenously for the influence of several global factors represented in MERGE. Therefore, the results of these two models are not expected to be identical. Schulz (2007) presents a baseline scenario in which electricity production reaches around 78 TWh by 2050 and it is mainly produced with hydropower and nuclear, with shares of 57% and 32%, respectively. These shares are similar to those obtained in the reference case here, but the absolute value is smaller. This is due to lower GDP projections in Schulz (2007) and greater substitution of non-electric energy with electricity in the results presented here driven, as mentioned above, by high prices of non-electric energy carriers. Weidmann et al. (2009) present a baseline scenario with an electricity production by 2050 of 83 TWh. Once again, the reasons for the lower electricity demand are lower GDP assumptions and less substitution of non-electric energy with electricity. Another important difference is that NGCC plays an important role in the electricity generation in Weidmann et al. (2009), with a share of approximately 27% in 2050. The remaining 73% corresponds to nuclear and hydropower generation. In the reference scenario in this thesis, NGCC does not contribute to electricity generation in Switzerland. This is due to the impact of global resource availability that is not modeled endogenously in the analysis of Weidmann et al. (2009). Natural gas is a scarce resource that is demanded by other world regions and sectors, leading to higher prices that make NGCC uncompetitive for electricity generation in Switzerland. The gas price assumed by Weidmann et al. (2009) is 5.7 USD2000/GJ in 2050 compared to the 8 USD2000/GJ obtained in the reference scenario in this dissertation. This highlights the additional insights provided by a global model such as MERGE, to complement more technologically detailed domestic analyses of Switzerland in studies such as Schulz (2007) and Weidmann et al. (2009) that provide important inputs concerning final demand technologies for different sectors, such as residential, transportation, industry and services.

4.7.2 Emissions targets and global agreements

The different radiative forcing stabilization targets can be translated into emission targets for climate policies. Energy-related CO_2 emissions increase to 174 billion tons CO_2 by 2100 in the reference scenario, which is a very high emission level due to the large use of coal-based technologies in both the electricity and the non-electric energy sectors. However, this scenario assumes no climate policy in all world regions, which is considerably unlikely since different regional policies are taking place to avoid production of CO_2. Indeed, the emission levels in the scenarios with climate change mitigation targets are substantially lower, even in the less stringent case, where emissions in 2100 are 75.1 billion tons CO_2. Carbon emissions and atmospheric concentration by 2100 are summarized in Table 4.5, showing the different climate policy alternatives needed to achieve the different long-term radiative forcing targets.

TABLE 4.5: *Climate stabilization scenarios: 2100 CO_2 emissions and atmospheric concentration*

Scenario	ref	rf85	rf60	rf45	rf35	rf30	rf26	GlobTax	1stMove
Emissions[GtCO_2]	173.9	75.1	21.9	10.9	3.5	1.1	-5.9	6.1	3.1
Concentration[ppm]	1296	1063	680	522	434	395	372	430	473

Furthermore, the first move case shows how a delay in global action would imply additional efforts in the later periods and even with those efforts the atmospheric CO_2 concentration is substantially higher than with a coordinated global action. This result shows an important need for international agreements to achieve climate change mitigation, and the role that developed countries (or regions) such as the EU and Switzerland can play is fundamental to lead the discussion and demonstrate the feasibility of different policies and measures.

4.7.3 Energy efficiency and electrification

Stringent climate stabilization pathways imply both globally and in Switzerland a reduction in non-electric energy and electricity demand and a substitution of non-electric energy with electricity. The reduction in energy demand requires energy efficiency improvements on the demand side, that is, in end-use technologies in the residential, industrial, services and transport sectors; and some reduction in economic activity. MERGE-ETL does not model end-use technologies, instead a substitution between capital and energy demand is used to model this improvement in the technologies. However, the feasibility of large demand reductions remains uncertain given the increase in global population and the possible increase in economic output, especially in developing regions.

Furthermore, the electrification of the non-electric energy sector will most likely imply the deployment of electric technology alternatives to supply non-electric energy demands, such as electric vehicles for transportation or heat pumps for space heating. This is also the case in Switzerland in which the decarbonization of the space heating and transportation is likely to imply a shift to electricity as discussed by Boulouchos et al. (2011).

4.7.4 Technology pathways

The climate stabilization pathways imply a change in the energy production globally and in Switzerland towards a renewable and hydrogen economy with the use of nuclear and carbon-capture as transition technologies. Weidmann et al. (2009) analyzed a Swiss climate mitigation scenario with the target of reducing emissions by 60% in 2050, consistent with the Swiss climate policy proposal. They obtained a Swiss electricity demand by 2050 of approximately 86 TWh, comparable with the reference climate scenario in this thesis, where the electricity demand by 2050 is 82.8 TWh. The electricity in Weidmann et al. (2009) is produced mainly with hydropower (37 TWh, 42%) and nuclear (25 TWh, 29%), as in this work, with a difference in the nuclear share, which is lower in our results due to higher uranium prices. Moreover, in Weidmann et al. (2009) renewable-based technologies account for the rest of the electricity production, including: solar PV (10TWh, 11%), wind (2.2 TWh, 2.6%) , biomass (13.5TWh, 11.7%), and geothermal (1.4TWh, 1.6 %), similar to the results in this thesis, with exception of the geothermal technology that is not included in this analysis.

The most stringent scenarios require the deployment of carbon capture and storage (CCS) technologies to achieve negative emissions levels. However, CCS technologies have not been proved to work in large scale sizes, thus the feasibility of such scenarios depends largely on research and development efforts and policies to support the deployment of CCS technologies. Chapter 5 discusses the implications of not deploying this technology in more detail.

In the electricity generation, nuclear energy has the potential to play a major role in the future energy system, but conventional natural uranium resources are likely to be depleted during the course of the 21st century, thus limiting the long-term potential of nuclear technologies to contribute to climate change mitigation (Chapter 8 presents different scenarios on global resources and Chapter 6 analyses the case in which alternative nuclear reactors are available). Therefore, renewable-based technologies: wind, solar, hydro and biomass, represent 60 to 80% of the electricity generation by 2100 in the climate stabilization scenarios. The integration of this large share of intermittent renewables is likely to create major challenges for electricity system reliability, requiring improved grid integration and management, and demand-side management options. The technical feasibility of such a large-scale integration of intermittent sources requires further analysis (building on some existing studies such as PriceWaterHouseCoopers (2010)). Furthermore, policies such as feed-in tariffs can be used to promote the development of solar power technologies for decentralized use. For example, Italy increased its SPV cumulative capacity in 2011 by over 50% as a consequence of the “Salva Alcoa” law that benefits the new installations with feed-in tariffs (EPIA, 2011).

Under climate stabilization scenarios, non-electric energy is supplied mainly with hydrogen technologies, including production from coal and biomass gasification and the solar thermal process. This shows an important potential of hydrogen as the future energy carrier, but the realization of this energy system implies important efforts in the deployment of the required infrastructure for hydrogen transportation and delivery. Gül (2008) analyzed different options for hydrogen delivery routes from the production facility to the costumers. Gül (2008) showed that the infrastructure development is initialized by pilot projects using “pipelines and combined systems with pipeline delivery to terminals and gaseous truck delivery to fueling stations” (Gül, 2008); and in the long-term the optimal distribution of hydrogen would be an extensive pipeline network. Besides the challenges concerning infrastructure for hydrogen distribution, some of the technologies included in the analysis, such as production of hydrogen with solar thermal processes, have not been proved to work in large-scale. Chapter 5 analyses possible consequences of the not-deployment of this technology.

4.7.5 Carbon tax

Besides the policy implications concerning cap in emissions and the deployment of a renewable portfolio, the different scenarios analyzed in this chapter could be translated into carbon taxes. Table 4.6 presents the different carbon taxes resulting from the radiative forcing scenarios in 2050 and 2100. The reference climate scenarios, has a carbon tax of 58 and 247 USD2000/tCO_2, in 2050 and 2100. This carbon tax in 2100 corresponds to 8.6% the value in the most stringent scenario.

TABLE 4.6: *Climate stabilization scenarios: CO_2 taxes*

Scenario	ref	rf85	rf60	rf45	rf35	rf30	rf26
2050[USD2000/tCO_2]	0	2.1	16.6	58.3	246.6	574.7	594
2100[USD2000/tCO_2]	0	27.3	97.7	249.6	537.3	800.2	2895.4

4.8 Implications for the Swiss energy system

The different global radiative forcing targets have important effects on the Swiss energy system, despite the already Swiss decarbonized electricity mix in the reference scenario (see Figure 4.3B), showing important spillovers from global developments to Switzerland. On one hand, the increase in the stringency of the target implies higher energy demand reductions, which would require efficiency improvements in the end-use sectors. Furthermore, the results show a tendency towards the electrification of the non-electric energy production with the increase in the stringency of the climate target. Thus, electric vehicles, heat-pumps and more efficient end-use technologies would help realizing stringent climate targets. Besides the energy demand reductions, the use of renewable-based technologies for electricity production and the use of hydrogen for non-electric energy supply increase with the increase in the stringency of the climate target. In the electricity sector wind, solar and hydropower are the dominant technologies by the end of the century. The deployment of wind and solar generation is supported by reductions in investment costs due to global technology learning. This global learning-by-doing is driven by the global climate policy and arises due to technology experience gained mainly by other world regions, such as the EU, China and USA. Electricity production in Switzerland is affected by the availability of the resources, in particular depletion of uranium, determined by economic growth and strong climate policies in other world regions. The depletion of uranium produces higher prices of uranium implying a shift from nuclear generation to renewable-based electricity production. Concerning the non-electric energy supply, coal-FT used in the reference scenario is replaced by hydrogen technologies, mainly biomass gasification with and without carbon capture; and, in some periods, imports of hydrogen from the EU. These results show that a hydrogen economy is an alternative solution to supply non-electric energy demand, especially in the transportation sector. However, a hydrogen economy requires considerable efforts to develop the appropriate infrastructure for the distribution of the hydrogen. Finally, the results show that larger reductions in energy-related emissions in Switzerland are required to realize more stringent global climate mitigation objectives. The first move case shows some potential first mover benefits concerning global availability of uranium and the important role that developed countries such as Switzerland can play to lead the global climate mitigation discussion.

Chapter 5

Technology deployment

5.1 Introduction

A sustainable future energy system implies the improvement of current technologies and the development of new ones to realize sustainable development objectives such as climate mitigation and energy access. Future climate policies set climate change mitigation targets, such as caps on GHG emissions or maximum temperature increases (European Comission, 2007; United Nations Framework Convention on Climate Change, 1998). The realization of these different climate targets is directly linked to technology change. Technological change refers to development of new technologies or technical and economical improvements in a particular technology. This technological change does not occur autonomously, it depends on different uncertain elements including political support, public acceptance, research efforts done to improve a specific technology, policies concerning the use of the technologies, among others. In the same way, technology inventions resulting from research and development carried out by governments or private actors or technology breakouts are considerably unpredictable processes.

The realization of a global sustainable energy system that supplies current and future energy demands while mitigating greenhouse gas emissions, might require the development of renewable-based technologies, carbon capture and storage options, nuclear generation and production of liquid fuels or hydrogen based on renewable energy sources, as presented in the Energy Technology Perspectives from the IEA (2010c) and the Fourth Assessment Report from the Intergovernmental Panel in Climate Change (IPCC) (2007a), and discussed in Chapter 4. In Switzerland, the development of these technologies can also play an important role in the realization of climate mitigation targets. Furthermore, Switzerland might benefit from global technological developments. However, which technologies will be developed and the cost at which they will be available is highly uncertain, due to the unpredictability of the technology invention and the uncertainty concerning its development. Thus, this chapter analyzes different technological uncertainties including technology costs, the potential of technology learning and technology availability to identify the possible effects of technology uncertainty for the realization of the Swiss sustainable energy system.

This chapter is organized as follows: in the first section the characteristics of current and future technologies included in MERGE-ETL are discussed; the second section presents scenarios to explore one of the uncertainties in technology characteristics, namely: costs; the third section discusses scenarios on global technology learning; the fourth section analyzes different scenarios of nuclear availability, which has become of special relevance after the nuclear accident in Fukushima in March 2011; the fifth section analyzes different scenarios of technology availability including carbon capture and solar thermal production of hydrogen; and finally the policy implications of the different cases analyzed are discussed.

5.2 Energy technology characteristics

Energy technologies included in MERGE-ETL are presented in Tables 3.1 and 3.2. Electricity technologies comprise the production of electricity with fossil-based, nuclear, and renewable-based power plants; and non-electric energy production includes oil refining; direct use of natural gas, coal and biomass; and production of synthetic oil and hydrogen (from biomass, coal, natural gas, electrolysis, thermochemical production from nuclear energy and solar-thermal processes).

Due to the importance of technology deployment in the future energy systems, in this thesis, 33 studies (see Table 5.1) including, the 12 studies compared in "Projected cost of generating electricity" from the IEA and NEA (2010), the Annual Energy Outlooks 2001-2011 (EIA, 2001, 2002, 2003, 2004, 2005, 2006b, 2007, 2008, 2009, 2010, 2011), Energie-Spiegel 2010 (Hirschberg et al., 2010) and Energy technology perspectives (IEA, 2010c); and 8 studies for non-electric energy technologies, have been analyzed to determine the technology characteristics and two scenarios of high and low electricity technology cost. Appendix B presents a summary of the data analyzed from the different studies.

TABLE 5.1: *Studies included in the technology costs analysis*

Year	Author	Study
2001-2011	EIA	Annual Energy Outlook 2001-2011 (EIA, 2001, 2002, 2003, 2004, 2005, 2006b, 2007, 2008, 2009, 2010, 2011)
2003	MIT	Future of Nuclear Power (Ansolabehere et al., 2003)
2004	CERI	Levelized unit electricity cost comparison of alternate technologies for baseload generation in Ontario (Ayres et al., 2004)
	RAE	The Cost of Generating Electricity (RAE, 2004)
	UnCh	The economic future of nuclear power (University of Chicago, 2004)
2005	IEA/NEA	2005 Projected costs of generating electricity (IEA, 2005a)
2006	DTI	The Energy Challenge (UK Department of Trade and Industry, 2006)
2007	MIT	Future of Coal (Ansolabehere et al., 2007)
2008	CBO	Nuclear Power's Role in Generating Electricity (US Congressional Budget Office, 2008)
	EC	Energy sources, production costs and performance of technologies for power generation, heating and transport (European Comission, 2008)
	EPRI	Program on Technology Innovation: Integrated Generation Technology Options (EPRI, 2008)
	HL	The Economics of Renewable Energy (House of Lords, 2008)
2009	MIT	Update of the MIT 2003 Future Cost of Nuclear Power (Deutch et al., 2009)
2010	PSI	Sustainable Electricity: Wishful thinking or near-term reality? in Energie-Spiegel 2010 (Hirschberg et al., 2010)
	IEA	Energy technology perspectives (IEA, 2010c)
	IEA/NEA	2010 Projected costs of generating electricity (IEA and NEA, 2010)

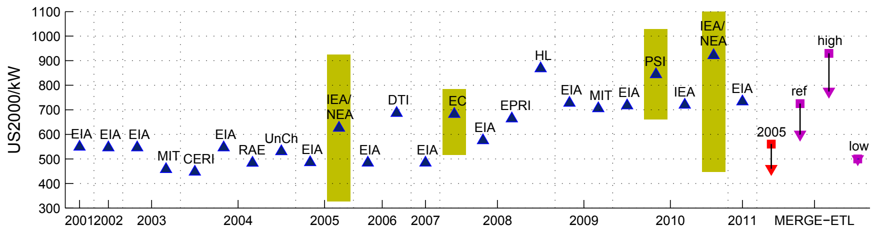
TABLE 5.1: *Studies included in the technology costs analysis (continued)*

Year	Author	Study
MERGE-ETL		
2005	PSI	Kypreos (2005)
2012	ref	Reference scenario in this PhD thesis
	high	High cost scenario in this PhD thesis
	low	Low cost scenario in this PhD thesis
2003	IIASA	Integrated Energy Systems for the 21st Century: Coal Gasification for co-producing Hydrogen, Electricity and liquid fuels (Yamashita and Barreto, 2003)
2004	NRC	The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs (NRC, 2004)
2005	UKSHEC	Technological Characterisation of Hydrogen Production Technologies (Hawkins and Joffe, 2005)
2006	H2A	H2A spreadsheet models (H2A, 2006)
	Hamelinck and Faaij (2006)	Outlook for advanced biofuels
2007	Felder (2007)	Well-to-wheel analysis of renewable transport fuels: synthetic natural gas from wood gasification and hydrogen from concentrated solar power
	Mueller-Langer et al. (2007)	Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term
2009	Pregger et al. (2009)	Prospects of solar thermal hydrogen production processes

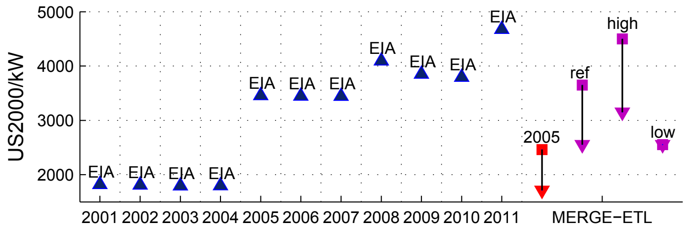
This section describes each of the technologies included in MERGE-ETL in the context of this thesis. In Section 5.3 three scenarios on technology costs are presented, including a reference case, and low and high investment costs scenarios. In this section, the costs in the three scenarios for each technology are presented, including both the initial cost and the floor cost for endogenous technology learning. The reference scenario is the case with medium investment costs for all the technologies. The low cost scenario corresponds to a scenario with low initial investment costs, and in most of the cases, without further technology learning. Generally, the initial costs are estimated based on the studies presented in Table 5.1. The floor costs for all the technologies were estimated using the *2010 Energy Technology Perspectives* from the IEA (2010c).

5.2.1 Natural gas-based power plants

New natural gas-based power plants included in MERGE-ETL comprise natural gas combined cycle (NGCC) plants and gas fuel cells (gas-FC). NGCC technologies use a gas turbine together with a steam unit to obtain higher efficiencies compared to simple gas turbines. The estimated investment cost for NGCC power plants in the different studies (see Figure 5.1A) shows an increasing trend from 2000 to present, possibly related to increase in material costs. The investment cost in the reference scenario in this PhD thesis is estimated as an average of the global studies from 2007 to 2011 (see Table B.2 in Appendix B), to include the most recent costs estimations. Stationary gas fuel cells produce electricity by an electrochemical reaction of the natural gas with air and/or oxygen. Molten carbonate fuel cells have been used as experimental power plants (EIA, 2006a) but the use of fuel cells to produce electricity on a large scale has not been proven. Investment cost of natural fuel cells are considerably higher, around 5 times the investment cost per unit of installed capacity of the NGCC technology (see Figure 5.1B).



(A) *NGCC*



(B) *Fuel cells*

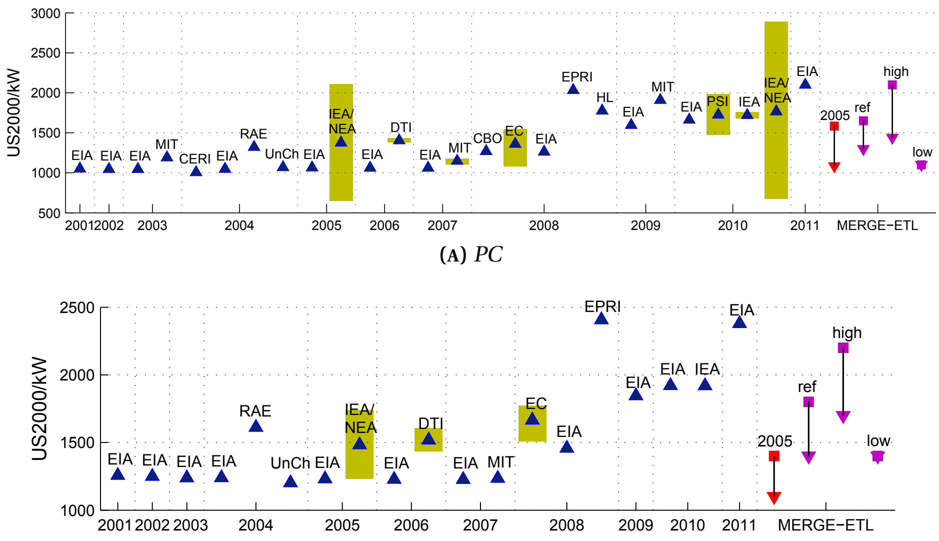
FIGURE 5.1: *Investment costs of natural gas-based technologies*

Although NGCC technologies can achieve relatively high load factors (the range in the reviewed studies is from 80 to 90%, see Table B.2) in this thesis gas technologies are assumed to be flexible technologies that can supply peak demands, therefore, a load factor of 65% is assumed for all of them.

5.2.2 Coal-based power plants

Coal technologies produce today the largest share of global electricity, particularly in China and India. China increased the installed capacity of coal-fired power plants from 20 GW in 2000 to around 75 GW in 2007. India has also increased substantially the coal generation capacity, and coal-fired generation accounted for 70% of its total electricity in 2005 (IEA, 2007a). Pulverized coal technologies (PC) include plants operating at both supercritical and ultrasupercritical conditions; the main difference between them is the temperature and pressure at which they can operate and, therefore, the efficiency they can reach. Development of more advanced materials that perform well at higher temperatures and pressures permits the construction of larger and more efficient power plants. Based in the different studies presented in Table B.3 in Appendix B, in this thesis, PC power plants are assumed to have an efficiency of 37% that corresponds to an average between supercritical and ultrasupercritical conditions. Integrated gasification combined cycle (IGCC) plants are another option to generate electricity from coal, with relatively higher efficiencies than a PC plant (40% compared to 37%). The process involves the production of synthetic gas by the gasification of coal using oxygen and/or steam at high pressures; and then the production of electricity with a combined cycle gas turbine (gas turbine with a steam unit as in the NGCC power plant).

Figure 5.2 presents the evolution of the estimated investment costs from 2000 to 2011 for both PC and IGCC technologies. In general, the estimations have been increased considerably, e.g. the PC costs in the EIA studies has doubled from 2000 to 2011 (2100 USD2000/kW compared to 1052 USD2000/kW). The investment costs in the reference scenario of this thesis are estimated as an average of recent studies (from 2008). Compared to the costs in the previous version of MERGE-ETL (Kypreos, 2005), these new estimations imply a small increase in the costs of PC technologies (4%) and a higher increment for the IGCC technology (28.5%).



(B) *IGCC*

FIGURE 5.2: *Investment costs of coal-based technologies*

Coal-based technologies are assumed in this work to be used as base-load generation; therefore, a load factor of 85% is assumed.

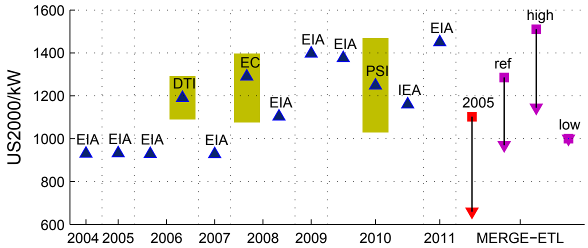
5.2.3 Technologies with carbon capture and storage

Technologies with carbon capture and storage may play an important role in future energy production, since they allow the use of fossil fuels with the advantage of reducing the CO_2 emissions. The process of CO_2 capture and storage involves three steps: capture, transportation and storage of the CO_2. Demonstration plants have proven the operation of each of these processes individually but no fully integrated plant has been developed as of 2009 (IEA, 2010c).

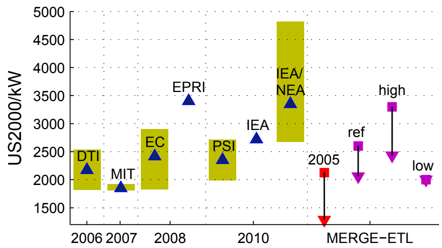
The capturing of the CO_2 in the production of electricity can be done using mainly three different processes: pre- and post-combustion capture and oxyfuelling (Intergovernmental Panel in Climate Change (IPCC), 2005). Pre- and post-combustion capture options are included in MERGE-ETL.

The post-combustion process captures the CO_2 from the flue gases produced in the combustion of the fossil fuel, i.e. coal or natural gas, through chemical absorption (Intergovernmental Panel in Climate Change (IPCC), 2005). In MERGE-ETL, pulverized coal with CCS (PC(CCS)) and NGCC with CCS (NGCC(CCS)) use this process. The design of the post-combustion capture unit depends on the type of energy carrier used. Capture of CO_2 coming from coal-fired plants requires additional steps before the capture to remove other air pollutants such as SO_X, NO_X or particulates (Intergovernmental Panel in Climate Change (IPCC), 2005). Hence, adding carbon capture has different effects on the investment costs, with lower cost increases for the NGCC technology. In the reference scenario in this thesis adding the CCS unit is assumed to increase investment costs by 560 and 950 USD2000/kW, for the NGCC and PC technologies, respectively (see Figure 5.3).

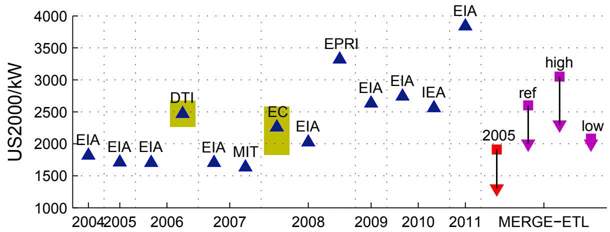
Pre-combustion capture is used in technologies that include the production of synthesis gas, such as IGCC(CCS). The synthesis gas is reacted with steam in a shift converter that produces a mixture of CO_2 and hydrogen; the CO_2 is separated and the resulting hydrogen can be used to generate electricity in the combined-cycle gas turbine (IEA, 2008a; Intergovernmental Panel in Climate Change (IPCC), 2005). Based on the costs presented in different studies (see Table B.4 in Appendix B), an increase in the investment cost of the IGCC technology when using the pre-combustion CCS is estimated in this thesis to be around 800 USD2000/kW (see Figure 5.3).



(A) *NGCC(CCS)*



(B) *PC(CCS)*



(C) *IGCC(CCS)*

FIGURE 5.3: *Investment costs of CCS technologies*

The capture of CO_2 and its pressurization are processes that consume energy, reducing the overall efficiencies of technologies with carbon capture; typically 6 to 12 percentage points (IEA, 2008a). In this thesis the efficiencies for the technologies with CCS are assumed to be 5 to 8 percentage points less than the corresponding technology without carbon capture, slightly lower than in IEA (2008a) to account for possible technology improvements.

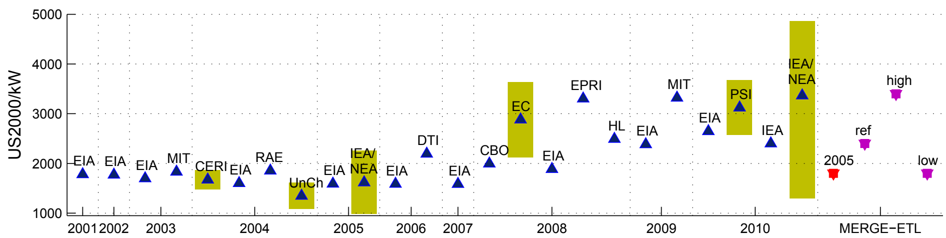
After being captured with one of the previously described processes, the CO_2 has to be transported and stored. CO_2 is transported using mainly high-pressure pipelines. This method has been used in the United States and Canada for the last 30 years (IEA, 2010c)[1]. Finally, the storage of the CO_2 is done by injecting it into geological formations, including remaining and depleted oil and gas fields, or saline formations.

[1] Note that the transport of the captured CO_2 is not directly modeled in MERGE-ETL.

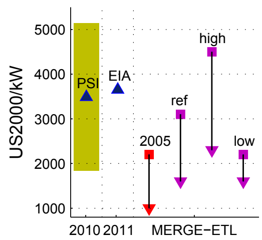
5.2.4 Nuclear technologies

Nuclear power is a mature technology that uses nuclear fission to generate electricity. In 2008, nuclear generation provided 13.5% of global electricity (IEA, 2010a). It has been largely deployed specially in the developed regions of the world. In the OECD countries it had a share in 2008 of 21.29%, with a very large contribution in some countries such as France (77.9%), Sweden (45%) and Switzerland (42.2%), while in the non-OECD countries, in 2008 nuclear power accounted for 4.8% (IEA, 2010a).

In MERGE-ETL, two types of nuclear power plants are included, representing light water reactors and fast reactors as a future alternative. Current nuclear power plants include pressurized and boiling water reactors. The estimated investment cost of nuclear technologies has increased in the recent years as shown in Figure 5.4A. The reference investment cost for the LWR in this dissertation is assumed to be 2400 USD2000/kW, which corresponds to an average of the analyzed studies from 2007 to 2010 (see Table B.5 in Appendix B). The cost assumed for the high cost scenario is 41.7% higher than the reference cost, representing the high uncertainty in nuclear costs showed in the Figure 5.4A by the large bars in some of the studies. The cost for the FBR is based on few studies (EIA, 2011; Hirschberg et al., 2010) that include a cost estimation for this technology (see Figure 5.4B).



(A) *LWR*



(B) *FBR*

FIGURE 5.4: *Investment costs nuclear technologies*

5.2.5 Renewable-based technologies

Renewable energy is the energy coming from non-exhaustible natural resources, including biomass, water, sunlight, wind, tides, geothermal heat, among others. According to the IEA (2010a) in 2008 about 18.5% (3701 TWh) of global electricity generation was produced with renewable-based technologies. Hydropower accounted for the larger share among renewable resources with 87% of the 3701 TWh, followed by biomass that accounted for 7.2% and wind with a 5.9%. The technology characteristics for renewable based technologies in the different reviewed studies are presented in Table

B.6 in Appendix B.

Biomass

Biomass is a diverse energy source that can be used to generate electricity or to supply different non-electric demands, such as heating or transportation. When it is used to produce electricity, different conversion processes can be utilized, including direct combustion or gasification or anaerobic digestion, e.g. in a gas turbine, among others. Therefore, estimated costs for biomass cover a considerable range, which depends on the type of conversion process (see Figure 5.5). The biomass technology in this thesis corresponds to the process of gasification followed by combustion in a gas turbine. The investment cost of this process is based on an average of the different studies reviewed. Biomass generation is considered to have zero CO_2 emissions, based on the assumption that when the biomass crop is growing it captures an amount of CO_2 that balances the quantity emitted in the generation process. CO_2 capture is possible when gasifying the biomass; in this thesis this additional feature is assumed to increase the cost of the technology by 700 USD2000/kW and reduce the efficiency by 10 percentage points.

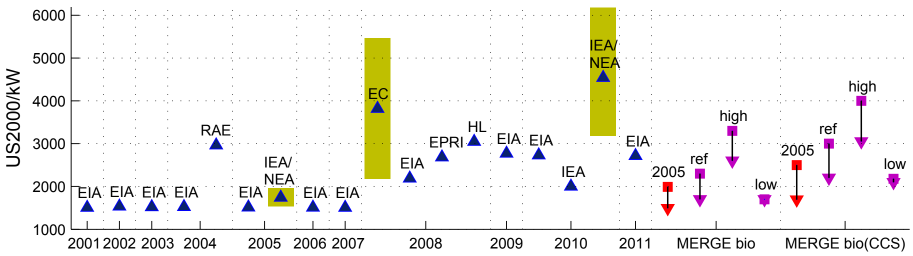


FIGURE 5.5: *Biomass investment costs*

Solar technologies

Solar-generated electricity is an important low-carbon technology highly deployed in recent years, with a global installed capacity reaching 23 GW in 2009 and 67.4 GW in 2011 (around 0.5% of the world electricity capacity), with the largest deployment in the EU, Japan and USA (EPIA, 2011; Intergovernmental Panel in Climate Change (IPCC), 2012). Solar technologies comprise two options: solar photovoltaic (SPV) and concentrated solar power. Photovoltaic cells convert the energy from the sun to direct current using semiconductors. Commercial SPV cells are generally crystalline silicon and thin films (IEA, 2010c). Concentrating solar power uses the heat from the sun, collected with a solar concentrator, to produce electricity with a turbine.

In recent years, estimated investment costs of solar technologies show a decreasing tendency from 2009, as shown in Figure 5.6. According to the IEA (2010c) investment costs of photovoltaic modules have decreased in the latest years with a learning rate of 15 to 22%[2]. The cost in MERGE-ETL has been reduced in this thesis from 5000 (Kypreos, 2005) to 4300 USD2000/kW. Solar photovoltaic panels are in different stages of technology development, with some relatively mature alternatives and some others

[2]The learning rate represents the decrease in the cost with a doubling in the installed capacity.

with high potential of development (IEA, 2010c). Concentrating solar power is a technology in the early stage of development. Therefore, a significant potential for technology learning is expected, and this is reflected in the assumptions included in this work, with floor costs that correspond to around 30-49% of the initial costs.

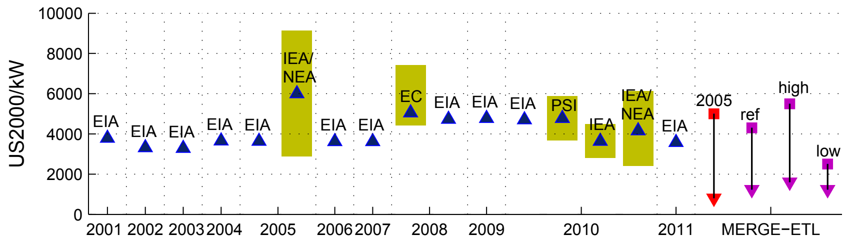


FIGURE 5.6: *Solar investment costs*

A global load factor of 25% is assumed for the solar technologies, representing the intermittence of sunshine.

Hydropower

Hydropower is a mature technology that includes both run-of-river and dam power plants and represents the most used renewable technology today. Dam hydro can be used to supply peak demand due to its flexibility to dispatch. Since it is a mature technology, endogenous technology learning is not considered significant for hydropower. The estimated costs in the different studies show a considerable divergence (see Figure 5.7) since they include both run-of-river and dam alternatives with variable sizes. This range in the investment costs of hydropower is partially covered by the three scenarios on technology costs developed in this thesis.

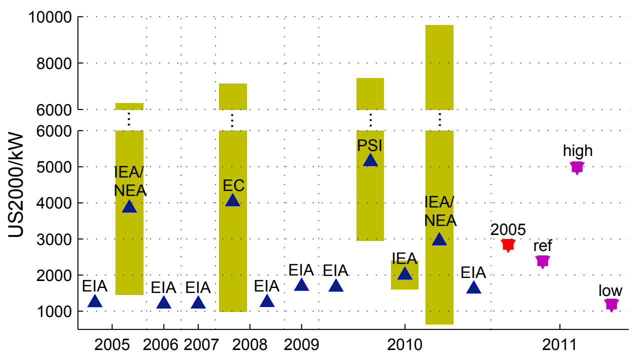


FIGURE 5.7: *Hydropower investment costs*

Wind power

The use of wind turbines started in the 1970s and has grown rapidly in the last decades to reach 1.8% of the world electricity production in 2009 (Intergovernmental Panel in Climate Change (IPCC), 2012). The estimated investment costs in the different studies show an increasing tendency from 2001 to 2011 since the realization of larger wind turbines requires additional material for stability issues (see Figure 5.8). Compared to the previous version of MERGE-ETL (Kypreos, 2005), the cost in the reference scenario is increased by 300 USD2000/kW, from 1200 to 1500 USD2000/kW. Research and development of wind turbines includes the use of lighter materials to produce turbines with larger capacities as well as alternative turbine configurations with better efficiencies. Therefore, some potential for technology learning is included in this thesis with floor costs corresponding to 76-77% of the initial costs.

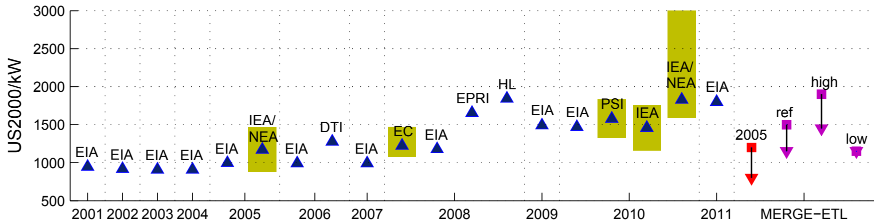


FIGURE 5.8: *Wind investment costs*

A global load factor of 30% for the wind power is assumed in this thesis.

5.2.6 Synthetic fuels production

Hydrocarbon synthetic fuels constitute an alternative to oil products, particularly for transportation where fewer alternatives are available. They are produced using a Fischer-Tropsch (FT) process that converts synthesis gas - a mixture of carbon monoxide and hydrogen - into liquid hydrocarbon fuel. The synthesis gas can be produced through the gasification of a range of feedstock: coal (coal-FT), natural gas or biomass (bio-FT) (IEA, 2004). Partial carbon capture in synthetic fuel production (bio-FT(CCS)) is possible because the synthesis gas produced in the gasification process has a high concentration of CO_2 (Yamashita and Barreto, 2005). It uses a pre-combustion CO_2 process as the one described above for IGCC. The technology characteristics for the technologies producing synthetic fuels is based on Yamashita and Barreto (2003) and Hamelinck and Faaij (2006).

5.2.7 Hydrogen production technologies

"Hydrogen is widely considered to be the transportation fuel of the future" (IEA, 2004) because it deals with the issues of energy security and climate change. Although hydrogen is an abundant element on earth, it does not exist purely in the nature and has to be extracted from hydrogen-rich materials. MERGE includes hydrogen production from gas, coal, biomass, electrolysis and thermochemical nuclear and solar processes:

- Hydrogen is produced from natural gas (gas-H2) using steam reformation. It is currently the most widely used and cheapest process to produce hydrogen. It consists on the reaction of natural gas with high-temperature steam on a catalytic surface to produce syngas (a mixture of hydrogen and carbon monoxide). Using a water shift reaction the carbon monoxide is then transformed into hydrogen and CO_2 (Hawkins and Joffe, 2005; IEA, 2005b).
- Production of hydrogen from coal (coal-H2) involves gasification of the coal to produce syngas

(as in the IGCC power plant), chemical cleaning of the syngas from impurities; and then the use of a water shift reactor (Hawkins and Joffe, 2005).

- Hydrogen from biomass (bio-H2) can be produced using gasification or pyrolysis followed by a reforming process similar to the one used to produce hydrogen from natural gas (Hawkins and Joffe, 2005).

- Electrolysis (electrolysis-H2) uses electricity to produce hydrogen by splitting water into hydrogen and oxygen.

