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Analyzing Energy Technology Options for Switzerland in the Face of Global Uncertainties- An Overview of the MERGE Model

By
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Analyzing Energy Technology Options for Switzerland in the Face of Global Uncertainties:

An Overview of the MERGE Model

Report to NCCR Climate, Phase 3 (2009-2013)
Climate Variability, Predictability and Climate Risks
P4.2 Climate vulnerability, risk assessment and management in a Post-Kyoto World
Task 4: Mitigation and sustainable energy strategies under global uncertainty.

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Preface

This report describes development of the MERGE model and some preliminary analyses for the first 18 months of Task 4 (Mitigation and sustainable energy strategies under global uncertainty) of P4.2 (Climate vulnerability, risk assessment and management in a Post-Kyoto World) in WP4 of Phase 3 of the Swiss National Centre for Competence in Research on Climate (NCCR Climate). The support of NCCR Climate and the Swiss National Science Foundation (SNSF) is gratefully acknowledged.

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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 [26]. 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"[8]. 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"[15]. Attaining this sustainable Swiss energy system, often associated with the vision of a 2000-Watt society, implies achieving economic growth as planned, while mitigating climate change (reducing CO_2 emissions) and guaranteeing energy independence and security. These objectives may be all the more difficult owing to the fact that from 2010 the long-term import contracts of electricity with France will start expiring and from 2020 a third of the Swiss nuclear capacity will be retired.

Worldwide policy makers, seeking to realize more sustainable energy systems, are facing the challenge of deciding on resource management; technology use and development; and the allocation of 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.

Given these uncertainties, the overall objective of this work 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 (e.g., the European Emissions Trading Scheme, post-Kyoto commitments, and measures to address carbon-related trade issues (such as leakage and embodied carbon)); patterns of energy and resource trade, extraction and depletion; and trends in global economic and technological development. This will be realized by applying a global model with explicit representation of Switzerland.

The global model to be used is a MERGE model (Model for Estimating the Regional and Global Effects of greenhouse gas reductions). MERGE is considered the ideal analytical framework because it represents global energy and economic systems including such features as trade, resources, technology deployment, capital stocks and economic growth. Furthermore, it is a dynamic optimization framework that will facilitate the analysis of scenarios in which global welfare is maximized while ranking the technological options and policy targets needed to achieve a set of goals of the Swiss and global energy systems.

This report is organized as follows: In the first chapter we describe the MERGE-ETL model. We describe the four submodels included in MERGE, that is, economic; energy; emissions and climate; and damage assessment. We also present the changes done to the model in the development of the project. In the second chapter we describe the baseline scenario developed with the model, which corresponds to the base case of development without climate policy. We discuss the basic drivers, the model calibration and some preliminary results. The baseline will be used as a starting point for subsequent analysis of uncertainties. Finally we discuss the outlook of the project.

Chapter 2

MERGE model

2.1 Introduction

MERGE-ETL (Magne et al. [19]) is an enhanced version of the MERGE model, including endogenous technological learning (ETL). It is a well established model for analyzing the economic impact of GHG policies and the role of technologies to fulfill climate targets; and for conducting cost-benefit analyses of climate policies, among others. MERGE combines a top-down model of the economy and a bottom-up description of the energy sector to determine optimal technological choices to provide energy services (Manne and Richels [21]). The combination of the two approaches adds a value to MERGE compared to bottom-up or top-down only models. Unlike bottom-up only models, MERGE is able to account for linkages between economic activity and energy demand in its intertemporal general equilibrium submodel and thus determine endogenously energy demands and prices as well as realized GDP. Compared to top-down only models, the role of technological change can be analyzed with more detail in MERGE's bottom-up submodel, which includes a detailed description of electric and non-electric technologies.

MERGE-ETL integrates four submodels governing: economic production; the energy sector; climate and emissions; and damage assessment. In Figure 2.1 we present a diagram with the structure of the model showing the inputs, outputs and linkages between submodels.

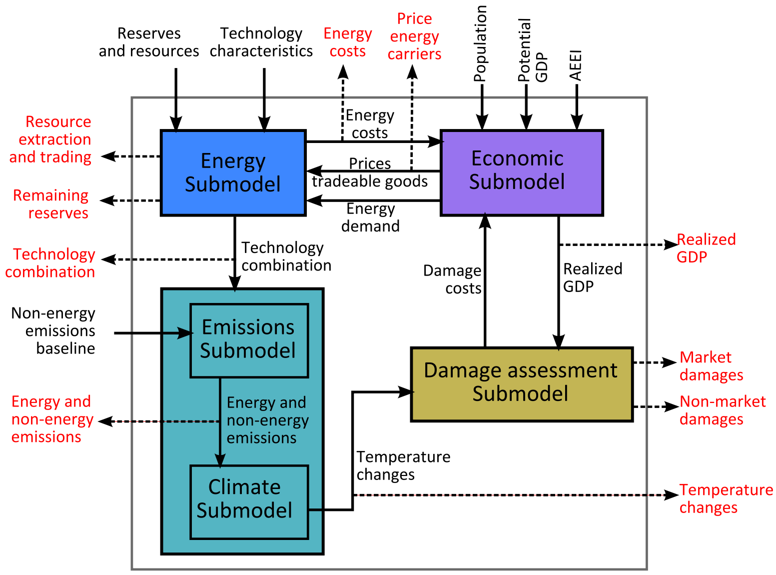


Figure 2.1: MERGE model structure. Inputs are indicated with the black arrows outside the model; outputs, are indicated with red; and linkages between the submodels are indicated with the black arrows inside the model.

2.2 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. Every time period, supplies and demands are equilibrated through the prices of traded goods, which include energy commodities 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. [20]).

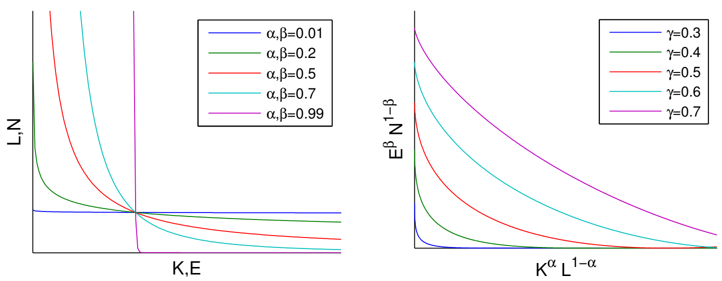
2.2.1 Domestic supply and demand

MERGE represents the total output in each region through a nested Cobb-Douglas production function. Production of new economic output ($Y_{r,t}$), for each region r, in each period t, is determined by four inputs: capital ($K_{r,t}$), labour ($L_{r,t}$), electricity ($E_{r,t}$) and non-electric energy ($N_{r,t}$), thus,

$$Y_{r,t} = \left[a \left(K_{r,t}^{\alpha} L_{r,t}^{1-\alpha} \right)^{\gamma} + b \left(E_{r,t}^{\beta} N_{r,t}^{1-\beta} \right)^{\gamma} \right]^{1/\gamma} \tag{2.1}$$

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 [20];
- interfuel substitution between electricity and non-electric energy. As the capital-labour substitution, this substitution exhibits unit elasticity and β is the optimal value share between the inputs [20]. Figure 2.2a presents the isoquant curves for these first two types of substitution. When the share 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 more substitutable. In the model α and β change among regions. In the current version, the share for the capital-labour bundle is assumed to be around 0.3 and the share for the energy bundle is 0.45 in all the regions. This means that the 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 capital-labour ($K^{\alpha} L^{1-\alpha}$) and energy ($E^{\beta} N^{1-\beta}$) [21]. Figure 2.2b presents the isoquant curves for the CES production function. When the value of σ tends to 0 the bundles are modeled as perfect compliments; and when it tends to 1 they are modeled as perfect substitutes. In the model the values used change among regions and they are around 0.5.



(a) Isoquant curves K-L and N-E (b) CES isoquant curves

Figure 2.2: MERGE production function

The parameters a and b represent productivity factors, i.e. they account for effects in total output not caused by inputs in the production function. They are estimated to calibrate the model to a reference scenario of energy demand. This reference scenario is based on GDP growth and an autonomous energy efficiency improvement (AEEI) parameter. This parameter accounts for changes in energy consumption not driven by prices, e.g. increase in the efficiency of electrical appliances, or structural changes to either more or less energy intensive types of industry, etc.

From the consumption side, the economic output for each region r in every period t can be allocated between investment ($I_{r,t}$), consumption ($C_{r,t}$), and energy costs ($EC_{r,t}$). Thus,

$$Y_{r,t} = I_{r,t} + C_{r,t} + EC_{r,t} \tag{2.2}$$

The energy costs represent the total expenditures of extracting a certain amount of resources and supplying electric and non-electric energy.

2.2.2 Intertemporal optimization

In MERGE each region is modeled by a single representative producer-consumer. Decisions are taken to maximize the intertemporal discounted utility. On a global scale, a global utility is calculated using the utility of each region weighted by means of Negishi weights. The utility is modeled as the logarithm of the consumption, therefore, it shows decreasing marginal utility (Manne et al. [20]). The global objective function is given by:

$$\max \sum_r w_r \sum_t \frac{1}{\left(1+\rho_{r,t}\right)^t} \log\left(C_{r,t} \cdot \mathrm{ELF}_{r,t}\right)$$

where $C_{r,t}$ and $\rho_{r,t}$ are the consumption and the social discount factor of region r in period t, respectively; and w_r is the Negishi weight of the region. Notice that in this case the utility is measured as the logarithm of the consumption adjusted by the $\mathrm{ELF}_{r,t}$ parameter, which represents an economic loss factor due to the impact of climate change (see Section 2.4.3).

2.3 Energy submodel

The energy submodel supplies the electric and non-electric inputs to the rest of the economy, i.e. E and N in Equation 2.1. It determines the optimal combination of technologies for energy supply. Each region is modeled by a reference energy system as presented in Figure 2.3. In the first step the resources are either extracted in the region or imported from another region. The resource technologies include the extraction of oil, gas, coal, uranium and biomass. After obtaining the primary energy carrier, it goes to one of the conversion technologies, which convert it to final energy, that is, electricity or non-electric energy.

2.3.1 Resource extraction technologies

Resources are extracted from different resources categories representing different costs of extraction (e.g. coal-1, coal-2, ...). Total discovered and undiscovered resources of exhaustible energy carriers, i.e. oil, coal, gas and uranium, are given exogenously to the model. Proven reserves of these resources are depleted by the resource extraction and augmented by the discovery of new resources coming from the undiscovered resources. New discoveries are limited to a certain percentage of the remaining undiscovered resources in any time period [20].