- Thermochemical production of hydrogen from nuclear energy (nuc-H2) consists on a sulphur-iodine cycle where water is split and hydrogen is thermally produced. The required heat is provided by nuclear energy (Nuclear Energy Agency, 2006b).

- Solar-thermal hydrogen (sth-H2) production uses a thermochemical process called hydrolysis that converts water into hydrogen and oxygen using zinc as catalyst (IEA, 2011b).

MERGE includes the possibility of carbon capture for hydrogen production from gas (gas-H2(CCS)), coal (coal-H2(CCS)) and biomass (bio-H2(CCS)) which requires an additional capture unit usually added after the water shifting reaction (Hawkins and Joffe, 2005).

The characteristics of hydrogen production technologies are based on the different studies presented in Table 5.2. In the last column the initial and the floor costs as well as the efficiencies assumed in this thesis for each technology are presented.

TABLE 5.2: *Hydrogen technologies: Investment costs and efficiencies. In the last column the values used in this dissertation are presented; floor costs are presented in parenthesis*

Investment cost [$/kW]						
	NRC (2004)	Yamashita and Barreto (2003)	Hawkins and Joffe (2005)	H2A (2006)	Mueller-Langer et al. (2007)	This thesis
gas-H2		272-400	230-2350	260	272-794	800
gas-H2(CCS)		312-432	320-1220	328	310	1000 (900)
coal-H2		808-896	440-580	843	680	1200 (1000)
coal-H2(CCS)		828-1040	450-600	971	781	1400 (1100)
bio-H2			1500-3070	528	760	1600 (1000)
bio-H2(CCS)			1530-3140			1800 (1100)
nuc-H2			1207	1635-1797		2000 (1500)
ele-H2	2150-3220			553-1073	897	900
	Felder (2007)	Pregger et al. (2009)				
sth-H2	765	2336-6328				4300 (2000)
Efficiency						
	Yamashita and Barreto (2003)	Hawkins and Joffe (2005)	H2A (2006)	Mueller-Langer et al. (2007)	This thesis	
gas-H2	0.74-0.81	0.74-0.78	0.74	0.7-0.84	0.75	
gas-H2(CCS)	0.79-0.8	0.70	0.74	0.65-0.79	0.7	
coal-H2	0.59-0.65	0.75-0.8	0.47-0.54	0.49-0.56	0.6	
coal-H2(CCS)	0.54-0.79	0.75-0.80	0.47-0.59	0.44-0.51	0.55	
bio-H2		0.5-0.7	0.45-0.55	0.5-0.6	0.55	
bio-H2(CCS)					0.52	
ele-H2				0.64-0.74	0.7	

5.3 The effects of technology cost on a sustainable energy system

5.3.1 Scenarios on technology cost

In this section the effect of future and present technology costs on the future energy system is analyzed using three scenarios on investment costs of the electricity technologies: low, a high and a reference case. Figure 5.9 presents the levelized investment costs for each technology, using a 5% discount rate. As discussed in Section 3.2.2, MERGE-ETL includes different extraction costs for the fuel stocks, representing levels of accessibility to the resource. Hence, in Figure 5.9 for every technology two bars are presented, representing the levelized investment cost using the cheapest (on the left) and the most expensive (on the right) fuel stock. The two bars presented for the investment costs represent the initial and floor costs assumed for technology learning. Furthermore, the costs for the low and high costs scenarios are presented using an interval bar. It is important to note that the operation and maintenance cost of nuclear technologies depend on the fuel cycle; the costs included in this plot are assuming both technologies use only natural uranium to generate the electricity. These three scenarios on technology costs cover a substantial part of the estimated costs in the literature; however, for some of the technologies the full uncertainty range is not covered, excluding extreme cases.

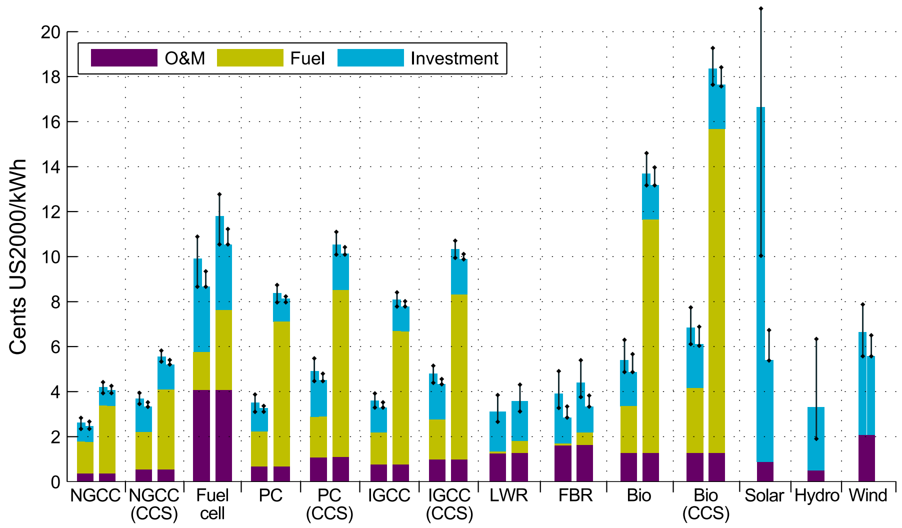


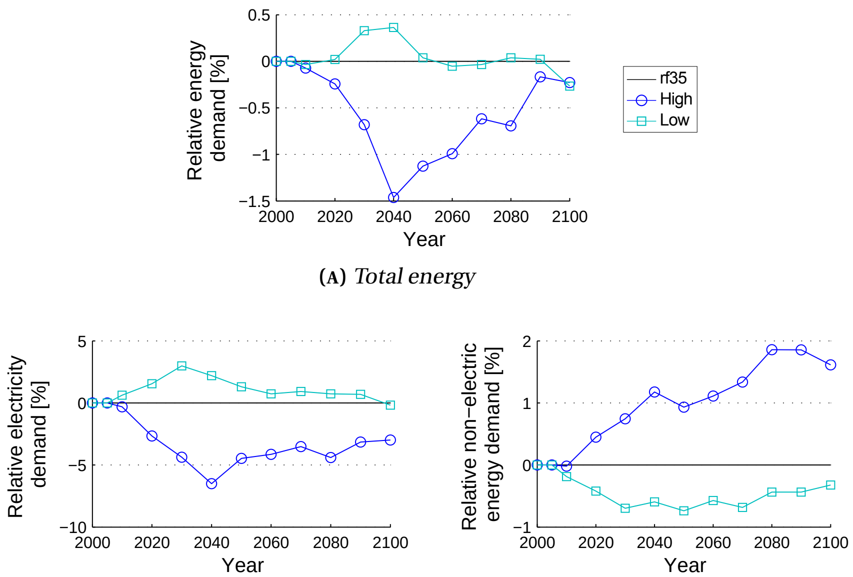
FIGURE 5.9: *Levelized costs scenarios. For every technology the bar on the left represents the cheapest fuel stock and the one on the right the most expensive one. The two bars for investment costs represent the initial and floor costs assumed for technology learning. The uncertainty range represents the costs for the low and high costs scenarios*

For some of the technologies, such as NGCC or biomass the fuel cost has a large effect on the levelized investment cost. While for other renewable-based technologies, i.e. solar, wind and hydro, the investment cost represents the main part of the levelized cost. In the reference case with the lowest fuel costs, NGCC is the cheapest technology and solar is the most expensive before technology learning, but with a large potential of reducing the costs due to both learning-by-doing and learning-by-searching processes. Electricity technologies using coal can be significantly affected by coal price, however coal resources are relatively abundant and cheap, and therefore it is unlikely that the most expensive resource category will be utilized in the foreseeable future. The costs for non-electric energy technologies do not change across the technology costs scenarios to analyze technology pathways for electricity supply.

These scenarios assume independent variations on the technology costs for all the technologies, representing changes in the costs due to higher or lower material costs, which would affect all technological alternatives.

5.3.2 Energy demand

The effect of the different investment costs scenarios has been analyzed under a climate mitigation policy with a long-term radiative forcing target of 3.5 W/m^2. This corresponds to the reference climate scenario presented in Section 4.5. One of the consequences of higher or lower technology costs is a change in energy demand[3]. Total energy demand is decreased in the high costs scenario and increased in the low cost one (see Figure 5.10A). Since costs of non-electric energy technologies remain unchanged in the three scenarios, electricity is partially substituted with non-electric energy in the high costs scenario, and non-electric energy demand decreases in the low costs scenario (see Figure 5.10). Nevertheless, in the high-cost case this substitution effect compensates only partially the reduction in electricity demand and, for this reason, total energy demand is also reduced.



(A) *Total energy*

(B) *Electricity*

(C) *Non-electric energy*

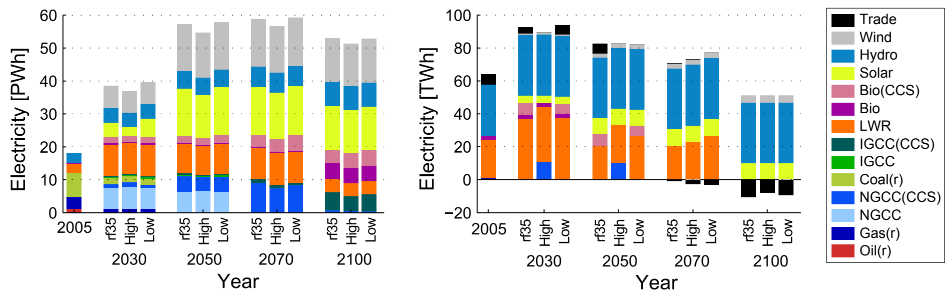
FIGURE 5.10: *Technology costs scenarios: Relative demand change*

5.3.3 Energy technology pathways

Despite the change in electricity demand, the technology preferences remain relatively unchanged. Figure 5.11 presents the technology mix for the three scenarios of technology costs with a radiative

[3]Note that the costs assumes for efficiency, i.e. substitution of energy with capital and labor, are assumed to be the same in the three costs scenarios.

forcing target of 3.5 W/m^2. The change in the investment costs has a relatively small effect on the portfolio of technologies, which includes in all scenarios a large share of renewable-based generation and technologies with carbon capture.



(A) *World* (B) *Switzerland*

FIGURE 5.11: *Technology costs scenarios: Electricity generation*

In Switzerland, the preferred technologies continue to be hydropower, nuclear, wind and solar. However, an important change in the electricity mix from 2030 to 2060 is a replacement of the biomass with carbon capture generation with NGCC with CCS in the high costs scenario. This is due to the assumption in the high cost case of significantly larger increase in the biomass technology cost compared to NGCC(CCS). Table 5.3 presents the increment in the levelized costs of both technologies in the high cost scenario compared to the reference case[4].

TABLE 5.3: *Technology cost scenarios: Increase in levelized cost in the high costs scenario*

	2010	2020	2030	2040	2050-2100
NGCC(CCS) [%]	12.9	13.2	11.6	12.5	12.4
Bio(CCS) [%]	21.1	20.2	21.1	22.5	23.4

5.3.4 Effects of technology costs in Switzerland

The replacement of biomass with NGCC with CCS in the high cost scenario implies a small increase in energy-related emissions in the Swiss region in 2030-2040 as shown in Figure 5.12, while the low cost case has an emissions pathway similar to the reference case.

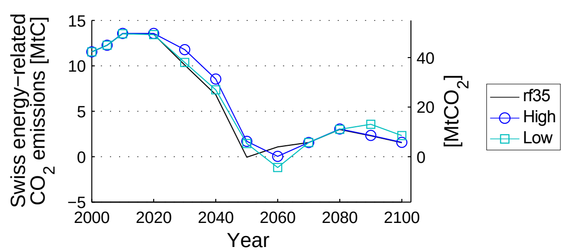


FIGURE 5.12: *Technology costs scenarios: Swiss energy related emissions*

[4]Note that the levelized costs change with time due to technology learning.

Even if the preferred technologies do not change across the cost scenarios, the cost changes have consequences for the economy. Figure 5.13 presents the GDP losses and gains for Switzerland in the two scenarios compared to the reference climate scenario (rf35). The gains in GDP in the low cost scenario are relatively low from 2050 due to reduction of costs in the rf35 scenario realized through technology learning, which in the high cost case reduces investment costs up to the levels assumed in the low cost scenario. The losses in GDP in the high cost scenario reach a peak in 2040 of 0.75% and reduce, due to technology learning, to 0.25% by the end of the century.

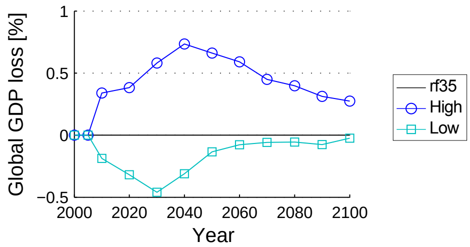


FIGURE 5.13: *Technology costs scenarios: Global GDP losses and gains*

5.4 Technology learning spillovers

Many integrated assessment models (IAMs) have modeled technology learning to analyze the impact of policy incentives on technology development. One approach has been to consider exogenous technology learning (see Nakicenovic (2000)), assuming decreasing investment cost for technologies with time. Other approaches include modeling endogenous technology learning by means of learning curves (see Bosetti et al. (2006); Kypreos and Bahn (2003); Magne et al. (2010); Manne and Barreto (2004)). Despite these important efforts, not all elements of the technology learning process are represented in IAMs. For instance, IAMs with endogenous learning usually include one parameter that models the "learning-by-doing" process; and in some cases a second parameter representing "learning-by-searching" processes, but they generally do not account for the variations in technology spillovers between different regions. Clarke et al. (2008) highlighted the importance of spillovers for technology change. In that direction, Bosetti et al. (2008) have modeled variable or partial international R&D spillovers using the WITCH model, showing that "international knowledge spillovers tend to increase free-riding incentives and decrease the investments in energy R&D".

In this analysis the effect of reduced global technology spillovers among regions is analyzed, aiming to provide a better understanding of the effect of technology spillovers on global and regional climate mitigation efforts. This is of important relevance in Switzerland, since the Swiss region benefits from global technology learning carried out by experience and research in other world regions. However, whether a full cooperation and technology transfer across the regions will occur is not certain. Thus, we analyze effects on the achievement of a sustainable Swiss energy system coming from reduced knowledge transfer among countries.

5.4.1 Technology spillovers in MERGE

As mentioned by Clarke et al. (2008) two-factor learning curves neglect the effect of spillovers on technological change or do not account for barriers to spillovers, since the transfer of knowledge among regions is neglected or assumed to be a 100%. In MERGE-ETL the transfer of knowledge is not limited since the learning process occurs on a global level. As mention in Section 3.2.2 the learning process in MERGE-ETL is assumed to occur on the level of key components, which represent common elements across technologies, such as turbines or gasifiers. Key components learn from global cumulative production and R&D expenditures, which means that full spillovers are assumed between all world regions. In this thesis a new version of the learning process in MERGE-ETL, modeling direct spillovers, was developed. This new learning model includes limits to technology spillovers in addition to the two learning factors presented in Equation 3.6, based on the idea that the transfer of knowledge can be limited, e.g. companies can protect their inventions or technology developments with patents; or improvements in the production of technologies in a certain region do not necessarily imply the same enhancement level in another region. Bosetti et al. (2008) have included international R&D spillovers in the WITCH model. They model an international pool of knowledge as a public good from which every region can absorb a fraction of the knowledge for its domestic research and development. The approach used in this thesis follows their proposal but instead of modeling a single global pool of knowledge, we account for region-to-region spillovers.

Technological development occurs in every region, divided into innovators and imitators. The innovators are assumed to be the high-income countries that set the global technological frontier. Imitators are thus assumed to be the developing regions for which the absorption of knowledge from other regions drives local technology development. Innovators also act as imitators of other innovators, and these technology spillovers are not negligible since high income countries have better access to information. This process of transfer of knowledge is presented in Figure 5.14. The thickness of the arrows represents the amount of knowledge assumed to be transferred between two regions. These spillovers are modeled by an exogenous parameter called the absorption parameter a_{ij}, that represents the spillover coefficient from region i to region j.

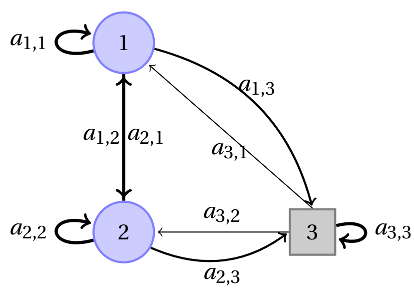


FIGURE 5.14: *Region-by-region knowledge transfer*

Spillovers for the learning-by-doing (LBD) process, in addition to the R&D spillovers, are included. The LBD spillovers represent international transfers of experience and know-how and spillovers of learning-by-searching (LBS) model international transfers of knowledge generated by R&D efforts. Exogenous absorption parameters represent the fraction of experience or knowledge from each region absorbed by other regions. Thus, the investment cost of the y-key factor, is given by,

$$inv_{y,r} = \begin{cases} A_y \cdot \left(\sum_{i\in R} a_{i,r} CC_{i,y}\right)^{-b_y} \left(\sum_{i\in R} a_{i,r} CRD_{i,y}\right)^{-c_y} & \text{if } inv_y \geq l_y, \\ l_y & \text{otherwise,} \end{cases} \tag{5.1}$$

where for the y-technology A_y represents a constant calibrated with the initial cost and capacity; $a_{i,r}$ is the spillover coefficient from the region i, $CC_{i,y}$ is the cumulative capacity of region i; b_y is the learning index; $CRD_{i,y}$ is the cumulative research and development expenditures in the i-th region; and l_y is the floor cost.

5.4.2 Scenarios on technology learning spillovers

Four scenarios of different levels of technology and knowledge transfer among regions are evaluated, which allows the analysis of the relevance of international cooperation and the effect of a possible over-estimation of the spillovers effect in determining technology pathways. Table 5.4 presents the diagrams and absorption matrix (the element in row i and column j indicates the absorption parameter a_{ij}, that is, the absorption parameter from j to i-region).

TABLE 5.4: *Spillover Scenarios*

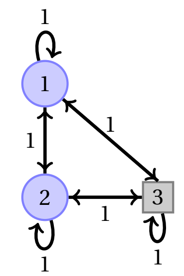
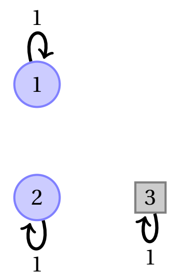
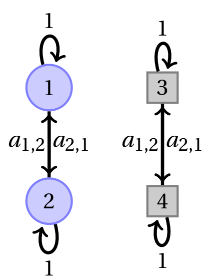
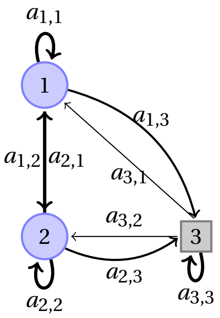
Scenario	Diagram	Absorption matrix	EUP	SWI	RUS	MEA	IND	CHI	JAP	USA	CANZ	ROW
100%		EUP	1	1	1	1	1	1	1	1	1	1
		SWI	1	1	1	1	1	1	1	1	1	1
		RUS	1	1	1	1	1	1	1	1	1	1
		MEA	1	1	1	1	1	1	1	1	1	1
		IND	1	1	1	1	1	1	1	1	1	1
		CHI	1	1	1	1	1	1	1	1	1	1
		JAP	1	1	1	1	1	1	1	1	1	1
		USA	1	1	1	1	1	1	1	1	1	1
		CANZ	1	1	1	1	1	1	1	1	1	1
		ROW	1	1	1	1	1	1	1	1	1	1
			EUP	SWI	RUS	MEA	IND	CHI	JAP	USA	CANZ	ROW
0%		EUP	1	0	0	0	0	0	0	0	0	0
		SWI	0	1	0	0	0	0	0	0	0	0
		RUS	0	0	1	0	0	0	0	0	0	0
		MEA	0	0	0	1	0	0	0	0	0	0
		IND	0	0	0	0	1	0	0	0	0	0
		CHI	0	0	0	0	0	1	0	0	0	0
		JAP	0	0	0	0	0	0	1	0	0	0
		USA	0	0	0	0	0	0	0	1	0	0
		CANZ	0	0	0	0	0	0	0	0	1	0
		ROW	0	0	0	0	0	0	0	0	0	1
			EUP	SWI	RUS	MEA	IND	CHI	JAP	USA	CANZ	ROW
Groups		EUP	1	1	0	0	0	0	1	1	1	0
		SWI	1	1	0	0	0	0	1	1	1	0
		RUS	0	0	1	1	1	1	0	0	0	1
		MEA	0	0	1	1	1	1	0	0	0	1
		IND	0	0	1	1	1	1	0	0	0	1
		CHI	0	0	1	1	1	1	0	0	0	1
		JAP	1	1	0	0	0	0	1	1	1	0
		USA	1	1	0	0	0	0	1	1	1	0
		CANZ	1	1	0	0	0	0	1	1	1	0
		ROW	0	0	1	1	1	1	0	0	0	1

TABLE 5.4: *Spillover Scenarios (continued)*

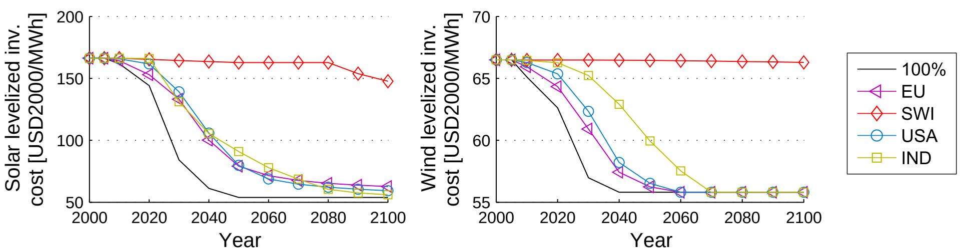
Scenario	Diagram		EUP	SWI	RUS	MEA	IND	CHI	JAP	USA	CANZ	ROW
			Absorption matrix									
Regional		EUP	1	0.9	0.2	0.2	0.2	0.5	0.8	0.8	0.8	0.2
		SWI	0.9	1	0.2	0.2	0.2	0.5	0.8	0.8	0.8	0.2
		RUS	0.6	0.6	1	0.2	0.2	0.5	0.6	0.6	0.6	0.2
		MEA	0.6	0.6	0.2	1	0.2	0.5	0.6	0.6	0.6	0.2
		IND	0.6	0.6	0.2	0.2	1	0.5	0.6	0.6	0.6	0.2
		CHI	0.6	0.6	0.2	0.2	0.2	1	0.6	0.6	0.6	0.2
		JAP	0.8	0.8	0.2	0.2	0.2	0.5	1	0.8	0.8	0.2
		USA	0.8	0.8	0.2	0.2	0.2	0.5	0.8	1	0.8	0.2
		CANZ	0.8	0.8	0.2	0.2	0.2	0.5	0.8	0.8	1	0.2
		ROW	0.6	0.6	0.2	0.2	0.2	0.5	0.6	0.6	0.6	1

The 100% scenario is the case with hundred percent spillovers among all the regions and corresponds to the assumption used in all the scenarios developed in this dissertation; in the 0% scenario no spillovers among regions are considered; the Groups scenario corresponds to the case where spillovers occur only within each group of regions; and the Inter-regional is the scenario where we model high spillovers among innovators, slightly lower spillovers from innovators to imitators and weak knowledge transfer from imitators to innovators and other imitators.

All the scenarios are analyzed with a long term radiative forcing target of 3.5 W/m^2, thus the 100% spillovers scenario corresponds to the reference climate scenario presented (rf35) in Section 4.5.

5.4.3 Technology deployment

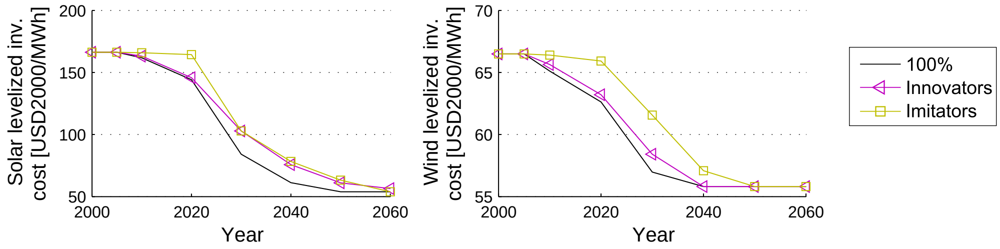
The impact of technology learning spillovers is considerable on the deployment of those technologies that have high initial investment cost since they are highly dependent on the learning process. Examples include wind and solar generation. Figure 5.15 presents the levelized cost of the wind and solar technologies for the 0% case compared to the 100% spillovers case. This case with no spillovers shows an important difference among regions: in general imitators achieve the same cost reductions as innovators but with some delay. The region that is particularly affected by not having a global learning is Switzerland, due to its relatively small size.



(A) *Solar* **(B)** *Wind*

FIGURE 5.15: *Levelized investment costs in 0% spillovers scenario*

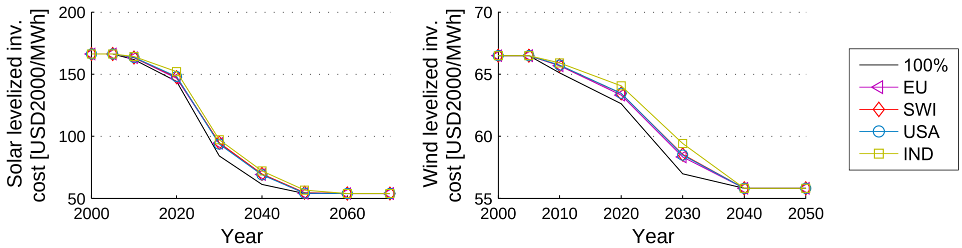
Figure 5.16 shows the levelized cost of the wind technology for the Group spillovers case. For both technologies imitators catch up with innovators, driven by the learning-by-doing and to additional R&D efforts done by imitators when learning spillovers are not modeled.



(A) *Solar* (B) *Wind*

FIGURE 5.16: *Levelized investment costs in group spillovers scenario*

Finally, Figure 5.17 presents the levelized costs of the wind and solar technologies in the regional case spillovers. In these scenarios, learning occurs faster than in the previous cases, showing the relevance of knowledge and experience transfer across imitators and innovators. In this regional case, imitators have slightly higher levelized costs than innovators and overall the difference to the 100% spillover case is reduced compared to the previous cases. This shows how transfer of knowledge and know-how among countries can help achieving climate mitigation targets by reducing investment costs of particular technologies. A small country as Switzerland can benefit from both learning-by-doing and learning-by-searching carried out in larger countries and can contribute with technological development.

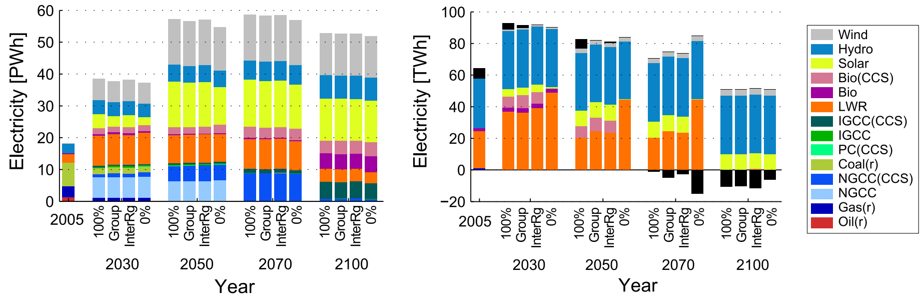


(A) *Solar* (B) *Wind*

FIGURE 5.17: *Levelized investment costs in regional spillovers scenario*

5.4.4 Electricity production

Figure 5.18 shows the global technology mix for the climate scenario with a long-term radiative forcing target of 3.5W/m^2 in the four spillover cases. A reduction of electricity demand is observed when no global learning spillovers are assumed, both globally and in Switzerland. Note that in 2070 electricity production in Switzerland in the 0% spillovers case is greater than in the other scenarios, however, a considerable part of this electricity is exported to the EU; this is due to the modeling of vintages of technologies that force Switzerland to keep the installed nuclear capacity for its entire lifetime. Despite the energy demand reductions, globally, the deployed technologies are basically the same across scenarios. In Switzerland, important changes result in the scenario without spillovers, where SPV and biomass technologies are replaced by nuclear generation.



(A) *Global* (B) *Switzerland*

FIGURE 5.18: *Spillover scenarios: Technology mix for electricity generation*

5.4.5 Economic costs and R&D expenditures

Even tough the technology portfolio among spillovers scenarios does not change significantly (except for the zero spillovers case in Switzerland), less technology and knowledge transfer might imply higher cost of climate policies. Figure 5.19 presents the GDP losses in the different scenarios on learning spillovers. The costs of achieving the stringent climate policy with a target of 3.5 W/m^2 increase with the decrease in technology and knowledge transfer. The greater losses occur by the middle of the century, since is the period where technology learning is slowed down due to less spillovers.

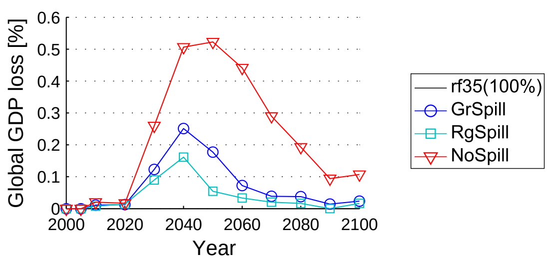


FIGURE 5.19: *Spillover scenarios: Global GDP losses*

The R&D expenditures do not change for innovators across scenarios. However, as presented in Figure 5.20 for India, the scenarios with less spillovers result in increasing research and development investment for imitators.

5.5 Nuclear phase out

The nuclear accident in Fukushima, Japan, in March 2011 increased worldwide the uncertainty regarding nuclear policy. Different policy responses may lead to different pathways of energy system development. In Switzerland, the federal cabinet decided in May 2011 to gradually decommission all Swiss nuclear power plants to reach a complete phase out by 2034 (Swiss Federal Council, 2011). Since

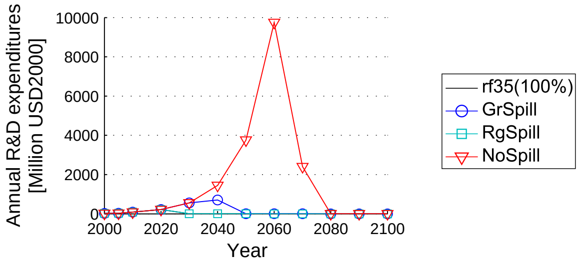
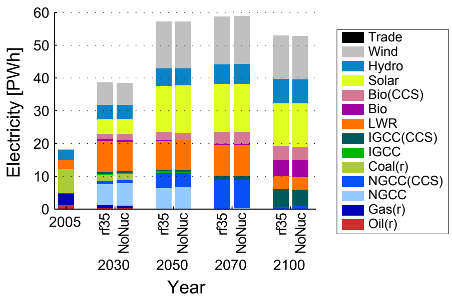


FIGURE 5.20: *Spillover scenarios: R&D expenditures for India*

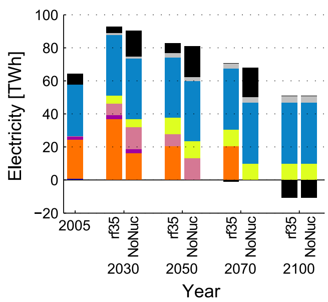
nuclear power accounts for around 60% of current Swiss electricity generation, the cabinet decision raises important questions concerning alternative technologies and energy-saving measures needed to achieve these targets. Therefore, we seek to analyze the possible effect of changed technology preferences (both globally and domestically) after the recent nuclear accident in Fukushima, Japan on the future Swiss energy system. This work is based on the paper submitted to the Swiss Journal of Economics and Statistics (Marcucci and Turton, 2012).

5.5.1 Nuclear phase-out in Switzerland and Japan

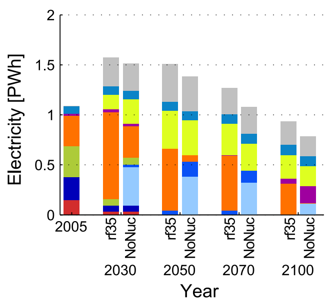
One of the possible outcomes from the accident in Fukushima is a phase-out of nuclear power plants (assumed to have a 50 years lifetime) in some of the regions with large shares of nuclear generation. This scenario analyzes the case in which both Switzerland and Japan opt for this policy.



(A) *World*



(B) *Switzerland*



(C) *Japan*

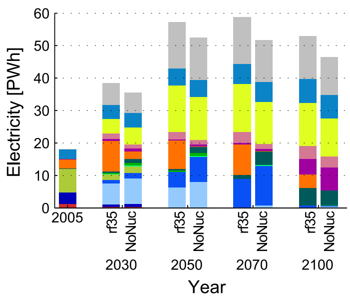
FIGURE 5.21: *Nuclear phase-out in Switzerland and Japan: Electricity generation*

Figure 5.21 presents the electricity production in 2030, 2050, 2070 and 2100 for the world, Switzerland

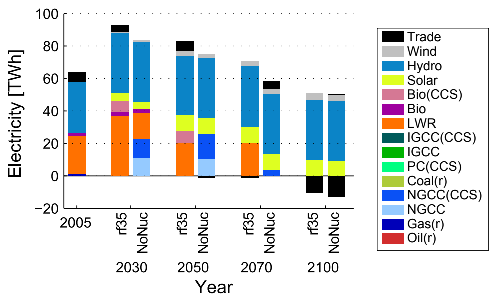
and Japan for the climate mitigation scenario with radiative forcing target of 3.5 W/m^2. Globally, there is a small reduction in the demand, arising from demand reductions in Japan. There is an important difference between the Swiss and the Japanese regions. In this scenario, Swiss electricity demand decreases only slightly due to the ability to replace nuclear generation with electricity imports from the EU (it is also worth noting that global nuclear output is largely unchanged, thus the implication is that the Swiss reactors largely relocate to the EU). Unlike Switzerland, the electricity demand in Japan is reduced by around 3.7, 8.4, 15.9 and 16.6 % by 2030, 2050, 2070 and 2100, respectively, and imports are assumed not to be available. Japan has a limited carbon storage capacity, and, therefore CCS technologies are only deployed to a small extent to replace nuclear power. Thus, besides additional efficiency (and reduced demand due to lower economic activity), nuclear generation is replaced by NGCC and biomass in Japan.

5.5.2 Global nuclear phase-out

Another possible consequence of the Japanese accident is a global nuclear phase-out, that is, no replacement of the current nuclear power plants (assumed to have 50 years lifetime). Figure 5.22 presents the rf35 scenario with and without nuclear deployment globally. There is a reduction in global electricity demand in the case in which no new nuclear power plants are built. This implies additional efficiency improvements and, to some extent, reduced demand due to lower economic activity. Additionally, in the middle of the projection period nuclear generation is partially replaced with additional NGCC with carbon capture, and IGCC and PC technologies with CCS, deployed after 2030. Due to the depletion of natural gas resources by 2100 electricity is produced with IGCC(CCS) and renewable-based technologies. By 2100 renewable technologies, i.e. wind, solar and biomass, represent 88% of the total global generation when no nuclear technologies are available (compared to 80% in the reference climate scenario). As in the reference climate scenario, the large share of intermittent renewables is likely to create major challenges and trade-offs related to electricity supply reliability and security.



(A) *World*



(B) *Switzerland*

FIGURE 5.22: *Nuclear phase-out: Electricity generation*

For Switzerland, the picture is different to the case presented in Figure 5.21, where only Switzerland and Japan adopted a no-nuclear policy. In the global no-nuclear case, Switzerland does not import as much electricity from the European Union since this region also adopts a nuclear moratorium. Instead, Switzerland implements additional efficiency measures and deploys NGCC with and without carbon capture between 2050 and 2070 to replace the nuclear power generation. Unlike Switzerland, the Japanese electricity production is very similar to the case presented in Figure 5.21.

5.5.3 Implications for Swiss emissions

The nuclear phase out scenario has important consequences on the Swiss energy-related emissions (see Figure 5.23).

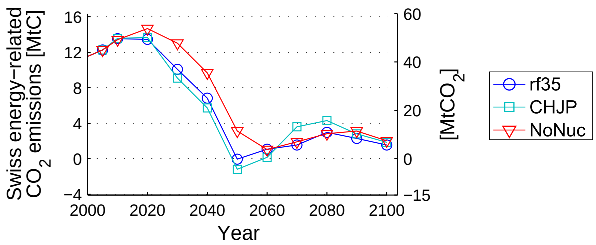


FIGURE 5.23: *Nuclear phase-out: Swiss energy-related CO_2 emissions*

A nuclear moratorium policy just in Switzerland and Japan does not increase substantially Swiss emissions. However, it implies imports of electricity from the EU. In EU, electricity generation has some fossil component, coming until 2030 from the remaining gas and coal power plants and from 2050 from new NGCC and IGCC plants with CCS. Since Switzerland imports the electricity from 2020 until 2080, some of the emissions produced in the EU correspond to leakage of emission from Switzerland. Table 5.5 presents the leakage of emissions from Switzerland to the EU, defined as the change in emissions in the EU divided by the change in Switzerland.

TABLE 5.5: *Nuclear phase-out: CO_2 leakage from Switzerland to the EU*

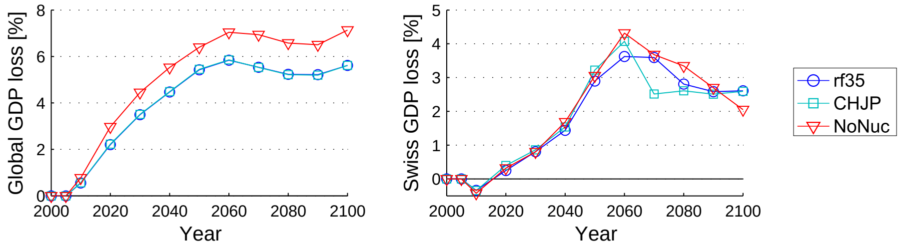
2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
14.5	-9.3	-3.6	-2.7	-3.9	-5.4	-1.2	-6.5	-25.9	-31.8

When the nuclear moratorium is applied globally, Swiss energy-related emissions increase considerably from 2020 to 2060 (28.9% in 2030) compared to the climate scenario where nuclear technologies are available.

5.5.4 Economic implications of nuclear moratoria

The global GDP losses in the no-nuclear scenario (see Figure 5.24A) compared to the reference scenario (scenario without climate policy presented in Section 4.3) reach a maximum of 7% by 2060 and stay relatively constant after. The no-nuclear policy leads to an additional reduction in global GDP compared to the rf35 case with nuclear, with losses around 0.94 percentage points higher in 2030 and 1.52 percentage points higher in 2100.

Swiss GDP losses in the global no-nuclear scenario (see Figure 5.24B), like global GDP losses, increase substantially in the period 2040-2060, driven by earlier investment in solar technologies and additional measures to reduce demand. However, as mentioned above, if only Switzerland and Japan forgo nuclear, while the rest of the world continues to use this technology, then the Swiss GDP losses



(A) *World* (B) *Switzerland*

FIGURE 5.24: *Nuclear phase-out: GDP losses*

are substantially lower from 2070 (although reliance on imports is greatly increased). After 2070, Swiss electricity in the rf35 scenario is produced mainly with hydropower, solar and wind generation, due to high prices of uranium driven by global depletion. For this reason, Swiss GDP losses after 2070 are similar in the rf35 and the two no-nuclear scenarios.

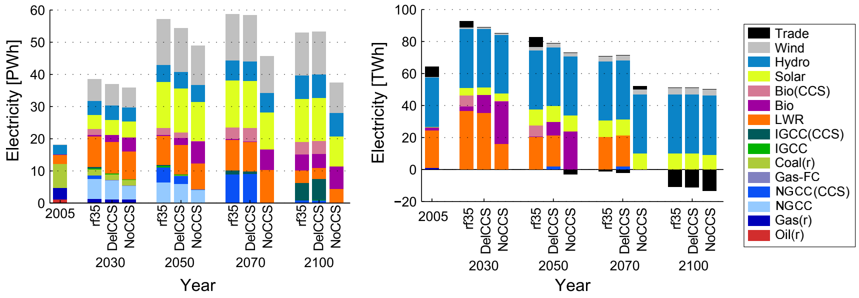
5.6 Technology availability

Chapter 4 showed that for the different climate mitigation scenarios, technologies with carbon capture are important in achieving the long-term climate targets. However, this technology is still in the development phase and has not been proven to work on a large scale. Moreover, if CCS technologies are proven to work on commercial scales, its use might have important limits concerning public and policy acceptance. Furthermore, the development of a high pressure network is required to transport CO_2 to the storage sites, the construction of which can delay the use of CCS technologies. Therefore, this section analyzes the implications for the future energy system and the achievement of global climate mitigation targets of a delay in the availability of CCS technologies (delCCS) or if CCS is not available at all (noCCS). The delay scenario assumes that CCS technologies are available only from 2050.

Besides CCS technologies, the production of hydrogen using a solar thermal process has shown an important contribution to non-electric energy supply in a great part of the climate scenarios (see Figure 4.16B). However, the deployment of this technology on large scales and the development of the appropriate distribution network for hydrogen make the large use of the sth-h2 technology considerably uncertain. Hence, a scenario without the deployment of this technology (noSTH) is also analyzed.

5.6.1 Technology pathways without carbon capture technologies

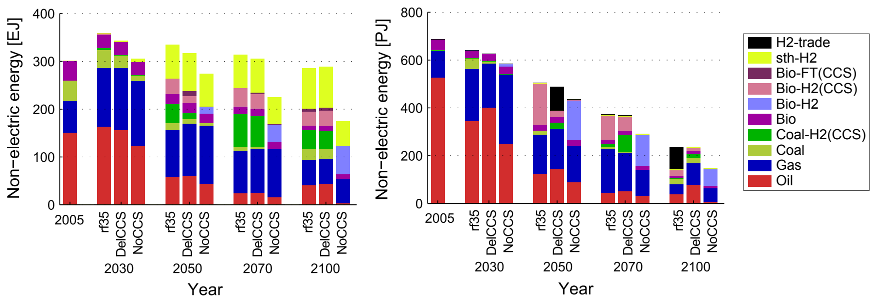
In the rf35 scenario, three technologies with carbon capture and storage are used to generate electricity at different times during the 21st century, namely: NGCC(CCS), bio(CCS) and IGCC(CCS). When CCS is not available or delayed, biomass without carbon capture is used to partially replace these three technologies, since it has low CO_2 emissions per kWh (see Figure 5.25). Furthermore, electricity demand is reduced to compensate the absence or delay in the deployment of CCS technologies. In Switzerland, the contribution of electricity generation with biomass increases, while nuclear power is phased out earlier due to the increase in uranium price driven by the increase in nuclear deploy-



(A) *Global* **(B)** *Switzerland*

FIGURE 5.25: *CCS deployment scenarios: Electricity production*

ment in other world regions. The delayed deployment scenario is an intermediate case between the reference climate case and the scenario where CCS is not available. There, biomass is used temporally until CCS technologies are available but by the end of the century the energy system in the delayed CCS scenario is very similar to the reference case.



(A) *Global* **(B)** *Switzerland*

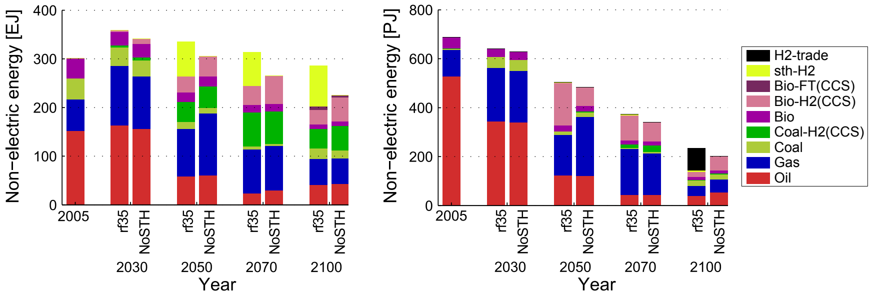
FIGURE 5.26: *CCS deployment scenarios: Non-electric energy production*

In the non-electric sector (see Figure 5.26), the most important consequences are a reduction in demand when no CCS technologies are deployed, and a shift from hydrogen produced with coal and biomass with carbon capture to hydrogen produced from biomass, both globally and in Switzerland. Additionally, in the delayed CCS scenario, the use of fossil fuels from 2030 to 2060 is increased, implying an increase in the CO_2 emissions from the non-electric energy sector.

5.6.2 Technology pathways without solar thermal hydrogen production

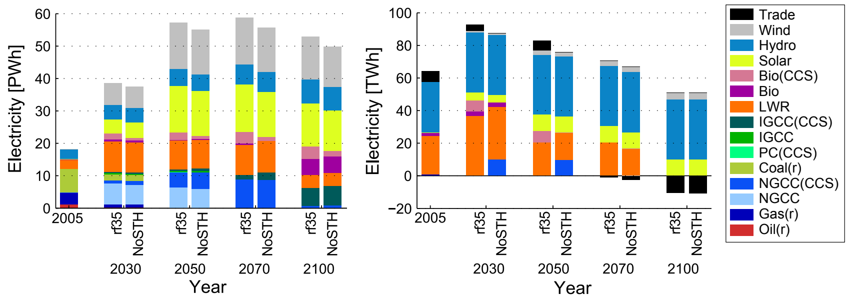
When solar thermal production of hydrogen is not available natural gas and production of hydrogen from biomass act as substitutes (see Figure 5.27). Globally, biomass is shifted from electricity to hydrogen production, implying a slight reduction in total electricity demand, although lower than the decrease in non-electric demand, implying additional electrification of the non-electric energy sector (see Figure 5.28).

In Switzerland, higher global demand of biomass produces higher biomass prices and therefore, natural gas replaces biomass used to supply non-electric demands and the NGCC(CCS) technology becomes the preferred alternative from 2030 to 2060 to generate electricity.



(A) *World* (B) *Switzerland*

FIGURE 5.27: *No STH-H2 deployment: Non-electric energy generation*

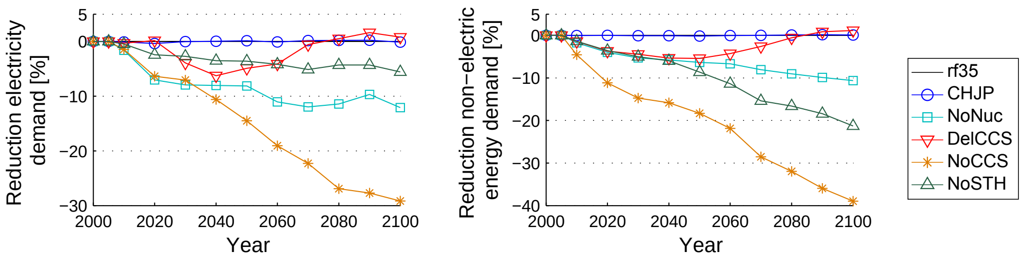


(A) *World* (B) *Switzerland*

FIGURE 5.28: *No STH-H2 deployment: Electricity generation*

5.6.3 Technology availability and energy efficiency

As shown in Figures 5.22, 5.25, 5.26, 5.27 and 5.28, one of the main consequences of not having available lower carbon technologies is the reduction in the energy demand. Figure 5.29 presents the reductions in energy demand in the evaluated cases on technology availability, including: nuclear phase-out in Switzerland and Japan (CHJP), global nuclear phase-out (NoNuc), delayed CCS deployment (delCCS), no CCS technologies (NoCCS) and no production of hydrogen with solar-thermal processes (NoSTH) compared to the reference climate scenario (rf35).

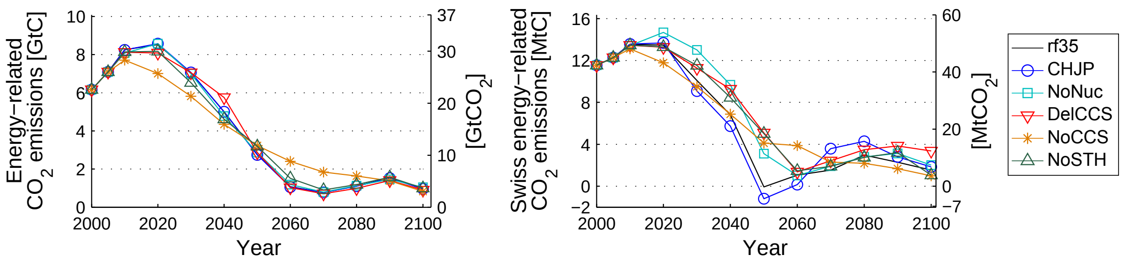


(A) *Electricity* (B) *Non-electric energy*

FIGURE 5.29: *Technology availability scenarios: Reductions in energy demand*

Large demand reductions, implying important improvements in energy efficiency, are observed in the scenarios without nuclear, solar thermal production of hydrogen and CCS technologies. The technology with the greatest impact on both electricity and non-electric energy demand is CCS, since this group of technologies including NGCC(CCS), PC(CCS), bio(CCS), bio-H2(CCS) and coal-H2(CCS), have a substantial share in the energy production in the reference climate scenario (rf35) from 2050 due to its large capacity to reduce emissions. Total energy demand reductions without the development of CCS technologies reach 16.9% and 35.1% by 2050 and 2100, respectively. When the deployment of carbon capture technologies is delayed to 2050 the energy demand is slightly reduced only while the technology is not available. A nuclear phase out in just Switzerland and Japan does not have an effect on global energy demand. With a global nuclear moratorium, electricity is partially substituted with non-electric energy, but there are considerable energy efficiency improvements in both sectors, with total energy demand reductions of 7 and 11.2% by 2050 and 2100, respectively. Finally, the scenario without the development of solar thermal production of hydrogen (noSTH), contrary to the nuclear phase out, implies some level of electrification of the non-electric energy sector and large energy demand reductions, 6.7% in 2050 and 15% in 2100.

5.6.4 Climate implications



(A) *Global* (B) *Swiss*

FIGURE 5.30: *Technology availability scenarios: Energy-related CO_2 emissions*

Although the radiative forcing target in all the technology scenarios is 3.5 W/m^2, the optimal CO_2 emissions pathways change across scenarios as a consequence of the optimal technology mix. Figure 5.30 shows the global and Swiss emissions pathways for the five scenarios on technology availability compared to the reference climate scenario (rf35). Globally, the main change in emissions occurs in the scenario without CCS. Biomass technologies with CCS have negative emissions coefficients, assuming that when growing the biomass crops capture the CO_2 that is emitted in the future combustion. Thus, when technologies with CCS are not deployed, the optimal emissions are substantially reduced in the first half of the century, since they can not be captured by growing biomass crops. Compared to the delayed CCS scenario, the emissions pathways have an opposite behavior, in the first half of the century CO_2 emissions are larger than in the case without CCS deployment, because the option of capturing the CO_2 is available from 2050. The global emissions in the other scenarios are similar to the reference climate scenario. In Switzerland, the emission pathways have a large variation across the technology scenarios. The scenario with a local nuclear phase out has lower emissions until 2050, due to an earlier and larger use of biomass resources to partially replace the nuclear power, and higher emissions in the second half of the century. In all the other scenarios additional fossil fuel based technologies are used, e.g. in the scenario without the development of hydrogen production from solar-thermal processes the additional use of natural gas (NGCC and directly in the non-electric sector) produces an increase in the Swiss energy-related emissions of 14.2% and 24.2% in 2030 and

2040, respectively.

5.6.5 Economic implications

The carbon price obtained in the different technology scenarios is presented in Figure 5.31. As expected, the nuclear phase out in Switzerland and Japan produces the same CO_2 price as in the reference climate scenario, since the global energy system is almost unchanged. The scenario with the largest carbon price is the noCCS case, in which the carbon price reaches 448, 1339 and 2639 USD/tCO_2 in 2050, 2070 and 2080, respectively. All the other scenarios imply an increase in carbon price lower than that in the scenario without CCS.

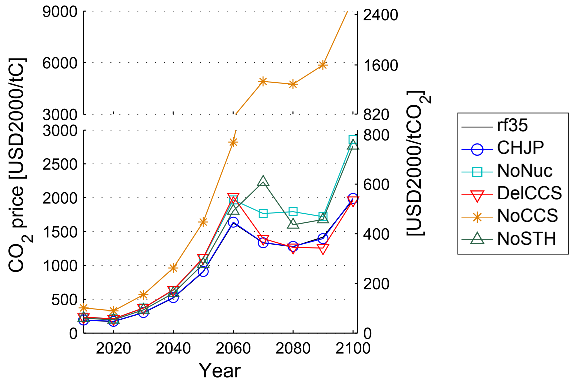


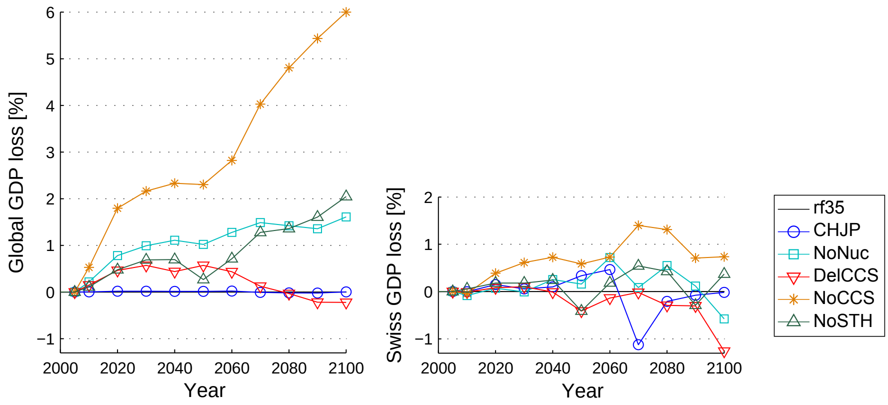
FIGURE 5.31: *Technology availability scenarios: Carbon price*

Finally, GDP losses are consistent with the demand reductions, being almost 3 times larger in the noCCS scenarios compared to the noNuc and noSTH cases, which have similar GDP losses. Losses in GDP in Switzerland are generally lower than global losses, due to the considerable share of hydropower in the electricity generation, which deployment is less uncertainty than that of nuclear, CCS or solar thermal production of hydrogen. In Switzerland, as in the global case, the technology with the largest effect on the costs of achieving the climate mitigation target is CCS, since it can play an important role in the production of hydrogen for non-electric energy supply. The scenario on global nuclear phase-out shows some reductions in Swiss GDP, around 0.2-0.8% from 2040 to 2090, due to the needed changes to the Swiss energy system. However, the nuclear moratorium in Switzerland and Japan has higher GDP losses in the first half of the century, when imports of electricity from the EU are needed; and implies some economic gains (negative losses) from 2070 to 2090, when emissions are leaked from Switzerland to the EU (as presented in Figure 5.23). In the same way, this CO_2 leakage produces GDP gains in the delayed CCS scenario from 2050.

5.7 Discussion

5.7.1 Technology costs

The costs of technologies have an important economic impact on the achievement of climate mitigation targets. The costs scenarios analyzed in this chapter assume the same variation in all tech-



(A) *Global* (B) *Switzerland*

FIGURE 5.32: *Climate scenarios: GDP losses*

nologies, representing changes in the costs due to higher or lower material costs, which would affect all technology alternatives. These changes in the investment costs do not affect the portfolio of preferred technologies. In all the scenarios, independently from the assumed technology costs, renewable based technologies, nuclear power and technologies with CCS are deployed. However, other costs scenarios are also possible, including higher costs of particular technologies due to increase in safety requirements, e.g. higher costs of nuclear power to improve safety. This could have an important effect on the technology portfolio.

5.7.2 Technology learning

The analysis of the different regional learning spillovers alternatives show that transfers of knowledge and know-how between developed and developing regions is important to guarantee a learning of the technologies through the acquisition of experience and research and development efforts. However, these spillovers might also result, as found in the analysis in this thesis consistent with the results presented by Bosetti et al. (2008), in free riding from those regions considered imitators. Furthermore, the results show that global technology pathways are not affected by different levels of spillovers, since low-carbon technologies are needed to achieve stringent climate policies. Nevertheless, the reduction in regional spillovers implies considerably high costs for the different regions since the technology development processes is carried out independently.

For Switzerland, technology spillovers were found to have an important effect. Due to its size, not having global learning processes implies lower technology learning of important technologies for the achievement of climate targets, such as wind and solar. However, the 0% spillovers case is unlikely for Switzerland, since this country is highly integrated with the EU, e.g. many companies that invest in electricity generating technologies are located all across Europe, including Switzerland.

5.7.3 Technology availability

Nuclear technologies

Nuclear technologies have the capacity of producing electricity with low CO_2 emissions. However, the development of nuclear reactors has important limits concerning public acceptance and policy support, especially after the nuclear accident in Fukushima in 2011.

Analysis of nuclear phase-outs in only Switzerland and Japan reveal somewhat divergent results. While both countries have very limited natural resources (including carbon storage potentials), Switzerland has more ready access to imported electricity. Assuming that a large reliance on imports is acceptable to Swiss policymakers, nuclear energy could be largely replaced by imports, producing only minimal economic effects (in effect, the Swiss reactors shift to the EU). This illustrates an important potential trade-off in Switzerland between a domestic phase-out of nuclear energy, maintaining self sufficiency in electricity supply, and achieving ambitious climate targets. However, should the rest of the world implement the same policy, access to cheap low-carbon electricity imports becomes limited, requiring more drastic action in Switzerland. For Japan, access to electricity imports is limited in all cases, so a domestic phase-out of nuclear requires significant changes to the energy system, while a global phase-out of nuclear has relatively little incremental effect.

The current Swiss nuclear policy has important effects on the energy related emissions. Even though a local phase-out of nuclear power does not increase Swiss emissions, it results in a shift of electricity production to the EU, which implies a leakage of emissions from Switzerland. Indeed, when Swiss electricity generation does not rely on imported electricity, energy-related emissions increase substantially.

Weidmann et al. (2012) analyzed the implications of a nuclear phase out in Switzerland using two bottom-up models, the Swiss MARKAL energy system model (SMM) and Swiss TIMES electricity sector model (STM). These represent different modeling approaches to MERGE-ETL. SMM and STM are Swiss national models with a highly detailed energy sector and do not include the linkages between economic activity and energy demand, i.e. energy costs and energy service demands are exogenous inputs. Thus, Weidmann et al. (2012) analyze from a domestic perspective the consequences of the nuclear phase out policy on the Swiss end use sectors and electricity generation schedules. In contrast, MERGE-ETL is a global integrated assessment model that allows us to analyze the effect of the nuclear phase out policy in Switzerland from a global perspective, including the effects of resources depletion, trading, technology learning and endogenous energy prices and demands. It should be noted that Weidmann et al. (2012) apply some different scenario driving forces (GDP, population), but the broad results can still be compared for similar scenarios. We focus in particular on the climate policy scenarios with a nuclear phase-out.

Efficiency improvements are modeled in different ways in the two modeling approaches: in MERGE-ETL electricity can be substituted by additional investments representing improvements to the technologies; while in Weidmann et al. (2012) efficiency is modeled using an expensive technology that can be used to reduce electricity demand. Despite the differences in the modeling approach, for the nuclear phase out analyzes, both studies show that achieving stringent climate targets without nuclear generation results in higher energy costs and requires further energy demand reductions, which implies additional energy efficiency measures. In both studies hydropower is deployed to its maximum potential of 37-38 TWh. Weidmann et al. (2012) found that dam hydro facilities contribute to supply security through their storage capability, which allows imports of cheap electricity during the night and their dispatch during the day. By 2050, solar and wind generation play an important role in both studies. In SMM and STM the remaining electricity is produced with biomass and gas while in our study it is imported from the EU. This difference is driven by two factors. First, in MERGE-ETL global depletion of gas resources leads to high gas prices such that gas generation is uncompetitive for Switzerland (in comparison Weidmann et al. (2012) assume an exogenous gas price). This also means that gas is less attractive in the non-electric sector, and thus biomass resources are used here rather than for electricity production. Second, Weidmann et al. (2012) did not consider cases with a large reliance on electricity imports, and placed a higher emphasis on self sufficiency.

Technologies with carbon capture

Technologies with carbon capture and storage play a very important role in the achievement of a sustainable future energy system globally. Nevertheless, this technology is still in the demonstration phase without commercial projects being developed yet. Furthermore, many questions concerning safety and possible leakages from CO_2 repositories raised some public skepticism that could imply public acceptance issues. Furthermore, even if the technology has political support and public acceptance, the development of the appropriate network for captured CO_2 could imply delays in the deployment of CCS options.

Biomass options without CCS to produce both electricity and non-electric energy are shown to be an interesting alternative in the case in which carbon capture and storage is not deployed. Besides the shift to biomass, when CCS technologies are not available large energy demand reductions are observed. The change in the technology portfolio together with the demand reduction have important consequences in the costs of achieving the climate targets, which are higher in this scenario compared to the reference climate case.

Thus, governmental support to research and development on this technology is important to achieve stringent climate targets at lower costs. Furthermore, technology transfer mechanisms to guarantee the deployment of the technology in today's developing regions are also needed. Another important aspect for CCS technologies is the transport of CO_2. The construction of high-pressure pipelines networks connecting power plants and the storage facilities is required. The development of such a network involves different challenges including planning, public acceptance, regulation, which need to be addressed by governments (IEA, 2010c).

Hydrogen production with solar thermal process

The production of hydrogen using solar thermal processes can have an important contribution to the supply of non-electric energy. However, the development of this technology has important uncertainties concerning commercial scales and development of the network. In the case in which the sth-H2 technology is not available additional electrification and efficiency improvements are observed, hence, higher costs of realizing stringent climate targets. Besides reductions in the electricity and non-electric energy demand, the production of hydrogen with solar thermal processes is partially replaced with hydrogen produced from biomass and coal with CCS.

5.8 Implications for Switzerland

Technology spillovers were found to have an important effect since the accumulation of experience is relatively small in Switzerland due to its size. Therefore, a sustainable Swiss energy system that aims for mitigating climate change in a global level needs technology transfer agreements with both developed and developing regions to assure that technological improvements help achieving global climate targets.

Renewable-based technologies bring stability to the future energy system since the uncertainty concerning its deployment is relatively low. However, the scenarios concerning the availability of nuclear, CCS technologies and hydrogen production from solar-thermal processes show the importance of efficiency improvements to achieve demand reductions. However, these reductions might not be feasible considering limits to technological improvements.

The analyses showed that technologies with CCS have an important role for climate mitigation purposes in Switzerland. If these technologies were not developed, realizing a sustainable Swiss energy system would imply higher economic consequences due to additional reductions in the energy-related emissions and the lower energy demands. Thus, support to research and development of such technologies can contribute substantially to the achievement of sustainable objectives.

The phase-out of the nuclear power in Switzerland has important trade-offs with the self-sufficiency of the Swiss energy system, since the electricity coming from nuclear technologies is replaced mainly with imports of electricity from the EU.

The analysis concerning the availability of solar-thermal processes for hydrogen production do not show an important effect in the Swiss energy system due to the relatively low potential assumed for this technology. However, as in the rest of the world, this alternative could play an important role for non-electric energy supply; hence research and development of large scale solar-thermal hydrogen production could contribute in the realization of a sustainable Swiss energy system.

In many of the scenarios biomass is shown to be an interesting alternative for the Swiss energy system. An important part of the biomass used in Switzerland is imported and, therefore, issues concerning the not development of CCS technologies, nuclear power plants or solar thermal production of hydrogen; or the use of biomass for food production, can imply higher global competition for biomass resources. Hence, Switzerland would need alternative fuels, such as natural gas, that might be a threat for security of supply and the climate mitigation objectives of the sustainable Swiss energy system.

Chapter 6

Nuclear fuel cycle options for a sustainable energy system

6.1 Introduction

Nuclear-based electricity generation has the capacity of producing electricity with low CO_2 emissions. In 2008, nuclear generation provided 13.5% of global electricity (IEA, 2010a). However, deployment of nuclear power has had historically and has today important challenges related to policy support and public acceptance for safety and radiative waste concerns, rather than technological (IEA, 2010d). In 1980's, the Three Mile Island and Chernobyl accidents triggered strong anti-nuclear movements in many OECD countries. As a consequence of these movements some countries decided to delay nuclear expansion, phase-out their nuclear fleet or abandon their nuclear programs. However, other countries, such as Switzerland and France, continued the development and use of nuclear power. In 2011, the nuclear accident in Fukushima, Japan, revived concerns regarding safety of nuclear reactors and increased uncertainty in the use of nuclear power for the future energy system. Some countries, including Germany and Switzerland, opted for a phase-out of their nuclear power plants.

An important characteristic of nuclear energy is the capacity of reprocessing the used fuel to recover uranium or plutonium that can be re-used to produce electricity. Reprocessing of spent fuel is accepted in many countries, including Switzerland and France; Russia and Japan. Currently nuclear reactors in operation correspond mostly to light (or heavy) water reactors. These technologies use either Uranium Oxide (UOX) or Mixed Oxide (MOX). Uranium oxide is produced from low enriched uranium, which is obtained from converted natural uranium. Mixed oxide (MOX) fuel is produced from reprocessed spent fuel as an alternative to low enriched uranium. It is a combination of natural uranium with reprocessed uranium, depleted uranium or plutonium. In 2009, 26 of the 343 reactors in the OECD countries used MOX fuel to generate electricity; 20 of these reactors were located in France (Nuclear Energy Agency and the International Atomic Energy Agency, 2010). However, spent fuel reprocessing has important concerns regarding proliferation, that is, the misuse of nuclear materials or facilities for terrorism, weapon production or other non energy related purposes.

FBRs can generate electricity using depleted and reprocessed uranium, and plutonium. Demonstration and prototype fast breeder reactors, with electrical power output from 250 to 1200 MW, have been developed since the 1960's (IAEA, 2011). Currently, the research on fast reactors is developed by the Generation IV International Forum and the International Atomic Energy Agency (IAEA) (International project on Innovative Nuclear and Fuel Cycles - INPRO); as well as different national incentives for research, including countries such as Russia, China and India.

Some models for energy analysis, such as TIMES or MARKAL (Gül, 2008; Reiter, 2010; Weidmann et al., 2012) use a general representation of the nuclear reactors, modeling them as conversion technologies that convert natural uranium into electricity with an assumed efficiency. However, the analysis of the future role of nuclear power requires a more detailed modeling of the nuclear cycle, to include different fuel and reactor alternatives and the appropriate representation of waste disposal and spent fuel reprocessing. In this thesis, a nuclear cycle including these features was modeled within MERGE-ETL to improve the understanding concerning the role of nuclear cycle options to realize sustainable global and Swiss energy system.

In this chapter the developed nuclear cycle is presented and different scenarios representing different levels of nuclear support are analyzed. The FBR is assumed to be available from 2040, which is an ambitious but still possible starting date assuming some of the technical limitations of the technology are overcome[1].

6.2 Enhanced nuclear fuel cycle

The fuel cycle presented in Section 3.2.2 represents a simplified nuclear cycle that includes the use of FBRs as an alternative to light water reactors. However, this fuel cycle does not include the use of mixed-oxide fuels for LWR, does not model explicitly fuel production and uses a non-specific model of waste disposal. For these reasons, in this thesis an enhanced version of the nuclear cycle was developed. This enhanced model addresses these issues by considering different fuel types for both LWRs and FBRs, two reprocessing methods and describing more precisely waste disposal. The new nuclear cycle gives more flexibility in the analysis of the role of the nuclear technologies and the effects of a nuclear phase out in Switzerland or worldwide to achieve climate change mitigation targets.

The enhanced nuclear fuel cycle developed in this thesis models electricity production with light water (LWR) and fast breeder reactors (FBR) including fuel production, electricity generation and waste reprocessing and disposal. The static version of this fuel cycle model, developed by Parada et al. (2011)[2] is based mainly on the fuel cycle analysis published by Shropshire et al. (2007). Based on the static fuel cycle developed by Parada et al. (2011), in this thesis a dynamic nuclear cycle was developed and included in MERGE-ETL. The dynamic component was introduced including a time dependency in the fuel cycle equations and the possibility of storage of nuclear fuels to be used in later periods.

Figure 6.1 presents the diagram of the fuel cycle for one period and one region. It includes fuel production comprising (1) uranium conversion, (2) low and high uranium enrichment, (3) the production of two types of fuel for each reactor: mixed and uranium oxide for the LWR and ceramic and metallic fuel for the FBR. The fuel cycle also models: the temporal storage of spent nuclear fuel; (4) fuel repro-

[1] Note that some of the research aims to have a Generation IV demonstration reactor in operation by around 2030 (IAEA, 2011).

[2] This work was pursued at the Energy Economics Group at Paul Scherrer Institute and was supervised by the author of this PhD thesis.

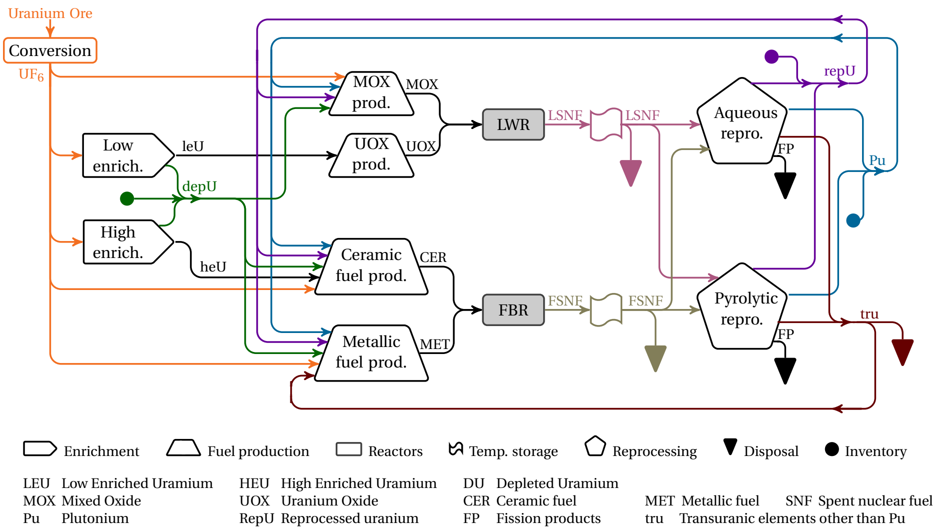


FIGURE 6.1: *Nuclear cycle model*

cessing with aqueous and pyrolytic processes; and (5) geological disposal. It is important to note that trading of nuclear fuels other than uranium is not modeled.

(1) Conversion: The cycle starts with the uranium ore coming from the uranium resources. In the conversion process, yellow cake coming from uranium mining (U_3O_8) is converted to uranium hexafluoride (UF_6) using either wet or dry chemical processes. According to Shropshire et al. (2007) the cost of the conversion process accounts for around 4% of the fuel cycle cost. Nevertheless, additional costs come from the transport of the uranium hexafluoride to the enrichment plant.

(2) Enrichment: After being converted to UF_6, uranium is enriched for use in light water reactors (LWR) or fast breeder reactors (FBR), producing low or high enriched uranium (leU or heU) and large amounts of depleted uranium (depU). The cost of enrichment is determined by the amount of work needed in the process. Following Glasstone and Sesonske (1994), the work done to convert a mass F of feed (UF_6 with a ^{235}U content x_f of 0.711%) into a mass E of enriched uranium with a certain ^{235}U content (x_e) and waste of mass W (with a ^{235}U content x_w) is expressed in terms of separative work units (SWU), thus,

$$\mathrm{SWU} = E \cdot V(x_e) + W \cdot V(x_w) - F \cdot V(x_f),$$

where $V(x)$ is the so-called *value function*, corresponding to

$$V(x) = (1-2x)\ln\frac{1-x}{x},$$

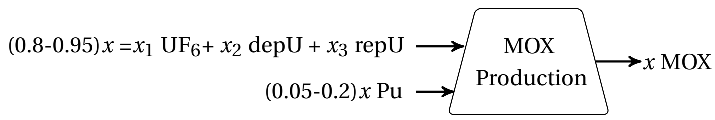
where x is the assay of the material.

Shropshire et al. (2007) estimated an enrichment cost of 91 USD2000 per separative work unit (SWU). To obtain the cost per kilogram of enriched uranium a fixed ratio of tailing to enriched uranium and a fixed enrichment level requirement in each reactor is assumed. A typical LWR requires fuel comprising 3-5% ^{235}U (leU) (Shropshire et al., 2007), therefore, we assumed a concentration of 4% and a ratio of 9:1. The FBR uses high enriched uranium (heU), which is assumed to have a ratio of tailing and enriched uranium of 29:1 and an enrichment level of 15%. Using the definition of SWU[3] the enrichment costs correspond to 443.9 and 2921.3 USD2000 per kg of leU and heU, respectively.

(3) Fuel production:

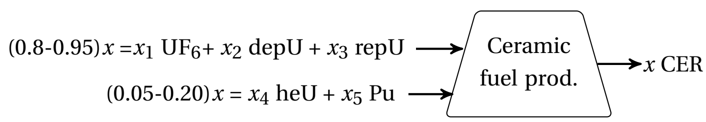
(a) Uranium oxide (UOX) fuel for LWR: UOX is used in the form of ceramic pellets produced from low-enriched uranium. Shropshire et al. (2007) estimate fuel production costs in the range from 183 to 267 USD2000 per kg UOX (including packaging and transportation costs from the production plant to the reactor). Additionally, the uranium oxide production requires the transportation of the leU to the facility, thus this transport cost is also included.

(b) Mixed oxide (MOX) fuel production for LWR: MOX fuel are ceramic pellets of fertile material and fissile material assembled inside metallic fuel rods. The fuel contains 80-95% fertile material and 5-20% fissile material (plutonium). The fertile material is obtained from natural uranium (UF_6), depleted uranium (depU) coming from the enrichment processes, or reprocessed uranium (repU) obtained from reprocessing of nuclear spent fuel; we assume that these three fuels are interchangeable.



Shropshire et al. (2007) estimate MOX production costs of around 2656 USD2000 per kg MOX (including packaging, transportation from the production plant to the reactor and intermediate storage costs). Additionally, the transport costs from enrichment or reprocessing plants are included. Despite the high costs of producing MOX fuel compared to UOX, this fuel brings the possibility of using reprocessed uranium obtained from spent nuclear fuel that would be otherwise dispose.

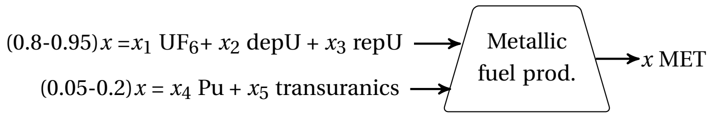
(c) Ceramic (CER) fuel for FBR: Ceramic fuel contains 5-20% fissile material consisting of plutonium (Pu) or high enriched uranium (heU); and 80-95% of fertile material from depleted uranium (depU), reprocessed uranium (repU) or natural uranium (UF_6), which are considered interchangeable.



Shropshire et al. (2007) estimate ceramic fuel production costs between 2988 and 3320 USD2000 per kg CER (including packaging, transportation from the production plant to the reactor and intermediate storage costs). Additionally, the transport costs from enrichment or reprocessing plants are included.

[3]Mass balance is assumed for the enrichment process, thus $F = E + W$ and $Fx_f = Ex_e + Wx_w$.

(d) Metallic (MET) fuel for FBR: Metallic fuel for FBRs is produced using a remote-handled process due to the high radioactivity of the materials involved. Compared to ceramic fuel, fissile materials other than plutonium can be used (fissile transuranics). In this model we assume that all transuranics can be used as inputs to metallic fuel production. The production of metallic fuel requires a share of fissile material from 5 to 20% and the rest corresponds to fertile material, namely: depleted (depU), reprocessed (repU) or natural (UF_6) uranium.

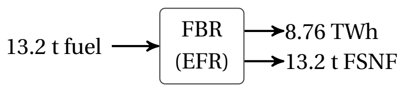


The cost estimated in Shropshire et al. (2007) for the metallic fuel production is USD2000 4565 per kg MET (including packaging, transportation from the production plant to the reactor and intermediate storage costs). Transport costs from enrichment or reprocessing plants are also included.

(4) Reactors

(a) Light water reactor (LWR): The LWR uses both MOX or uranium oxide (UOX) fuels and produces spent nuclear fuel (LSNF) that can be either disposed or reprocessed with aqueous or pyrolytic reprocessing technologies. The fuel cycle of the light water reactor is modeled based on the European Pressurized Reactor (EPR). Assuming that the quantity of mass converted to energy is negligible, the mass in the reactor is balanced to estimate the amount of fuel needed. The following diagram shows the input-output relation for the EPR (with an annual output of 11.46 TWh) based on Chakravorty et al. (2009).

(b) Fast breeder reactor (FBR): The FBR uses both metallic and ceramic fuel and produces spent nuclear fuel (FSNF) that can be either disposed or reprocessed in aqueous or pyrolytic reprocessing technologies. The Fast Breeder Reactor is modeled based on the European Fast Reactor (EFR), with the input-output relation presented in the following diagram (based on Chakravorty et al. (2009)).



(c) Temporary storage, conditioning and packaging of spent fuel: Spent nuclear fuel (SNF) produced by the reactors is stored temporarily in a wet or dry storage and then conditioned and package for shipping to reprocessing or disposal sites. The costs assumed for this process are an average for wet and dry storage costs estimated by Shropshire et al. (2007).