2.3.2 Resource and electricity trading

As shown in Figure 2.3 natural resources and electricity can be traded between regions. In the current version of the model the electricity trading occurs only between European Union and Switzerland. Besides the energy carriers and the electricity, MERGE includes international trading of the numeraire

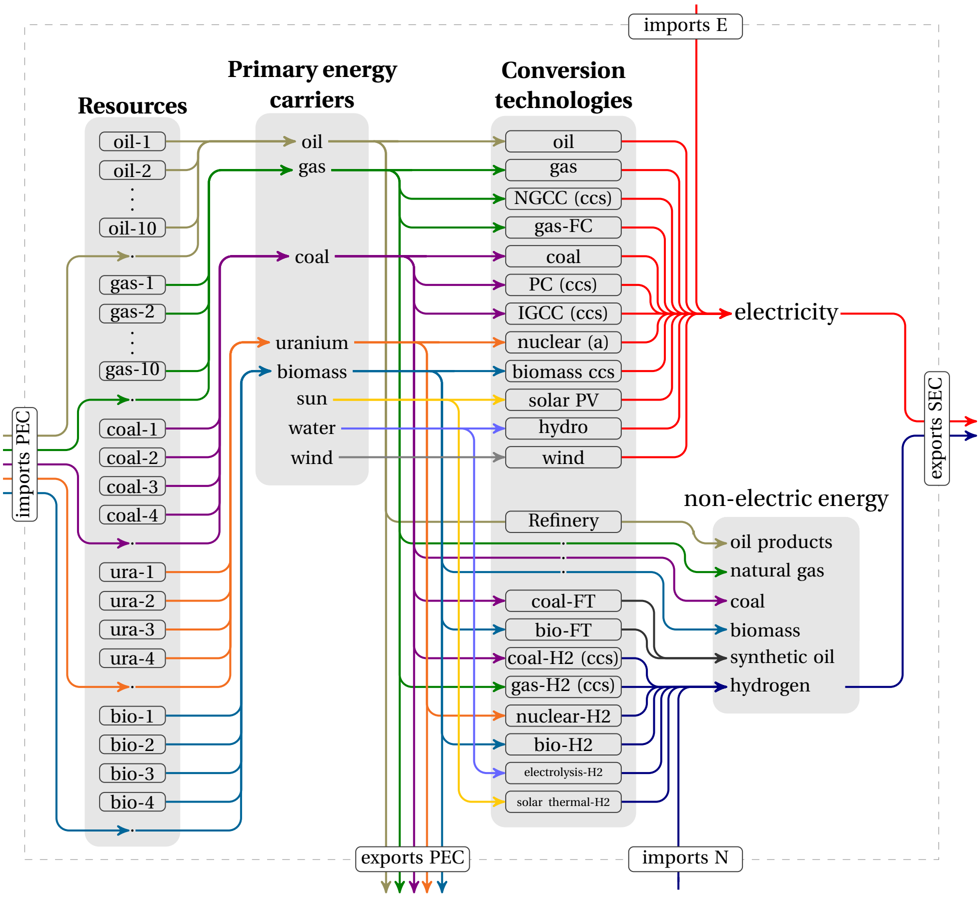


Figure 2.3: Reference Energy System

good, emissions permits and energy intensive products, such as steel and cement [21]. In every period, the net exports (X) of each tradeable good trd should be balance, thus,

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

where $X_{r,t,trd}$ corresponds to the imports minus exports of the region r, in the period t, for tradeable good trd. Each of these balance equations has a price associated that corresponds to the projected market price of the tradeable good [21]. The net exports of the numeraire good are subtracted from the economic output of the region shown in Equation 2.2.

2.3.3 Conversion technologies

Conversion technologies transform the primary energy carriers to either electricity or non-electric energy. Table 2.1 presents the description of the conversion technology options included in the model. The conversion processes occur at a certain levelized cost and producing carbon emissions. MERGE estimates for every technology in each period a global levelized cost of producing a kWh of electricity or a GJ/a of non-electric energy. These levelized energy costs are highly uncertain values since they summarize various uncertain parameters of the technologies, such as efficiency, load factor, investments cost and operation and maintenance costs. In Section 3.1 we present the levelized costs used in the baseline scenario.

Upper bounds are imposed on the expansion rates of each electricity and non-electric technology to account for construction capacities. Neither the original MERGE developed by Manne and Richels [21]

	Name	Description
Electricity	oil	Oil existing
	gas	Gas existing
	NGCC (ccs)	Natural Gas Combined Cycle
		Natural Gas Combined Cycle with carbon capture and storage (CCS)
	gas-FC	Gas fuel cell
	coal	Coal existing
	PC (ccs)	Pulverized coal
		Pulverized coal with CCS
	IGCC (ccs)	Integrated Gasification Combined Cycle
		Integrated Gasification Combined Cycle with CCS
	nuclear (a)	Nuclear (Light water reactor)
		Nuclear Advanced (Fast breeder reactor)
	bio ccs	Biomass with CCS
	spv	Solar photovoltaic
	hydro	Hydropower generation
	wnd	Wind
Non-electric energy	coal-FT	Coal to synthetic fuel (Fischer-Tropsch)
	bio-FT	Biomass to synthetic fuel (Fischer-Tropsch)
	coal-H2 (ccs)	Coal to Hydrogen
		Coal to Hydrogen with CCS
	gas-H2 (ccs)	Gas to Hydrogen
		Gas to Hydrogen with CCS
	nuc-H2	Nuclear to Hydrogen
	bio-H2	Biomass to Hydrogen
	electrolysis-H2	Water to Hydrogen using electrolysis
	sth-H2	Solar thermal to Hydrogen

Table 2.1: Conversion technologies

nor the MERGE-ETL model [19] included explicitly considerations about installed capacity nor vintages of technologies. In these versions of the model lifetimes were modeled by applying an upper bound on the contraction rate of each technology. We have modified the model to include vintages of electric technologies, while the lifetimes of the non-electric technologies are still modeled using maximum contraction rates. The vintages of technologies are modeled using a capacity variable $CAP_{r,t,y,age}$, that represents the installed capacity in a region r, in period t, of a certain technology y with an age age. Thus,

$$\begin{aligned} CAP_{r,t+1,y,age+1} &= CAP_{r,t,y,age} \\ \sum_{i\in age}^{lf} CAP_{r,t,y,age} &= PE_{r,t,y}, \end{aligned}$$

where lf represents the lifetime of the y-technology; and $PE_{r,t,y}$ the electricity produced with the y-technology, in region r, in period t.

Each technology also has an upper bound upon its share of the total energy production [20]. This is highly relevant for the contribution of renewable technologies on 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. In this sense, it is not possible to produce all the electricity with them or it is necessary to include some backup technologies that will replace the intermittent sources when they are not available. MERGE does not include backup capacity for these sources, therefore, this bound is the way of assuring security of supply for the optimal technology combination.

2.3.4 Nuclear cycle

Nuclear generation contributes an important share to current global electricity generation and it has a considerable potential to provide carbon-free electricity. However, the conversion from natural uranium to electricity is more complicated than the conversion process with fossil fuels. To represent this, this new version of MERGE includes a nuclear cycle (see Figure 2.4) to give a more accurate representation of the actual generation process and resources availability. This nuclear cycle includes two type of reactors, a light water and a fast breeder, and models the flows of the different type of uranium, plutonium and wastes. It is based on Chakravorty et al. [1].

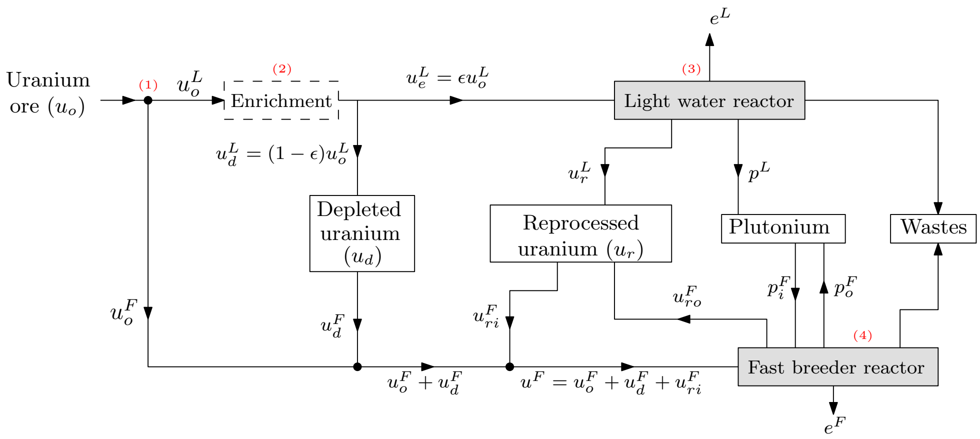


Figure 2.4: Nuclear Cycle

(1) The cycle starts with the uranium ore coming from the uranium resources (ura-1 to ura-4 or imports). Uranium ore (u_o) is divided into the uranium going to the LWR (u_o^L) and the one going to the FBR (u_o^F).

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

(3) Light Water Reactor (LWR): Uses the enriched uranium and produces energy (e^L), reprocessed uranium (u_r^L), plutonium (p^L) and wastes. 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 enriched uranium needed by the reactor, thus,

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

In Figure 2.5 we present the input-output relation for the EPR (with an annual output of 11.46 TWh) and the coefficients for the reactor used in the model.

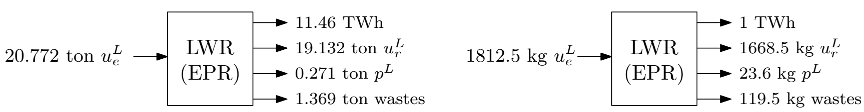


Figure 2.5: Inputs and outputs of the LWR

(4) Fast breeder reactor (FBR): Uses the uranium coming from uranium ore (u_o^F); the depleted uranium from the enrichment process (u_d^F); and the reprocessed uranium coming for both reactors

(u^F_{ri}). We assumed these types of uranium are substitutes and, therefore, their stocks merge into one: $u^F = u^F_o + u^F_{ri} + u^F_d$. Besides the uranium the FBR uses plutonium (p^F_i). The uranium and plutonium inputs most be used in a fixed proportion, $\dfrac{u^F}{p^F_i} = k$. The FBR produces energy (e^F), reprocessed uranium (u^F_{ro}), plutonium (p^F_o) and wastes. The uranium input and output also need to be used in a fixed proportion, $\dfrac{u^F}{u^F_{ro}} = k_u$. The Fast Breeder Reactor is modeled based on the European Fast Reactor, which input-output relation we present in Figure 2.6.

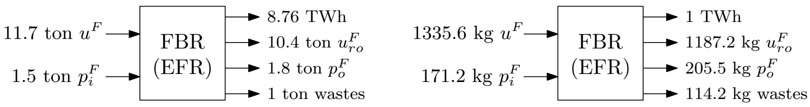


Figure 2.6: Inputs and outputs of the FBR

2.3.5 Endogenous technology learning

Endogenous technology learning is a determinant for the development of the energy system and technology choice. It captures the possibility to achieve long-term competitiveness for those technologies with high investment cost in the present. To account for the fact that accumulation of experience and knowledge may produce declining investment costs, this enhanced version of MERGE estimates endogenously the investment cost for some technologies. This is done by means of a two-factor learning curve. The first factor corresponds to the so called “learning-by doing” (see Figure 2.7), describing the investment cost as a function of the cumulative capacity, which is used as a proxy for the cumulative experience with the technology (Magne et al. [19]).

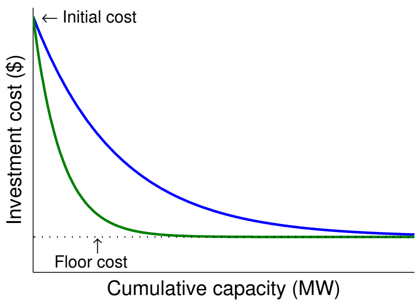


Figure 2.7: Endogenous technology learning

For this factor, the investment cost for the y-technology declines with the installed capacity until it reaches a floor cost, thus,

$$inv_y \propto \cdot CC_y^{-b_y}$$

where CC_y is the cumulative capacity; and b_y is the learning index, which reflects the effectiveness of the learning process for the y-technology. The two different learning curves presented in Figure 2.7 illustrate an example of two technologies with the same initial investment cost, the same floor cost but different learning indexes. The second factor of the learning curve accounts for the fact that knowledge is also accumulated through investments on research and development. This factor corresponds to so called “learning-by-searching”, thus the investment costs decline proportionally to both the cumulative capacity and the cumulative research and development expenditures (CRD),

$$inv_y \propto \cdot CC_y^{-b_y} CRD_y^{-c_y} \tag{2.3}$$

where c_y is the learning-by-searching index. The cumulative R&D expenditures are exogenously estimated.

Importantly, in MERGE-ETL technology learning is assumed to occur as a collective evolutionary process, following the paradigm of technology clusters described in [31]. This approach is based on the observation that a number of “key components” are often used across different technologies. Thus, experience with one technology may benefit other technologies if they share the same key component that is affected by learning processes.

Accordingly, the two factor learning represented in Equation 2.3 is applied at the level of key components. The key components included in MERGE and their relationship with the conversion technologies are presented in Table 2.2.

		Gasifier	Gas turbine	Biomass balance of plant	Coal balance of plant	Advanced coal	Carbon capture			Stationary fuel cell	New nuclear		Wind	Solar	
							Pre combustion	Post combustion	H_2 production		Power production	H_2 production		PV power	Thermal H_2 prod
Electricity	oil														
	gas		x												
	NGCC		x												
	NGCC (ccs)		x					x							
	gas-FC									x					
	coal														
	PC					x									
	PC (ccs)				x		x								
	IGCC	x			x										
	IGCC(ccs)	x			x		x								
	nuclear														
	nuclear (a)										x				
	bio ccs	x		x			x								
	spv													x	
	hydro														
	wnd												x		
Non-electric energy	coal-FT	x			x										
	bio-FT	x		x											
	coal-H2	x													
	coal-H2 (ccs)	x							x						
	gas-H2														
	gas-H2 (ccs)								x						
	nuc-H2											x			
	bio-H2	x		x											
	electrolysis-H2														
	sth-H2														x

Table 2.2: Key learning components of the conversion technologies

2.4 Emissions, climate and damage assessment submodels

In addition to the economics and energy submodels, MERGE includes submodels on emissions and climate change. MERGE focuses on three main gases: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The emissions of each greenhouse gas are divided into two categories: energy and non-energy related emissions.

The other GHGs included in MERGE are short-lived (slf) and long-lived F-gases (llf). The first group includes all the hydrofluorocarbon with a life time of less than 100 years. LLF includes the hydrofluorocarbon with a life time greater than 100 years, SF_6 and prefluorocarbons (PFC’s). The emissions of these gases are calculated in MERGE, using an exogenous baseline and abatement curves for different world regions.

2.4.1 Emissions and abatement

Energy-related CO_2 emissions are estimated using emission coefficients for both current and future technologies. These coefficients are given exogenously and represent how much carbon dioxide is produced whenever coal, oil and gas are burned in the generation of electricity and in the production and end-use of non-electric energy. The other emissions related to energy production are fugitive methane emissions. These are calculated proportional to gas extraction using regional emission coefficients.

Non-energy emissions are specified with an exogenous baseline [21]. The model allows the abatement of these emissions using abatement cost curves (also given exogenously) or by technical advances.

2.4.2 Temperature increase

In MERGE global temperature increase is estimated assessing the impact of future concentrations of greenhouse gases on the earth's radiative forcing balance. With the emission factors the model estimates the emissions in each period. From the level of emissions and the pre-industrial level, the current stock of each greenhouse gas is estimated (CO_2, CH_4 and N_2O). The impact of these atmospheric concentrations on radiative forcing relative to 1990 levels (CO_{2o}, CH_{4o} and N_2O_o)is estimated as:

Gas	Change in net flux [W/m^2]
CO_2	$6.3\ln\left(\frac{CO_2}{CO_{2o}}\right)$
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	$0.14\left(N_2O^{0.5}-N_2O_o^{0.5}\right)-f(CH_{4o},N_2O)-f(CH_{4o},N_2O_o)$

where $f(CH_4,N_2O)=0.47\ln\left[1+2.01\cdot10^{-5}\cdot(CH_4\cdot N_2O)^{0.75}+5.31\cdot10^{-15}\cdot CH_4\cdot(CH_4\cdot N_2O)^{1.52}\right]$. Based on [20].

The aggregate effect (ΔF) is calculated adding up the radiative forcing of each GHG. And finally, the potential temperature change (ΔPT), defined as the long-run temperature that will occur if forcing level is kept constant indefinitely, is calculated as,

$$\Delta PT = d\cdot\Delta F$$

where $d = 0.555°\texttt{C/W/m}^2$. The actual temperature increase (ΔAT) is delayed from the potential temperature change, since the oceans take a long tome to warm up, thus,

$$\Delta AT_{t+1}-\Delta AT_t = c\,(\Delta PT_t-\Delta AT_t)$$

where ΔAT_t represents the actual temperature change in the period t compared to the base year and the constant c represents a 20 year mean lag (based on [20]).

2.4.3 Damages

Market and non-market damages of climate change can be assessed 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 [21]. At higher or lower temperatures than 2.5°C the losses are estimated proportionaly to the temperature increase. Market damages are substracted from the economic output (Y_t) shown in Equation 2.2.

For non-market damages, in MERGE the expected losses are assumed to increase quadratically with the temperature increase. This is modeled by means of an "economic loss factor" (ELF), that is given by:

$$\text{ELF}_t=\left(1-\left(\frac{\Delta AT_t}{catt}\right)^2\right)^{hsx}$$

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%. 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 [21].

2.5 Regions and time horizon

2.5.1 Regions

An important development of MERGE for analysing the impact of global uncertainties on Switzerland is the creation of an explicit Swiss region in the model. In the previous version of MERGE-ETL, the world was divided into 9 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) (see Figure 2.8).

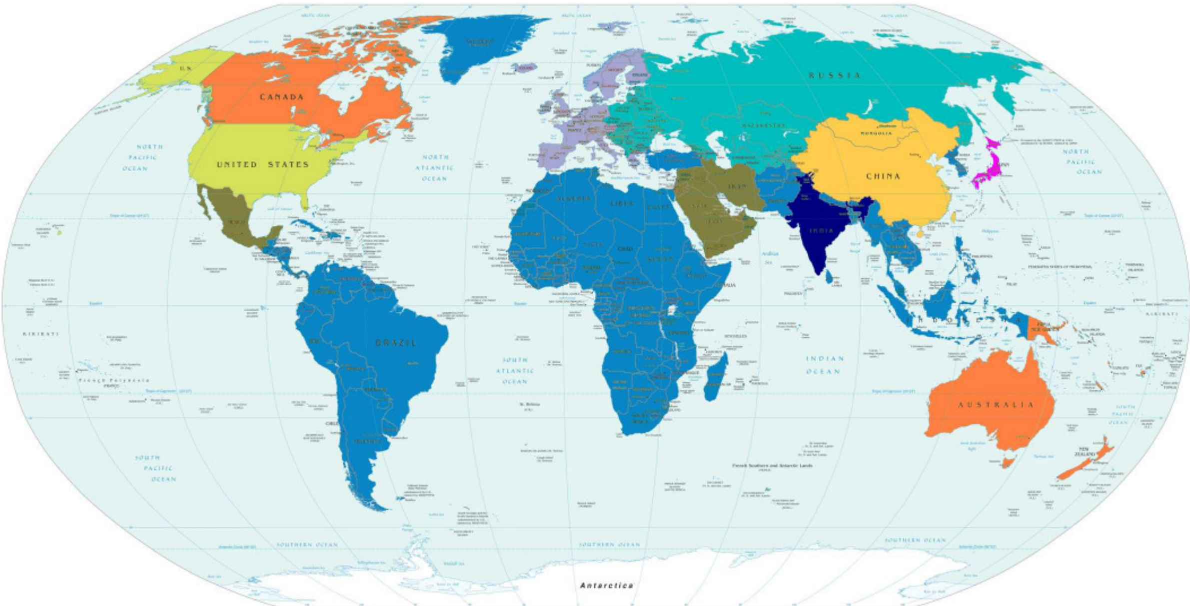


Figure 2.8: Previous Regions Definition

In addition to separating Switzerland from the existing WEUR region, additional changes were made to better reflect important political-economic groupings:

- WEUR and EEFSU: We created European Union[1]; Switzerland and Russia. The countries that belonged to the Former Soviet (except Russia) are now included in the Rest of the World region.
- MOPEC: Due to the geographical distance between Mexico and Middle East, we moved Mexico to ROW and created a Middle East region.

With these changes the new region definition includes 10 regions: European Union (EUP); Switzerland (SWI); Russia (RUS); Middle East (MEA); India (IND); China (CHI); Japan (JPN); Canada, Australia and New Zealand (CAN), United States (USA); and the Rest of theWorld (ROW). (see Figure 2.9).

2.5.2 Time horizon

The model is calibrated in the years 2000 and 2005 and the projection periods correspond to the years 2010 to 2100 in steps of 10 years.

[1]We include in the European Union region some countries that are not part of the European Union: Andorra, Faroe Islands, Gibraltar, Holy See, Iceland, Liechtenstein, Monaco, Norway, San Marino, Svalbard and Jan Mayen, Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia and Montenegro.