(5) Reprocessing: The reprocessing plant separates components of spent nuclear fuels for recycling, decay management and disposal. The spent fuel is composed by reprocessed uranium (repU), plutonium, fission products (FP) that have to be geologically disposed, and transuranics (tru).

The composition of the reprocessed fuel depends on the type of spent fuel: LSNF or FSNF coming from the LWR or the FBR, respectively. Table 6.1 presents the input-output relationships for both types of nuclear spent fuels (Chakravorty et al., 2009).

Input	**Outputs**			
	repU	Pu	FP	tru
x LSNF	$0.92x$	$0.013x$	$0.066x$	$0.002x$
x FSNF	$0.788x$	$0.136x$	$0.076x$	-

TABLE 6.1: *Reprocessing input-output relationships*

Two types of reprocessing technologies are included: aqueous and pyrolytic, which differ in terms of process and costs.

(a) Aqueous reprocessing: Consist on the separation of spent nuclear fuel using aqueous processes to achieve chemical separation (Shropshire et al., 2007).

(b) Pyrolytic reprocessing: In this type of reprocessing the spent nuclear fuel is separated electrochemically using a molten salt electrolyte. This type of process has been demonstrated in research reactors but has not been used on a commercial scale (Shropshire et al., 2007) and, therefore, the costs are relatively high.

(6) Storage and disposal: The developed nuclear fuel cycle includes interim storage and permanent disposal of the different materials. Interim storage is modeled for depleted uranium, reprocessed uranium, spent fuel and plutonium and the costs depend on length of the storing period. Permanent geological disposal is modeled for depleted uranium, reprocessed uranium, fission products, plutonium and other transuranics. These processes have different costs depending on the material and its origin.

Table 6.2 summarizes the costs of all the processes included in the nuclear fuel cycle.

TABLE 6.2: *Nuclear cycle: Costs of the processes. Estimated from Shropshire et al. (2007)*

Process	**Cost**	**Unit**
(1) Conversion	8.3	USD/kgU in UF_6
(2a) Low enrichment	444	USD/kg of leU
(2b) High enrichment	2921	USD/kg of heU
(3a) Uranium oxide production	224	USD/kg UOX
(3b) Mixed oxide production	2656	USD/kg MOX
(3c) Ceramic fuel production	3154	USD/kg CER
(3d) Metallic fuel production	4565	USD/kg MET
(4c) Temporal storage and conditioning	327	USD/kg LSNF or FSNF
(5a) Aqueous reprocessing	417	USD/kg LSNF or FSNF
(5b) Pyrolytic reprocessing	2241	USD/kg LSNF or FSNF
(6) Interim storage	230	USD/kg Pu/year
	0.4	USD/ kg depU/year
	1.3	USD/kg repU/year
(6) Disposal depU	26	USD/kg depU
(6) Disposal repU	66	USD/kg repU
(6) Disposal spent nuclear fuel	438	USD/kg LSNF or FSNF
(6) Disposal Pu and tru	11458	USD/kg Pu or tru
(6) Disposal fissions products	4990	USD/kg FP

Initial conditions: Nuclear material inventories

Some of the fuels included in the model have an existing inventory that can be used by the fuel cycle (see Table 6.3). The regional inventory of depleted uranium is based on IAEA (2001), plutonium inventory on Albright and Kramer (2005) and spent fuel from the national reports of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (International Panel on Fissile Materials, 2011; People's Republic of China, 2008; Swiss Department of Environment, Transport, Energy and Communications, 2005).

TABLE 6.3: *Nuclear material inventories 2005*

	EUP	SWI	RUS	MEA	IND	CHI	JPN	USA	CANZ	ROW
Depleted Uranium [ktHM]	227		495		4	20		47	4	
Plutonium [tHM]	430.3	13	83		12	25.3	106	388	130	103.6
Spent UOX [ktHM]	32.2	0.74	13			1.3	19	61	37.3	10.9

6.3 Scenario without climate policy

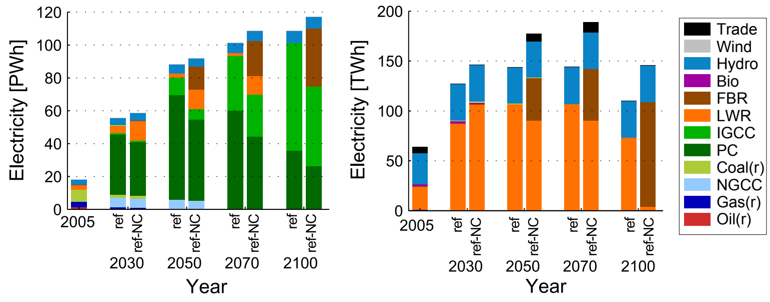
Economic costs to achieve climate targets are usually estimated compared to a future energy system without climate policy. In Section 4.3 a reference scenario without including the use of MOX fuel and FBRs was presented. This scenario is used to determined the costs of different climate policies without MOX fuel and FBRs in Chapter 4. However, this chapter analyses the implications of different nuclear policies to achieve a sustainable energy system, thus a scenario without climate policy with MOX fuel and FBRs being an alternative for electricity production brings an initial point for determining climate policies and technology pathways. This scenario uses the enhanced nuclear cycle developed in this thesis and includes the use of MOX fuel for LWR and FBR technologies are assumed to be available for all the regions from 2040.

Figure 6.2 compares the electricity production in the two scenarios without climate policy: reference scenario in Section 4.3 and the no-climate policy case with the enhanced nuclear cycle (ref-NC). The no-climate policy scenario with the enhanced nuclear cycle results in higher electricity consumption than the reference case, 4.4 and 7.9% in 2050 and 2100, respectively. Nuclear technologies start being an attractive option to generate electricity even in the absence of climate policies, partially replacing coal technologies. In Switzerland the electricity demand is also increased considerably and the LWR is fully replaced with the fast reactor alternative by 2100.

The partial shift from coal to nuclear technologies results in a slight reduction of energy-related CO_2 emissions, from 174 to 148 billion tons of CO_2 by 2100.

6.4 Climate and nuclear policy scenarios

Although nuclear technologies account for an important share of the electricity generation and CO_2 emissions in the absence of a climate policy are lower than without MOX fuels and FBR, the radiative forcing in the ref-NC scenario reaches by 2100 9 W/m^2 (compared to the 9.7 W/m^2 in the reference



(A) *World* (B) *Switzerland*

FIGURE 6.2: *Enhanced nuclear cycle: Electricity generation in reference scenario*

scenario). This radiative forcing level is likely to produce a temperature increase from pre-industrial levels of 5.4°C; therefore, climate policies are still needed to mitigate climate change.

As discussed in the introduction, the deployment of nuclear technologies has important challenges concerning policy support and public acceptance, due to issues related to safety, waste management and proliferation. Thus, different nuclear polices can affect the availability of nuclear rectors or spent fuel reprocessing technologies, which are considered of high risk for proliferation resistance. Nuclear and climate policies have an impact on the future energy system. To assess the impact of these policies different scenarios of nuclear options with (rf35) and without (ref) a radiative forcing target of 3.5 W/m^2 are analyzed (see Table 6.4).

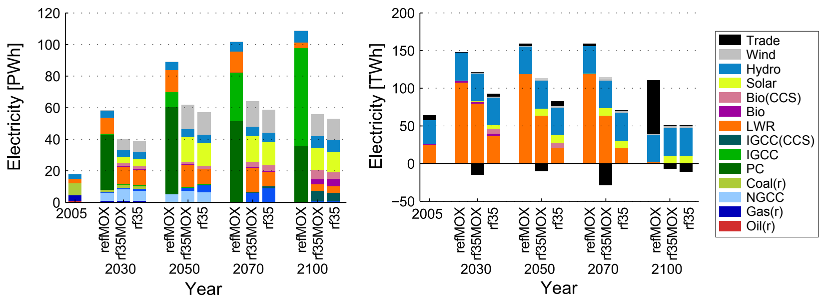
TABLE 6.4: *Nuclear fuel cycle scenarios*

Scenario description	Name	Nuclear options		
		UOX	MOX	FBR
100% nuclear support	NC	x	x	x
No new nuclear technologies	NoFBR	x	x	
New nuclear technologies + No MOX	NoMOX	x		x
Non proliferation	NoProl	x		
No LWR in Switzerland and Japan	NoLWR			x
(with 100% support in the other regions)				

The first scenario corresponds to full global support for new nuclear technologies and fuel reprocessing (NC); the second scenario excludes the development of fast reactors to model technology development constraints (NoFBR); the third scenario represents a nuclear policy in which reprocessing of spent fuel in the LWR is not accepted, and therefore, the MOX fuel option is not included (NoMOX); the fourth scenario is a non-proliferation scenario where the FBR and MOX fuel are not a viable alternative since they required reprocessing of nuclear spent fuel (NoProl). The last scenario aims to represent the current Swiss policy regarding nuclear (noLWR). In Switzerland, the federal cabinet decided in May 2011 to gradually decommission all current Swiss nuclear power plants (Swiss Federal Council, 2011) but left the door open to new nuclear technologies with higher safety. Therefore, in this scenario new LWR are not deployed in Switzerland and Japan (assuming Japan follows the same policy after the accident in Fukushima) but new fast reactors can be utilized.

6.4.1 MOX fuel as an alternative to climate change (noFBR scenario)

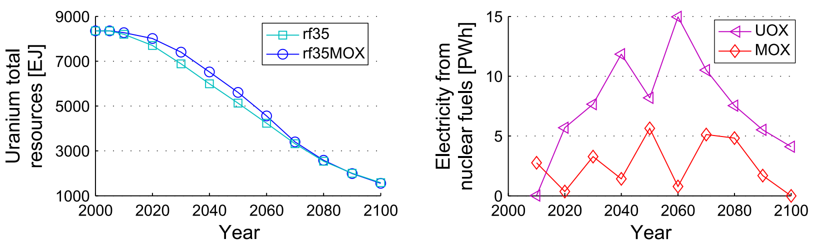
In the reference climate stabilization scenario discussed in Section 4.5 nuclear technologies make an important contribution to electricity production until uranium resources become scarce. An alternative fuel to deal with these resource problems is mixed oxide fuel. This scenario considers the future energy system in which current nuclear technologies that use both uranium and mixed oxide fuels are used but fast reactors are not developed.



(A) *World* **(B)** *Switzerland*

FIGURE 6.3: *Enhanced nuclear cycle: Electricity generation in climate scenario with MOX fuel*

Figure 6.3 presents the electricity production using both UOX and MOX fuel for the LWR (w/o FBR) with (rf35MOX) and without (refMOX) a radiative forcing target of 3.5 W/m^2 compared to the reference climate stabilization scenario rf35 (presented in Section 4.5). Comparing the climate mitigation scenarios with and without MOX fuel, when adding this fuel option, nuclear technologies contribute considerably more to the electricity mix, reducing slightly the use of NGCC with CCS, while renewable-based generation continues to make an important contribution. Uranium resources are depleted as they were in the reference climate scenario (see Figure 6.4A), but the use of MOX fuel helps overcome this resource constraint that reduced the contribution of nuclear power in the reference climate scenario (rf35). Figure 6.4B shows the contribution to electricity production of UOX and MOX fuels[4]. Electricity from MOX fuel represents from 0 to 50% of the nuclear generation. The contribution of MOX fuel is limited by the amount of plutonium needed in its production: in this scenario the optimal share of plutonium is 5% in all regions and periods, which corresponds to the minimum possible plutonium quantity.



(A) *Uranium resources* **(B)** *Electricity from UOX and MOX fuels*

FIGURE 6.4: *Enhanced nuclear cycle: Global resources in climate scenario with MOX fuel*

The global fuel flows (in t or kt) for the year 2050 are presented in the diagram in Figure 6.5. UOX is

[4]Note that the year 2010 is a result of the model, thus it is not calibrated to the energy statistics

the most used fuel in all the periods, implying a high consumption of natural uranium to produce low enriched uranium (148.68 kt in this period). MOX fuel is produced using mainly depleted uranium; and some reprocessed uranium and plutonium. Furthermore, all the spent fuel produced by the LWR is reprocessed (rather than geologically disposed) and the reprocessed uranium (repU) obtained is stored and used in later periods (this is represented by a negative number in the disposal flow).

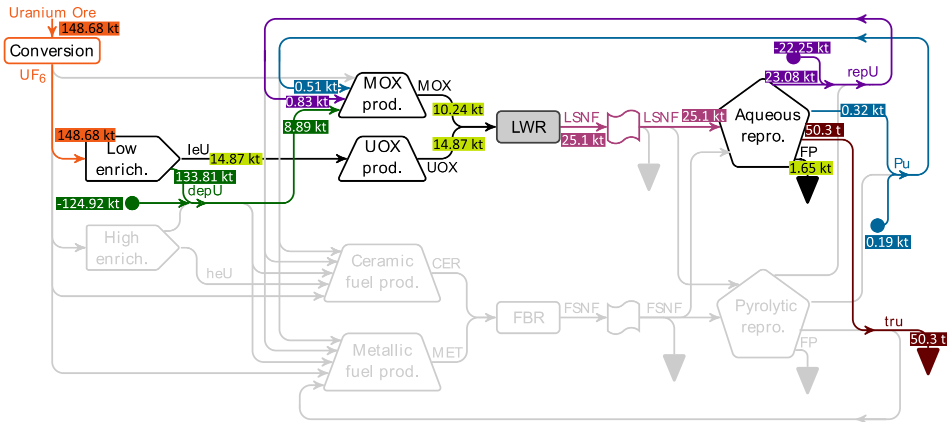
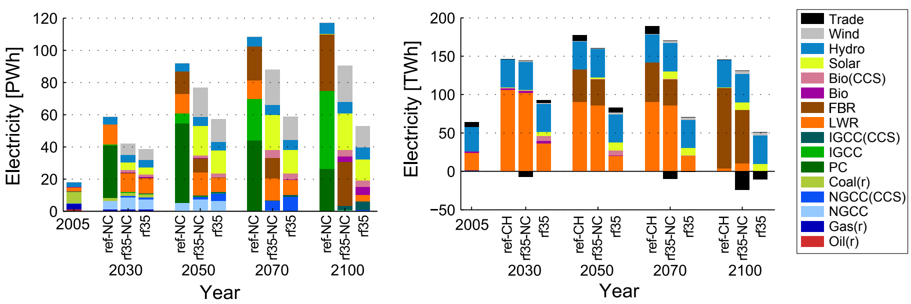


FIGURE 6.5: *Enhanced nuclear cycle: 2050 global fuel flows in climate scenario without FBR*

6.4.2 Full nuclear support policy (NC scenario)

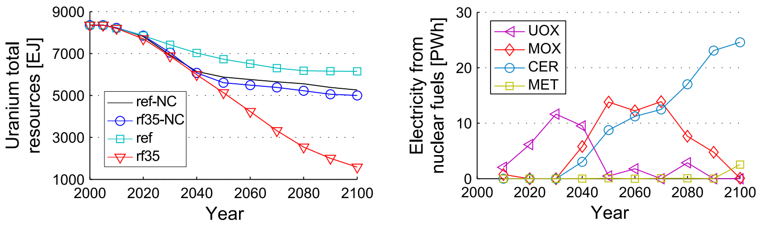
In this scenario a nuclear policy that supports the development of new nuclear and reprocessing technologies worldwide is assumed. While in the absence of FBRs and MOX fuel, the scarcity of uranium resources implies a reduction in the contribution of nuclear technologies, an energy policy that supports nuclear technologies and the reprocessing of spent fuel is likely to overcome these resource constraints (see Figure 6.7A). This is reflected in the production of electricity (see Figure 6.6) where nuclear technologies account for an important share, first with the LWR and by the end of the projection period with a large increase in the use of fast reactors. The increased nuclear deployment leads to a reduction in the contribution of NGCC with carbon capture and storage. Besides nuclear technologies, intermittent renewable-based technologies have an important contribution to electricity generation, as in the reference climate scenario (rf35).



(A) *World* (B) *Switzerland*

FIGURE 6.6: *Enhanced nuclear cycle: Electricity generation in scenario with 100% nuclear support*

Furthermore, Figure 6.7B presents the production of electricity with the different nuclear fuels. Until 2050 the LWRs are the dominant technology using first UOX and later in the century (from 2030) MOX fuel. UOX is used mainly from 2010 to 2050, with a peak by 2030. Compared to the scenario where no new nuclear technologies are developed (see Figure 6.4B), the constraint on MOX fuel production coming from the availability of plutonium is reduced by the reprocessing of spent fuel from the FBR. From 2080 onwards, the FBR reactor using ceramic fuel becomes the preferred fuel option.



(A) *Uranium resources* (B) *Electricity from nuclear fuels*

FIGURE 6.7: *Enhanced nuclear cycle: Global resources in climate scenario with 100% nuclear support*

The global fuel flows (in t or kt) for the year 2040 are presented in Figure 6.8. As shown in Figure 6.7B the UOX is the dominant fuel in this period, implying considerable consumption of natural uranium (171.51 kt) to produce low enriched uranium. MOX fuel is produced using depleted uranium, reprocessed uranium and plutonium with a share of 5% in all the regions. Depleted and reprocessed uranium are stored to be used in the following periods for the production of ceramic and MOX fuels. Finally, the pyrolytic reprocessing is not used due to its considerably higher costs compared to the aqueous option. High costs of geological disposal of transuranics drive the slight use of metallic production, which is not relevant in the overall global picture. Figure C.1 in Appendix C presents the global fuel flows diagrams for the years 2070 and 2100.

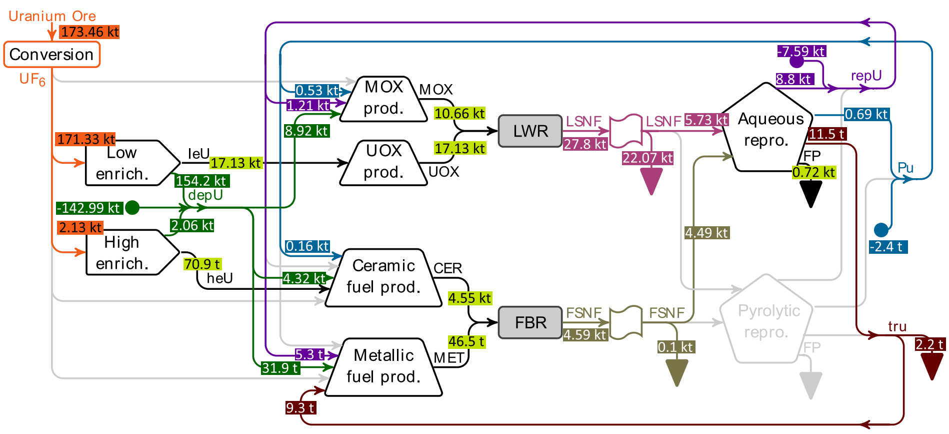


FIGURE 6.8: *Enhanced nuclear cycle: 2040 global fuel flows in climate scenario with 100% nuclear support*

6.4.3 Non proliferation policies (noMOX and noProl scenarios)

Nuclear proliferation refers to the use of nuclear materials or facilities (reactors or reprocessing plants) for theft, terrorism or other purposes not related to energy production. This is one of the main concerns from governments and society regarding nuclear power. Thus, it is possible that policies to prevent proliferation prohibit the development of reprocessing facilities. The non-proliferation scenarios embrace two possible restrictions on the available nuclear technologies. The first corresponds to the restriction on reprocessing of spent fuel coming from current technologies (LWRs), which would preclude the use of MOX fuel. In this case (rf35noMOX) the deployment of fast reactors is delayed compared to the scenario with full nuclear support (rf35NC) due mainly to nuclear fuel availability. While in the rf35NC scenario the production of ceramic fuel starts rapidly using the stored plutonium from the reprocessing of spent MOX fuel, when no MOX fuel is used ceramic fuel is replaced by metallic fuel and its production starts at a slower rate (see Figures 6.7B and 6.9).

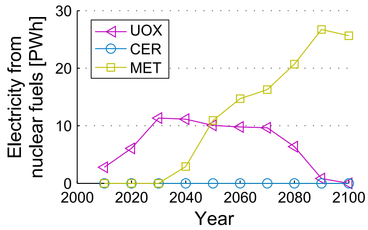
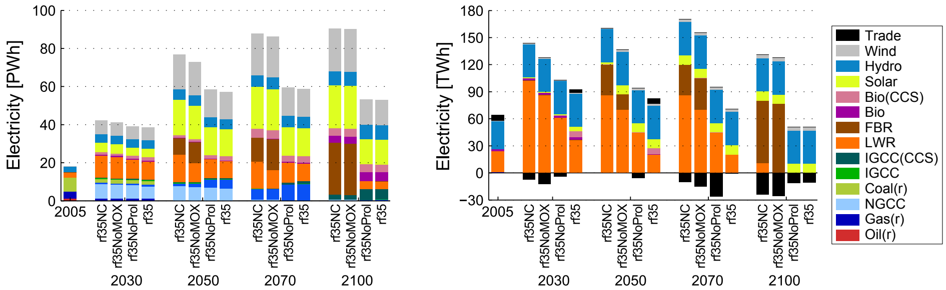


FIGURE 6.9: *Enhanced nuclear cycle: Electricity from nuclear fuels in noMOX scenario*

The second non-proliferation scenario (rf35NoProl) considers a case where support for more advanced and complex nuclear technologies is reduced, i.e. the FBR is assumed to be unavailable and MOX fuel can not be used. This scenario corresponds to the climate reference scenario presented in Section 4.5. The minor differences in the total electricity demand are due to different cost assumptions for the nuclear fuel cycle, but the deployed technologies are the same. Electricity generation comprises mainly renewable technologies with a contribution of nuclear power before the uranium resources are depleted.

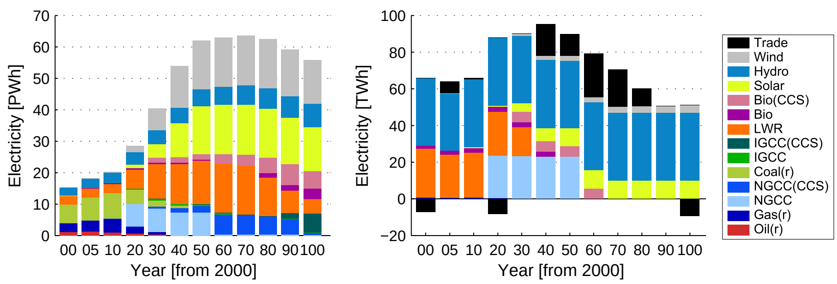


(A) *World* (B) *Switzerland*

FIGURE 6.10: *Enhanced nuclear cycle: Electricity generation in non proliferation scenarios*

6.4.4 Swiss nuclear policy (noLWR scenario)

After the accident in Fukushima, Japan, in March 2011, the Swiss parliament decided to gradually phase-out the current nuclear power plants in Switzerland by retiring the existing reactors at the end of their lifetimes and not replacing them (Swiss Federal Council, 2011). Section 5.5 analyzed the consequences of this nuclear policy in the case in which the world continues using nuclear power plants with an open cycle, where the electricity is produced only from uranium oxide. This scenario showed important trade-offs between the nuclear policy and self-sufficiency, since imports of electricity from the EU replace nuclear-based electricity. The enhanced nuclear fuel cycle developed in this PhD thesis allows the analysis of the nuclear phase out in Switzerland when the world besides using uranium oxide uses as well MOX fuel. Figure 6.11 presents the results of this scenario. The global electricity production in this case corresponds to the noFBR scenario, where MOX fuel helps overcoming the constraint on uranium resources and, therefore, less natural gas is used to produce electricity. In Switzerland, nuclear-based electricity is partly replaced with imports from the EU (as in the scenario in Section 5.5). Besides the imports of electricity, natural gas combined cycle is used as a transition technology, which was not used in the scenario in Section 5.5. This difference comes from less natural gas resources used globally. The use of NGCC implies an increase in energy-related CO_2 emissions in Switzerland, hence, a trade-off between the new nuclear policy and the achievement of climate change mitigation objectives.

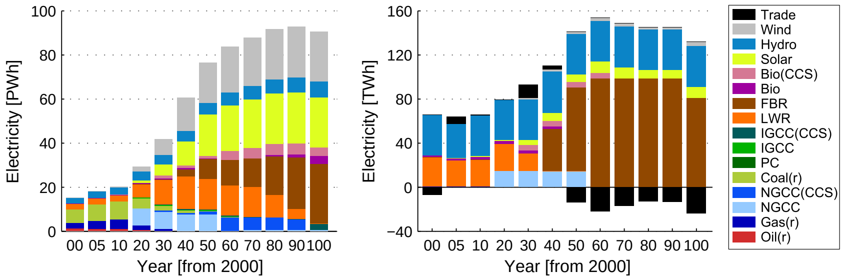


(A) *Global* (B) *Switzerland*

FIGURE 6.11: *Enhanced nuclear cycle: Electricity production in nuclear phase-out in Switzerland scenario*

However, in September 2011, an amendment to the Swiss Parliament decision in May 2011 of not replacing nuclear reactors was proposed by a Senate Committee, leaving open the door for “new generation reactors” that are proved to be safe. Thus, a new scenario on the nuclear phase-out in Switzerland where FBR are allowed is analyzed. This scenario assumes that the other regions of the world have 100% support to nuclear power and in Switzerland the current reactors are not replaced with new ones but FBRs can be used. Furthermore, FBR are assumed to be available from 2040 onwards. Figure 6.12 presents the global and Swiss electricity mix under this policy scenario. In this case, the FBRs are deployed rapidly, becoming the predominant technology by 2100.

Figure 6.13 shows that the electricity in Switzerland coming from nuclear power is produced mainly with ceramic fuel. This implies that local reprocessing of spent fuel becomes a key part of the Swiss energy system bringing a solution to the problems of uranium depletion that can affect Switzerland when using LWRs. It is important to notice that the deployment of FBRs in Switzerland is favored by global learning of the technology. It can be expected that if the nuclear policy in the rest of the world does not support the deployment of fast reactors, costs in Switzerland will be higher.



(A) *Global* (B) *Switzerland*

FIGURE 6.12: *Enhanced nuclear cycle: Electricity production in no LWR in Switzerland scenario*

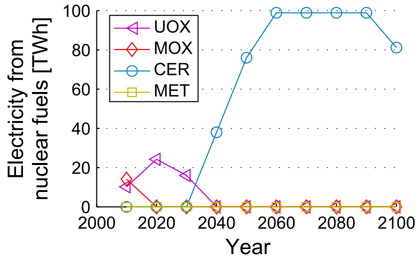


FIGURE 6.13: *Enhanced nuclear cycle: Swiss electricity from nuclear fuels in noLWR scenario*

6.4.5 Energy efficiency

One of the effects of the climate and nuclear policies is a reduction in energy demands. Table 6.5 presents the electricity reductions observed in each of the nuclear policy scenarios with and without climate policy relative to the scenarios with 100% nuclear support (in parenthesis the reductions relative to the corresponding reference scenario are included). The different nuclear policies have important implication for the availability of cheap low-carbon electricity, and hence affect energy demands. The largest demand reductions occur when the new fast technologies are not available, especially if this is part of a non-proliferation policy where MOX fuel is not an option either (global demand reductions in 2050 without climate policy are 3.2% and 3.3%, in NoFBR and NoProl, respectively). The effect of these two policies, NoFBR and NoProl, is considerably larger in Switzerland due to Switzerland's higher reliance on nuclear in the rf35NC scenario (demand reductions in 2100 without climate policy are 25.4% and 23.4%, in NoFBR and Noprol, respectively). When using the fast reactors, the Swiss region becomes almost independent from global uranium resources; hence, the needed demand reductions are larger when a policy that does not allow its deployment is imposed. The no-MOX policy, implies relatively lower reductions in electricity demand. The no-LWR reactor policy leads to a reduction in Swiss electricity demand in 2050, but a slight increase in 2100 (of 10.1%).

Regarding the climate policy, a radiative forcing target of 3.5 W/m^2 implies the implementation of efficiency measures to reduce electricity demand. Globally, nuclear policies have a small effect on electricity demand in the absence of climate policies. For Switzerland, in the no-climate policy scenario, when FBRs are not available, electricity demands are shown to be higher due to higher reliance on nuclear in the refFC scenario. In the climate scenarios, the observed electricity demand reductions due to the nuclear policies vary from 5 to 24% (and 3 to 25% in Switzerland), showing the important role of nuclear power in the achievement of climate mitigation targets. The values presented in parenthesis correspond to the electricity demand relative to the reference case with the same climate policy. These values show that climate policies have a larger effect on electricity demand when FBRs, MOX fuel and fuel reprocessing are not available.

TABLE 6.5: *Nuclear scenarios: Electricity demand reductions [%] relative to refFC scenario. The values presented in parenthesis correspond to the electricity demand relative to the reference case with the same climate policy*

	Global				Switzerland			
Name	2050		2100		2050		2100	
	ref	rf35	ref	rf35	ref	rf35	ref	rf35
NC	0.0	0.0 (16.6)	0.0	0.0 (22.8)	0.0	0.0 (8.1)	0.0	0.0 (25.7)
NoFBR	3.2	19.3 (30.5)	7.2	38.3 (48.7)	10.3	37.2 (35.6)	25.4	59.9 (60.1)
NoMOX	0.6	5.1 (20.3)	-0.2	0.5 (23.3)	1.7	16.7 (22.1)	1.0	3.4 (27.5)
NoProl	3.3	23.8 (34.3)	7.3	41.2 (51.0)	12.0	45.8 (43.4)	23.4	63.6 (64.7)
NoLWR	0.1	0.1 (16.6)	-0.1	-0.1 (22.8)	7.6	11.8 (12.2)	-10.1	-3.9 (29.9)

The non-proliferation scenario with climate policy includes largest reductions in demand (48.7% globally and 60.1% in Switzerland by 2100); while in the scenario with fast reactors and MOX fuel these values are reduced more than half (22.8% globally and 25.7% in Switzerland by 2100).

6.4.6 Economic costs

The energy demand reductions and the deployment of new technologies implied by the different policies have an impact on economic output. Table 6.6 presents the GDP losses in the nuclear policy scenarios with and without climate policy relative to the scenarios with 100% nuclear support (in parenthesis the losses relative to the corresponding reference scenario are included).

The nuclear policies have almost no effect on the economic output when no climate policy is imposed, but this result changes considerably in the presence of a climate scenario. The losses are larger when the fast reactors are not deployed, 2.1 and 2.6% by 2100 globally in the NoFBR and NoProl scenarios, respectively.

TABLE 6.6: *Nuclear scenarios: GDP losses [%] relative to refFC scenario. The values presented in parenthesis correspond to the GDP losses relative to the reference case with the same climate policy*

	Global				Switzerland			
Name	2050		2100		2050		2100	
	ref	rf35	ref	rf35	ref	rf35	ref	rf35
NC	0.0	0.0 (4.4)	0.0	0.0 (3.1)	0.0	0.0 (1.1)	0.0	0.0 (0.0)
NoFBR	0.1	0.9 (5.1)	0.2	2.1 (5.0)	0.2	1.7 (2.5)	0.5	2.4 (2.0)
NoMOX	0.0	0.1 (4.4)	0.0	0.0 (3.1)	0.1	0.5 (1.5)	0.1	0.0 (0.0)
NoProl	0.1	1.2 (5.4)	0.2	2.6 (5.5)	0.3	1.8 (2.6)	0.3	2.5 (2.2)
NoLWR	0.0	0.0 (4.4)	0.0	0.0 (3.1)	-0.1	0.1 (1.2)	0.0	0.1 (0.1)

6.5 Discussion

An enhanced nuclear fuel cycle for energy policy analysis was developed in this PhD thesis to improve the representation of nuclear-based electricity. The new cycle allows fuel flexibility in the production of nuclear-based electricity by including spent fuel reprocessing technologies to represent the important feature of nuclear energy that allows the re-utilization of used nuclear fuel. The new nuclear cycle gives more flexibility in the analysis of the role of the nuclear technologies since conventional uranium resources are limited and spent fuel reprocessing could play an important role for achieving a sustainable energy system in the long-term. Thus, the developed representation of the nuclear cycle brings important inputs for analysis of the effects of different nuclear policies in the achievement of climate change mitigation targets.

The developed enhanced cycle includes two types of nuclear reactors: a light water reactor and a fast breeder reactor representing possible future generation IV technologies. In 2009, 7.6% of the reactors in the OECD countries used MOX fuel (Nuclear Energy Agency and the International Atomic Energy Agency, 2010). Thus, LWRs are modeled so they can use both UOX and MOX fuel to produce electricity, representing the current status of fuel utilization. FBRs can use both ceramic and metallic fuel to generate electricity, giving the model flexibility in the share of fertile and fissile materials. Two types of reprocessing technologies are included, namely: pyrolytic and aqueous reprocessing. Pyrolytic reprocessing is not used in most of the nuclear scenarios due to its considerably higher costs compared to the aqueous option. A potential improvement to the nuclear cycle developed in this thesis is a restriction on reprocessing technologies depending on the type of spent fuel. For instance, spent MOX fuel should be reprocessed just using the pyrolytic option, representing the higher complexity of the process.

Using the developed nuclear cycle, the effect of alternative nuclear fuels and technology developments in the context of a climate mitigation policy was analyzed. Results show an important interaction between nuclear and climate policies. If nuclear light-water reactors are acceptable to global policymakers, conventional natural uranium resources are likely to be depleted during the course of the 21st century, thus limiting the long-term potential of nuclear technologies to contribute to climate change mitigation. However, the results in this chapter show that the use of mixed oxide fuel may have the potential to overcome these resource issues since its production can be done using reprocessed uranium or plutonium obtained from reprocessing of spent fuel. Furthermore, more advanced nuclear technologies, such as fast breeder reactors, may contribute to the achievement of a sustainable energy system assuming the closed fuel cycle, already proved to be feasible in demonstration reactors, works for large scale commercial reactors. When FBRs are available they are largely deployed since they provide low-carbon electricity without major resource constraints.

Nuclear technologies could provide the baseload needed to support the deployment of renewable-based technologies, which continue having an important share of the electricity generation but due to its intermittence characteristic required some backup capacity to guaranty electricity supply.

Furthermore, if FBRs are available lower economic costs of achieving the climate targets are observed. The costs for each of the processes are based on the fuel cycle analysis developed by Shropshire et al. (2007), however, these costs are considerably uncertain and future analyses could include additional sensitivity analyses concerning the costs of the processes.

Even tough results show that the use of nuclear fuel reprocessing to produce MOX fuel for LWR and ceramic or metallic fuel for FBRs can have an important role in the achievement of stringent climate targets, the large deployment of reprocessing alternatives and FBRs would require high support to nuclear energy research and additional safety measures and efforts to ameliorate proliferation risks. The further development of nuclear power plants requires policy support of the national governments and public acceptance, and, in addition, the appropriate regulatory framework concerning managing of the nuclear facilities should be defined by the governments to reduce proliferation and safety risks.

6.6 Implications for Switzerland

Switzerland has a high reliance on nuclear-based electricity accounting for about 40% of current generation. After the nuclear accident in Fukushima, the new nuclear policy decided the phase-out of the nuclear power plants by the end of their lifetimes without building new reactors. The first part of Section 6.4.4 analyzed the consequences of this nuclear policy, showing important trade-offs with self-sufficiency and climate mitigation targets, since imports of electricity from the EU and CO_2 emissions are increased. However, in September 2011, an amendment to the Swiss Parliament decision in May 2011 of not to replace nuclear reactors was proposed by a Senate Committee, leaving open the door for "new generation reactors". Thus, using the enhanced nuclear cycle, an additional nuclear scenario that analyzes the case in which the light water reactors are phased-out in Switzerland but FBR can be deployed was developed.

When FBR are available and LWR are phased-out, fast reactors are largely deployed because they provide a source of low-carbon electricity without major resources constraints. Renewable-based technologies including hydropower, wind and solar are also deployed to their maximum assumed potential. Besides the technology portfolio, the availability of fast reactors affects the energy demand reductions in the new Swiss climate policy scenario: less electricity demand reductions to achieve the climate mitigation targets are observed when FBRs are available compared to the nuclear phase-out scenario, with an electricity demand of 126.8 and 108.1 TWh in 2050 and 2100, respectively, compared to the 81.1 and 40.4 TWh in the same years for the phase-out scenario without FBRs.

Despite the potential role of new nuclear technologies and reprocessing spent fuels, the feasibility of deploying such technologies has various limits. On the one hand, FBR is a technology under development that still requires research and development. On the other hand, when FBRs are available, the electricity in Switzerland coming from nuclear power is produced mainly with ceramic fuel. This implies that local reprocessing of spent fuel becomes a key part of the Swiss energy system bringing a solution to the problems of uranium depletion that can affect Switzerland when using LWRs. Thus, a large deployment of new technologies requires public acceptance and policy support to reprocessing of nuclear spent fuel. Furthermore, Swiss government would "need to put in place the essential legal, regulatory and institutional framework", which includes regulation of nuclear facilities and radiative waste management (IEA, 2010d).

Chapter 7

Economic development

Energy demand depends on economic and population development. Historical trends (see Figure 7.1) show that higher economic development levels imply higher energy demands. For example, the slope in the plot of energy versus GDP in China increases substantially from 2005, showing the increase on energy demand due to economic development. At the same time, economic development brings technological improvements and structural changes that lead to energy efficiency, reducing the energy consumption per capita and per unit of economic output. See for instance in Figure 7.1 that the energy consumption in most of the OECD countries (United States, Germany, Japan, New Zealand and Switzerland), contrary to the tendency in China, flats down after a certain time, e.g. around 1990 in New Zealand and 1987 in Switzerland, even as GDP continued to grow.

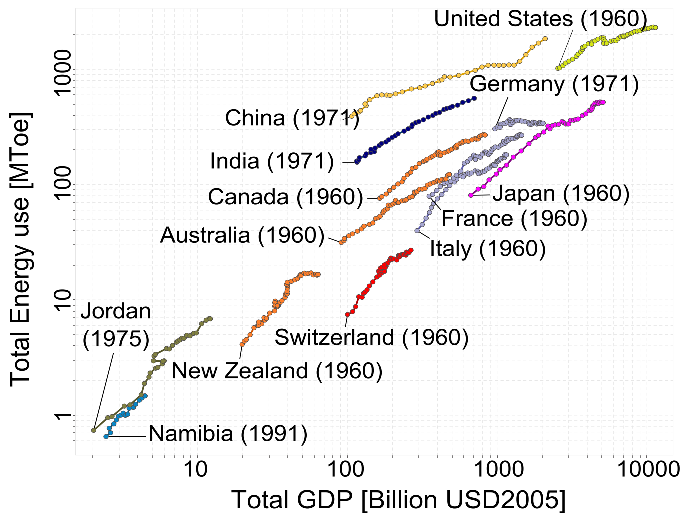
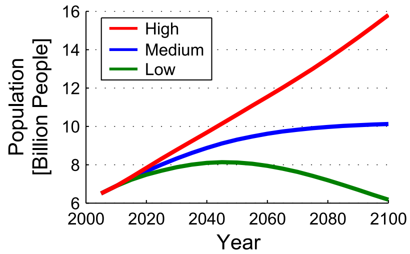
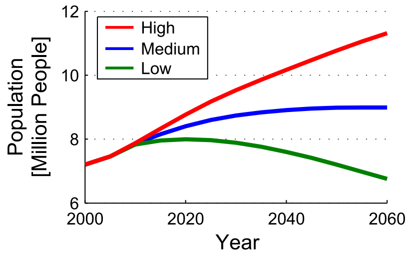


FIGURE 7.1: *Historical relationship between energy consumption and GDP. Source World Bank (2012) and United Nations (2012) through* `www.gapminder.org`

Population and economic development are highly uncertain variables. The main uncertainty for future population growth is fertility rates. The 2010 Revision of United Nations World Population Prospects (United Nations. Population Division, 2011) presents three scenarios on population growth with different levels of fertility (see Figure 7.2A) . The low fertility scenario reaches a population by 2100 of 6.18 Billion while the high fertility case projects a population in 2100 of 15.8 Billion, more than two times the population in the low fertility scenario. In Switzerland, the BFS (2010) published as well three population scenarios until 2060 (see Figure 7.2B), with levels in 2060 of 6.8 to 11.3 Million People (around ± 25% difference between the reference scenario and the high and low cases).



(A) *UN global populations scenarios*



(B) *Swiss populations scenarios*

FIGURE 7.2: *Population scenarios and projections*

In the same way as population growth is uncertain, economic development has a great uncertainty since it depends on industry development, population growth, among other uncertain parameters and might be affected by particular unexpected events such as economic crises and even natural disasters. The IPCC Special Report on Emissions Scenarios (Nakicenovic, 2000) presented a wide range of economic scenarios with average global capita incomes by 2100 ranging from USD2000 13.33 to 98.87 thousand. More recent studies such as the IPCC Fourth Assessment Report (Intergovernmental Panel in Climate Change (IPCC), 2007a) present a large variation of GDP projections used in the literature with an 85th percentile from Trillion USD2000 187 to 406.1. The uncertainties in future economic output are related to productivity growth and population development concerning the total output. Some scenarios assume a considerable growth of developing regions, reaching even the same per capita economic level by 2100 of developed regions, while other scenarios assume a regional divergence, where the gap between poor and rich countries stays the same or increases compared to today's levels.

All these uncertainties in global economic and population development are likely to have an impact on the development of the future energy system concerning resources availability and prices, technological development and technology costs. Thus, policies to achieve a sustainable energy system that includes objectives such as climate mitigation and security of supply are likely to be affected. In Switzerland, changes in global energy demands driven by economic or population developments can affect the realization of a sustainable energy system, since availability of global resources and deployment of new technologies are influenced or led by regions other than Switzerland. That is, different global development pathways are likely to imply different levels of demand reductions, different technology pathways driven by higher or lower costs of technologies and resource availability, or different greenhouse gas emissions pathways, thus, alternative climate mitigation policies.

In this chapter the implications on the global and Swiss future energy systems of three scenarios of economic and population development are analyzed. The chapter is organized as follows: the following section describes the analyzed scenarios; in the second section the implications concerning technology pathways, demand reductions and carbon emissions are presented; the last section includes a discussion of the results.

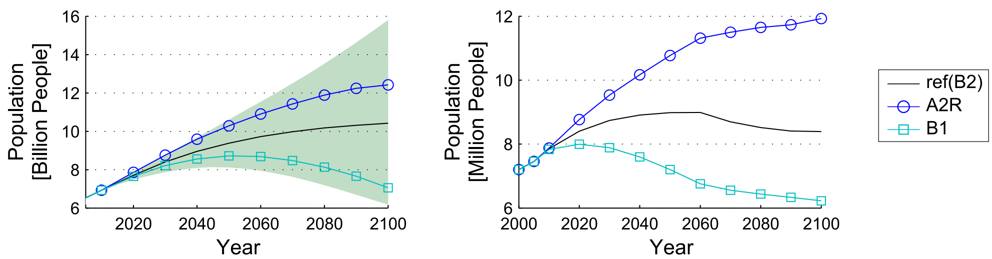
7.1 Scenarios on economic development

The scenarios on economic development analyzed in this thesis are based on the three scenarios proposed by Riahi et al. (2007) as an update to the IPCC SRES scenarios (Nakicenovic, 2000). A summary of the three scenarios is presented in Table 7.1. The reference scenario (presented in Section 3.5.1) corresponds to an intermediate population and economic development scenario (based on the B2 scenario in Riahi et al. (2007)). The other two cases analyzed in this thesis correspond to the A2R and B1 scenarios.

TABLE 7.1: *Economic development scenarios*

	Ref(B2)	**A2R**	**B1**
Global population in 2100	10.4 Billion	12.4 Billion	7.1 Billion
Economic development	Intermediate convergence	"Poor stay poor"	Catch-up developing regions
Global GDP per capita (Thousand USD2000)	25.41	20.53	53.41
Efficiency improvements	Intermediate	Low	High

The population in the three scenarios is presented in Figure 7.3A compared to the population range from the UN 2011 Population prospects (United Nations. Population Division, 2011). Global population in 2100 reaches 12.4, 10.4 and 7.1 billion in the A2R, reference and B1 scenarios, respectively. The population in 2100 in the A2R scenario is 19% larger than in the reference case, while the population in the B1 scenario is 32% lower, covering a considerable part of the range in the UN population scenarios. Swiss population is based until 2060 on the BFS (2010) projections and afterwards on the scenarios developed by IIASA (Riahi et al., 2007), reaching 6.22, 8.39 and 11.9 million by 2100: that is, a variation from the reference scenario of -25% and +42%, in the B1 and A2R scenarios, respectively.



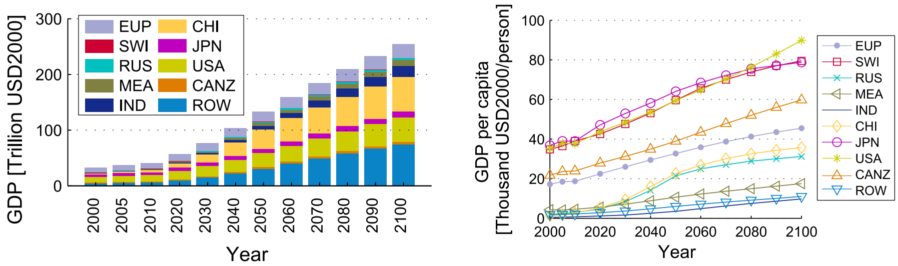
(A) *Global populations scenarios* (B) *Swiss populations scenarios*

FIGURE 7.3: *Population scenarios in the thesis*

7.1.1 The A2R scenario

The A2R scenario describes a world with high population growth, reaching 12.4 Billion by 2100. The A2R scenario update developed by Riahi et al. (2007) presents a lower population compared to the original A2 scenario in the IPCC SRES scenarios (Nakicenovic, 2000) where the world population reached 15 billion by 2100. This update assumes a faster decline in fertility rates in developing regions to reflect the "most recent consensus of demographic projections toward lower future population levels" (Riahi et al., 2007). This scenario also assumes a moderate convergence of fertility rates across regions, where fertility rates in developing regions start declining just after 2030, leading to the relatively high estimate in population.

The A2R scenario represents a heterogeneous world where the "poor stay poor". Figure 7.4 presents the total GDP and GDP per capita in this scenario for the 10 world regions used in this PhD thesis, showing a growth up to USD2000 255 trillion (close to the global GDP in the reference scenario) and little convergence between developing and developed regions, thus the global per capita income by 2100 is USD2000 20.53 thousand.



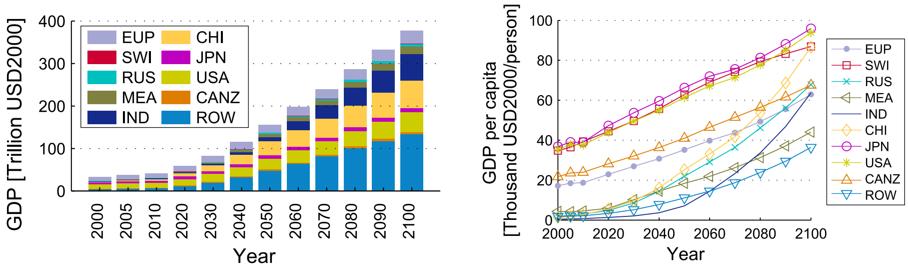
(A) *GDP* **(B)** *GDP per capita*

FIGURE 7.4: *A2 Scenario: Potential GDP per capita*

The slow global per capita economic growth implies less energy efficiency improvements that produce lower autonomous energy efficiency improvements compared to the reference scenario presented in Section 3.5.1. This is reflected in the reference final energy demand per unit of GDP (estimated based on the autonomous energy efficiency improvements for the electricity sector and the non-electric sector). The reference final energy demand per capita in this scenario is 8.8 and 9.4 MJ/USD2000 in 2050 and 2100, respectively, while in the reference scenario the reference final energy per capita is 5.9 and 3.5 MJ/USD2000 in 2050 and 2100, respectively.

7.1.2 The B1 scenario

The B1 storyline represents a world with low population growth, reaching 7.1 Billion by 2100, due to fertility levels that "converge towards sub-replacement levels" but with some regional differences (Riahi et al., 2007). The economic development, reflects this convergence across regions, and assumes high per capita growths, the highest of the three scenarios analyzed in this thesis.



(A) *GDP* **(B)** *GDP per capita*

FIGURE 7.5: *B1 Scenario: Potential GDP per capita*

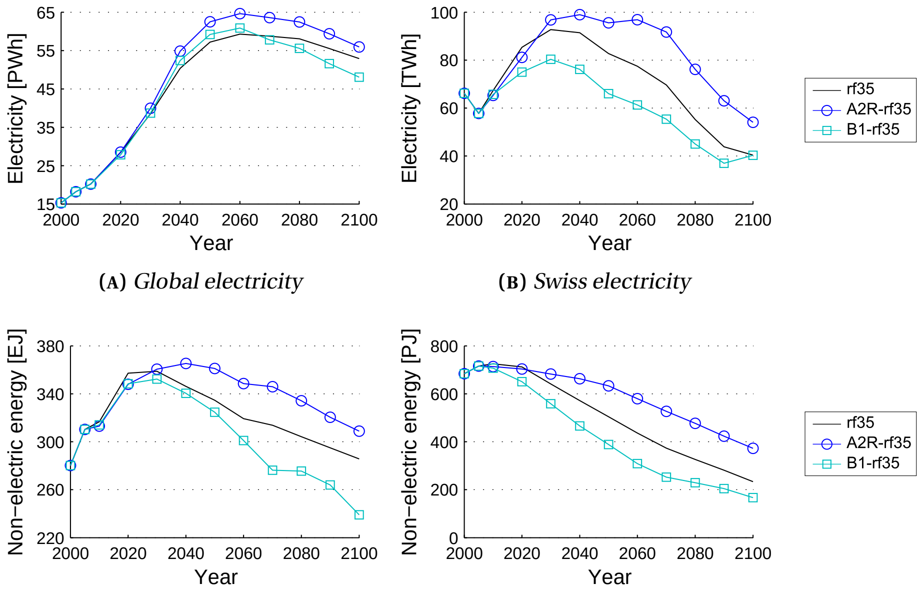
This higher economic development implies as well higher efficiency achievements that are reflected in the reference final energy demand per unit of GDP that corresponds in the B1 scenario to 4.4 and 1.8 MJ/USD2000 in 2050 and 2100, respectively, while in the reference scenario it is 5.9 and 3.5 MJ/USD2000 in 2050 and 2100, respectively.

7.2 Energy systems under different economic developments

The previously described scenarios of economic and population development and the reference scenario presented in Section 3.5.1 are studied using MERGE-ETL under a stringent climate scenario with a long term radiative forcing target of 3.5 W/m^2. Thus, the three scenarios analyzed in this Chapter and described in the following sections are: (1) the reference climate policy scenario (rf35) described in Section 4.5; (2) the A2R scenario with a radiative forcing target of 3.5 W/m^2 (A2R-rf35); and (3) the B1 scenario with a radiative forcing target of 3.5 W/m^2 (B1-rf35).

7.2.1 Reduction in energy demands

The first implication of different economic developments is different energy demands due to higher or lower populations and potential economic growth assumptions. Figure 7.6 presents the energy demand in the world and the Swiss region, showing an increase in total electricity and non-electric energy demand in the A2R scenario with large population and low efficiency improvements. The B1 scenario, due to the lower population projections and the high efficiency assumptions leads to lower demands in both the world and Switzerland.



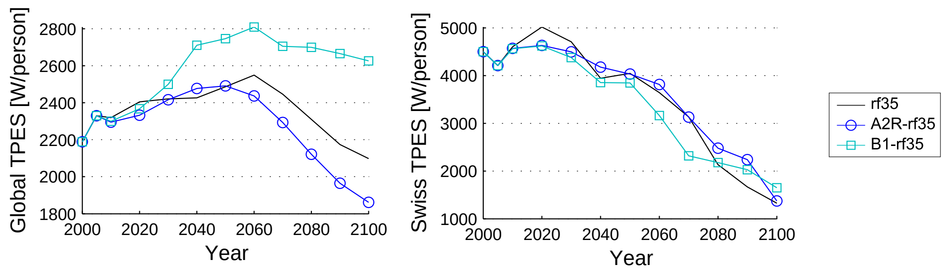
(A) *Global electricity* (B) *Swiss electricity*

(C) *Global non-electric energy* (D) *Swiss non-electric energy*

FIGURE 7.6: *Economic scenarios: Energy demand*

The autonomous efficiency improvements assumed in each scenario has an important effect on the energy intensity (primary energy demand per unit of GDP), which correspond in 2100 to 2.6, 3 and 1.5 MJ/USD2000 for rf35, A2R and B1, respectively. Thus, the B1 scenario results in the higher energy intensity reductions since this is the case with higher economic growth and, therefore, higher autonomous energy efficiency improvements.

Despite this increase or decrease in the energy demand, the primary energy supply per capita has a different behavior among scenarios. Figure 7.7 presents the primary energy supply per capita in both the world and the Swiss region[1]. Globally, the large increase in the energy demand in the A2R scenario, presented in Figure 7.6 is compensated by the increase in population and the slow economic growth, leading to a lower global primary energy supply per capita compared to both the reference and the B1 scenarios. While in the B1 scenario, despite the higher assumption on efficiency improvements, the lower population and higher economic growth, especially in the today's developing regions, implies a higher primary energy supply per capita. The differences between the A2R and B1 scenarios are driven mainly by the developing regions, whose economic growth differs substantially. In Switzerland, the picture is different to the global view, with small changes across the scenarios, since Switzerland is considered a developed region in all the cases. Therefore, the higher energy efficiency improvements assumed in the B1 scenario lead to a slightly lower primary energy supply per capita in Switzerland between 2050 and 2080, but with all three scenarios showing a long-term trend in primary energy supply towards a 2000 W society (Jochem et al., 2002).



(A) *Global* **(B)** *Switzerland*

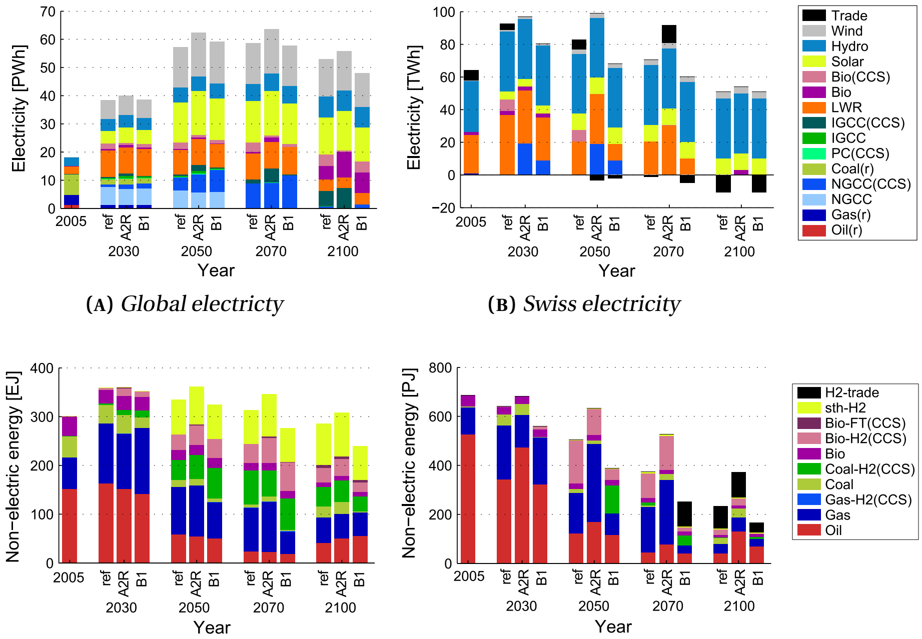
FIGURE 7.7: *Economic scenarios: Total primary energy supply per capita*

7.2.2 Technology deployment

The second important consequence of the different economic scenarios under a climate mitigation policy constraint is the different set of deployed technologies. Figure 7.8 presents the technology deployment for energy production in the three scenarios.

Globally, the additional electricity demand in the A2R scenario, compared to the B1 and reference cases, is supplied with gas and coal technologies with carbon capture - NGCC(CCS) and IGCC(CCS); and the additional non-electric energy demand is supplied using additional gas and biomass to produce hydrogen. This additional global demand for biomass increases biomass prices by 57.2% and 91.3% in 2050 and 2100, respectively, compared to the reference climate scenario rf35. Global demand for natural gas also increases but biomass is the preferred option since it has the possibility

[1] A 100% efficiency is assumed for renewable resources including hydropower, wind and solar.



(A) *Global electricty* (B) *Swiss electricity*

(C) *Global non-electric energy* (D) *Swiss non-electric energy*

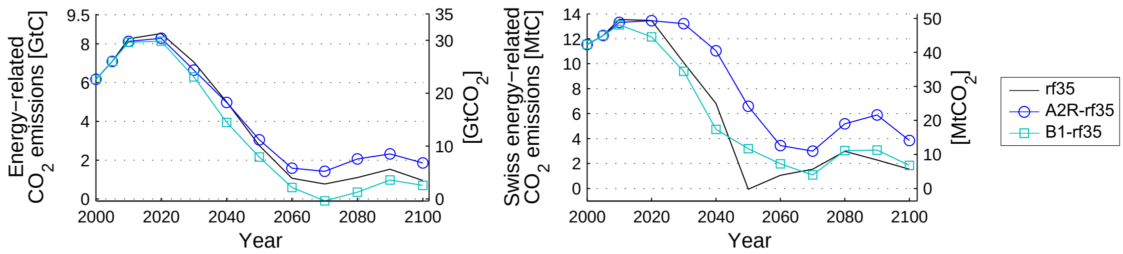
FIGURE 7.8: *Economic scenarios: Energy production*

of producing negative CO_2 emissions when it includes CCS, helping to the realization of the climate targets. Therefore, due to higher global demand for biomass, Switzerland reduces its use in both electricity and non-electric energy production. Thus, in the electricity sector in Switzerland, NGCC with carbon capture and storage is deployed to supply the higher demand in this scenario and to replace biomass electricity production; and in the non-electric energy sector, the use of gas increases substantially to supply the larger demand and to compensate the decrease in hydrogen production from biomass compared to the reference climate scenario. By 2100, the imports of hydrogen from the EU constitute an attractive option for the non-electric energy supply, as is the case in the reference scenario. However, the higher demand in A2R compared to the reference climate scenario leads to a higher consumption of oil products.

In the B1 scenario, the lower energy demand means that the radiative forcing target of 3.5 W/m^2 can be met without the need for some more expensive low-carbon supply options. Therefore, in the electricity sector, NGCC with carbon capture is deployed instead of biomass with CCS globally and in the Swiss region. For the same reason, the production of hydrogen from coal with carbon capture is higher in the B1 scenario compared to the rf35 case, particularly between 2050 and 2080.

7.2.3 Implications on emissions pathways

Even though the climate target is equivalent in all the scenarios, the different technologies deployed produce a change in the global and Swiss energy-related emissions (see Figure 7.9). Global emissions in the A2 scenario are slightly higher than in the other two cases from 2050, mainly due to larger demand and larger use of gas in both electricity and non-electric energy production. These emissions are compensated by additional cooling effects coming from larger energy-related sulfate emissions until 2040.



(A) *Global* (B) *Switzerland*

FIGURE 7.9: *Economic scenarios: Energy-related CO_2 emissions*

In Switzerland, the changes across scenarios are larger than the changes in the global emissions, especially in the A2R case. Swiss emissions in the A2R scenario increase compared to the reference case from 0 to 24.15 $MtCO_2$ and from 5.65 to 14.1 $MtCO_2$ by 2050 and 2100, respectively. These substantial increases are due to the change from biomass to gas in both the electricity and the non-electric sectors driven by large biomass demand in the other regions of the world. In the B1 scenario, Swiss energy-related emissions are generally similar to the reference climate scenario, except in 2050 and 2060 due to the use of NGCC(CCS) in electricity production and hydrogen from coal with CCS in the non-electric sector, both replacing biomass-based technologies.

7.3 Discussion

The future development of the global energy system is strongly affected by economic trends, which depend on factors including population growth and regional productivity. Different economic development pathways can have an impact on energy efficiency achievements, which can lead to lower or higher global energy demand. In this section three scenarios of economic development under a stringent climate scenario were analyzed, namely: a reference case based on the IIASA B2 scenario, and the A2R and B1 scenarios from Riahi et al. (2007). The reference scenario is a dynamic-as-usual scenario with middle population and economic growth and a gradual catch-up of less developed world regions. The A2R scenario represents a world with high population growth but slow economic development, where the “poor regions stay poor”, with a relatively low gains in efficiency due to the low economic growth. Finally, the B1 scenario represents a world with low population growth but with high economic development, and a catch-up of developing regions to the levels of the developed regions by the end of the century. This high economic growth also implies higher levels of efficiency improvements.

Globally, the results show that lower or higher total energy demands depend mainly on the lower or higher population growth, being the A2R scenario the one with the largest electricity and non-electric energy demands. However, autonomous energy efficiency improvements due to economic growth have an important consequence on energy intensity. The three scenarios resulted in energy intensities of 2.6, 3 and 1.5 MJ/USD2000 for rf35, A2R ad B1, respectively. This is in line with the results in Riahi et al. (2007), who showed that "higher economic growth does not necessarily translate into a proportional growth in energy demand and resulting emissions". Consistently with the results presented in this chapter, they found that with a climate stabilization pathway, the A2R scenario has the largest energy intensity, followed by the B2 scenario and finally the B1 scenario, in which technology improvement is higher. Thus, economical development could imply higher productivity, capital turnover and technology development, leading to reduction in energy intensity. However, in terms of energy per capita, even though economic development implies larger energy efficiency improvements that lead to energy demand reductions, in the B1 scenario, the economic "catch up" of today's development of regions such as China and India could lead to higher per capita primary energy supply. These results show the considerable uncertainty of future energy demand coming from economic and population development. However, independently from the economic pathways, global climate mitigation policies should aim for energy efficiency improvements that lead to reduction in energy intensity.

Technology wise, the different economic scenarios exhibit some convergence. The stringent climate mitigation target implies a shift towards low-carbon electricity and non-electric energy production with nuclear, hydropower, solar and wind technologies being largely deployed to produce electricity; and a shift from oil to gas as transition technology and to hydrogen by the end of the century for the non-electric energy production. The scenario with considerable differences, especially by the middle of the century, is the A2R scenario, where additional fossil fuels are required to supply the additional energy demands, leading to a larger deployment of the NGCC(CCS) technology. There results show the importance of policy support for deployment of renewable-based and CCS technologies.

7.4 Swiss energy system under different economic development scenarios

The different economic scenarios analyzed in this chapter have three important consequences to the Swiss energy system. The first one is a robust tendency towards a 2000 W society by 2100 in the three scenarios, showing the importance of efficiency improvements in both the electricity and the non-electric energy end-use appliances. In the B1 scenario, while the global TPES per capita reaches a level of 3000 W, in Switzerland it is around 2000 W. The high global TPES per capita level is driven by today's developing regions, which have a fast economic growth but have less energy demand reductions due to less energy efficiency improvements and capital turnover. However, regardless of global economic and population developments, a sustainable Swiss energy system implies energy demand reductions with a long-term target of 2000 W per person.

The second important consequence is on technology deployment. The technology options deployed in the different scenarios show on one hand the importance of renewable-based electricity and on the other hand the use of biomass to supply non electric energy. Hence, the development of the Swiss energy system that aims to achieve global climate mitigation should include a policy supporting deployment of renewable-based options. On the other hand, natural gas showed to be an important technology to supply additional electricity and non-electric energy demands in the A2R scenario, with the development of NGCC(CCS) and the use of additional natural gas in the non-electric energy production.

Finally, the scenarios of economic development presented a possible challenge to the Swiss energy system concerning resource availability. When economic growth produces high global energy demand, higher global prices of biomass lead to a substitution of biomass with natural gas in the Swiss energy supply, producing and increase in the Swiss energy-related emissions.

Chapter 8

Resource availability

Fossil fuels, uranium and renewable sources are needed for energy supply. However, how much resources are available and how much renewable sources can be integrated in the electricity share are highly uncertain variables.

Fossil fuel resources can be divided in conventional and unconventional resources. One possible definition considers conventional resources to be those that can be extracted with current technologies, alike unconventional resources (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). Other definition is related to the economic competitivity of the resources, defining conventional resources as those economically competitive. However, this definition is ambiguous, for instance, in Brazil, some phosphate deposits that are classified by the Nuclear Energy Agency and the International Atomic Energy Agency (2010) as unconventional uranium resources are considered economically competitive; therefore, they are reported as conventional resources. In this dissertation, unconventional resources comprise: unconventional oil including oil sands, extra-heavy oil and oil shale; unconventional gas corresponding to tight gas, shale gas and coal-bed methane; and unconventional uranium comprising phosphate rocks, non-ferrous ores, carbonite and black schist.

Availability of fossil fuels is limited by the physical accessibility to the resources and the actual amount of oil, gas or coal in each reservoir, but it is also limited by technological, environmental and even public acceptance constraints. For instance, oil sand or heavy oil extraction in open-pit mining requires large amounts of water for transportation, extraction and refining; and surface mining requires large amount of land. In the same way, the production of unconventional gas has important regulatory and public opposition constraints. In France, for example, due to public opposition hydraulic fracturing[1] was prohibited (IEA, 2011a). In the same way, biomass availability could be affected by factors such as food or water supply; and the potential of other renewable resources is highly uncertain and it might be limited by restrictions on integration to the network or limits to intermittent energy sources in the energy mix.

Additional larger amounts of unconventional fossil fuels have negative consequences to the global climate if countries do not commit to climate change mitigation efforts, since they imply additional use of fossil fuels for electricity generation and non-electric energy uses, leading to higher carbon emissions and higher global temperature increase in the long term. In the same way, the availability of

[1] The production of the three types of unconventional gas includes hydraulic fracturing.

large renewable resources could help achieving climate targets since they provide low-carbon energy. Thus, the achievement of climate policies and a sustainable energy system can be affected by the availability of energy resources.

Switzerland, in particular, has a limited amount of own resources, especially fossil fuels and uranium and, therefore, the Swiss supply of energy carriers depends on global availability of renewables, fossil fuels and uranium, which can affect substantially energy technology choices. This chapter analyzes the effect of resource availability on the future global and Swiss energy system, including scenarios with unconventional fossil fuels and uranium and different potentials for renewable sources.

8.1 Unconventional resources

8.1.1 Unconventional Oil

Global conventional oil estimates used in the reference scenario (see Section 3.5.2) correspond to 271 Gt (German Federal Institute for Geosciences and Natural Resources (BGR), 2008), with the Middle East, Rest of the World and Russia being the regions with the largest resource shares. Unconventional oil includes oil sands (also called natural bitumen), extra-heavy oil and oil shale:

- Oil sands: “Oil sands are naturally occurring mixes of bitumen, water, sand and clay” (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). According to the 2007 Survey on Energy Resources (World Energy Council, 2007), 596 deposits of natural bitumen exist in more than 20 countries around the world with a considerably large potential of around 481 Gt of which 96.9% are located in Canada, Kazakhstan and Russia (World Energy Council, 2007). Canada has the largest oil sand resources, located in the province of Alberta, covering an area of more than 140000 km^2.
- Extra-heavy oil: Corresponds to oil with high density (≥ 1 g/cm^3) (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). According to the 2007 Survey on Energy Resources (World Energy Council, 2007), around 166 deposits of extra-heavy oil exist in the world with a global potential of around 348 Gt of which 98.4% are located in Venezuela (in the Orinoco Belt). Today the major producers of extra-heavy oil are Venezuela, UK and Azerbaijan, with shares of 35, 28 and 21%, respectively (German Federal Institute for Geosciences and Natural Resources (BGR), 2009).
- Oil shale: Is a sedimentary rock with a large proportion of organic material (kerogen) that under natural conditions has not turned into petroleum and which can be found in fresh and salt water (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). The World Energy Council (2007) estimate global oil shale resources to around 409 Gt in around 40 countries, with a large share located in the United States (73.8%). Besides energy supply purposes, oil shale can be used as raw material in the production of chemical products.

Estimates of unconventional oil resources are based on the 2007 Survey of Energy Resources of the World Energy Council (2007). Figure 8.1 presents the total conventional and unconventional oil resources by region. The addition of unconventional resources increases global estimate from 10.4 to

62.1 ZJ, with the largest resources additions coming from oil sand and oil shale in Russia, oil shale in the US, oil sands in Canada, and extra-heavy oil in Venezuela in ROW.

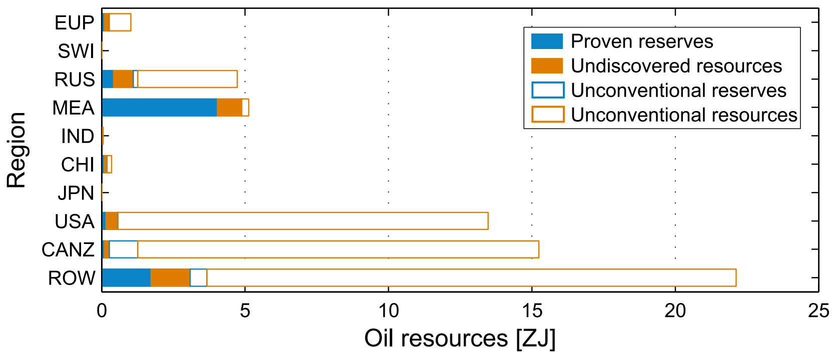


FIGURE 8.1: *Oil resources: conventional and unconventional*

Costs of unconventional oil extraction are based on the estimations from the IEA (2008b) and presented in Table 8.1.

TABLE 8.1: *Unconventional oil: production costs (IEA, 2008b)*

Oil source	**Cost [USD2000/GJ]**
Oil sands and extra-heavy oil	5.25 - 10.49
Oil shales	6.56 - 13.11

8.1.2 Unconventional Gas

Global conventional gas resource estimates in the reference scenario (see Section 3.5.2) correspond to 427 trillion cubic meters (TCM) (German Federal Institute for Geosciences and Natural Resources (BGR), 2008). Today, unconventional gas resources are estimated to be double the amount of recoverable conventional gas resources (IEA, 2011a). Even more, unconventional gas is more evenly distributed across regions than conventional resources, which are located mainly in Russia, the Middle East and the Rest of the World (in Algeria, Nigeria, Kazakhstan and Turkmenistan). The IEA (IEA, 2008b, 2011c) includes three types of unconventional natural gas, namely: Tight gas, shale gas and coal bed methane (CBM).

- Tight gas: Is the natural gas that occurs in sandstone or carbonate reservoirs, which are rocks with very low permeability compared to conventional reservoirs. "The assessment of recoverable reserves from tight reservoirs contains large uncertainties due to the particular characteristics of these occurrences" (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). According to Holditch et al. (2007) the major resources of tight gas occur in the United States, Middle East, Pacific (OECD) and Latin America.

- Shale gas corresponds to the natural gas in mudstone (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). According to the IEA (2011a) a considerable number of countries are looking into the production of shale gas. According to Holditch et al. (2007) the major resources of shale gas occur in the United States, Latin America and Russia.

- Coal-bed methane (CBM) groups all the natural gas that is associated with coal; therefore, in theory all the regions with hard coal deposits have coal-bed natural gas. The increase in natural gas prices has made coal-bed natural gas an attractive option, to the point that in some countries it is included within the production of conventional natural gas (German Federal Institute for Geosciences and Natural Resources (BGR), 2009). Canada accounts for the largest estimates of CBM (with 44.9% of the global estimates), followed by USA (28.9%) and Australia (15.2%) (German Federal Institute for Geosciences and Natural Resources (BGR), 2009).

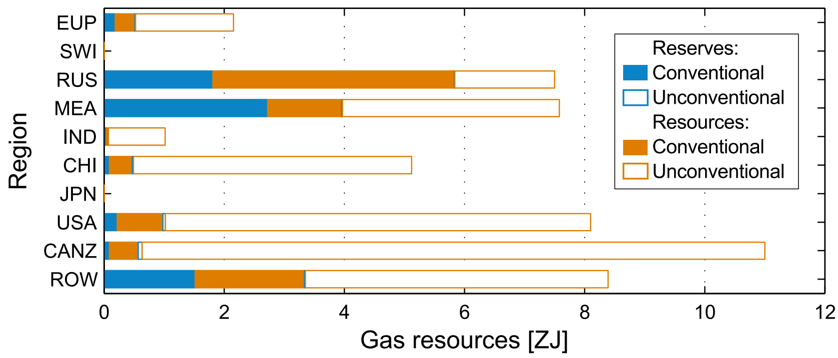


FIGURE 8.2: *Gas resources: conventional and unconventional*

Figure 8.2 presents the total natural gas resources by region, including conventional and unconventional resources based on the *Energy Resources 2009* from the German Federal Institute for Geosciences and Natural Resources (BGR) (2009) and Holditch et al. (2007). The addition of unconventional resources increases global natural gas resources estimates from 15.7 to 50.9 ZJ. The largest regional additions occur in CANZ, coming from CBM in Canada and shale gas in the pacific OECD accounting for 42% and 24% of the CANZ unconventional gas resources, respectively; the USA, Middle East and ROW (with a considerable potential of shale gas in Latin America). Despite these large potentials, the production of unconventional gas has important limitations including environmental concerns and public opposition. In France, for example, due to public opposition hydraulic fracturing, needed to produce three types of unconventional gas, was prohibited (IEA, 2011a).

Production costs of unconventional gas are based on the estimations from the IEA (2011c) and presented in Table 8.2.

TABLE 8.2: *Unconventional gas: production costs (IEA, 2011c)*

Gas source	Cost [USD2000/GJ]
Tight gas	2.27 - 6.07
Shale gas	2.27 - 5.31
CBM	2.27 - 6.07

8.1.3 Unconventional uranium

Unconventional uranium resources come from phosphate rocks, non-ferrous ores, carbonite and lignite. Currently exploited unconventional uranium resources are dominated by phosphate rocks. In Brazil, some phosphate deposits are even considered economically competitive; therefore, they are reported as conventional resources. Table 8.3 summarizes global unconventional resources by origin based on the *2009 Red Book* (Nuclear Energy Agency and the International Atomic Energy Agency, 2010)[2].

TABLE 8.3: *Unconventional uranium resources (Nuclear Energy Agency and the International Atomic Energy Agency, 2010)*

Source	Resources [kton U]
Phosphate rocks	6979 - 7202
Non-ferreous ores	16.04-34.31
Carbonite	15.5
Black schist, lignite	307.5 - 313.5

Another important unconventional uranium resource is seawater. Estimated at 4 billion tU, the ocean is virtually inexhaustible and is accessible by any country with a coastline. The Nuclear Energy Agency and the International Atomic Energy Agency (2010) estimated the extraction costs to be around 700 USD2008/kgU (approx. 2.6-times the highest cost of conventional uranium resources). In this thesis, the unconventional uranium resources coming from seawater where not included.

8.1.4 Supply curves

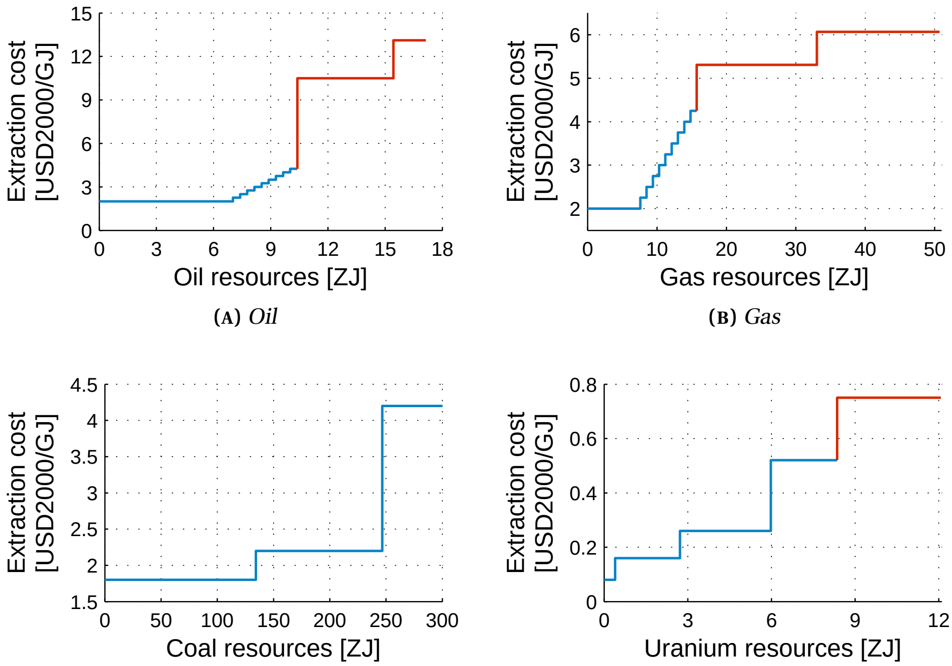
The supply curves including conventional and unconventional resources categories for oil, gas, coal and uranium are presented in Figure 8.3. For oil and gas the last two categories correspond to the unconventional resources, while for uranium just the last category includes unconventional uranium. Coal is the energy carrier with the largest resource estimations.