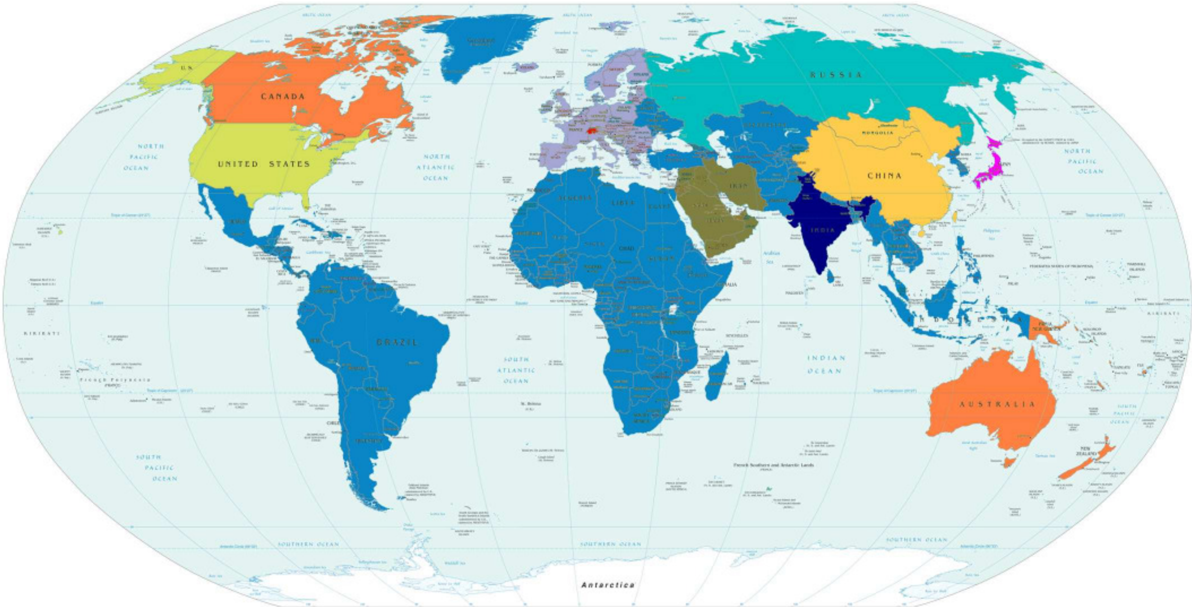


Figure 2.9: New Region Definition

2.6 Data upload

In the original version of MERGE the data was uploaded directly in the GAMS code. All the required data was distributed along a series of flies that made part of the complete model. In the new version of MERGE the data is uploaded from an Excel file. This is done using the GAMS GDX tools [7, 28]. The file is divided in 17 tabs, each one corresponding to a different type of information, including, macroeconomic; trading; carbon relaxation; carbon storage; greenhouse gases, climate, greenhouse gases baseline, abatement, climate scenarios, energy intensive sector, resources, non-electric energy, electricity, nuclear and learning. This way of uploading the data gives flexibility to the model for the development of scenario analyses.

Chapter 3

Baseline Scenario

3.1 Basic drivers

The baseline scenario is developed as a first step before analysing other scenarios to explore the impact of some of the global uncertainties on energy system development (both globally and in Switzerland). The baseline is based on elements of the B2 scenario from the IPCC's Special Report on Emissions Scenarios [22]. 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. In the baseline we do not consider climate change mitigation policies, or the impacts of climate change.

The basic scenario drivers for each region include:

- Population growth. The base years (2000 and 2005) are calibrated to the United Nations statistics [35] and the Swiss statistics [33]. The assumed growing rates correspond to a medium growth scenario, based on the BFS scenarios for population development [2] for Switzerland until 2050 and the IIASA B2 scenario [16] for the remaining regions and Switzerland after 2050. With these growing rates the global population is assumed to be 8.95 Billion by 2050 and 10.4 Billion by 2100 (Figure 3.1). Swiss population starts with 7.2 million in 2000, reaches 8.15 million by 2050 and after that year it starts declining, returning to 7.2 million by the end of the projection period.

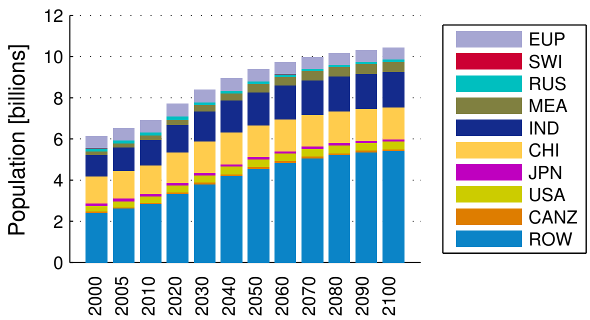
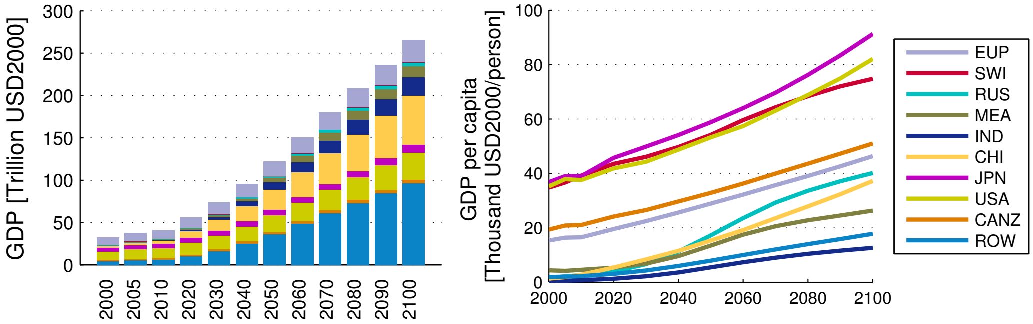


Figure 3.1: Baseline: Population

- Potential (or reference) growth in GDP. The base years are calibrated to World Economic Outlook [17] and the Swiss Statistics [34]. The potential GDP was calculated using the growing rate of the GDP per capita from Eidgenössisches Departement des Innern EDI, Schweizerische Eidgenossenschaft [3], State Secretary for Economic affairs (SECO) [32] and the IIASA B2 scenario [16]. With this projection, the potential GDP grows 3.74 times (up to 89.7 trillion USD 2000) between 2000 and 2050. In Figure 3.2 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 20 times from 2005 to 2100; while in EU29 it grows just 2.8 times in the same period. Switzerland starts with a yearly growth rate of potential GDP of 1.9% between 2005 and 2010; this growing rate decreases to around 0.7% for the period 2020 to 2050; and after 2050 the economic has a slow growth of 0.4%.



(a) GDP (b) GDP per capita

Figure 3.2: Baseline: 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 35 thousand US$/person; (2) CANZ and EU29, which GDP per capita is around 17 thousand US$/person; and (3) Russia, Middle East, India, China and ROW with an average GDP per capita of 2 thousand US$/person, but with a considerable difference between Middle East and India, which GDP per capita are 4.4 and 0.44 thousand US$/person, respectively. The first group of regions continues being the group with higher GDP per capita during the entire projection period. The other 2 groups spread considerably and by 2100 two countries of the third group (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 2.2 this variable reflects non-price driven changes in the economy-wide energy intensity. The rate of AEEI for the baseline is presented in Figure 3.3, estimated from the IIASA B2 scenario [16] projections for final energy consumption and GDP. In other versions of MERGE, the value of the AEEI was assumed to be 0.5% per year for all regions and periods [20]. In this baseline the values vary in the range 0 to 4%, with the exception of China in the first two periods, where the higher value reflects the fast growth in the economy and the rapid turn over of capital stock, leading to efficiency improvements. Until 2050 the group of less developed regions, i.e. India, China, Middle East, Russia and ROW are those with the higher AEEI. After 2050 all the regions have a similar AEEI, 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 3.2). Swiss autonomous energy efficiency starts in 1% and stays relatively constant during all the projection period, ending up in 0.8% by 2100.

- 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. For the baseline we assumed the values presented in Table 3.1. 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 [37, 38]; Undiscovered resources of oil, gas and coal are based on the conventional resources presented by the Federal Institute for Geosciences and Natural Resources [6]; proven reserves of Uranium are based on the Reasonably Assured Resources (RAR) from the 2007 Red Book [25];

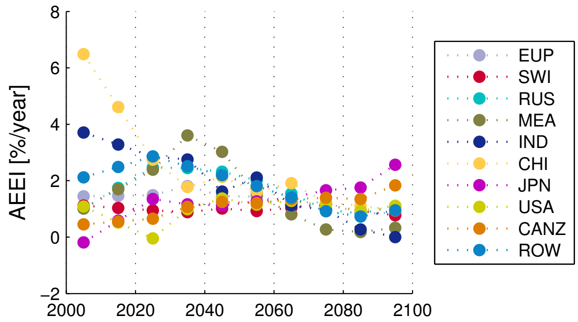


Figure 3.3: Baseline: Autonomous Energy Efficiency Improvement

and undiscovered resources of Uranium are estimated as Inferred Resources + Prognosticated Resources + Speculative Resources from the 2007 Red Book [25].

Energy carrier	Extraction costs [USD 2000/GJ]	Proven reserves by 2005 [EJ]	Undiscovered resources by 2005 [EJ]
Oil	3 to 5.25 (10 cost categories)	6640	3760
Gas	2 to 4.25 (10 cost categories)	6693	9046
Coal	1.6 to 5.5 (4 cost categories)	21883	449625
Uranium	20, 60, 100 and 130 USD 2000/kgU	1669	6335

Table 3.1: Natural resources. Based on [6, 25, 37, 38]

- Technology characteristics: As shown in Figure 2.1 the technology characteristics are an important input for the model. In Table 3.2 we present the values used in the baseline for the levelized costs taken from Magne et al. [19]. As mentioned in Section 2.3.1 MERGE includes different cost of extracting resources, therefore the values used to estimate these levelized costs correspond to the cheapest resource category. Additionally, these levelized costs change with the technology learning, in this case we used the initial investment costs. The discount rate used is 5%.

	Technology	Total levelized cost [cents$/kWh]
Electricity	oil	6.28
	gas	4.93
	NGCC	3.07
	NGCC (ccs)	4.89
	gas-FC	5.66
	coal	3.68
	PC	4.26
	PC (ccs)	6.39
	IGCC	3.43
	IGCC(ccs)	4.63
	nuclear	2.13
	nuclear (a)	2.65
	bio ccs	8.02
	spv	16.12
	hydro	5.26
	wnd	4.48

	Technology	Total levelized cost [$/GJ/a]
Non-electric energy	coal-FT	9.34
	bio-FT	14.85
	coal-H2	10.42
	coal-H2 (ccs)	10.93
	gas-H2	9.20
	gas-H2 (ccs)	9.61
	nuc-H2	10.87
	bio-H2	12.64
	electrolysis-H2	5.93
	sth-H2	41.28

Table 3.2: Conversion technologies levelized costs

The levelized costs of the nuclear technologies are based on the unit costs of the nuclear cycle presented in Table 3.3. We have estimated the maximum operation costs for both the LWR and the FBR, that is, we have assumed that all the uranium used in the FBR is natural uranium; and that the produced plutonium in the LWR and FBR has to be stored for 30 years.

Name	Description	LWR	FBR
m	Conversion	5	
mS	Separation + enrichment	80	-
mLf, mFf	Fuel fabrication	250	2500
mLr, mFr	Fuel reprocessing	700	2000
Storage	Depleted uranium storage	3.5	-
	Reprocessed uranium storage	60	
	Plutonium storage	1500	
	Waste disposal	400	100

Table 3.3: Nuclear fuel cycle cost data. All costs are in $/kg except costs except for Plutonium storage where they are $/kg per year. Based on [1]

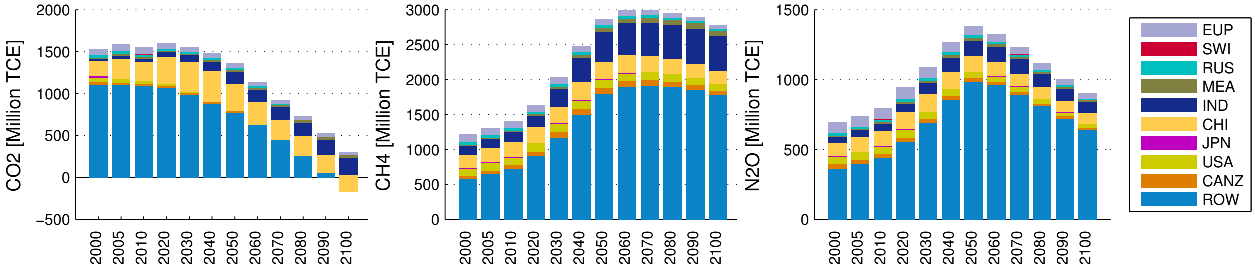
3.2 Calibration of the model to the years 2000 and 2005

The baseline was calibrated for the years 2000 and 2005 to the energy statistics concerning the following variables:

- Energy carrier consumption and resources capacities. The values are based on the IEA energy balances [11–14] and uranium from Nuclear Energy Agency [24], Nuclear Energy Agency and the International Atomic Energy Agency [25].
- International trade. The trade values for coal, oil, gas and electricity are based on the IEA energy balances [11–14].
- Atmospheric stock of CO_2. The 2000 value is based on the IPCC Scientific Basis [10] and corresponds to 368.7 ppm. The 2005 value is 378.5 ppm and is based on [23].
- Atmospheric stock of non-CO_2 gases. The 2000 value is based on the IPCC Scientific Basis [10] and the 2005 value was estimated base on the historical trends presented in the same report [10].
- Energy-related GHG emissions: Are based on the EDGAR 4.0 database [5]. The global 2000 value corresponds to 6.17 billion tons of carbon equivalent 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.

3.3 Baseline non-energy emissions

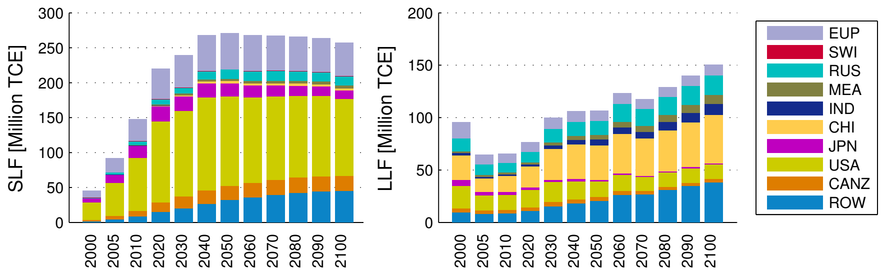
As mentioned in Section 2.4.1, MERGE also accounts for non-energy GHG emissions based on an exogenous baseline and abatement cost curves. The baseline emissions are calibrated for the base years (2000 and 2005) to the EDGAR database [5] and projected using the growth rates for the same set of emissions from the IIASA B2 scenario [16]. As mentioned before, this scenario corresponds to a world with intermediate demographic, economic and technological developments [27]. In Figure 3.4 we present the baseline of the major GHG, including CO_2, CH_4 and N_2O. The decrease in the CO_2 non-energy emissions is due to “slowing population growth, increasing agricultural productivity and increasing scarcity of forest land. These factors allow for a reversal of the current trend of loss of forest cover” [22, Summary for policy makers, p. 7]. The non-energy methane emissions correspond mainly to rice production and enteric fermentation. The first of which shows an increasing trend until the middle of the 21st century and then stabilize; while methane emissions from enteric fermentation show an upward trend until the end projection period [22]. The N_2O non-energy emissions correspond to natural emissions, i.e. oceans, tropical and temperate soils; and anthropogenic sources including agriculture and animal production systems, therefore the nitrus oxide emissions are dominated by “the land-use changes and changes in agricultural output and practices” [22, p. 147].



(a) CO_2 (b) CH_4 (c) N_2O

Figure 3.4: Baseline non-energy emissions: major GHG

In Figure 3.5 we present the other GHG's included in the model. As mentioned in Section 2.4 SLF represents the group of short-lived F-gases including all the hydrofluorocarbon (HFC) with a lifetime of less than 100 years. The main contributor to the SLF is HFC-134. In the IIASA B2 scenario HFC's emissions are estimated based on an assumed future replacement of chlorofluorocarbons (CFCs) by HFCs and the main drivers are population and economic growth [22]. LLF represents the long-lived F-gases, it includes the hydrofluorocarbons with a lifetime greater than 100 years, SF_6 and prefluorocarbons (PFC's). The main contributors to LLF are SF_6 and CF_4. SF_6 has two main sources: its use as gas insulator in high-voltage electricity equipment and its use to prevent oxidation of molten magnesium in magnesium foundries. The drivers for these two uses are electricity demand and magnesium production, which can be related to population growth and economic development. The production of CF_4 is driven mainly by the production of aluminum, which is generally modeled using GDP projections [22]. Therefore, the increase in SLF and LLF emissions is driven mainly by the increase in population and GDP, with a higher growth rate in the SLF due to the assumed replacement of CFCs by HFCs.



(a) SLF (b) LLF

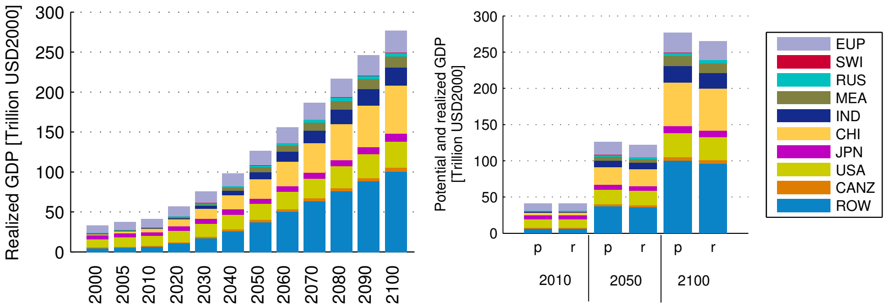
Figure 3.5: Baseline non-energy emissions: other GHG

3.4 Preliminary results

The scenario drivers described above were applied in the MERGE model to quantify the economic, energy technology and emissions implications of the baseline scenario. Results of this analysis are presented below. As mentioned earlier, the baseline scenario does not consider climate change mitigation policy, or the impacts of climate change.

3.4.1 Realized GDP

Figure 3.6a presents the realized GDP for the 10 regions. Figure 3.6b presents a comparison between the realized GDP and the potential GDP in three different years, 2010, 2050 and 2100. The realized and potential GDP are not the same because the realized GDP corresponds to the economy's output adjusted by energy-economy interactions and, in particular, energy prices and their impact on demand. Comparing the realized and the potential GDP is a way of checking the calibration of parameters of the economic model, they should be similar in the baseline.



(a) Realized GDP (b) Potential (p) and realized (r) GDP

Figure 3.6: Realized GDP

3.4.2 Energy production

Figure 3.7 presents the total primary energy supply. For the renewable technologies, i.e. hydropower, wind and solar photovoltaic, we assume an efficiency 38.5% 33% and 20%, respectively. Coal is the most used energy carrier since it has the lowest extraction cost and the highest proven reserves. This is also related to the fact that no climate policy is imposed to this scenario. Oil and gas are also used but the amount of reserves assumed in this new baseline is limited, and these resources are depleted over the time horizon (with oil production peaking in 2030, see Figure 3.9).

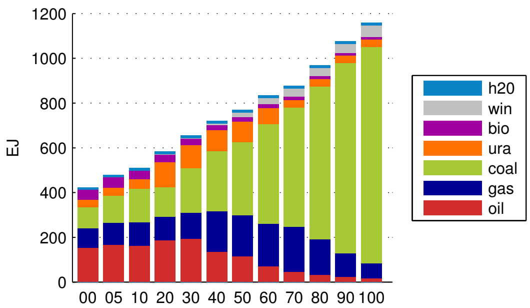
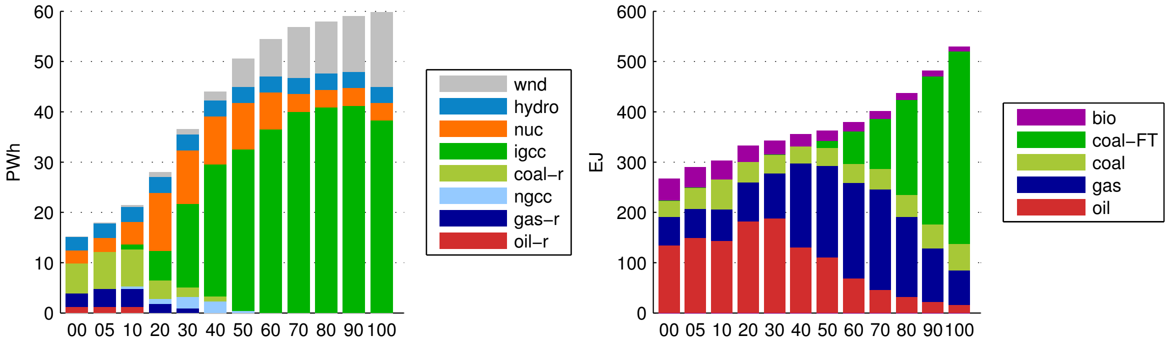


Figure 3.7: Total primary energy supply

Figure 3.8 presents global electricity and non-electric production. In the case of electricity, global demand increases considerably over time, driven primarily by the emerging economies (with demand decreasing for some of the slower growing regions, such as EU, Switzerland, Russia, Japan, USA and CANZ). In terms of production, in the first half of the century existing technologies are replaced mainly with coal IGCC and nuclear generation. Technology learning plays a role in making IGCC more attractive than other coal-based generation technologies. Later in the century the share of IGCC reaches 63% of the electricty generation by 2050 and 70% by 2090. This IGCC technology is deployed extensively in almost all regions. The exception is Japan and Switzerland, which electricity is based in nuclear, and nuclear and hydro, respectively. Nuclear energy slowly declines later in the century as uranium resources begin to be exhausted (noting that the fast breeder reactor option in Section 2.3.4 is assumed not to be available in this baseline scenario). Another important result is the increasing share of Wind in the electricity production. This considerable increase is driven by the technology learning which reduces the levelized electricity cost for this technology to competitive levels compared to the fossil fuel technologies.