8.2 Renewable resources

The reference climate scenario presented in Section 4.5 corresponds to an advanced technology scenario where wind and solar can grow to a maximum share of 25% each of the total electricity production; and biomass and hydropower have relatively large potentials. In this section two scenarios of renewable potentials and development of the required distribution network are analyzed, namely: moderate and advanced.

- Wind and solar: In the advanced scenario solar and wind have a maximum share of 25% each of the total electricity production, while in the moderate renewables scenario they are assumed

[2] This resources analysis was developed by Marcelo Parada in the course of his Master project (Parada et al., 2011). This work was pursued at the Energy Economics Group at Paul Scherrer Institute and was supervised by the author of this PhD thesis.



(A) *Oil* (B) *Gas*

(C) *Coal* (D) *Uranium (w/o seawater)*

FIGURE 8.3: *Supply curves conventional (in blue) and unconventional (in red) proven reserves and undiscovered resources*

to account for a total (solar+wind) of 25%. In Switzerland the advanced scenario potentials correspond to those in the reference scenario (Section 4.5) of 4 and 10 TWh by 2100 for wind and solar, respectively. The moderate potential for wind is based on the long-term estimates of the Energie Trialog (Energie Trialog Schweiz, 2009) with a potential by 2100 of 3 TWh. Swiss solar potentials in the moderate case are based on the low estimates of Hirschberg et al. (2005) and Energie Trialog Schweiz (2009) with a maximum potential of 8.5 TWh (from 2050).

- Small and large scale hydropower: The advanced scenario has a global potential 5.3 and 7.4 PWh by 2050 and 2100, respectively, which corresponds to the hydropower potential used in the reference scenario (see Section 3.5.2) based on the World Energy Council (2007) and the reference scenario estimated by Laufer et al. (2004) for Switzerland. The moderate scenario is based on the IPCC special report on Renewable Energy Sources and Climate Change Mitigation (Intergovernmental Panel in Climate Change (IPCC), 2012) and has a global potential of 5 and 6.9 PWh in 2050 and 2100, respectively. In Switzerland the potential for the moderate scenario is based on the BFE's pessimistic scenario (Laufer et al., 2004) with a maximum by 2035 of 35.7 TWh and a decrease afterwards reaching 35 TWh by 2050.

- Biomass: In the advanced scenario the long term biomass potential is 188.6 EJ. Based on the low estimate of the regional oriented scenario in UK Department of Trade and Industry (2006) the moderate potential corresponds to 120 EJ. In Switzerland, the advanced potential is based on the optimistic estimates of the BFE (Oettli et al., 2004) and the moderate scenario is based on their pessimistic estimates, with long term biomass resources of 126.52 to 95.7 PJ, respectively.

Table 8.4 summarizes the assumptions done in the advanced and moderate renewable resource scenarios in this dissertation.

TABLE 8.4: *Renewable resources scenarios*

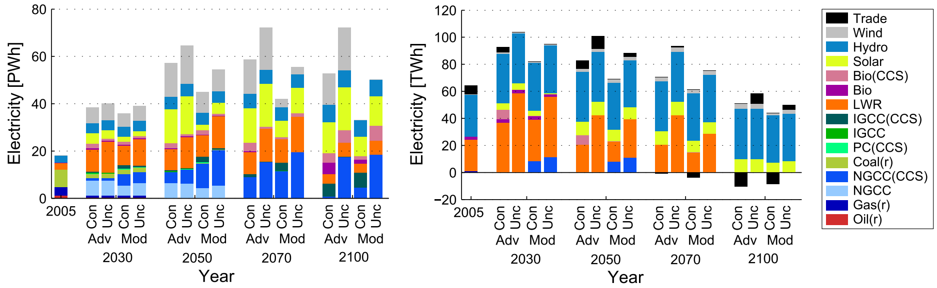
	Advanced	Moderate
Global		
Wind	25% of electricity production	25% of electricity production
Solar	25% of electricity production	
Hydropower	7.4 PWh by 2100	6.86 PWh by 2100
Biomass	Long term potential of 188.6 EJ	Long term potential of 120 EJ
Switzerland		
Wind	2.5 TWh (2050) - 4 TWh (2100)	3 TWh (2100)
Solar	10 TWh (2050)	8.5 TWh (2050)
Hydropower	37 TWh (2050)	35 TWh (2050)
Biomass	126.52 PJ	95.7 PJ

8.3 Energy strategies under different resource scenarios

Four scenarios on resource availability under a stringent climate change mitigation scenario with a radiative forcing target of 3.5 W/m^2 were developed, including a combination of advanced (adv) and moderate (mod) potentials for renewables and conventional (con) and unconventional (unc) fossil fuels and uranium.

Figure 8.4 presents the electricity production in the four scenarios on resource availability. Adding unconventional resources to the estimates of fossil fuels and uranium (unc. scenarios) produces an increase in the use of natural gas with carbon capture (NGCC(CCS)) and nuclear plants compared to the scenarios with just the conventional resources, with a consequent increase in electricity use. The scenarios with moderate renewable resources show three important consequences of reduced availability of renewables. First a large decrease in the electricity demand, second an increase in the share of the NGCC(CCS) technology to compensate the decrease in renewable-based electricity, and third a shift from wind to solar as the preferred renewable source for electricity production. In Switzerland, the scenarios on resources have important implications for the required energy efficiency achievements, with a substantial decrease in the electricity demand in the scenario with moderate renewables and conventional resources (68.9 TWh compared 82.8 TWh by 2050). Furthermore, in Switzerland the scenarios with unconventional resources exhibit an increase in the deployment of nuclear power plants, while NGCC with carbon capture and storage is needed in the moderate renewable case.

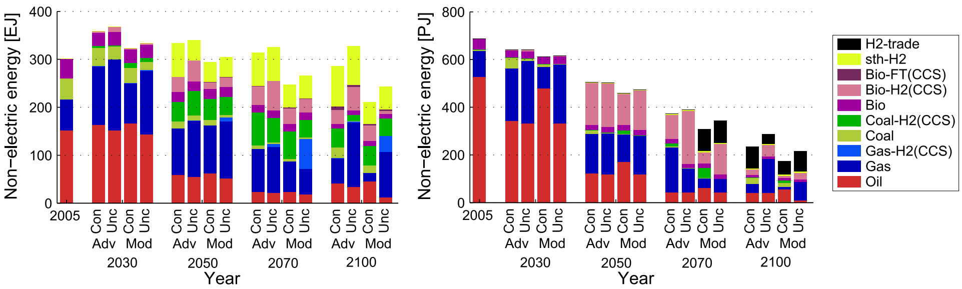
Regarding the non-electric energy production (see Figure 8.5), in the scenarios with advanced renewable resources the difference between the case with only conventional fossil fuels and uranium and the case with both conventional and unconventional resources is relatively small with a slight shift from hydrogen produced from coal to direct use of natural gas, especially at the end of the projection period. The moderate renewables cases imply lower demands and the use of additional gas to produce hydrogen when unconventional resources are available. In Switzerland, the changes in the resources estimates do not have large impacts on the deployed technologies, with a consistent large use of biomass to produce hydrogen from 2050. Just in the case with moderate renewable estimates, production of hydrogen from biomass with CCS is earlier replaced with imports of hydrogen from the



(A) *Global* **(B)** *Switzerland*

FIGURE 8.4: *Resource scenarios: Electricity production*

EU and production of hydrogen from coal (with CCS) due to a higher price of biomass.



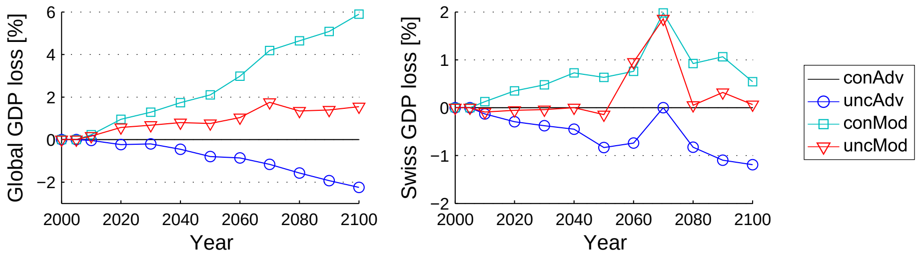
(A) *Global* **(B)** *Switzerland*

FIGURE 8.5: *Resource scenarios: Non-electric energy production*

The resulting changes in the energy demand and the deployed technologies affect economic costs of achieving the climate target. Figure 8.6 presents the GDP losses for each of the scenarios compared to the reference climate scenario (rf35 in Section 4.5 and referred as conAdv in this analysis), which corresponds to the advanced renewables with moderate resources case. The availability of unconventional resources, reduces the costs of achieving the climate target (a reduction in global GDP losses of around 2.1 percentage points by 2100) due the additional uranium and gas resources that support higher energy demands via more nuclear power and NGCC with carbon capture plants. When limiting the renewables resources from the advanced scenario to the moderate case, realizing the 3.5 W/m^2 long term target implies additional economic costs, especially large in the case in which fossils fuels and uranium resources are limited to the conventional resources (6% global GDP losses by 2100).

In Switzerland, additional global unconventional resources reduce up to 1% the GDP losses in 2100, mainly due to higher uranium resources. In the less optimistic scenarios of renewable resources, Swiss GDP losses depend on the global availability of unconventional fossil fuels and uranium. When including the unconventional uranium, Swiss costs remain the same until 2050 and increase substantially in 2060 and 2070, where additional global efforts are needed to keep the radiative forcing below 3.5 W/m^2. In contrast, when unconventional resources are not available, GDP losses are higher, reaching 0.7% by 2050 and 2% by 2070.

Resource availability also affects the carbon prices needed to achieve the climate target (see Figure



(A) *Global* (B) *Switzerland*

FIGURE 8.6: *Resource scenarios: GDP losses*

8.7). The scenarios with moderate renewables exhibit higher carbon price since renewable resources represent a source of carbon-free energy. The scenario with advanced renewables and unconventional resources has a lower carbon price compared to the reference climate scenario (conAdv) after 2060 due to the larger uranium resources that imply larger deployment of nuclear technologies at the end of the century.

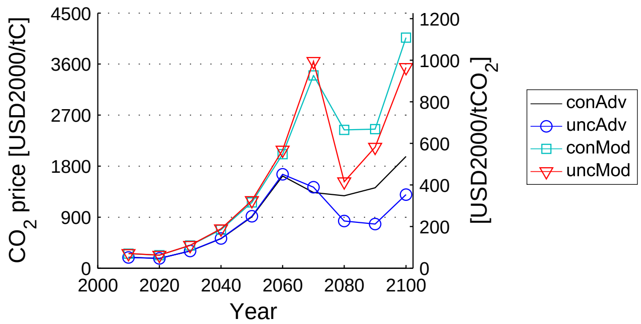


FIGURE 8.7: *Resource scenarios: Carbon price*

Finally, the availability of resources has implications on energy prices. Table 8.5 presents oil, gas, uranium and biomass prices in the different scenarios on resources in 2050 and 2100. The scenario with unconventional fossil fuels and uranium and advanced renewable resources results in the lower energy costs, due to the larger resource availability. In the same way, the scenario with the lowest resources estimations (conMod) produces the highest energy prices for all energy carriers. However, the intermediate cases present different behaviors. For the fossil resources, the change in the renewable estimations do not have and effect on the prices when including unconventional resources, hence the price of oil and gas is very similar in uncAdv and uncMod. In contrast, uranium and biomass prices increase substantially from the advanced to the moderate renewable resources case.

8.4 Discussion

The results in this chapter show the considerable effects of resource availability in the future energy system under stringent climate policy constraints.

First, even if a larger availability of fossil fuels that include unconventional resource could increase

TABLE 8.5: *Resource scenarios: 2050 and 2100 energy prices [USD2000/GJ]*

	2050				**2100**			
	Conventional		Unconventional		Conventional		Unconventional	
	Adv	Mod	Adv	Mod	Adv	Mod	Adv	Mod
Oil	7.2	7.6	5.7	4.8	15.8	18.8	5.2	5.1
Gas	8.2	10.8	5.9	6.1	22.9	38.2	6.5	6.9
Uranium	7.1	11.8	4	6.9	22.1	50.5	7.9	18.3
Biomass	15.6	20.6	16.6	20.2	23.6	35.9	11.4	32

greenhouse gas emissions, when assuming a global climate mitigation target, unconventional resources, especially uranium and gas to be used in NGCC power plants with carbon capture and storage, help in decreasing the costs of climate policies. Nevertheless, even if unconventional resources could decrease the economic costs of reaching long term climate targets, the extraction of unconventional resources would require countries to overcome different issues including regulatory, technological and public acceptance to establish the needed infrastructure for the commercial production of unconventional resources. Furthermore, the development of carbon capture and storage technologies is required to realize climate targets when more fossil fuels are used.

Second, the scenarios with unconventional fossil and uranium resources result in larger energy demands. This shows a trade-off between fossil fuels and uranium availability and energy efficiency improvements to achieve climate mitigation targets. However, the realization of these higher demands depends on the deployment of nuclear power, and the development of CCS and the appropriate technologies to extract the unconventional resources.

Finally, the results concerning the availability of renewable resources show their importance in the presence of a climate mitigation regime, with considerable decreases in the energy demand observed in the case in which the potential or the integration of the renewable-based electricity is limited. Even if sun or wind can be considered unlimited resources, their integration into the network and the intermittency issues have to be resolved in order to guarantee a sustainable energy supply.

8.5 Implications of global resource availability on the Swiss energy system

Limited global renewable resources have a greater impact on the Swiss energy system under climate mitigation scenarios than reduced estimates of fossil fuels. The pessimistic scenario on renewable resources requires higher efficiency achievements to reduce the energy demand and higher energy prices, therefore, higher economic costs. Renewable resources are limited by the actual availability but also by the integration of renewables in the energy mix. Overcoming this last constraint implies a need from Switzerland to deploy the appropriate network to integrate intermittent resources, the need to guarantee electricity supply using backup capacity, with for example hydropower pump storage, or the integration of the grid across the border. Regarding the non-electric energy use of the renewables, even if Switzerland has some own resources, an important part of the biomass used to produce hydrogen is imported from some developing regions. This can have potential risks for Switzerland, since these regions could have in the future issues with food supply or might need the biomass for their own energy supply, reducing the available biomass and increasing the price of imported biomass for Switzerland.

The availability of unconventional resources could allow Switzerland a reduction in the efficiency improvements needed to achieve a stringent long term climate target, especially unconventional uranium resources. Nevertheless, the shift to a renewable-based electricity energy production implies somehow a resource independence, due to Swiss relatively large own renewable resources.

Chapter 9

Swiss energy strategies under global uncertainty: Conclusions and outlook

The objective of this dissertation has been to improve understanding of how Swiss energy strategies can be affected by different global uncertainties and to determine robust technologies and policies to achieve a sustainable Swiss energy system. In this PhD thesis, a long set of scenarios covering different alternatives for climate policies, technology deployment, economic development and resource availability have been developed, quantified and described in the previous chapters, including:

- Climate change mitigation policies (Chapter 4): Climate change due to man-made greenhouse gas emissions is a global problem that has been actively discussed by governments, reaching regional accords including the Kyoto Protocol (United Nations Framework Convention on Climate Change, 1998) and the Copenhagen Accord (United Nations Climate Change Conference, 2009). However, regional commitments and the actual undertaken actions are highly uncertain. For instance, many developing regions responsible for an important part of global emissions, have not yet committed to reduce emissions. The climate policy scenarios analyzed in this thesis include global long-term radiative forcing targets from 2.6 to 8.5 W/m^2 (rf85, rf60, rf45, rf35, rf30 and rf26); which covers a large range of global and regional commitment. Additionally, a scenario on a global carbon tax (globTax) was developed as a representative measure that can include different regional commitments or trading of CO_2 permits. Europe and Switzerland have important greenhouse gas reduction targets and an active CO_2 permit market; therefore, as a more close-to-reality scenario, a case in which Switzerland and the EU apply the carbon tax 30 years earlier than the other world regions was also developed (firstMove).
- Technology scenarios (Chapter 5): Technology development has many uncertain aspects that include future technology costs, further development of current technologies such as nuclear power plants and the development of some new technologies such as carbon capture and storage or large-scale hydrogen production using solar thermal processes. The technology scenarios developed in this thesis include scenarios on technology costs (high, low and the medium cost scenario that corresponds to rf35 described in Section 5.3); spillover scenarios including no global spillovers, group and regional spillovers (NoSpill, GrSpill, RgSpill described in Section 5.4); and scenarios on technology deployment including nuclear phase-out globally and in

Switzerland and Japan, delayed CCS, no deployment of CCS and no large scale production of hydrogen from solar thermal processes (NoNuc, NoNucCH, LateCCS, NoCCS, NoSTH).

- Nuclear policy scenarios (Chapters 5 and 6): The accident in Fukushima, Japan in March 2011 generated high uncertainty on the development of nuclear power worldwide and in Switzerland, in particular. For this reason, different global and Swiss nuclear policies are analyzed in Chapters 5 and 6, including: global 100% nuclear support (100%Nuc), global no new nuclear technologies (noFBR), global non proliferation (NoProl), global no nuclear (NoNuc), Swiss nuclear phase-out (NoNucCH) and no LWR reactors in Switzerland but new technologies available (NoLWRCH).

- Economic development scenarios (Chapter 7): Future energy demand depends on economic development, population growth and efficiency achievements related to buildings, industrial processes and appliances used by the consumers. All these variables are highly uncertain and interrelated, for instance economic development depends, among other factors, on population and productivity growth and can affect efficiency achievements. In this thesis, three scenarios on economic development based on Riahi et al. (2007) have been analyzed including a "dynamic as usual scenario" (this corresponds to the reference climate scenario rf35); a scenario with large population growth, slow economic development and low convergence between developing and developed regions (A2R); and a scenario with low population growth but high economic development and high convergence among regions (B1).

- Resource availability (Chapter 8): Resource estimations depend on the physical availability and abundance of the earth resources but also on the technology deployment for the extraction of resources and the capacity to integrate different intermittent sources to the electricity mix. In this sense, the resource scenarios developed in this thesis include the combination of moderate and advanced renewable resources and conventional and unconventional fossil fuels and uranium: Advanced-unconventional (advUnc), moderate-conventional (modCon) and moderate-unconventional (modUnc); the scenario with advanced-conventional resources corresponds to the reference climate scenario (rf35).

Table 9.1 presents a summary of the scenarios developed in this PhD thesis.

In the next sections the different robust energy, technological and climate policies to achieve a sustainable Swiss energy system obtained from the broad scenario analysis are presented. The chapter finishes with some overall conclusions and an outlook for possible future work.

9.1 Towards electrification and the 2000 Watt society

Figure 9.1 presents the electricity demand in Switzerland for most of the scenarios developed in this thesis. In the less stringent scenarios, electricity demand exhibits higher growth since global electricity production is based on fossil fuels and less on low-carbon sources including nuclear, which leads to low uranium prices and, therefore, supports a larger development of nuclear power in Switzerland. The scenarios with the deployment of the fast reactors assume the reprocessing of spent nuclear fuel that leads to an extensive use of the FBR. In all the other scenarios electricity demand has a peak

TABLE 9.1: *Summary scenarios*

#	Name	Climate target	Technology				Economic	Resources		Nuclear policies					
			Cost	Spillovers	CCS	STH-H2		Renewables	Fossil and uranium	Global			Swiss		
										LWR		FBR	LWR		FBR
										UOX	MOX		UOX	MOX	
Climate change mitigation															
1	rf85	rf = 8.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
2	rf60	rf = 6.0 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
3	rf45	rf = 4.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
4	rf35	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
5	rf30	rf = 3.0 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
6	rf26	rf = 2.6 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
7	globTax	global CO_2-tax	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
8	firstMov	EU+CH CO_2-tax in 2020	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
Technology															
9	high	rf = 3.5 W/m^2	high	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
10	low	rf = 3.5 W/m^2	low	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
11	NoSpill	rf = 3.5 W/m^2	ref	0%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
12	GrSpill	rf = 3.5 W/m^2	ref	group	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
13	RgSpill	rf = 3.5 W/m^2	ref	regional	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
14	LateCCS	rf = 3.5 W/m^2	ref	100%	from 2050	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
15	NoCCS	rf = 3.5 W/m^2	ref	100%	-	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
16	NoSTH	rf = 3.5 W/m^2	ref	100%	x	-	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
Nuclear policies															
17	100%Nuc	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	x	x	x	x	x
18	NoFBR	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	x	-	x	x	-
19	NoProl	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	-	-	x	-	-
20	NoNuc	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	-	-	-	-	-	-
21	NoNucCH	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	x	-	-	-	-
22	NoLWRCH	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Conventional	x	x	x	-	-	x
Economic development															
23	A2R	rf = 3.5 W/m^2	ref	100%	x	x	A2R	Advanced	Conventional	x	-	-	x	-	-
24	B1	rf = 3.5 W/m^2	ref	100%	x	x	B1	Advanced	Conventional	x	-	-	x	-	-
Resources															
25	advUnc	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Advanced	Unconventional	x	-	-	x	-	-
26	modCon	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Moderate	Conventional	x	-	-	x	-	-
27	modUnc	rf = 3.5 W/m^2	ref	100%	x	x	ref (B2)	Moderate	Unconventional	x	-	-	x	-	-

in 2040 and decreases considerably afterwards. The lowest electricity demand corresponds to the economic scenario B1, due to lower population assumptions, and the scenario with no deployment of carbon capture and storage technologies, due to less biomass and uranium resources available driven by the absence of CCS.

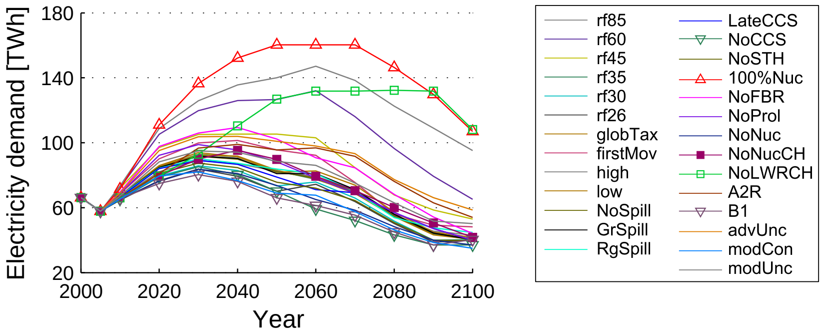


FIGURE 9.1: *Swiss scenarios: Electricity demands*

The Swiss Federal Office of Energy (BFE, 2011) published two scenarios for the future energy system in Switzerland, namely: "business as usual" and "new energy policy". The growth in the electricity demands in the BFE scenarios for the years 2035 and 2050 compared to the level in 2000 are summarized in Table 9.2.

TABLE 9.2: *Growth in energy demand in the scenarios from BFE (2011)*

Scenario	**Electricity**		**Non-electric energy**	
	2035/2000	**2050/2000**	**2035/2000**	**2050/2000**
Business as usual (BAU)	+37.2%	+52.1%	-12%	-12.1%
New energy policy (NEP)	+11.7%	+7.5%	-38.3%	-50.9%

Figure 9.2 presents the electricity demands from the BFE (2011) scenarios compared to the electricity demands in the scenarios in this thesis. The average scenario demand among all the scenarios implies an increase in the electricity demand of 23% from 2000 to 2050, which is in the range proposed by the BFE (2011) of between 7.5 and 52%. Additionally, Figure 9.2 compares the nuclear phase out scenario in Switzerland to the BFE (2011) scenarios, and shows that the optimal efficiency improvements resulting from the scenario are similar to those in the BFE business as usual scenario.

Regarding the non-electric energy sector, Figure 9.3 shows the demand in most of the scenarios developed in this PhD thesis. All the scenarios show a decrease in non-electric energy demand from today's levels. This implies important efficiency improvements on the demand side, e.g. insulation to reduce space heating demand or more efficient end-use appliances or vehicles[1].

Among the developed set of scenarios, the average decrease in non-electric energy demand by 2050 (compared to 2000) is -33%, compared to the 23% increase in electricity demand. Therefore, besides the improvements in energy efficiency, the decrease in non-electric energy demand results also from further electrification. That is, for example, the use of electric vehicles for transportation or heat

[1] Note that MERGE-ETL does not include details on the end-use demand technologies. See Weidmann et al. (2012) for a comparison of two Swiss bottom-up models.

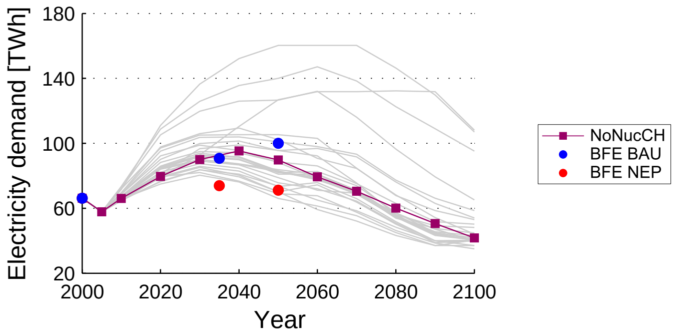


FIGURE 9.2: *Swiss scenarios: Electricity demands and BFE policy*

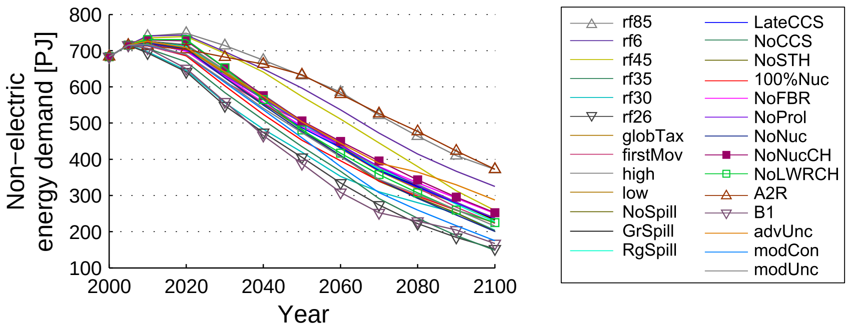


FIGURE 9.3: *Swiss scenarios: Non-electric energy demands*

pumps for space heating. The scenario with the greatest electrification corresponds to the case in which the fast reactors are deployed (100%Nuc), while the scenario with least electrification is the no-nuclear in Switzerland scenario (NoNucCH), showing the importance of nuclear deployment to reach high electrification levels. Figure 9.4 compares the non-electric energy demands in the scenarios in this thesis to the demands in the scenarios developed by the BFE (2011) (see Table 9.2). Again the nuclear phase out scenario (NoNucCH) is consistent with the BAU from the BFE (2011). Furthermore, the non-electric energy demand in the new energy policy scenario from the BFE (2011) is lower than the energy demands in all the scenarios in this thesis, showing that the levels of energy efficiency and electrification obtained in this analysis are not overly optimistic.

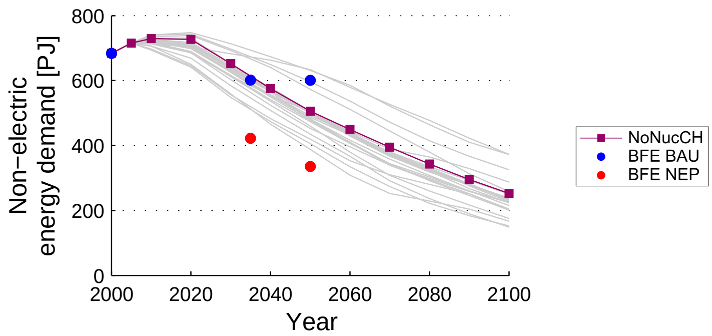


FIGURE 9.4: *Swiss scenarios: Non-electricity demands and BFE policy*

Total energy demand (both electric and non-electric energy) reductions can be compared to the often discussed 2000 W society originally proposed by Jochem et al. (2002). Many of the scenarios realize a primary energy supply per capita of 2000 W as a long term target by 2080 (see Figure 9.5[2]), while the original 2000 W society referred to a 2 kW TPES per capita by 2050, which would imply additional and faster changes to the Swiss energy system.

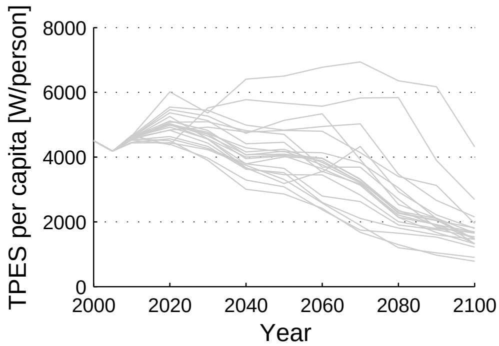


FIGURE 9.5: *Swiss scenarios: Total primary energy supply per capita*

Realizing the energy demand reductions towards the 2000 W society has large implications on efficiency improvements. Which levels of efficiency improvements can be achieved is not certain, but the reductions in energy demand obtained in most of the scenarios in this thesis are within the range of the demands in the scenarios from the Swiss Federal Office of Energy (BFE, 2011). The needed steps towards the 2000 W society include, among others, efficiency improvements in buildings, especially insulation to reduce the space heating demand; improvements in large equipment such as power plants and industrial machines; and improvements in the efficiency of vehicles (Jochem et al., 2002).

9.2 Renewables and hydrogen society

Figure 9.6 presents the optimal electricity technology combination for Switzerland in most of the scenarios developed in this PhD thesis. The first important outcome of these scenarios is the robustness of renewable-based generation in the presence of a climate policy. In all the scenarios, wind- and solar-based electricity generation starts being deployed up to the maximum potential from 2030, with except of the less stringent climate scenario (rf85 scenario, scenario #1, first column on the left of the climate scenarios) where solar and wind technologies are deployed later due to higher availability of uranium since other world regions deploy coal-based electricity. In Switzerland, hydropower, wind and solar are the dominant technologies by 2100. This implies important intermittency issues that need to be considered. One option for the Swiss energy system is the use of pumped-storage hydroelectricity as back-up capacity, using the surplus electricity coming from intermittent renewables to store the water and generating the hydroelectricity when the intermittent resources are not available. The other option is improved integration with the European grid, which provides geographic diversification and reduces the risk of wind or solar power not being available. It would be desirable that such electricity trading is done with countries where electricity is produced production using low CO_2

[2]Scenarios using the FBR are not included in this plot since the estimations of the primary energy supply from electricity produced using reprocessed fuels make the results of those scenarios not comparable.

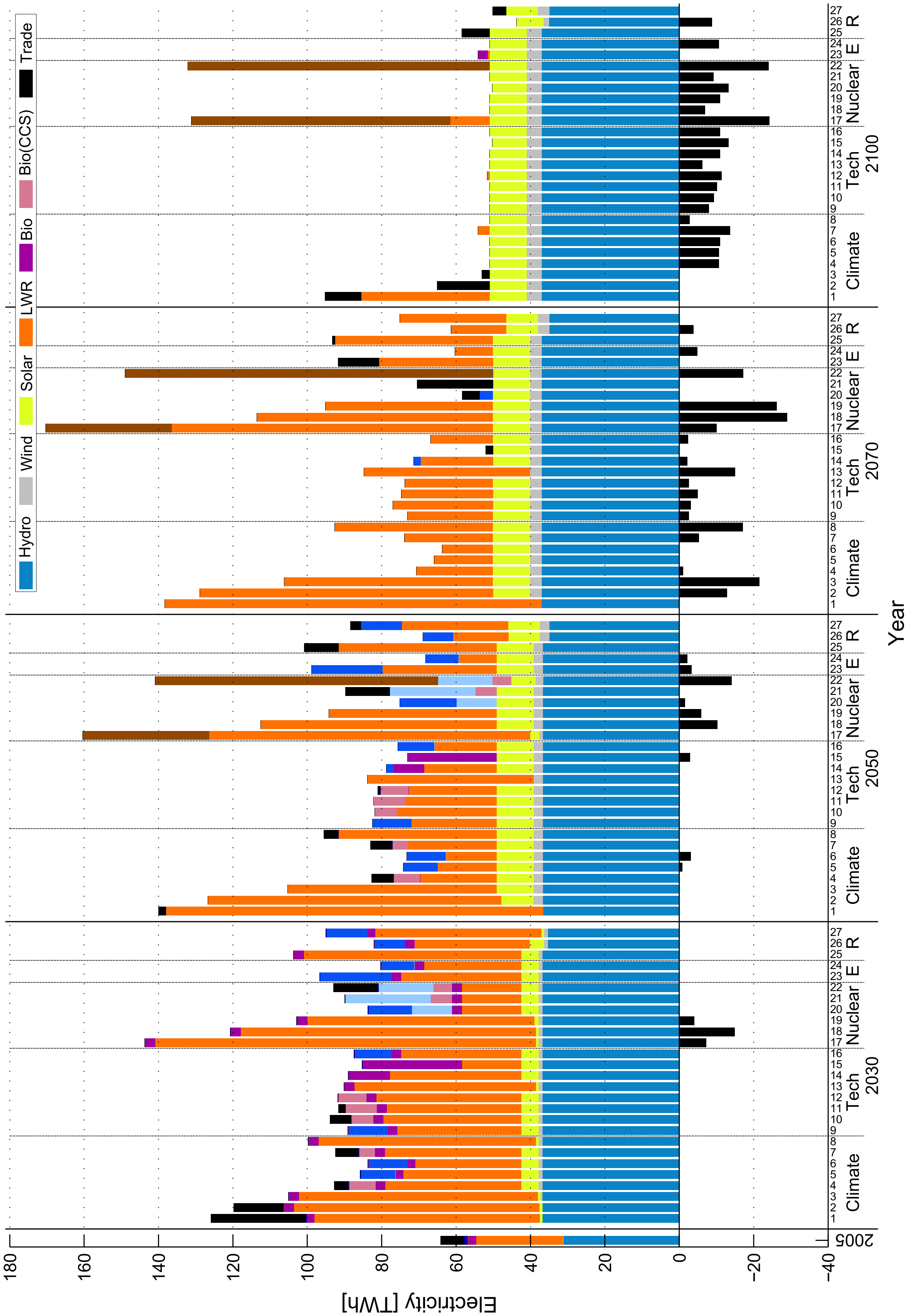


FIGURE 9.6: *Swiss scenarios: Electricity technologies in climate, technology (Tech), nuclear policy (Nuclear), economic (E), and resources (R) scenarios*

emissions technologies, avoiding leakage of emissions from Switzerland to other countries. Additional analysis of the reliability of an electricity system reliant on renewable-based generation needs to be done. A model with more detailed load curves and seasonal considerations than MERGE-ETL could provide relevant inputs[3].

The complete shift towards a renewable-based electricity system requires transition technologies from today's generation mix. The main technologies involved in this transition process in the different scenarios include nuclear power, natural gas combined cycle with or without carbon capture and storage, and biomass-based electricity generation with and without CCS.

The most robust transition technology in all the analyzed cases is nuclear power. The total amount of nuclear-based electricity is slightly affected by uranium resources, but it is around 40 and 30 TWh in 2030 and 2050, respectively. This corresponds to 4-5 GW[4] of installed capacity: around 3-4 power plants of the size of Leibstadt (the largest power plant in Switzerland with a net capacity of 1.165 GW). Nevertheless, the decision of the Swiss federal cabinet in May 2011 to keep the current power plants until the end of their lifetimes and not to build new reactors (Swiss Federal Council, 2011) has important implications for the transition towards a renewable-based electricity system. In the absence of nuclear power (scenario # 21, second last bar in nuclear scenarios in Figure 9.6), the preferred transition alternatives are NGCC and imports from the EU, which increases CO_2 emissions and dependency on electricity produced abroad. Thus, the nuclear phase-out in Switzerland has important trade-offs with self sufficiency and climate mitigation objectives. In September 2011, an amendment to the Swiss Parliament's decision in May 2011 to not replace nuclear reactors was proposed by a Senate Committee, leaving open the door for "new generation reactors". The additional nuclear scenarios developed in this thesis with the enhanced nuclear cycle presented in Chapter 6 allow the analysis of different nuclear policies including a "new generation reactor" (fast breeder reactor). Two scenarios include the fast reactor as an alternative to produce electricity: 100% nuclear support and noLWR in Switzerland, corresponding to scenarios # 17 and 22 in the nuclear policy scenarios in Figure 9.6. In both cases, the FBR is deployed at the maximum feasible rate because it brings a base-load low-carbon technology that allows Switzerland to be relatively resource independent from the other regions. However, the feasibility of deploying such a technology has various limits. On the one hand, it is a technology under development that still requires research and development concerning technological, safety and reprocessing issues. On the other hand, its construction needs public acceptance of new nuclear technologies and reprocessing of nuclear spent fuel.

Besides nuclear power, NGCC and biomass are the two other options for electricity production in the transition period. Natural gas combined cycle or biomass with carbon capture and storage are deployed in almost all the scenarios from 2030 to 2060. The substitutability of these two technologies depends on technology costs (scenarios # 9 and 10 in technology scenarios in Figure 9.6) and global biomass and gas resources. When carbon capture and storage technologies are delayed or not available due to technology development or public acceptance issues (scenarios # 14 and 15 in the technology scenarios in Figure 9.6), biomass without CCS is utilized. Therefore, the deployment of biomass-based generation technologies may represent a heading strategy to realize low energy-related CO_2 emissions with and without the development of carbon capture and storage in Switzerland. Contrary to the biomass case, the deployment of NGCC is optimal when carbon capture and sequestration

[3] See for example the Swiss Times model (Ramachandran and Turton, 2011)
[4] Assuming a load factor of 85%.

is available. However, as discussed in Chapter 5, the use of CCS requires research and development efforts, to further develop the technology to commercial levels, public acceptance and policy support. Furthermore, the development of the high pressure network required to transport the captured CO_2 is needed.

Regarding non-electric energy sector, Figure 9.7 presents the deployed technology mix for most of the scenarios developed in this PhD thesis. The consistent long-term trend in the non-electric energy supply is a shift from fossil fuels to hydrogen. In the first periods, oil and gas constitute the main energy carriers, with a substantial contribution from oil products. By the middle of the century, about one third of the non-electric energy demand is supplied by oil products, one third with natural gas and the last third with hydrogen production from biomass with carbon capture and storage. The contribution of hydrogen to the non-electric energy supply increases by 2070 and 2080, with biomass being the main feedstock used for its production. By the end of the century, hydrogen production is significantly reduced due to the decrease in the demand and the continuing electrification tendency, but also due to increase in biomass prices due to higher global demand.