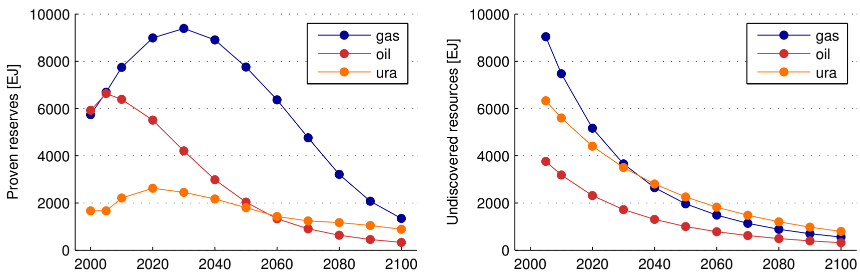
(a) Electricity production (b) Non-electric production

Figure 3.8: Results energy sector

For the non-electric energy, as the oil and gas reserves are depleted coal-FT starts playing an important role and becomes a major source of fuels by 2100. The global demand of non-electric energy is increasing in the projection period, although somewhat less than electricity demand. Again, much of the growth is driven by the developing regions, predominantly the Middle East, India, China and the Rest of the world, with China and the Rest of the world accounting for the highest share. Most other regions have declining non-electric energy demand over the time horizon.

3.4.3 Resources

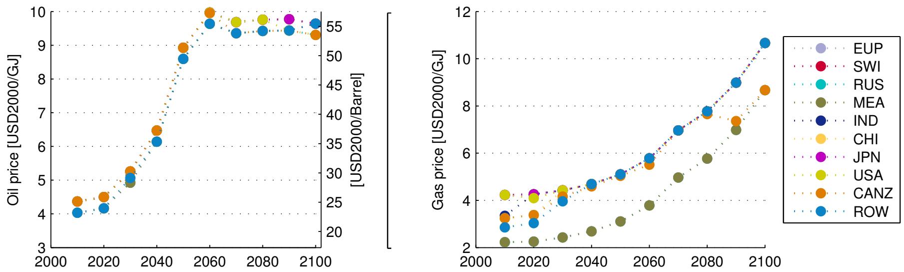
Figure 3.9 presents the development over time of proven reserves and undiscovered resources of oil, gas and uranium. All of them are considerably depleted by 2100, especially oil that reaches 334 EJ (58127 Mbarrels) of proven reserves. Due to the large amount of undiscovered resources of gas the proven reserves increased until 2040 and after that period decline reaching 1347 EJ by 2100.



(a) Proven reserves (b) Undiscovered resources

Figure 3.9: Baseline resources

Oil and gas prices showed in Figure 3.10 reflect the scarcity of the resource. Oil reserves decline faster than gas reserves and in the same way the oil price increases faster than the gas price. The oil price varies among regions but shows the same trend in the world, starting with a price around 25 US$/barrel in 2010, increasing up to around 55 US$/barrel by 2060 and staying constant in this value until the end of the projection period. Gas price has a large variation among regions and it can be divided in two groups. The first group includes Middle East and Russia, with a relative lower price (2.2 US$/GJ in 2010 to 8.2 US$/GJ in 2100). Middle East and Russia are the regions with the higher reserves of natural gas and therefore they have a lower gas price. The second group includes the rest of the regions which show a higher gas price, i.e. around 3 US$/GJ in 2010 to 10 US$/GJ in 2100.

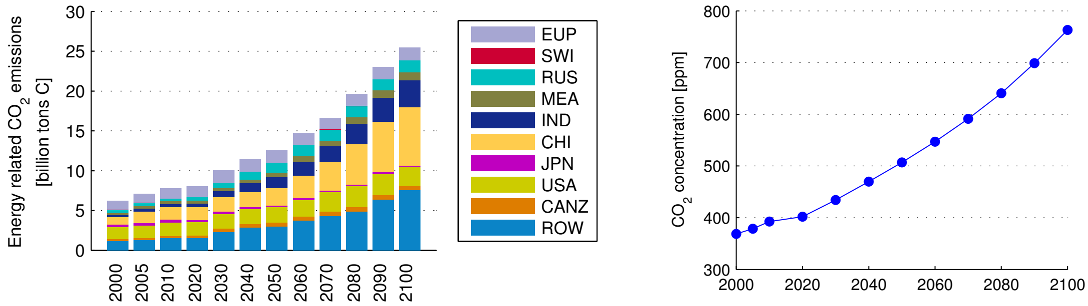


(a) Oil price (b) Gas price

Figure 3.10: Oil and gas prices

3.4.4 Emissions

In the baseline scenario the energy related CO_2 emissions increase to 25.8 billion tons CO_2 by 2100, which corresponds to a CO_2 concentration level of 763 ppm. This considerable increase on the energy related emissions is due to large use of coal in the electricity and non-electric energy production.



(a) Energy related CO_2 emissions (b) CO2 concentration

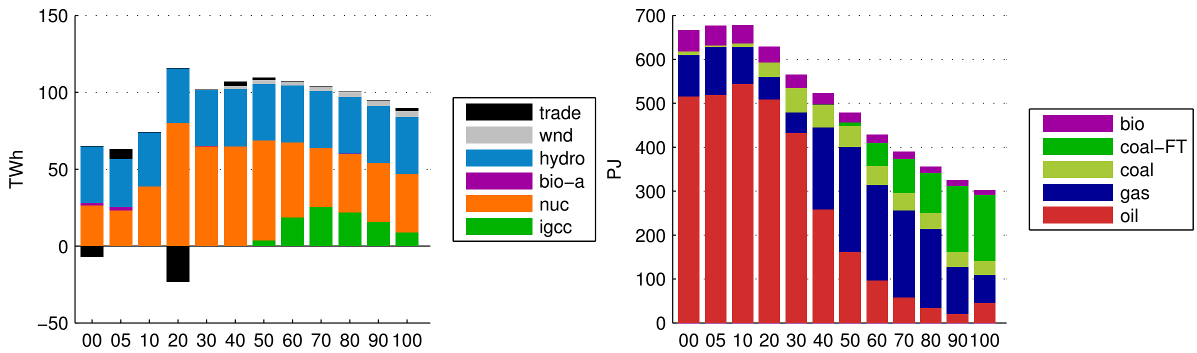
Figure 3.11: Emissions

3.4.5 Swiss region

The energy production for the baseline in Switzerland is presented in Figure 3.12. It is dominated throughout the scenario time frame by nuclear and hydropower, as is currently the case. However, nuclear generation declines later in the century as availability of uranium decreases and it is replaced by IGCC. Wind has an increasing share over time due to the global technology learning (i.e., illustrating a global influence that appears to have the potential to affect technology choices in Switzerland)[1]. The total electricity production increases from 66.1 TWh to a peak by 2050 of 109.5 TWh and then declines

[1] We use a potential for hydropower generation based on Laufer et al. [18]. They assume an initial increase due to efficiency improvements and development of small scale hydropower plants. By 2030 the potential peaks at 37.29 TWh/a and then declines due to the regulation of residual water. After 2050 we assume the hydropower potential stays constant at 37 TWh/a. For wind generation, we use a potential of 2 TWh/a by 2050 based on [4]. After 2050 we assume an increase in the potential that reaches a maximum of 4 TWh by 2100, a value that corresponds to the maximum estimated potentials for both wind parks and individual installations in [9, 30]. For the solar photovoltaic technology, the potential is based on [9]. It includes a limitation on available roofing surface. We assume by 2050 a potential electricity production of 10 TWh, this value is consistent with those estimated in [4, 36]. After 2050 we assume the potential remains constant.

to 90 TWh by 2100. This decrease is due mainly to the declining population after 2050 and ongoing efficiency improvement (see Section 3.1). The trading of electricity represents the bilateral next exports to the European Union. A negative value indicates exports to the EU and a positive value indicates imports from this region. The 2000 and 2005 values are calibrated to the IEA energy balances [12, 14]. In 2020 Switzerland exports 23.3 TWh to the EU; and in 2040, 2050 and 2100 Switzerland imports 2.7, 1.6 and 1.8 TWh, respectively. The considerably large value exported to the EU in 2020 is due to the interplay of three factors: increasing demand in EU, restriction in the IGCC expansion and vintages of technologies. The preferred technology in EU by 2020 is IGCC, it reaches its maximum growth rate and the demand is not supply yet. The second best alternative is nuclear generation and, since electricity trading is possible between Switzerland and EU, the model decides where to build it. The vintages of technologies (see Section 2.3.3 imply that once a technology is built it has to be used for its entire lifetime. In this sense, it is better for the global output to build the nuclear capacity in Switzerland that will need it in the upcoming periods and export this electricity to the EU. On the other hand, the non-electric energy demand and output drops considerably, starting from 667 PJ and declining to 302.5 PJ by 2100. This decline is driven partly by the decreasing population (after 2050) and the efficiency improvements, but it is accelerated by increasing prices for non-electric energy carriers, particularly oil, which leads to additional efficiency and substitution by electricity. Oil is replaced by gas and coal-to-liquids after 2050. Much of this is driven by depletion of oil and gas resources, primarily by countries other than Switzerland. This illustrates another 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).



(a) Electricity production (b) Non-electric energy production

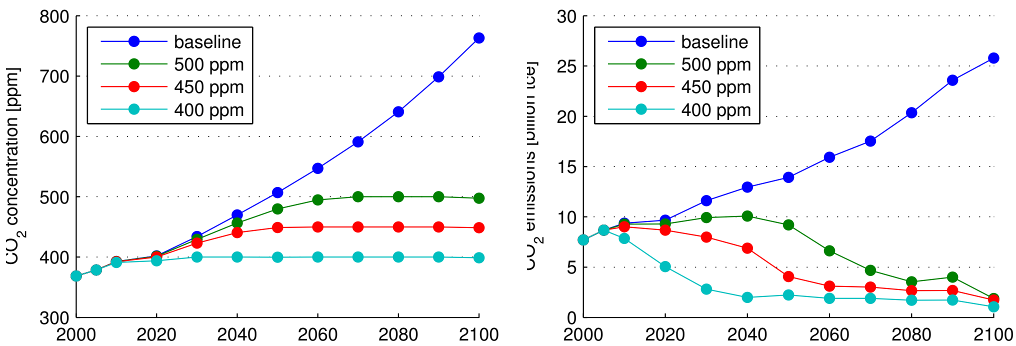
Figure 3.12: Swiss energy production

Schulz [29] and Weidmann as part of the Energie Trialog Schweiz [36] have analysed previously the 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. Compared to MERGE, it includes a more detailed energy sector but the linkages between economic activity and energy demand can not be modeled explicitly, that is, energy prices and 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 [29] presents in the baseline scenario an electricity production by 2050 around 78 TWh 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 baseline here, but the absolute value is smaller. This is due to a less optimistic GDP projections in [29] and the substitution of non-electric energy with electricity driven, as mentioned above, by high prices of non-electric energy carriers. Weidmann et al. [36] present a baseline scenario with an electricity production by 2050 of 300 PJ (83 TWh). In this analysis, the total electricity produced by 2050 is 20 TWh less than in the baseline here. Once again, the reasons are the GDP assumptions and the substitution of non-electric energy with electricity. Another important difference to this work is that NGCC plays an important role in the electricity generation, with a share of approximately 27%. The remaining 73% corresponds to nuclear and hydropower generation. This high share of NGCC in Weidmann et al. [36] is due to the no-nuclear expansion policy modeled in their baseline and not considered in the MERGE baseline. Furthermore, global gas availability and technology learning make gas generation even less competitive in our baseline. Natural gas is a scarce resource that is demanded by other world regions and sectors, leading to higher prices which make NGCC uncompetitive for electricity generation in Switzerland; and learning of the IGCC technology makes it a more competitive alternative.

These results for the baseline scenario appear to provide a good basis for further scenario development to analyse future global uncertainties and their impact on development of the Swiss energy system. This includes further development and refinement of the baseline scenario. The next steps outlined in the following section describe the range of global factors that will be analyzed, along with some further developments to the MERGE model.

3.4.6 Climate change mitigation scenarios

The baseline scenario reaches a CO_2 emissions level by 2100 of 25.5 billion tce. This level of emissions corresponds to a CO_2 concentration level of 763 ppm, a concentration that will most likely lead to undesirable climate change. In this context, we have analyzed three climate scenarios with long-term targets for CO_2 concentration of 500, 450 and 400 ppm. Figure 3.13 presents the CO_2 concentration for the three scenarios compared to the baseline and the corresponding CO_2 emissions. After 2050 the most stringent scenarios (400 and 450 ppm) have similar emissions, since the energy systems are similar.

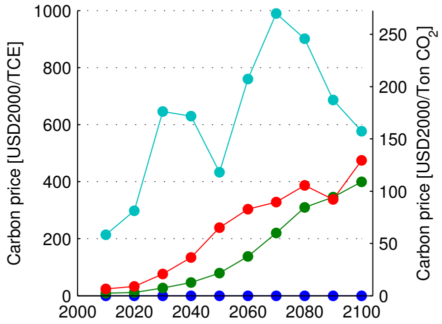


(a) CO_2 concentration (b) CO_2 emissions

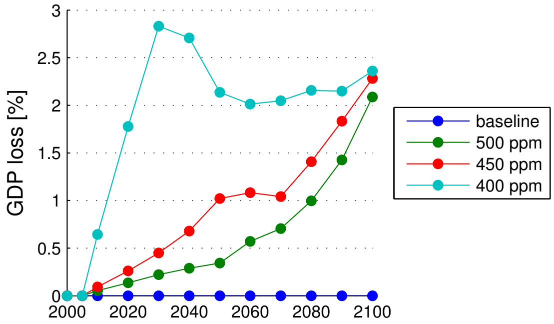
Figure 3.13: CO_2 emissions climate scenarios

Figure 3.14 presents the carbon price and the GDP loss for the climate scenarios. The 400ppm scenario has a considerably higher carbon price than the other scenarios at the beginning of the projection period. This is because earlier and larger investment is needed in carbon-free technologies which also leads to a considerably larger GDP loss. Due to technology learning, by the end of the projection period the 500 and 450 ppm scenarios have similar carbon prices, 109 and 129.5 US$ per ton of CO_2. The maximum GDP loss is 2.83% in 2030 for the 400 ppm scenario. In these analyses we have not included the savings due to avoided damages for the estimation of the realized GDP.

Figures 3.15a and 3.15b present the electricity production across the climate scenarios and the average electricity price. The global electricity production is reduced 16.4, 17.3 and 19.5 TWh by 2100 for the 500, 450 and 400 ppm scenarios, respectively. The electricity generation in the 450 and 500 ppm scenarios is similar after 2050, and therefore, the total electricity produced is approximately equal. The electricity price starts by 2010 around 4 Cents/kWh for all the scenarios. After 2030, the electricity price in the baseline stays relatively constant at around 3.5 Cents/kWh. The climate mitigation scenarios



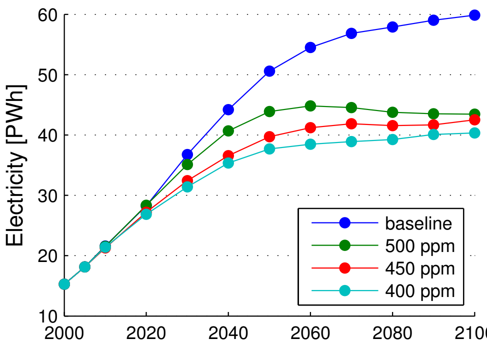
(a) CO_2 price



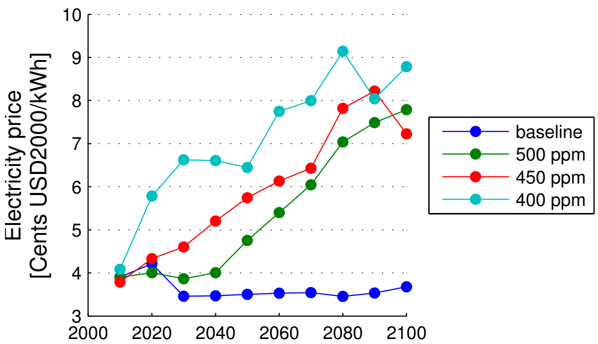
(b) GDP loss

Figure 3.14: Climate scenarios: Carbon price and GDP loss

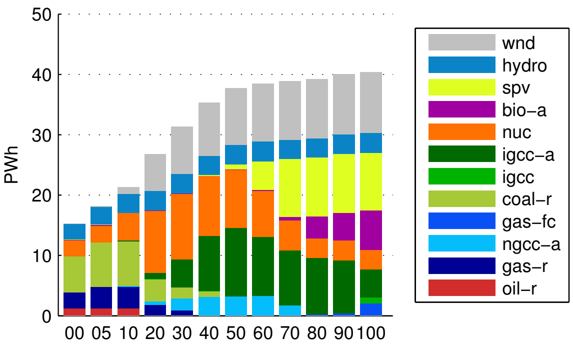
have increasing electricity prices, reaching by 2050 4.8, 5.7 and 6.4 Cents/kWh in the the 500, 450 and 400 ppm scenarios, respectively. By 2100 all the scenarios reach an electricity price that is at least twice the initial price. This increase in the price is due mainly to the large use of carbon free technologies.



(a) Electricity production



(b) Average electricity price

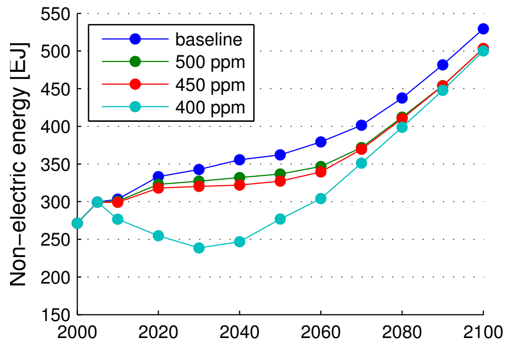


(c) 400 ppm scenario

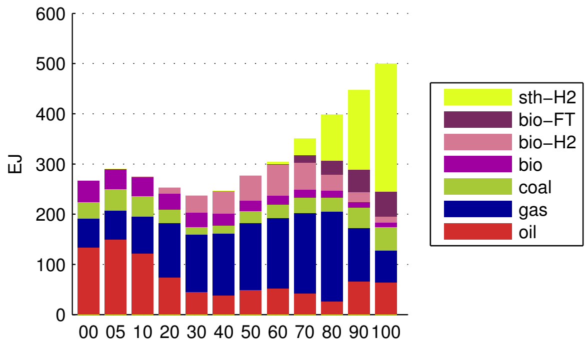
Figure 3.15: Climate scenarios: Electricity

Figure 3.15c presents the breakdown of global electricity. Compared to the baseline, production with IGCC is replaced by renewable technologies, such as wind, solar photovoltaic, and biomass; and IGCC with carbon capture. The NGCC technology with carbon capture is deployed as a transition technology from the current situation to a carbon free electricity generation.

Figure 3.16 presents the non-electric energy production in the climate change scenarios and the breakdown among technologies for the 400ppm scenario. Non-electric energy production in the mitigation scenarios stays relatively close to the baseline level, except in the 400 ppm scenario. This is mainly because the reduction in electricity demand and the shift to renewables is sufficient to reach the climate mitigation target in the 500 and 450 ppm scenarios. In all the scenarios, coal-FT liquids production is replaced by biomass technologies and solar thermal hydrogen production.



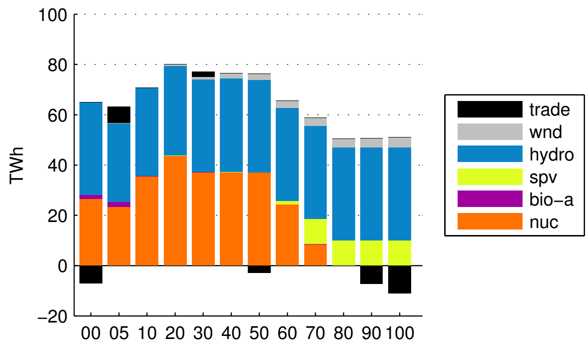
(a) Non-electric energy production



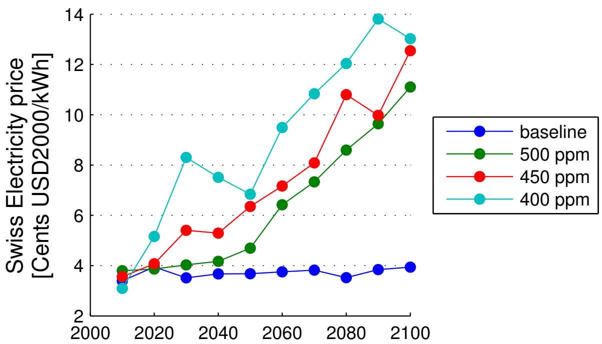
(b) Non-electric energy 400 ppm scenario

Figure 3.16: Climate scenarios: Non-electric energy

Figure Figure 3.17 presents the detailed electricity production for the 400ppm scenario in the Swiss region and the electricity price in the four scenarios. In the 400ppm scenario, Switzerland exports 2.9, 7.3 and 11 TWh to the EU in 2050, 2090 and 2100. This is due to the relatively large solar capacity installed by 2070 which generates an excess of produced electricity to supply the swiss demand. Nuclear generation, due to the higher prices of uranium coming from larger use of nuclear generation in other world regions, such as India, China and the USA, is replaced by solar photovoltaic generation after 2070. Wind, solar PV and hydropower reach their maximum potentials by 2070. The electricity price increases from an average of 3.75 Cents/kWh in 2010 to 11-14 Cents/kWh by 2100 in the different scenarios.