The shift from oil to natural gas, as a transition energy carrier, and later in the century to hydrogen requires appropriate incentives. Today, heating oil and gasoline are relatively cheap in Switzerland. In 2007, the price of heating oil in Switzerland was the cheapest after Japan in the OECD countries and gasoline cost 19.4% less than in France, 20.9% less than in Italy and 23.5% less than in Germany (IEA, 2007c). These low prices are explained by lower taxes applied in Switzerland. The current Swiss CO_2 tax has increased from 8 CHF per ton of CO_2 in 2008 to the current CHF 36 per ton of CO_2 (Swiss Federal Office of Environment (BAFU), 2009), which corresponds to 9 cents per liter of heating oil. In 2011, the Swiss parliament started discussing the new CO_2 regulation that will apply from 2013. According to the first proposal, the CO_2 price could increase to 60 CHF/tonCO_2 by 2014 and up to 120 CHF/tonCO_2 in 2018 (Swiss Federal Office of Environment (BAFU), 2012a). This proposal for the increase in the CO_2 price is in line with the carbon taxes required in the most stringent climate policy scenarios in this thesis, 50-110 USD2000/tonCO_2 by 2020 presented in Figure 4.18 in Chapter 4.

Furthermore, the production of hydrogen with biomass was shown to be the preferred alternative with carbon capture and storage being an interesting option that helps to further reduce CO_2 emissions, but, as discussed above, the development of these technologies is considerably uncertain. However, the scenarios in which CCS is delayed or not available (scenarios # 14 and 15 in the technology scenarios in Figure 9.7) show that production of hydrogen with biomass (w/o CCS) is an attractive alternative for Switzerland. Therefore, the use of biomass to supply non-electric energy demands is one robust technology option for Switzerland. Whether the biomass is used to produce hydrogen or synthetic fuels depends on the technology development, concerning costs and efficiencies. However, potential challenges for Switzerland could come from higher biomass prices due to higher global demand (as shown in the scenarios on economic pathways in Chapter 7) or limited biomass resources due to future issues such as food or water supply (as discussed in Chapter 8).

Finally, one option to overcome the issue of resource availability for the production of hydrogen is the solar thermal process. The potential assumed in this PhD thesis for this technology in Switzerland is relatively low; however the development of this technology could imply higher potential, hence making it a possible option for dealing with resource availability issues. Therefore, continuous efforts on research and development of hydrogen production technologies are needed. Another option that

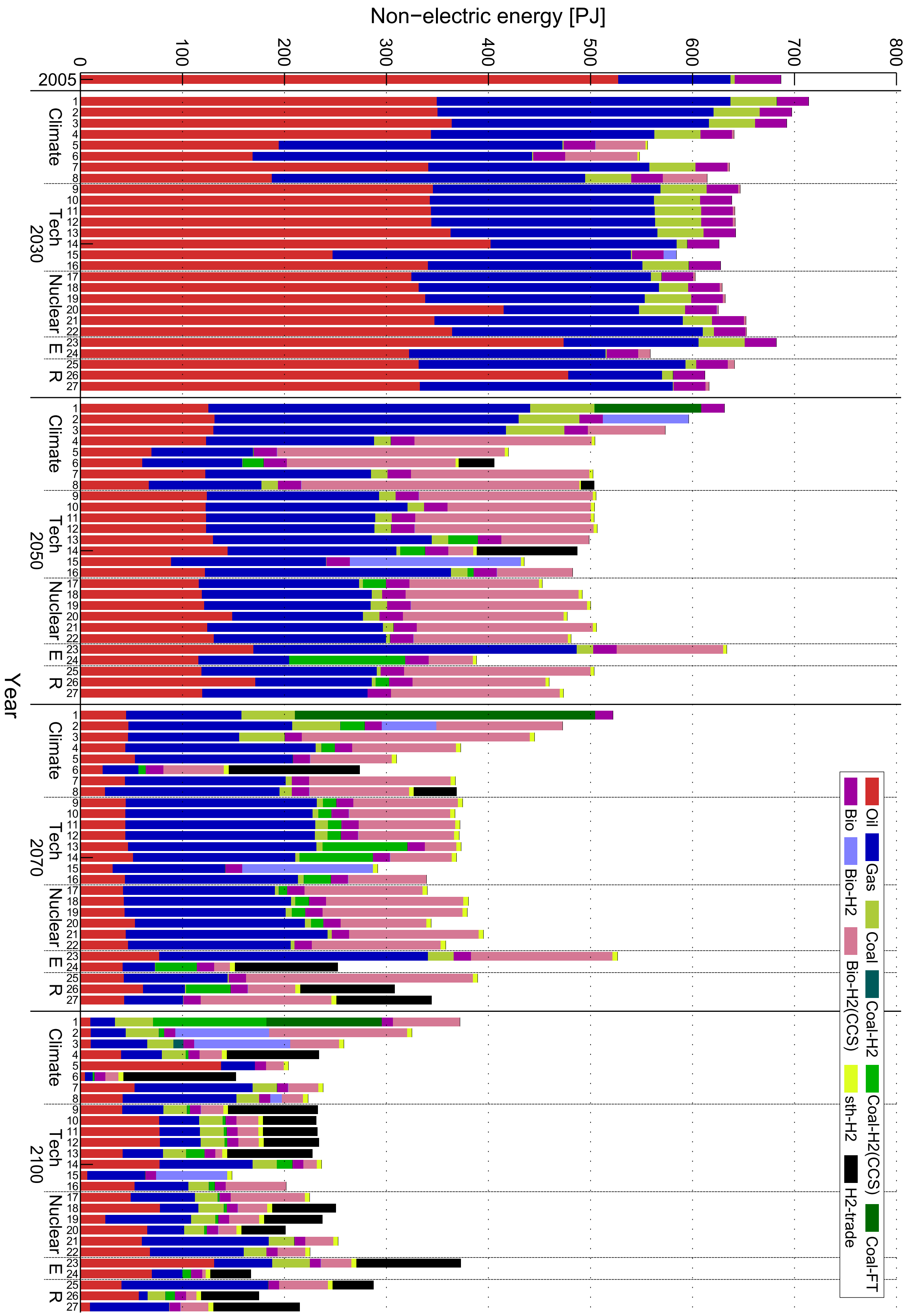


FIGURE 9.7: *Swiss scenarios: Non-electric energy technologies in climate, technology (Tech), nuclear policy (Nuclear), economic (E), and resources (R) scenarios*

appears with special relevance, especially in 2100, is trading of hydrogen with the EU.

9.3 Swiss climate policy

Figure 9.8 presents energy-related emissions in Switzerland for the different scenarios developed in this dissertation. Emissions peak in all the scenarios by 2020 with a substantial decrease afterwards. The case with the largest emissions corresponds to the less stringent climate policy case (rf85), which has the largest energy-related emissions with a maximum by 2070 of 69 $MtCO_2$. Different scenarios build the frontier of the minimum emissions: the most stringent climate policy case (rf26) until 2040 and from 2080, the first move scenario in 2050 (with the overall minimum in emissions on -10.8 $MtCO_2$), no nuclear scenarios in 2070 and the scenario with advanced renewable and unconventional resources by 2080.

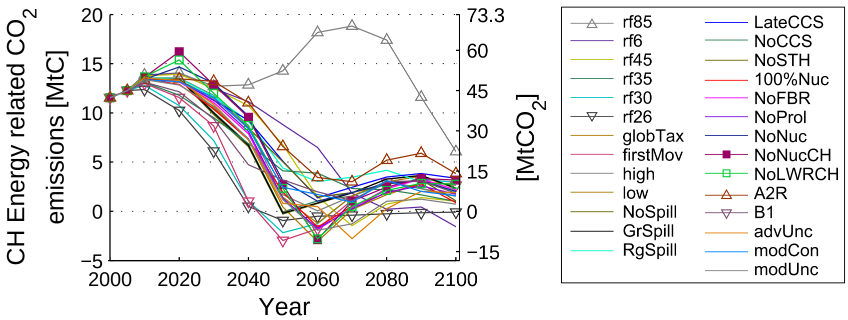


FIGURE 9.8: *Swiss scenarios: Energy-related emissions*

The first move climate tax scenario shows the importance of international climate policies. The optimal abatement of Swiss energy-related emissions in this case is considerably higher compared to most of the other scenarios. Since climate change is a global problem, a Swiss climate policy should also include the participation in global treaties and the avoidance of carbon leakage to other countries by imports of energy intensive products or electricity produced with CO_2-intensive technologies.

Furthermore, as mentioned in the previous section, the phase-out in Switzerland of nuclear electricity production has negative consequences on the energy-related emissions, especially in the first half of the century. The two scenarios of nuclear phase-out (NoNucCH and NoLWRCH) result in higher initial emissions compared to the other scenarios, with a higher peak in 2020 of 59.4 and 56.4 $MtCO_2$ for the NoNucCH and NoLWRCH, respectively, compared to 51.5 $MtCO_2$ for rf85.

The OcCC (2007) proposed a domestic emissions reduction target for CO_2 of 20% by 2020 and 60% by 2050 compared to 1990 levels, that is energy-related emissions of 35.2 and 17.6 $MtCO_2$, respectively[5]. Figure 9.9 presents the energy-related emissions in the scenarios developed in this thesis compared to the OcCC policy proposal. The proposed reduction of 20% by 2020 implies emissions lower than the obtained in all scenarios in this dissertation. By 2020, the average of the energy-related emissions across the scenarios corresponds to an increase of 10% compared to 1990 levels. This increase is even

[5]According to the Swiss Federal Office of Environment (BAFU) (2012b), Swiss energy-related emissions in 1990 were 44.043 $MtCO_2$.

larger in the nuclear phase out scenarios: 28 and 35% with and without FBR, respectively. On the other hand, the CO_2 energy-related emissions resulting from a 60% reduction by 2050 are higher than the optimal emissions pathways in the analyzed scenarios. By 2050, the average emissions reduction among all the scenarios corresponds to a decrease of 80% compared to 1990 levels. Therefore, a robust Swiss climate policy that is consistent with reaching global climate change goals (even at the high end of the radiative forcing levels needed to avoid 2°C) should aim for a reduction in emissions by 2050 of 80% compared to 1990 levels but with a less stringent initial pathway.

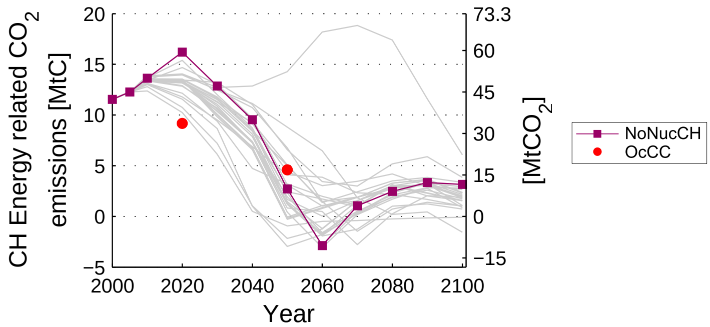
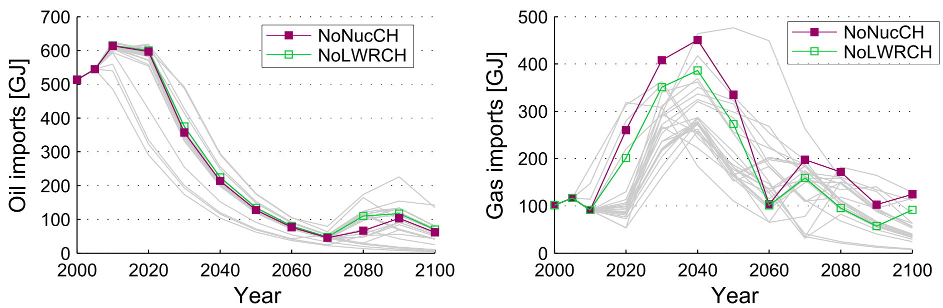


FIGURE 9.9: *Swiss scenarios: Energy-related emissions compared to OcCC (2007) climate policy proposal*

9.4 Energy security

Another important aspect of a sustainable Swiss energy system is related to energy security. In Section 9.2 the implications concerning intermittence problems of a renewable-based electricity system for energy security were discussed. Besides this aspect, dependency on imported energy resources also plays an important role in the security of the Swiss energy system. Figure 9.10 presents the imports of oil and gas for the scenarios in this PhD thesis.



(A) *Oil* **(B)** *Gas*

FIGURE 9.10: *Swiss scenarios: Oil and gas imports*

The Swiss energy system is highly dependent on imported oil in the first half of the century. This brings a potential risk to the energy system concerning security of supply. This risk could be addressed through the diversification of transportation and heating technology options.

While the dependency on imported oil decreases with time across the scenarios, imports of natural gas increase substantially until 2060, due to its use as transition energy carrier in both the electricity and the non-electric energy sectors, implying considerable risks to security of supply, due to potential stability issues or conflicts in or with the regions from where natural gas is imported or transported. This is more pronounced in the nuclear phase-out scenario, where imports of gas are larger compared to the other climate mitigation scenarios (see Figure 9.10B). This implies additional trade-offs of the current Swiss nuclear policy with energy security, besides the already mentioned consequences for carbon emissions and self-sufficiency. An alternative that could increase security of supply in the face of short term disruption, by increasing the flexibility of the energy system, is interruptible contracts of both gas and electricity. These are contracts where consumers allow interruptions to electric or gas supply in exchange for financial compensation at the time of the interruption or an overall reduction in the electricity or gas price. In some cases consumers, such as industries, would be required to have stocks of heating oil or back-up diesel generators (IEA, 2007c). Additionally, energy security could be increased by more coordination with the neighboring countries (Germany, France, Austria or Italy) to guarantee natural gas supply in case of disruptions in Switzerland.

Furthermore, energy security and the stability of the Swiss energy system could be affected by international conflicts. To analyze these aspects two scenarios in which for political reasons Russia does not export gas for 2 decades from 2030 and the Middle East does not export oil for 10 years from 2020 have been analyzed[6]. These analyses showed an important stability of the Swiss energy system. When imported oil from the Middle East is not available it is replaced by oil from other regions and natural gas. And when no supply of natural gas from Russia is available, it can be replaced by oil in the non-electric energy sector. However, this implies important additional costs to achieve stringent climate policies. Furthermore, in the no-nuclear case, where natural gas combined cycle is used in the electricity generation, without the supply of natural gas from Russia, the share of this technology does not decrease, since the alternatives remain more expensive - notably biomass. This indicates that the risks of energy security are harder to manage with the nuclear phase-out policy.

9.5 Conclusions

In this dissertation the first analysis on the impact of global uncertainties in the Swiss energy system including climate policies, technology deployment, resource availability and economic development was developed. The different global scenarios developed in this PhD thesis have different implications for the Swiss energy system. However, robust energy, technological and climate policies required to achieve a sustainable energy system can be derived from the scenario analysis. This section summarizes the main findings of this PhD thesis.

9.5.1 Towards a long-term 2000 W society

In this PhD thesis it is found that energy efficiency improvements and their consequently energy demand reductions are required to achieve stringent climate mitigation targets. Thus, a long-term 2000

[6]The author would like to thank Prof. Hungerbühler for suggesting this analysis on the stability of the Swiss energy system.

W per capita society by 2080 with intermediate steps of 3500 W per capita by 2050 is found to be a robust pathway for the Swiss energy system. Steps to improve energy efficiency include implementing higher building standards; and improvements in efficiency of vehicles or other end-use technologies. This policy is in line with the BFE (2011) scenarios on demand reductions. However, whether enough efficiency improvements are feasible to achieve the energy demand reductions remains uncertain.

9.5.2 Transformation of energy use: electrification

The transformation of the energy use, regarding a trend towards electrification of the "non-electric" energy sectors is found to be the second robust development for a sustainable Swiss energy system. This implies the introduction of electric vehicles for transportation and heat-pumps for space heating. Realizing these sectorial changes would require considerable government support, including incentives to renovation of space heating systems in households or differential electricity tariffs for charging electric vehicles.

9.5.3 Long term shift to renewables and biomass energy production

The analysis in this dissertation showed that regardless of the achieved levels of efficiency, the robust Swiss technology pathway leads by the end of the century to renewable-based electricity system and biomass-based non-electric energy (for production of hydrogen or synthetic oil depending on the development of the technologies). This implies important intermittency issues, especially in electricity supply, that need to be considered by Swiss policy-makers and utilities. Options to deal with the intermittency of renewable based electricity include the use of pumped-storage hydropower or further grid integration with neighboring countries.

In the electricity sector, the transition to this renewable-based energy system would require the use of nuclear power, natural gas or biomass based technologies to meet the intermediate climate targets. The phase-out of the nuclear power, decided by the Swiss Parliament, implies the deployment of additional natural gas combined cycle and the need for imported electricity from the European Union. In the non-electric energy sector, today's oil supply is replaced by gas in the middle of the century and biomass by 2070. The achievement of this shift from oil requires the definition of incentives to reduce or replace the use of gasoline, diesel and heating oil.

Carbon capture and storage showed to be an interesting alternative to the electricity production since it would help to reduce energy-related emissions. However, the availability of this technology is highly uncertain due to technology development and public acceptance.

9.5.4 Swiss nuclear policy: feasible but...

The analysis of the scenarios incorporating the new Swiss nuclear policy of phasing out the current reactors at the end of their lifetimes showed important trade-offs with self-sufficiency, energy related CO_2-emissions reductions and energy security. Nuclear electricity is replaced by imports from the EU and the deployment of natural gas combined cycle plants, reducing self-sufficiency and increasing energy-related CO_2-emissions, respectively. Furthermore, the deployment of NGCC technologies increases the dependency on imported gas, thus, further increasing energy security risks.

In this dissertation a new fuel cycle model for improved analysis of nuclear generation in long-term scenarios was developed. This allowed the analysis of different global and Swiss nuclear policies. The analysis showed that the global development of a new generation reactor could enable nuclear generation to make a large contribution to global and Swiss electricity production, by providing a base load source of low carbon electricity. However, the development of such a reactor, the public acceptance of this technology and whether it is considered safe to be deployed in Switzerland is highly uncertain.

9.5.5 Stringent climate policies

In this dissertation a robust Swiss climate policy with a stringent emissions reduction target of around 80% by 2050 compared to 1990 levels is found to be consistent with efforts to reduce global climate change to below a CO_2 concentration by 2100 of 430ppm. Additionally, the analysis done on an early climate policy from the EU and Switzerland and the rest of the regions acting 30 years later, showed the importance of the participation of Switzerland in international agreements to cope with climate change.

9.5.6 Energy security

The scenarios analysis conducted in this thesis showed a high dependence of Switzerland on imported oil and natural gas in the first half of the century. By 2100, the shift towards the renewable-based energy production implies higher stability of the Swiss energy system if intermittency issues are addressed since Switzerland would be less dependent on global resources. However, in the transition periods, the dependency on imported energy carriers has important risks for security of supply of the Swiss energy system. Alternatives to deal with these issues include interruptible contracts of electricity and natural gas to manage possible short term demand disruption and increasing coordination with the neighboring countries.

9.6 Potential improvements and future work

This dissertation has analyzed the impact of different global uncertainties on the realization of a sustainable Swiss energy system. However, it is important to note some of the limitations of the scenario modeling analysis presented in this thesis. Furthermore, despite the extensive set of developed scenarios, additional scenarios and analyses can complement the results presented in this thesis.

9.6.1 Analytical framework

The climate in MERGE-ETL is modeled with relatively simple CO_2 and non-CO_2 cycles and a simplified estimation of the temperature increased based on the radiative forcing estimations. However, more detailed description of the climate can bring important insights on the consequences of green-house gas emissions. Furthermore, the linkages between greenhouse gas emissions and temperature rise have important uncertainties, thus, additional scenario analysis regarding climate sensitivities, carbon cycle or radiative forcing estimations can bring complementary insights to the analysis presented in this dissertation.

Concerning the energy submodel, additional technologies such as geothermal electricity generation could have an important role for climate change mitigation. This technology could be either modeled explicitly within the electricity technologies in MERGE-ETL or other models with a more detailed technology representation can be used to complement the analysis presented in this dissertation. Furthermore, the developed nuclear fuel cycle can be improved to include additional nuclear technologies that use, for example, thorium resources. This would improve the analysis of future nuclear options for the realization of a sustainable energy system. In the same way, the analysis on learning spillovers can be further developed including endogenous absorption parameters that could provide a different perspective of the issue of technology spillovers.

9.6.2 Further scenario development

The scenario analysis developed in this thesis can be complemented by including different combination of scenarios to analyze additional possible global developments. For example, high economic development, with a pessimistic renewable case in a nuclear phase-out context is one possible alternative. However, the large set of scenarios developed here provide an initial basis for understanding some of the trade-offs and implications of different technology options using an integrated approach.

Besides the possible combination of the scenarios analyzed in this thesis, other type of climate mitigation scenarios would bring additional inputs, including analysis of current climate policies and analysis regarding the energy intensive sector and carbon leakage. In the same direction, other technology analysis could include scenarios on different learning curves due to the importance of technology learning in the development of the future energy system. Moreover, the analyzed scenarios on technology costs focused on increase or reduction in costs due to higher material costs, scenarios including additional costs due to more strict safety requirements, for the nuclear technology in particular, would also provide important insights.

Concerning the developed nuclear cycle, further analysis can be done regarding other nuclear policies, such as limits to waste disposal or technology constraints for reprocessing MOX fuel. Moreover, the results in this dissertation show that availability of uranium resources are an important driver for future electricity production. An important unconventional uranium resource, not included in the resource scenarios in this thesis, is seawater. Analysis including these uranium resources can bring additional inputs to the analysis of constrained uranium resources and the possible development of nuclear technologies.

Some of the scenarios developed in this thesis show important dependency of Switzerland from imported resources. Additional scenarios to address this issue can be analyzed, including for example minimums on the diversification of the energy supply or limits on the imported fuels. This analysis is the special relevance to assess the feasibility of achieving the Swiss sustainable objectives of self-sufficiency and climate change mitigation in the context of a nuclear phase-out.

9.6.3 Areas for future analysis

With the results in this dissertation additional areas for future work can be identified. For instance, energy efficiency measures were identified as an important element in the global climate mitigation scenarios. However, MERGE-ETL does not model efficiency technologies explicitly, but instead accounts for an elasticity of substitution between energy and capital. Therefore, complementary analyses regarding efficiency improvements in end-use technologies are needed to further understand the feasibility of the combination of supply and demand-side changes presented in these scenarios. These analyses can provide insights concerning limits to energy demand reductions, hence, changes to the future global and Swiss energy system.

Regarding the technology pathways, additional analysis including load curves in the different seasons could be conducted in order to estimate the impact of a large share of intermittent sources on the Swiss electricity generation and the possible stability consequences. Other types of model, such as dispatch models or bottom-up descriptions of the energy system with high time resolution could bring important insights in this topic.

The analysis in this thesis focused primarily on the energy-related greenhouse emissions. However, the non-energy related emissions can also play an important role in the achievement of climate targets. Thus, analysis concerning the abatement curves in MERGE-ETL or using other models with more detailed representation of the non-energy emissions can have a significant input for definition of climate policies.

Renewable-based electricity generation was found in this dissertation to be a robust technology to realize a sustainable Swiss and global energy system. Additional analysis concerning the development of an electricity grid to manage the inclusion of intermittent renewable resources can provide insights concerning the feasibility of the renewable society and potential additional costs coming from the development of transmission and distribution infrastructure.

Furthermore, the achievement of sustainable energy system can include additional variables not analyzed in this dissertation, such as, impacts on air pollution of energy production and the interlinkages between food and water supply and resource availability for energy supply. This analysis can not be directly analyzed using the MERGE-ETL model, hence additional studies and models can complement the analysis in this dissertation.

Bibliography

Albright, David, and Kimberly Kramer. "Plutonium Watch: Tracking Plutonium Inventories." Technical report, Institute for Science and International Security (ISIS), 2005.

Ansolabehere, Stephen, Janos Beer, John Deutch, Denny Ellerman, Julio Friedmann, Howard Herzog, Henry D. Jacoby, Paul L Joskow, Gregory Mcrae, Richard Lester, Ernest J. Moniz, and Edward Steinfeld. "The future of Coal." Technical report, MIT, 2007.

Ansolabehere, Stephen, John Deutch, Michael Driscoll, Paul-E. Gray, John Holdren, Paul-L. Joskow, Richard-K. Lester, Ernerst J. Moniz, Neil Todreas, Eric-C Beckjord, Nathan Hottle, Christopher Jones, and Etienne Parent. "Future of Nuclear Power." Technical report, MIT, 2003.

AXPO. "Stromperspektiven 2020." Technical report, AXPO, 2005. `http://www.axpo.ch/`.

Ayres, Matt, Morgan MacRae, and Melanie Stogran. "Levelized Unit Electricity Cost Comparison of Alternate Technologies for Baseload Generation in Ontario." Technical report, Canadian Energy Research Institute (CERI), 2004.

Barreto, Leonardo, and Socrates Kypreos. "Endogenizing R&D and market experience in the bottom-up energy-systems ERIS model." *Technovation* 24: (2004) 615–629.

BFE. "Energy perspectives for 2035." Technical report, Swiss Federal Office of Energy (BFE), 2007.

———. "Grundlagen für die EnergieStrategie des Bundestates: Actualisierung der Energieperspektiven 2035 (energiewirtschaftliche Modelle)." Technical report, Swiss Federal Office of Energy (BFE), 2011.

BFS. "Szenarien zur Bevölkerungsentwicklung der Schweiz 2010-2060." Technical report, Swiss Federal Office of Statistics (BFS), 2010. `http://www.bfs.admin.ch/`.

Bosetti, Valentina, Carlo Carraro, Marzio Galeotti, and Emanuele Massetti. "WITCH. A World Induced Technical Change Hybrid Model." *The Energy Journal, Special Issue on Hybrid Modeling of Energy-Environment Policies* 13–38.

Bosetti, Valentina, Carlo Carraro, Emanuele Massetti, and Massimo Tavoni. "International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization." *Energy Economics* 30: (2008) 2912–2929.

Boulouchos, Konstantinos, Göran Andersson, and Lucas Bretschger. "Energiezukunft Schweiz." Technical report, ETh Zürich, 2011.

Bowman, A.F., T. Kram, and K. Klein-Goldewijk. “Integrated modelling of global environmental change. An overview of IMAGE 2.4.” Technical report, Netherlands Environmental Assessment Agency, 2006.

Bretschger, Lucas, and Christa Brunnschweiler. “The Swiss Approach to Sustainability: Challenges for environmental, energy, land use, and transport policies.” Technical report, Swiss Federal Institute of Technology Zürich (ETHZ), 2010.

Cascade Mints. “Case Study Comparisons and development of energy models for integrated technology systems.” Technical report, ICCS-NTUA (Greece), ECN (The Netherlands), LEPII-EPE (France), IIASA (Austria), JRC-EU (Belgium), PSI (Switzerland), ZEW (Germany), DLR (Germany), IER (Germany), CRSA-ERASME (France), 2003.

CDIAC (Carbon Dioxide Information Analysis Center). “Per capita CO2 emissions.” http://cdiac.ornl.gov/, 2012.

Chakravorty, Ujjayant, Bertrand Magne, and Michel Moreaux. “Can Nuclear Power Supply Clean Energy in the Long Run? A Model with Endogenous Substitution of Resources.” Technical report, University of Alberta, Department of Economics, 2009.

Clarke, Leon, John Weyant, and Jae Edmonds. “On the sources of technological change: What do the models assume?” *Energy Economics* 30: (2008) 409–424.

Deutch, John, Charles-W. Forsberg, Andrew Kadak, Mujid-S. Kazimi, Ernerst J. Moniz, John-E. Parsons, Du Yangbo, and Lara Pierpoint. “Update of the MIT 2003 Future Cost of Nuclear Power.” Technical report, MIT, Cambridge, United States, 2009.

EFD. “Long-term sustainability of public finances in Switzerland.” Technical report, Federal Department of Finance (EFD), 2008. `http://www.efd.admin.ch/dokumentation`.

EIA. “Assumptions to the Annual Energy Outlook 2001.” U.S. Energy Information Administration, 2001.

———. “Assumptions to the Annual Energy Outlook 2002.” U.S. Energy Information Administration, 2002.

———. “Assumptions to the Annual Energy Outlook 2003.” U.S. Energy Information Administration, 2003.

———. “Assumptions to the Annual Energy Outlook 2004.” U.S. Energy Information Administration, 2004.

———. “Assumptions to the Annual Energy Outlook 2005.” U.S. Energy Information Administration, 2005.

———. “Annual Energy Outlook 2006.” U.S. Energy Information Administration, 2006a.

———. “Assumptions to the Annual Energy Outlook 2006.” U.S. Energy Information Administration, 2006b.

———. "Assumptions to the Annual Energy Outlook 2007." U.S. Energy Information Administration, 2007.

———. "Assumptions to the Annual Energy Outlook 2008." U.S. Energy Information Administration, 2008.

———. "Assumptions to the Annual Energy Outlook 2009." U.S. Energy Information Administration, 2009.

———. "Assumptions to the Annual Energy Outlook 2010." U.S. Energy Information Administration, 2010.

———. "Assumptions to the Annual Energy Outlook 2011." U.S. Energy Information Administration, 2011.

Energie Trialog Schweiz. "Energie Strategie 2050: Impulse für die schweizerische Energiepolitik." Technical report, Energie Trialog Schweiz, 2009.

EPIA. "2011 Market report." Technical report, European Photovoltaic Industry Association - EPIA, 2011.

EPRI. "Program on Technology Innovation: Integrated Generation Technology Options." Technical report, Electrical Power Research Institute (EPRI), 2008.

European Comission. "Energy futures: The role of research and technological development." Technical report, 2006.

———. "Limiting Global Climate Change to 2 degrees Celsius: The way ahead for 2020 and beyond." Communication from the Commission to the Council, the European Parliament, the European Economic and Social Commitee of the Regions, 2007.

———. "Energy Sources, Production Costs and Performance of Technologies for Power Generation, Heating and Transport." Technical report, European Comission, 2008.

European Commission, Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL). "Emission Database for Global Atmospheric Research (EDGAR), release version 4.0.", 2009. `http://edgar.jrc.ec.europa.eu`.

European Environment Agency. "Tracking progress towards Kyoto and 2020 targets in Europe." Technical report, European Environment Agency, 2010.

Fahey, David, and Michaela Hegglin. "Twenty Questions and Answers About the Ozone Layer: 2010 Update." Technical report, World Meteorological Organization, 2011.

Felder, R. *Well-to-wheel analysis of renewable transport fuels: synthetic natural gas from wood gasification and hydrogen from concentrated solar power.* Ph.D. thesis, ETH Zürich, 2007.

Gapminder. http://www.gapminder.org/data/, 2012.

German Federal Institute for Geosciences and Natural Resources (BGR). "Reserves, Resources and Availability of Energy Resources." Technical report, 2008.

———. “Energy resources 2009.” Technical report, BGR, 2009.

Gielen, Dolf, and Fridtjof Unander. “Alternative Fuels: An Energy Technology Perspective.” Technical report, International Energy Agency, 2005.

Gül, Timur. *An energy-economic scenario analysis of alternative fuels for transport*. Ph.D. thesis, ETH Zurich, 2008.

Glasstone, Samuel, and Alexander Sesonske. *Nuclear Reactor Engineering*. Chaphnan and Hall, 1994.

Graymorea, Michelle, Neil Sipeb, and Roy Ricksonb. “Regional sustainability: How useful are current tools of sustainability assessment at the regional scale?” *Ecological Economics* 67: (2008) 362–372.

H2A. “H2A spreadsheet models. Unpublished data from the H2A Project at the U.S. Department of Energy’s Hydrogen Program and the National Renewable Energy Laboratory.”, 2006.

Hamelinck, Carlo, and André Faaij. “Outlook for advanced biofuels.” *Energy Policy* 34: (2006) 3268–3283.

Hawkins, Sam, and David Joffe. “Technological Characterisation of Hydrogen Production Technologies.” UKSHEC Social Science Working Paper No. 25, 2005.

Hendriks, Chris, Wina Graus, and Frank van Bergen. “Global Carbon Dioxide Storage Potential and Costs.” Technical report, Ecofys, 2004.

Hirschberg, Stefan, Christian Bauer, Peter Burgherr, Serge Biollaz, Wilhelm Durisch, Konstantin Foskolos, Peter Hardegger, Anton Meier, Warren Schenler, Thorsten Schulz, Samuel Stucki, and Frédéric Vogel. “Neue erneuerbare Energien und neue Nuklearanlagen: Potenziale und Kosten.” Technical report, Paul Scherrer Institute, 2005. `http://gabe.web.psi.ch/pdfs/PSI_Report/PSI-Bericht_05-04sc.pdf`.

Hirschberg, Stefan, Christian Bauer, Warren Schenler, and Peter Burgherr. “Sustainable Electricity: Wishful thinking or near-term reality?” In *Energie-Spiegel*, Paul Scherrer Institute, 2010.

Holditch, S. A., W. B. Ayers, J. A. Bickley, T.A. Blasingame, M. Hoefner, V. A. Jochen, Lee W. J., D. A. McVay, K. F. Peryy, M. M. Sharma, and C. Torres-Verdin. “Unconventional Gas.” Technical report, National Petroleum Council, 2007. `http://www.npc.org/Study_Topic_Papers/29-TTG-Unconventional-Gas.pdf`.

Hope, Chris. “The Marginal Impact of CO2 from PAGE2002. An Integrated Assessment Model Incorporating the IPCC’s Five Reasons for Concern.” *The Integrated Assessment Journal* 6: (2006) 19–56.

House of Lords. “The Economics of Renewable Energy.” Technical report, 2008.

IAEA. “Analysis of Uranium Supply to 2050.” Technical report, International Atomic Energy Agency, 2001.

———. “Climate Change and Nuclear Power.” Technical report, International Atomic Energy Agency, 2011.

IEA. “Energy Balances of NON-OECD Countries 1999-2000.” International Energy Agency, 2002.

———. “Energy Balances of OECD Countries 2000-2001.” International Energy Agency, 2003.

———. “Prospects for CO_2 Capture and Storage.” International Energy Agency, 2004.

———. “Projected Costs of Generating Electricity.” International Energy Agency, 2005a.

———. “Prospects of hydrogen and fuel cells.” International Energy Agency, 2005b.

———. “Energy Balances of NON-OECD Countries 2004-2005.” International Energy Agency, 2007a.

———. “Energy Balances of OECD Countries 2004-2005.” International Energy Agency, 2007b, 2009-19.

———. “Switzerland 2007 Review.” In *Energy Policies of IEA Countries*, International Energy Agency, 2007c.

———. “CO_2 Capture and Storage: A key carbon abatement option.” International Energy Agency, 2008a.

———. “World Energy Outlook 2008.” International Energy Agency, 2008b.

———. “IEA Indicators.”, 2009. `http://www.iea.org/Textbase/stats/index.asp`.

———. “Energy Balances of OECD Countries 2007-2008.” International Energy Agency, 2010a.

———. “Energy Statistics OECD Countries.” International Energy Agency, 2010b, 2009-19. `http://econpapers.repec.org/RePEc:ris:albaec:2009_019`.

———. “Energy Technology perspectives 2010: Scenarios and Strategies to 2050.” In *Energy Technology perspectives*, International Energy Agency, 2010c.

———. “Nuclear Energy.” In *Technology Roadmap*, International Energy Agency, 2010d.

———. “Natural Gas Information.” In *IEA Statistics*, International Energy Agency, 2011a.

———. “Solar Energy Perspectives.” In *Renewable energy technologies*, International Energy Agency, 2011b.

———. “Special report World Energy Outlook 2011: Are we entering a golden age of gas?” International Energy Agency, 2011c.

IEA and NEA. “Projected Costs of Generating Electricity.” International Energy Agency and Nuclear Energy Agency, 2010.

IIASA. “Greenhouse Gas Initiative (GGI) Scenario Database. Version 2.0.”, 2009. `http://www.iiasa.ac.at/Research/GGI/DB`.

IIASA and WEC. “Global Energy Perspectives to 2050 and Beyond.” Technical report, International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), 1995.

Intergovernmental Panel in Climate Change (IPCC). "An introduction to simple climate models used in the IPCC second assessment report.", 1997.

———. *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report.* Cambridge University Press, 2001a.

———. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report.* Cambridge University Press, 2001b.

———. *IPCC Special Report on Carbon Dioxide Capture and Storage.* Cambridge University Press, 2005.

———. *Guidelines for National Greenhouse Gas Inventories.* 2006.

———. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report.* Cambridge University Press, 2007a.

———. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report.* Cambridge University Press, 2007b.

———. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Cambridge University Press, 2012.

International Monetary Fund. "World Economic Outlook Database. Crisis and Recovery.", 2009. `http://www.imf.org/external/pubs/ft/weo/2009/01/weodata/index.aspx`.

International Panel on Fissile Materials. "Spent fuel from Nuclear Power." Technical report, International Panel on Fissile Materials, 2011.

Jochem, Eberhard, Daniel Favrat, Konrad Hungerbühler, Phipp von Rohr, Daniel Spreng, Alexander Wokaun, and Mark Zimmermann. "Steps towards a 2000-Watt Society." Technical report, ETH Bereich: PSI, WSL, EMPA and EAWAG, 2002.

Junginger, Martin, Wilfried van Sark, and André Faaij, editors. *Technological learning in the energy sector: Lessons for policy, industry and science.* Edward Elgar, 2010.

Knutti, Reto, and Gabriele Hegerl. "The equilibrium sensitivity of the Earth's temperature to radiation changes." *Nature geoscience* 1, doi:10.1038/ngeo337: (2008) 735–743.

Kypreos, Socrates. "The MERGE Model with Endogenous Technological Change and the Climate Change." In *Economic Modelling of Environmental Policy and Endogenous Technological Change Workshop*. 2000.

———. "Modeling experience curves in MERGE (Model for Evaluating Regional and Global Effects)." *Energy* 30: (2005) 2721–2737.

———. "A MERGE model with endogenous technological change and the cost of carbon stabilization." *Energy Policy* 35: (2007) 5327–5336.

———. "Stabilizing global temperature change below thresholds: Montecarlo analyses with MERGE." *Computational Management Science* 5: (2008) 141–170.

Kypreos, Socrates, and Olivier Bahn. "A MERGE model with endogenous technological progress." *Environmental Modeling and Assessment* 8: (2003) 249–259.

Laufer, Fred, Stephan Grötzinger, Marco Peter, and Alain Schmutz. "Ausbaupotential der Wasserkraft." Technical report, Bundesamt für Energie (BFE), 2004. `http://www.bfe.admin.ch/`.

Lutz, Wolfang, Warren Sanderson, and Sergei Scherbov. "The coming acceleration of global population ageing." *Nature* 452: (2008) 716–719.

Magne, Bertrand, Socrates Kypreos, and Hal Turton. "Technology options for low stabilization pathways with MERGE." *The Energy Journal. Special Issue 1* 31: (2010) 83–108.

Maier-Reimer, Ernst, and Klaus Hasselman. "Transport and storage of CO_2 in the ocean." *Climate Dynamics* 2: (1987) 63–90.