(a) Electricity



(b) Electricity Price

Figure 3.17: Climate scenarios: Electricity Swiss region

Regarding non-electric energy production in the 400ppm scenario (see Figure 3.18), coal-FT used in the baseline scenario is replaced by hydrogen technologies, i.e., sth-h2 and bio-h2[2], while natural gas continues to play an important role.

[2]Based on Energie Trialog Schweiz [4] we assume a maximum potential for biomass in Switzerland by 2050 of 130 PJ, assume to be constant after 2050. The sth-h2 potentials were estimated, based on the potential published by the Schweizerische Akademie der Technischen Wissenschaften (SATW) [30] for solar thermal heating, to 3.35 and 4.75 PJ for 2050 and 2100, respectively.

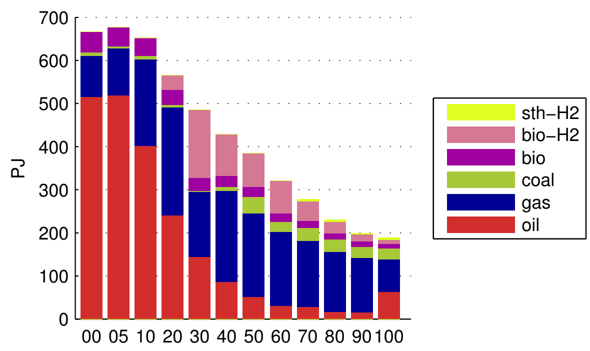


Figure 3.18: 400ppm scenario: Non-electric energy Swiss region

3.4.7 Fast breeder reactor

In this sub-case of the baseline the fast breeder reactor described in Section 2.3.4 is available for all the regions after 2040. Figure 3.19 presents the total primary energy supply for this scenario. The primary energy supply of the nuclear fuel needed in the FBR was estimated assuming an efficiency of 34.5%. Compared to the baseline without fast breeder reactor, the TPES increases by 2100 from 1159.1 EJ to 1590.7 EJ, due to the increase in the total electricity production, from 59.8 to 85.2 PWh in the same period.

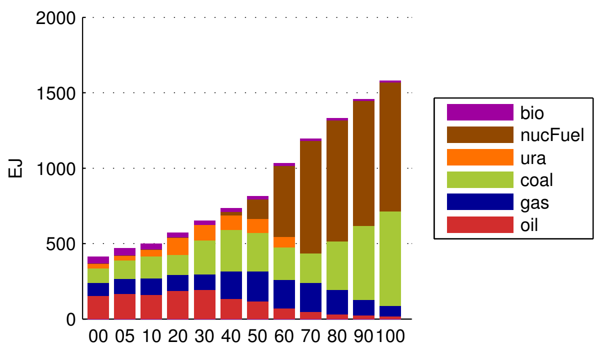
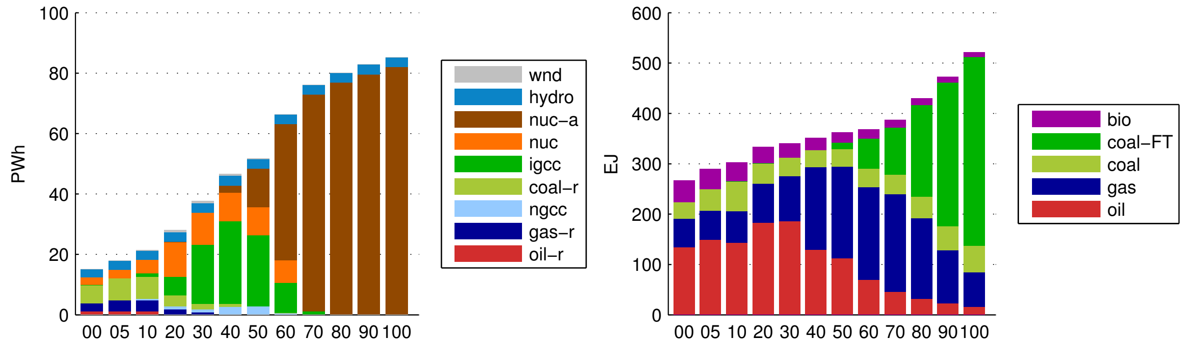


Figure 3.19: TPES with fast breeder reactor

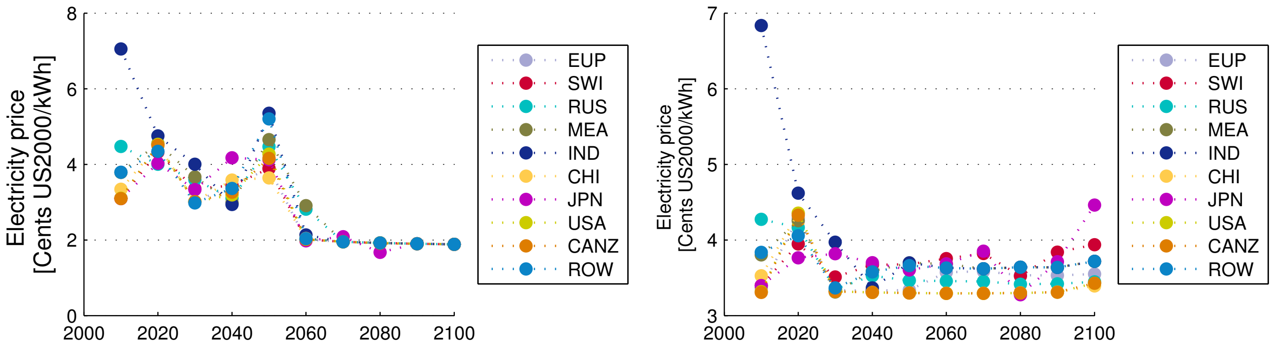
Figure 3.20 presents the global energy production for this scenario. As shown in the TPES, the nuclear fuel replaces coal as the most used energy carrier, indeed by the end of the projection period the nuclear advance technology accounts for 93% of the total electricity generation. This is due to the relatively low generation costs with the FBR. All the regions deploy the nuclear advanced technology at the fastest feasible rate. The non-electric energy production remains relatively unchanged in this scenario compared to the baseline.

Figure 3.21 presents the electricity price for all the regions with the FBR and the baseline. Compared to the electricity price in the baseline scenario the behavior before the FBR is available is identical. By 2040 the FBR becomes available, and therefore all the other technologies start to phase out. This means that no additional capacity is installed but the previously installed technologies have to be used until the end of their lifetimes. This produces a relatively high price in 2050 since wind, nuclear and NGCC are still used. After 2060 the electricity price remains constant around 2 cents/kWh for all the regions, which is implies a reduction compared to the baseline of 1.2 to 1.7 cents/kWh.



(a) Electricity production (b) Non-electric production

Figure 3.20: Results energy sector with fast breeder reactor



(a) FBR scenario (b) Baseline

Figure 3.21: Electricity price by regions

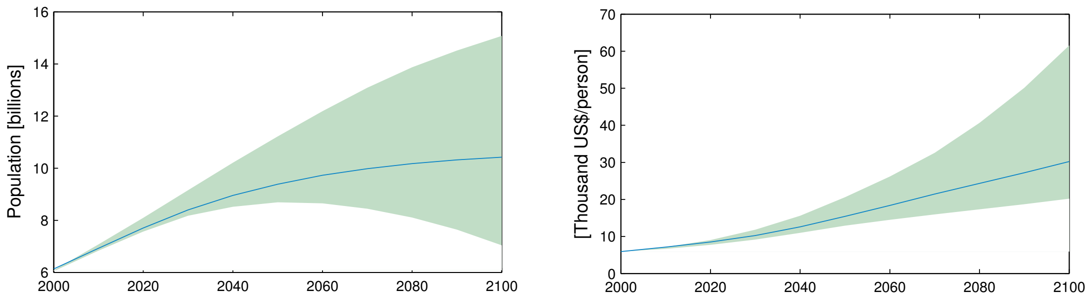
Chapter 4

Outlook

With the extended model and the baseline analysis of the global optimum welfare-maximizing deployment of energy technologies, we have tested assumptions and input data; identified all data requirements; and, critically, begun to analyze the competitiveness of different technology options.

The next immediate step is to finish the baseline analysis to get a complete overview of the optimal technology options for Switzerland in the case of no climate policy. After that, there are three main tasks to be undertaken to achieve the core aim of identifying how international developments will affect the realization of Swiss objectives. First at all, developing a range of alternative long-term international scenarios of:

- Global economic development. We presented in Section 3.1 the economic drivers used in the baseline. In the Figure 4.1 we present the considerable large uncertainty for global population and GDP per capita. The blue line corresponds to the current baseline.



(a) Population (b) GDP per capita

Figure 4.1: Different scenarios for economic development

- Resource availability: Potential of renewables and reserves of energy carriers are variables with high uncertainty. The resources of oil and gas included in the current baseline correspond to conventional resources. Thus, scenarios with different potential for renewables and different estimates for resources including unconventional oil and gas may be analysed.

- International climate policy: The development of future international climate policy is highly uncertain. Many alternatives are possible, including different regional commitments, permit allocation or burden sharing arrangements, alternative timings of regional participation in a global mitigation regime, and different global targets on temperature increase.

- Technology deployment: Technology deployment is a key aspect for achieving a sustainable energy system. The availability of different technologies, such as hydrogen for the non-electric sector; or fast breeder reactors or carbon capture technologies for the electricity sector are part of the possible scenarios. Another important uncertain variable is technology cost, including the potential for technology learning. Thus, scenarios with alternative technology learning rates, starting costs and floor costs may be considered.

- Trade: Different scenarios of carbon emissions or resources trading are of special interest for the Swiss case.

With the definition of these scenarios, an analysis of the main global uncertainties to determine robust energy technology strategies for Switzerland and potential threats (high dependency on the rest of the world) to the realization Swiss goals will be conducted. The second smaller task is defining the objectives for a sustainable Swiss energy system. These objectives will then be implemented for the Swiss region in the global model. Finally, the culmination of this work will comprise a scenario analysis using the extended global MERGE. The aim is to analyze how best to pursue Swiss objectives under different international conditions, and identify the circumstances under which it might not be possible to achieve these goals. This will lead to an identification of robust technology strategies for Switzerland; potential threats to the realization of Swiss objectives; and opportunities to manage uncertainty associated with international developments.

Units

1 barrel crude oil = 5.7534 GJ
1 kg uranium = 500 GJ

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