Manne, Alan. "Global 2100: An almost consistent model of CO2 emission limits." *Swiss Journal of Economics and Statistics* 127: (1991) 181–197.

———. "The rate of time preference." *Energy Pol* 23: (1995) 391–394.

Manne, Alan, and Leonardo Barreto. "Learn-by-doing and carbon dioxide abatement." *Energy Economics* 26: (2004) 621–633.

Manne, Alan, Robert Mendelsohn, and Richard Richels. "MERGE: A model for evaluating regional and global effects of GHG reduction policies." *Energy Policy* 23: (1995) 17–34.

Manne, Alan, and Richard Richels. "MERGE: An Integrated Assessment Model for Climate Change." Technical report, Stanford University and EPRI, 2004.

Marcucci, Adriana, and Hal Turton. "Swiss energy strategies under global climate change and nuclear policy uncertainty." *Swiss Journal of Economics and Statistics* 148(2): (2012) 317–345.

Meinshausen, Malte, Nicolai Meinshausen, William Hare, Sarah C. B. Raper, Katja Frieler, Reto Knutti, David J. Frame, and Myles R. Allen. "Greenhouse-gas emission targets for limiting global warming to 2 degree C." *Nature* 458: (2009) 514–517.

Mueller-Langer, F., E. Tzimas, M. Kaltschmitt, and S. Peteves. "Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term." *Hydrogen energy* 32: (2007) 3797–3810.

Nakicenovic. "Special Report on Emissions Scenarios." Technical report, Intergovernamental Panel on Climate Change (IPCC), 2000.

Nakicenovic, Nejobsa, Peter Kolp, Keywan Riahi, Mikiko Kainuma, and Tatsuya Hanaoka. "Assessment of emissions scenarios revised." *Environmental Economics and Policy Studies* 7: (2006) 137–173.

Nordhaus, William. *Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not. In The Economics of New Goods, pp 26-69.* The University of Chicago Press, Chicago., 1991.

———. "Roll the DICE again: the economics of global warming." Technical report, Yale University, 1999.

———. *A Question of Balance Weighing the Options on Global Warming Policies.* Yale University Press, 2008.

NRC. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* The National Academy Press, US National Research Council and National Academy of Engineering of the National Academies, 2004.

Nuclear Energy Agency. *Forty Years of Uranium Resources, Production and Demand in Perspective.* 2006a.

———. "Nuclear production of Hydrogen: Third Information Exchange Meeting." Technical report, Nuclear Energy Agency, 2006b.

Nuclear Energy Agency and the International Atomic Energy Agency. "Uranium 2007: Resources, Production and Demand." Nuclear Energy Agency and the International Atomic Energy Agency, 2008.

———. "Uranium 2009: Resources, Production and Demand." Nuclear Energy Agency and the International Atomic Energy Agency, 2010.

OcCC. "OcCC-Empfehlungen zur Schweizerischen Klimapolitik Post 2012." Technical report, The Advisory Body on Climate Change (OcCC), 2007. `http://proclimweb.scnat.ch/portal/ressources/33536.pdf`.

Oettli, Bernhard, Martina Blum, Martin Peter, and Othmar Schwank. "Potentiale zur energetischen Nutzung von Biomasse in der Schweiz." Technical report, Bundesamt für Energie (BFE), 2004. `http://www.bfe.admin.ch/`.

Parada, Marcelo, Adriana Marcucci, and Hal Turton. "A detailed model for the nuclear fuel cycle for integrated assessment analysis." Technical report, Paul Scherrer Institute, 2011.

People's Republic of China. "National Report for Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management." Technical report, 2008.

Perman, Roger, Yue Ma, James McGilvray, and Michael Common. *Natual Resource and Environmental Economics.* Pearson, 2003.

Piot, Michael. "Exkurs: Elektrizität aus Wasserkraft." Technical report, Bundesamt für Energie (BFE), 2006. `http://www.bfe.admin.ch/`.

Plattner, G.-K., R. Knutti, F. Joos, T.F. Stocker, W. von Bloh, V. Brovkin, D. Cameron, E. Driesschaert, S. Dutkiewicz, M. Eby, T. Edwards, N.R. amd Fichefet, J.C. Hargreaves, C.D. Jones, M.F. Loutre, H.D. Matthews, A. Mouchet, S.A. Müller, S. Nawrath, A. Price, A. Sokolov, K.M. Strassmann, and A.J. Weaver. "Long-Term Climate Commitments Projected with Climate - Carbon Cycle Models." *Journal of Climate* 21: (2008) 2721–2751.

Pregger, Thomas, Daniela Graf, Wolfram Krewitt, Christian Sattler, Martin Roeb, and Stephan Möller. "Prospects of solar thermal hydrogen production processes." *International Journal of Hydrogen Energy* 34: (2009) 4256–4267.

PriceWaterHouseCoopers. "100% renewable electricity. A roadmap to 2050 for Europe and North Africa." Technical report, PriceWaterHouseCoopers, 2010.

RAE. "The Cost of Generating Electricity." Technical report, Royal Academy of Engineering, 2004.

Ragettli, Martin. *Cost outlook for the production of biofuels: A cost comparison assessment of the future production of biofuels.* Master's thesis, Paul Scherrer Institute, ETH-Zürich, 2007.

Ramachandran, Kannan. "Documentation of the development Swiss TIMES electricity model." Technical report, Paul Scherrer Institute, 2011.

Ramachandran, Kannan, and Hal Turton. "Documentation on the Development of the Swiss TIMES Electricity Model (STEM-E)." Technical report, Paul Scherrer Institute, 2011.

Reichling, J.P, and F.A. Kulacki. "Comparative analysis of FischereTropsch and integrated gasification combined cycle biomass utilization." *Energy* 36: (2011) 6529–6535.

Reiter, Ulrich. *Assessment of the European Energy Conversion Sector Under Climate Change Scenarios.* Ph.D. thesis, ETH Zurich, 2010.

Rhodes, James S., and David W. Keith. "Engineering economic analysis of biomass IGCC with carbon capture and storage." *Biomass and Bioenergy* 29: (2005) 440–450.

Riahi, Keywan, Arnulf Grübler, and Nebojsa Nakicenovic. "Scenarios of long-term socio-economic and environmental development under climate stabilization." *Technological Forecasting and Social Change* 74: (2007) 887–935.

SATW. "Road Map Renewable Energies Switzerland: An Analysis with a view to harnessing existing potentials by 2050." Technical report, Swiss Academy of Engineering Science (SATW), 2007.

Schulz, Thorsten. *Intermediate steps towards the 2000-watt society in Switzerland: An energy economics scenario analysis.* Ph.D. thesis, ETH Zurich, 2007.

Seebregts, A., Bos S., Kram T., and G. Schaeffer. "Endogenous Learning and Technology Clustering: Analysis with MARKAL Model of the Western European Energy System." *International Journal of Energy Issues* 14: (2000) 289–319.

Shropshire, D. E., K. A. Williams, W. B. Boore, J. D. Smith, B. W. Dixon, M. Dunzik-Gougar, R. D. Adams, and D. Gombert. "Advanced Fuel Cycle Cost Basis." Technical report, Idaho National Laboratory, 2007.

Sims, Ralph, Rogner Hans-Holger, and Ken Gregory. "Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation." *Energy Policy* 31: (2003) 1315–1326.

Solomon, Susan, John S. Daniel, Todd J Sanford, Daniel M. Murphy, Gian-Kasper Plattner, Reto Knutti, and Pierre Friedlingstein. "Persistence of climate changes due to a range of greenhouse gases." *Proceedings of the National Academy of Sciences of the United Stated of America* 107: (2010) 18,354–18,359.

Stanton, Elizabeth. "Negishi welfare weights in integrated assessment models: the mathematics of global inequality." *Climatic Change* 107: (2011) 417–432.

Stern, Nicolas. *The Stern Review: The Economics of Climate Change.* HM Treasury, 2006.

Swiss Department of Environment, Transport, Energy and Communications. "Implementation of the Obligations of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management: Second National Report of Switzerland in Accordance with Article 32 of the Convention." Technical report, 2005.

Swiss Federal Council. "Federal Council decides to gradually phase out nuclear energy as part of its new energy strategy." Press release on 25.5.2011, 2011. `http://www.uvek.admin.ch/dokumentation/00474/00492/index.html?lang=en&msg-id=39337`.

Swiss Federal Office for the Environment - BAFU. "Residual Flows.", 2010. `http://www.bafu.admin.ch/gewaesserschutz/01284/index.html?lang=en`.

Swiss Federal Office of Energy (BFE). "Reale Entwicklung der Benzin- und Heizölpreise (in Franken von 2011).", 2012. `http://www.bfe.admin.ch/themen/00486/00487/index.html?lang=de\&dossier_id=00743`.

Swiss Federal Office of Environment (BAFU). "CO2-Abgabe auf Brennstoffen wird 2010 erhöht." Press release on 19.6.2009, 2009. `http://www.bafu.admin.ch/dokumentation/medieninformation/00962/index.html?lang=de&msg-id=27541`.

———. "Anhörung zur CO2-Verordnung eröffnet." Press release on 11.5.2012, 2012a. `http://www.bafu.admin.ch/dokumentation/medieninformation/00962/index.html?lang=de&msg-id=44510`.

———. "Switzerland: Greenhouse Gas Inventory 1990 to 2010." Technical report, BAFU, 2012b.

Swiss Federal Statistical Office - BFS. "Annual Population Statistics (ESPOP).", 2010a. `http://www.bfs.admin.ch/`.

———. "Gross domestic product: production approach.", 2010b. `http://www.bfs.admin.ch/`.

Tol, Richard S.J. "Multi-Gas Emission Reduction for Climate Change Policy: An Application of Fund." *The Energy Journal* 3: (2006) 235–250.

UK Department of Trade and Industry. "The Energy Challenge Energy Review Report." Technical report, 2006.

United Nations. "Key Global Indicators database.", 2012. `http://data.un.org/`.

United Nations Climate Change Conference. "Copenhagen Accord.", 2009.

United Nations Framework Convention on Climate Change. "Kyoto Protocol.", 1998.

United Nations. Population Division. "World Population Prospects: The 2008 Revision.", 2009. `http://esa.un.org/unpp/index.asp?panel=5`.

———. "World Population Prospects: The 2010 Revision.", 2011. `http://esa.un.org/wpp/Excel-Data/population.htm`.

University of Chicago. "The economic future of nuclear power." Technical report, University of Chicago, 2004.

US Congressional Budget Office. "Nuclear Power's Role in Generating Electricity." Technical report, Congress of the United States, 2008.

UVEK. "Aktionsplan Energieeffizienz: Best-practice-Strategie." Technical report, Department of Environment, Transport, Energy and Communications (UVEK), 2008a. `http://www.bfe.admin.ch/themen/00526/02577/index.html?lang=en&dossier_id=02578`.

———. "Aktionsplan Erneuerbare Energien." Technical report, Department of Environment, Transport, Energy and Communications (UVEK), 2008b. `http://www.bfe.admin.ch/themen/00526/02577/index.html?lang=en&dossier_id=02579`.

van Vuuren, Detlef, Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Alison Thomson, Kathy Hibbard, George Hurtt, Tom Kram, Volker Krey, Jean-Francois Lamarque, Toshihiko Masui, Malte Meinshausen, Nebojsa Nakicenovic, Steven Smith, and Steven Rose. "The representative concentration pathways: an overview." *Climatic Change* 109: (2011a) 5–31.

van Vuuren, Detlef, Jason Lowe, Elke Stehfest, Laila Gohar, Andries Hof, Chris Hope, Rachel Warren, Malte Meinshausen, and Gian-Kasper Plattner. "How well do integrated assessment models simulate climate change?" *Climatic Change* 104: (2011b) 255–285.

van Vuuren, Detlef, Isaac Morna, Zbiginiew Kundzewicz, Nigel Arnell, Terry Barker, Patrick Criqui, Frans Berkhout, Henk Hilderink, Jochen Hinkel, Andries Hof, Alban Kitous, Tom Kram, Reinhard Mechler, and Serban Scrieciu. "The use of scenarios as the basis for combined assessment of climate change mitigation and adaptation." *Global Environmental Change* 21: (2011c) 575–591.

Weidmann, Nicolas, Kannan Ramachandran, and Hal Turton. "Swiss climate change and nuclear policy: a comparative analysis using an energy system approach and a sectoral electricity model." *Swiss Journal of Economics and Statistics* 148(2): (2012) 275–316.

Weidmann, Nicolas, Hal Turton, and Alexander Wokaun. "Case Studies of the Swiss Energy System: Sensitivity to Scenario Assumptions Assessed with the Swiss MARKAL Model." Technical report, Paul Scherrer Institute, 2009. `http://www.energietrialog.ch/cm_data/Weidmann_MARKAL_2009.pdf`.

Wietschel, Martin, Ulrike Hasenauer, and Arend de Groot. "Development of European hydrogen infrastructure scenarios - CO2 reduction potential and infrastructure investment." *Enery Policy* 34: (2006) 1284–1298.

Wigley, Tom. “MAGICC: Model for the Assessment of Greenhouse-gas Induced Climate Change.”, . `http://www.cgd.ucar.edu/cas/wigley/magicc/about.html`.

World Bank. “World development indicators.” http://data.worldbank.org/, 2012.

World Comission on Environment and Development (WCED). “Our common future (Bruntland Report).” Technical report, United Nations, 1987.

World Energy Council. “2001 Survey of Energy Resources.”, 2001.

———. “2007 Survey of Energy Resources.”, 2007.

Yamashita, Kei, and Leonardo Barreto. “Integrated Energy Systems for the 21st Century: Coal Gasification for co-producing Hydrogen, Electricity and liquid fuels.” Technical report, IIASA, 2003.

———. “Energyplexes for the 21st century: Coal gasification for co-producing hydrogen, electricity and liquid fuels.” *Energy* 30: (2005) 2453–2473.

Appendices

Appendix A

Economic submodel

A.1 Reference scenario

The reference scenario comprises an important set of assumptions for the parametrization of MERGE and, therefore, the development of the future energy system. This appendix shows the assumptions and calculation of this reference scenario. It is calculated using as an input a scenario of potential (or reference) GDP and autonomous energy efficiency improvements (AEEI). The potential GDP pathway can be interpreted as representing economic output at constant energy prices. The AEEI measures changes in energy consumption not driven by prices, e.g. increase in the efficiency of electrical appliances, or changes to either more or less energy intensive types of industry, etc. (Manne et al., 1995)[1]. From this potential (or reference) GDP scenario and AEEIs the following can be calculated:

- A reference energy demand: This is the energy demand implied by the scenario of potential GDP growth (g) and the non-price AEEIs, in a hypothetical case with constant prices. It can be calculated as follows:

$$
\begin{aligned}
E_{ref,t+1} &= E_{ref,t}\left(1+g_t\right)\left(1-EAEEI_t\right)\\
N_{ref,t+1} &= N_{ref,t}\left(1+g_t\right)\left(1-NAEEI_t\right),
\end{aligned}
$$

  where $E_{ref,t}$ and $N_{ref,t}$ correspond to the electricity and non-electric reference demand in the period t; and *EAEEI* and *NAEEI* are the assumed autonomous energy efficiencies for the electricity demand and the non-electric energy carrier consumption, respectively.

- Reference prices: The reference scenario is estimated by solving the production problem in each region, that is,

$$
\max Y_t - \left(pk_t K_t + pl_t L_t + pe_t E_t + pn_t N_t\right),
$$

  where $Y_t = \left[a\left(K_t^{\alpha} L_t^{1-\alpha}\right)^{\gamma} + b\left(E_t^{\beta} N_t^{1-\beta}\right)^{\gamma}\right]^{1/\gamma}$ (see Equation 3.2); and pk_t, pl_t, pe_t and pn_t are the prices of capital, labor, electricity and non-electric energy in the period t. The relationship be-

[1] Note, although MERGE is a multiregional model, for simplicity equations below are presented without a region index.

tween the price of electricity and non-electric energy is obtained from the first-order optimality conditions, thus,

$$\begin{aligned} pe_t &= b\beta \cdot Y_t^{1-\gamma} \cdot E_t^{\beta\gamma-1} N_t^{(1-\beta)\gamma} \\ pn_t &= b(1-\beta) \cdot Y_t^{1-\gamma} \cdot E_t^{\beta\gamma} N_t^{(1-\beta)\gamma-1}. \end{aligned} \tag{A.1}$$

Therefore, for the reference case,

$$pe_{ref,t} = \frac{\beta \cdot pn_{ref,t} \cdot N_{ref,t}}{(1-\beta) \cdot E_{ref,t}}.$$

- Reference gross output: The gross output corresponds to the net output (GDP) plus the intermediate consumption, thus, the gross output in the reference scenario ($Y_{ref,t}$) is estimated as,

$$Y_{ref,t} = \text{GDP}_{pot,t} + pe_{ref,t} \cdot E_{ref,t} + pn_{ref,t} \cdot N_{ref,t}.$$

- Reference labour ($L_{ref,t}$): The reference labour is measured in "efficiency units" (Manne, 1991); it is assumed to be 1 in the base year and to grow with the growth rate of the potential GDP.

- Reference capital: The reference capital ($K_{ref,t}$) corresponds to:

$$K_{ref,t} = kgdp \cdot \text{GDP}_{pot,t},$$

where *kgdp* is the capital-GDP ratio assumed exogenously (based on (Manne et al., 1995)) .

- Productivity factors. Using Equations 3.2 and A.1, and the previously presented reference case, the parameters a_t and b_t are calibrated, thus,

$$b_t = \frac{pn_{ref,t} \cdot Y_{ref,t}^{\gamma-1}}{(1-\beta) \cdot E_{ref,t}^{\beta\gamma} N_{ref,t}^{(1-\beta)\gamma-1}} \quad \text{and} \quad a_t = \frac{Y_{ref,t}^{\gamma} - b_t \left(E_{ref,t}^{\beta} N_{ref,t}^{1-\beta}\right)^{\gamma}}{\left(K_{ref,t}^{\alpha} L_{ref,t}^{1-\alpha}\right)^{\gamma}}$$

A.2 Discount rate

Following Manne (1995), let's assume we have a single agent economy that acts as consumer, producer, investor and saver. Without depreciation, the capital formation for this economy is given by,

$$K_{t+1} = K_t + I_t \tag{A.2}$$

where K_t and I_t are, respectively, capital and investments in period t. Additionally, from equation 3.1, we know that the economy output (Y_t) can be allocated between consumption (C_t), investment and energy costs (EC_t), thus,

$$Y_t = I_t + C_t + EC_t. \tag{A.3}$$

Therefore, the social planner aims to maximize the discounted utility subject to Equations A.2 and A.3, thus,

$$\begin{aligned}
&\max \sum_{t=1}^{T} \frac{1}{(1+\rho)^t} \log(C_t) \\
&\text{s.t. } K_{t+1} = K_t + I_t \\
&\qquad Y_t = I_t + C_t + EC_t.
\end{aligned}$$

The restrictions of this problem can be combined into one, thus,

$$\begin{aligned}
&\max \sum_{t=1}^{T} \frac{1}{(1+\rho)^t} \log(C_t) \\
&\text{s.t. } Y_t = K_{t+1} - K_t + C_t + EC_t.
\end{aligned} \tag{A.4}$$

The Lagrangian for this optimization problem corresponds to:

$$\mathscr{L} = \sum_{t=1}^{T} \frac{1}{(1+\rho)^t} \log(C_t) + \sum_{t=1}^{T} \lambda_t (Y_t - K_{t+1} + K_t - C_t - EC_t)$$

The first order optimality conditions for this problem are:

$$\begin{aligned}
\frac{\partial \mathscr{L}}{\partial C_t} &= \frac{1}{(1+\rho)^t} \frac{1}{C_t} - \lambda_t = 0 \\
\frac{\partial \mathscr{L}}{\partial C_{t-1}} &= \frac{1}{(1+\rho)^{t-1}} \frac{1}{C_{t-1}} - \lambda_{t-1} = 0 \\
\frac{\partial \mathscr{L}}{\partial K_t} &= -\lambda_{t-1} + \lambda_t \left(\frac{\partial Y_t}{\partial K_t} + 1 \right)
\end{aligned} \tag{A.5}$$

From the three first order conditions in Equation A.5 we obtain:

$$\begin{aligned}
\frac{\partial Y_t}{\partial K_t} + 1 &= (1+\rho) \frac{C_t}{C_{t-1}} \\
mpc_t + 1 &= (1+\rho_t)(1+g_t)
\end{aligned}$$

where $\frac{\partial Y_t}{\partial K_t} = mpc_t$ is the marginal productivity of capital in period t and corresponds to the discount rate rate of goods and services; and g_t is the growth rate in period t of consumption, which for the optimal path equals the growth rate of output. Using the approximation $(1+\rho)(1+g)^{\epsilon} = 1 + \rho + \epsilon g$, where $\epsilon \in \mathbb{Z}^+$ and equals 1 in this case, we obtain,

$$mpc_t = \rho_t + g_t.$$

The approach used in the calibration of the model is to choose a marginal productivity of consumption exogenously and a scenario of potential GDP (see Appendix A.1). This scenario has a specific growth rate g_t and implies a certain utility discount factor that represents a choice between consumption by current and future generations.

Appendix B

Technology characteristics

Technology characteristics, including investment costs, efficiencies (eff), capacity factor (CF), and fixed and variable operation and maintenance costs (FOM and VOM) have an important effect on the future energy system. An exhaustive literature review was carried out in the development of this PhD thesis to estimate these technology characteristics. The analyzed studies are presented in Table B.1.

TABLE B.1: *Studies included in the technology analysis*

2001-2011	EIA	Annual Energy Outlook 2001-2011 (EIA, 2001, 2002, 2003, 2004, 2005, 2006b, 2007, 2008, 2009, 2010, 2011)
2003	MIT	Future of Nuclear Power (Ansolabehere et al., 2003)
2004	CERI	Levelized unit electricity cost comparison of alternate technologies for baseload generation in Ontario (Ayres et al., 2004)
	RAE	The Cost of Generating Electricity (RAE, 2004)
	UnCh	The economic future of nuclear power (University of Chicago, 2004)
2005	IEA/NEA	2005 Projected costs of generating electricity (IEA, 2005a)
2006	DTI	The Energy Challenge (UK Department of Trade and Industry, 2006)
2007	MIT	Future of Coal (Ansolabehere et al., 2007)
2008	CBO	Nuclear Power's Role in Generating Electricity (US Congressional Budget Office, 2008)
	EC	Energy sources, production costs and performance of technologies for power generation, heating and transport (European Comission, 2008)
	EPRI	Program on Technology Innovation: Integrated Generation Technology Options (EPRI, 2008)
	HL	The Economics of Renewable Energy (House of Lords, 2008)
2009	MIT	Update of the MIT 2003 Future Cost of Nuclear Power (Deutch et al., 2009)
2010	PSI	Sustainable Electricity: Wishful thinking or near-term reality? in Energie-Spiegel 2010 (Hirschberg et al., 2010)
	IEA	Energy technology perspectives (IEA, 2010c)
	IEA/NEA	2010 Projected costs of generating electricity (IEA and NEA, 2010)

B.1 Literature review

This section summarizes the technology characteristics in the different studies presented in Table B.1. All the data concerning costs is presented in US Dollars 2000.

B.1.1 Gas-based technologies

TABLE B.2: *Literature review: Gas-based technologies*

		NGCC					Fuel cell			
		Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]	Cost [$/kW]	Eff	FOM [$/kW]	VOM [$/MWh]
2001	EIA	549		0.49	14.54	0.53	1820	0.59	15.07	2.09
2002	EIA	546		0.50	14.46	0.52	1810	0.59	14.98	2.08
2003	EIA	546		0.49	9.91	1.98	1795	0.45	6.94	19.82
	MIT	458	0.85	0.47	14.66	0.48				
2004	CERI	447	0.90	0.49	9.82	1.96				
	EIA	546		0.49	9.93	1.99	1797	0.46	6.94	19.84
	RAE	484	0.90	0.58						
	UnCh	530		0.55-0.6						
2005	EIA	486		0.51	9.73	1.66	3458	0.43	4.70	39.86
	IEA/NEA	327-925	0.85							
2006	EIA	484		0.51	9.69	1.66	3446	0.43	4.69	39.71
	DTI	686	0.85	0.58						
2007	EIA	484		0.51	9.69	1.65	3443	0.43	4.68	39.68
	EC	516-785 (683)	0.85	0.58						
	EIA	576		0.51	10.01	1.72	4095	0.43	4.84	41.03
	EPRI	664	0.80	0.47						
	HL	868	0.81							
2009	EIA	728		0.51	9.71	1.66	3851	0.43	4.69	39.77
	MIT	706	0.85							
2010	EIA	718		0.51	9.57	1.63	3795	0.43	4.62	39.20
	PSI	661-1028								
	IEA	720		0.57-0.63	21.60					
	IEA/NEA	447-1450 (922)		0.4-0.59						
2011	EIA	734		0.53	11.55	2.46	4677	0.36	276.64	

B.1.2 Coal-based technologies

TABLE B.3: *Literature review: Coal-based technologies*

		PC					IGCC				
		Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]	Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]
2001	EIA	1052		0.36	23.54	3.40	1257		0.43	32.85	0.80
2002	EIA	1046		0.36	23.41	3.38	1250		0.43	32.67	0.80
2003	EIA	1047		0.38	23.78	2.98	1239		0.43	32.71	1.98
	MIT	1191	0.85	0.37	21.08	3.10					
2004	CERI	1006	0.90	0.38	23.57	2.95					

TABLE B.3: *Literature review: Coal-based technologies (continued)*

		PC					IGCC				
		Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]	Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]
	EIA	1047		0.38	23.82	2.98	1240		0.43	32.75	1.99
	RAE	1321	0.9-0.95	0.38			1612	0.9-0.95	0.48		
	UnCh	1068		0.3-0.35			1202		0.4-0.45		
2005	EIA	1066		0.39	22.90	3.82	1231		0.41	32.16	2.43
	IEA/NEA	645-2108	0.85				1228-1740	0.85			
2006	EIA	1062		0.39	22.81	3.80	1228		0.41	32.04	2.41
	DTI	1375-1432	0.90	0.44-0.46			1432-1606	0.90	0.45-0.48		
2007	EIA	1061		0.39	22.80	3.80	1227		0.41	32.01	2.42
	MIT	1106-1174 (1149)		0.39			1235	0.85	0.38		
2008	CBO	1269	0.85								
	EC	1075-1548 (1360)	0.85	0.47			1505-1774 (1666)	0.85	0.45		
	EIA	1262		0.37	23.58	3.92	1458		0.39	33.11	2.50
	EPRI	2034	0.80	0.38			2407	0.80	0.38		
	HL	1776	0.81								
2009	EIA	1596		0.37	22.85	3.81	1845		0.39	32.10	2.42
	MIT	1909	0.85								
2010	EIA	1662		0.37	22.52	3.75	1921		0.39	31.62	2.39
	PSI	1469-1983									
	IEA	1680-1760		0.42-0.46			1920		0.42		
	IEA/NEA	670-2893 (1766)		0.37-0.46							
2011	EIA	2100		0.39	23.45	3.36	2379		0.39	46.82	5.43

B.1.3 Technologies with carbon capture and storage

TABLE B.4: *Literature review: CCS technologies*

		NGCC (CCS)			PC(CCS)			IGCC (CCS)				
		Cost [$/kW]	CF	Eff	Cost [$/kW]	CF	Eff	Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]
2004	EIA	930		0.39				1818.2		0.36	38.85	2.43
2005	EIA	932		0.40				1710.8		0.35	37.84	3.69
2006	EIA	929		0.40				1704.4		0.35	37.71	3.68
	DTI	1089-1292	0.85	0.48	1812-2535	0.90	0.35	2265-2675	0.90	0.39		
2007	EIA	928		0.40				1703.7		0.35	37.68	3.68
	MIT				1805-1926 (1848)	0.85	0.29	1632.1	0.85	0.31		
2008	EC	1075-1397 (1290)		0.49	1827-2902 (2418)		0.35	1827-2580 (2257)		0.35		
	EIA	1104		0.40				2025.8		0.32	38.96	3.80
	EPRI				3403	0.80	0.27	3320.0	0.80	0.31		
2009	EIA	1397		0.40				2632.8		0.32	38.28	3.69
2010	EIA	1376		0.40				2741.6		0.32	37.72	3.63
	PSI	1028-1469			1983-2717							
	IEA	1160		0.49	2720		0.36	2560.0		0.33		
	IEA/NEA				2675-4823 (3350)		0.3-0.39					
2011	EIA	1450		0.45				3837.6		0.32	54.78	7.06

B.1.4 Nuclear technologies

TABLE B.5: *Literature review: Nuclear technologies*

		LWR					FBR		
		Cost [$/kW]	CF	Eff	FOM [$/kW]	VOM [$/MWh]	Cost [$/kW]	FOM [$/kW]	VOM [$/MWh]
2001	EIA	1781		0.33	57.54	0.42			
2002	EIA	1772		0.33	57.23	0.42			
2003	EIA	1698		0.33	56.73	0.42			
	MIT	1833	0.85	0.33	57.73				
2004	CERI	1476-1868	0.90						
	EIA	1602		0.33	56.80	0.41			
	RAE	1853	0.9-0.95		66.09				
	UnCh	1078-1617	0.85						
2005	EIA	1592		0.33	56.46	0.41			
	IEA/NEA	979-2255	0.85						
2006	EIA	1587		0.33	56.26	0.41			
	DTI	2195	0.85	0.36					
2007	EIA	1586		0.33	56.21	0.41			
2008	CBO	1996	0.90						
	EC	2118-3634 (2881)	0.85	0.35					
	EIA	1886		0.33	58.12	0.42			
	EPRI	3303	0.90	0.33					
	HL	2490	0.77						
2009	EIA	2385		0.33	74.72	0.41			
	MIT	3320	0.85						
2010	EIA	2646		0.33	73.63	0.41			
	PSI	2570-3672					1835-5140		
	IEA	2400		0.36					
	IEA/NEA	1291-4866 (3366)	0.85						
2011	EIA						3654	70.15	1.60

B.1.5 Renewable-based technologies

TABLE B.6: *Literature review: Renewable-based technologies*

		Biomass					SPV			Hydropower				Onshore wind		
		Cost [$/kW]	CF	Eff.	FOM [$/kW]	VOM [$/MWh]	Cost [$/kW]	CF	FOM [$/kW]	Cost [$/kW]	CF	FOM [$/kW]	VOM [$/MWh]	Cost [$/kW]	CF	FOM [$/kW]
2001	EIA	1508		0.38	45.20	2.91	3791		10.15							
2002	EIA	1536		0.38	44.95	2.90	3317		9.85							
2003	EIA	1522		0.38	44.56	2.87	3287		9.76					910		25.32
	EIA	1524		0.38	44.61	2.84	3658		9.68					911		25.35
	RAE	2966		0.24												
	UnCh															
2005	EIA	1515		0.38	44.35	2.78	3636		9.72	1240		11.61	4.32	996		25.20
	IEA/NEA	1527-1957	0.85				2872-9132	0.09-0.24		1439-6276	0.50			876-1468	0.17-0.38	
2006	EIA	1510		0.38	44.19	2.85	3623		9.68	1201		11.58	2.91	993		25.11
	DTI													1277	0.33	
2007	EIA	1508		0.38	44.16	2.60	3620		9.67	1200		11.56	2.90	992		25.09
	EC	2172-5461	0.85	0.29			4408-7418	0.11		968-7096	0.5-0.57			1075-1473	0.23	
							(5052)	0.11						(1225)		
	EIA	2191		0.38	55.18	5.75	4734		10.01	1241		11.96	3.00	1179		25.94
	EPRI	2685	0.80	0.28										1656	0.33	
	HL	3049	0.80											1844	0.27	
2009	EIA	2771		0.35	53.49	5.57	4773		9.69	1692		11.31	2.02	1492		25.15
2010	EIA	2731		0.36	52.71	5.49	4703		9.55	1667		11.14	1.99	1470		24.78
	PSI						3672-5875			2937-7343				1322-1836		
	IEA	2000					2800-4480			1600-2400				1160-1760		
	IEA/NEA	3179-6173	0.86				2388-6128	0.1-0.24		628-9626	0.29-0.8			1587-3084	0.2-0.41	
		(4541)					(4161)			(2948)				(1829)		
2011	EIA	2716		0.25	79.44	5.55	3579		20.58	1615		10.84	1.94	1801		22.18

B.2 Reference scenario

Based on the data presented in the previous section, the characteristics for the technologies used in this PhD thesis were estimated. Table B.7 presents the electricity technology characteristics for the reference scenario.

TABLE B.7: *Electricity technology characteristics for the reference scenario*

	Lifetime [a]	Efficiency [%]	Load factor [%]	Investment costs [$/kW]	Fixed OM [$/kW]	Var. OM [cents$/kWh]
NGCC	30	0.51	0.65	725	10	0.18
NGCC(CCS)	30	0.43	0.65	1285	16	0.26
gas-FC	30	0.43	0.65	3650	5	3.99
PC	40	0.37	0.85	1650	23	0.37
PC(CCS)	40	0.32	0.85	2600	57	0.33
IGCC	40	0.40	0.85	1800	35	0.29
IGCC(CCS)	40	0.32	0.85	2600	41	0.44
LWR	50	0.36	0.85	2400	Fuel cycle*	0.42
FBR	60	0.33	0.85	3100	Fuel cycle	0.69
bio	30	0.35	0.83	2300	57	0.50
bio(CCS)	30	0.25	0.83	3000	57	0.50
solar	20	1.00	0.25	4300	9	0.48
hydro	80	1.00	0.50	2400	11	0.25
wind	20	1.00	0.30	1500	20	1.31

* Fixed operation and maintenance cost of the nuclear technologies vary according to the path followed in the nuclear cycle presented in Section 3.2.2.

The characteristics of the non-electric energy technologies are presented in Table B.8. They are based on Gül (2008); Hamelinck and Faaij (2006); Hawkins and Joffe (2005); Magne et al. (2010); Mueller-Langer et al. (2007); Pregger et al. (2009); Reichling and Kulacki (2011); Yamashita and Barreto (2003).

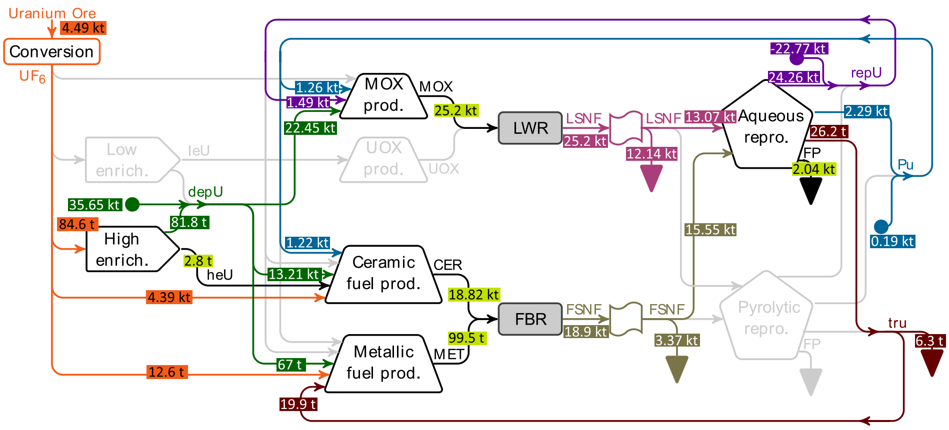
TABLE B.8: *Non-electric technology characteristics for the reference scenario*

	Lifetime [a]	Efficiency [%]	Load factor [%]	Investment costs [$/kW]	Fixed OM [$/kW]	Var. OM [$/GJ]
coal-FT	30	0.53	0.80	1250	80	1.0
bio-FT	30	0.51	0.80	2200	80	1.0
bio-FT(CCS)	30	0.46	0.80	2900	80	1.0
coal-H2	30	0.60	0.80	1200	60	3.0
coal-H2(CCS)	30	0.55	0.80	1400	60	3.0
gas-H2	40	0.75	0.90	800	60	3.0
gas-H2(CCS)	40	0.70	0.90	1000	60	3.0
nuc-H2	30	0.50	0.80	2000	Fuel cycle	2.0
bio-H2	30	0.55	0.80	1600	60	3.0
bio-H2(CCS)	30	0.52	0.80	1800	60	3.0
ele-H2	30	0.70	0.80	900	60	2.0
sth-H2	20	1.00	0.30	4300	0	3.0

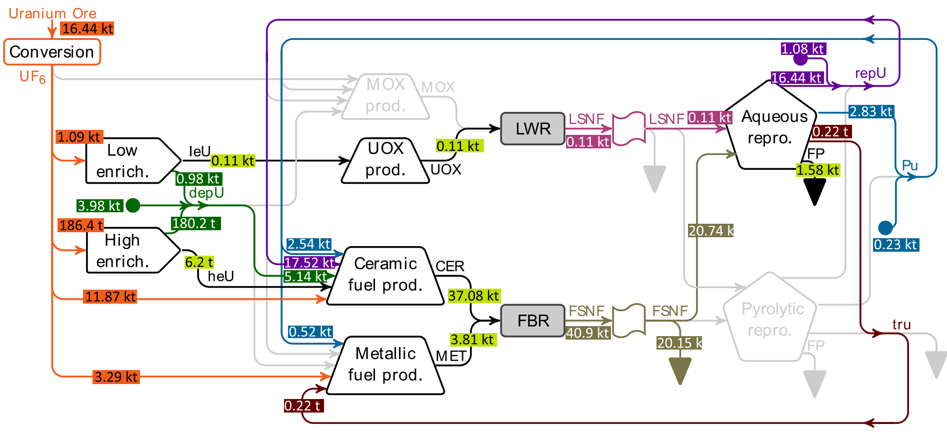
Appendix C

Enhanced nuclear fuel cycle

C.1 Global fuel flows in the reference climate scenario with full nuclear support



(A) *2070*



(B) *2100*

FIGURE C.1: *Enhanced nuclear cycle: Fuel flows in rf35NC scenario*

Units

Prefixes	
kilo (k)	10^3
mega (M)	10^6
giga (G)	10^9
tera (T)	10^{12}
peta (P)	10^{15}
exa (E)	10^{18}
zetta (Z)	10^{21}
Energy units	
Electricity production	PWh, TWh
Non-electric energy production	EJ, PJ
Content energy carriers	
Oil	1 barrel crude oil = 5.75 GJ
Natural gas	1 TCM natural gas = 37.93 EJ
Hard Coal	1 Gt= 24.67 EJ
Lignite	1 Gt= 11.95 EJ
Uranium	1 kg uranium = 500 GJ
Greenhouse gases	
Concentration	ppm, ppb
Emissions	$GtCO_2$
Economic units	
Currency	US Dollars 2000