PAUL SCHERRER INSTITUT

THE MERGE-ETL MODEL:
2012 ASSUMPTIONS AND MODEL CALIBRATION

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Contents

List of Tables

List of Figures

Chapter 1

Region definition

This version of MERGE-ETL includes 10 world regions (see Figure 1.1) including: European Union[1] (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).

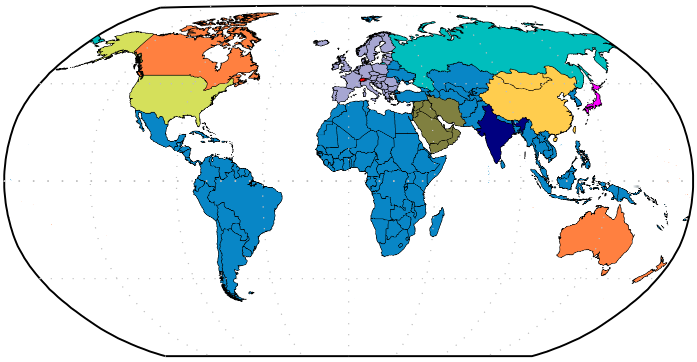


FIGURE 1.1: *Regions definition*

[1] 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.

Chapter 2

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 (2006); 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), 2001, 2007), 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) (2007, 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), 2007, 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).

Chapter 3

Calibration and technology data: 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.

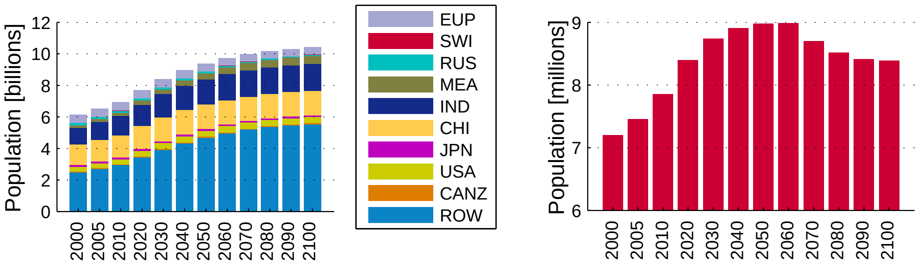
3.1 Economic development

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 the global energy system is modeled with an intermediate economic and population growth scenario.

3.1.1 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 3.1A). 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).

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



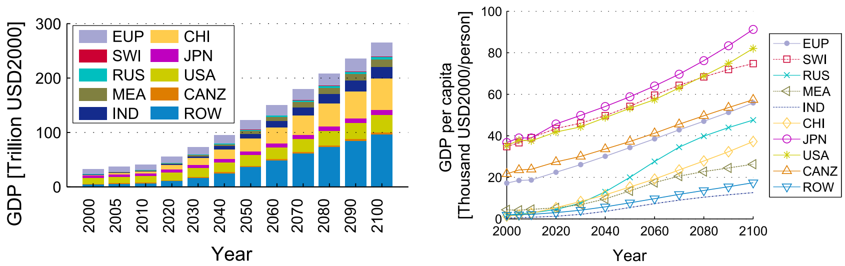
(A) *World* (B) *Switzerland*

FIGURE 3.1: *Reference scenario: Population*

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 3.1B).

3.1.2 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 3.2 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 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 3.2: *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.

3.1.3 Autonomous energy efficiency improvement (AEEI)

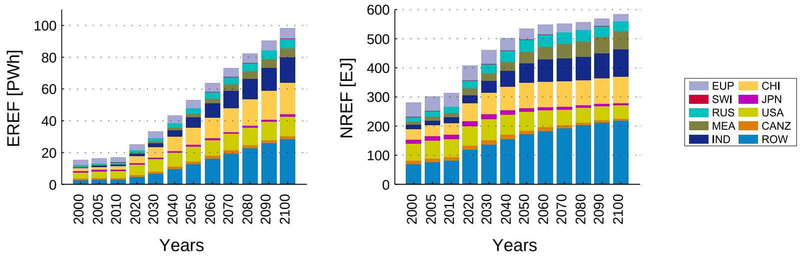
This variable reflects non-price driven changes in the economy-wide energy intensity. In previous versions of MERGE (Kypreos, 2007; Manne et al., 1995), the AEEI is assumed to be the same for both electricity and non-electric energy demand. Nevertheless, non-economic driven efficiency improvements for 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 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 3.2).

This scenario of electric and non-electric AEEI affects the reference electricity and non-electric demand. Figure 3.3 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.

3.2 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 for the reference scenario correspond to conventional resources.



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

FIGURE 3.3: *Reference electricity and non-electric energy demands*

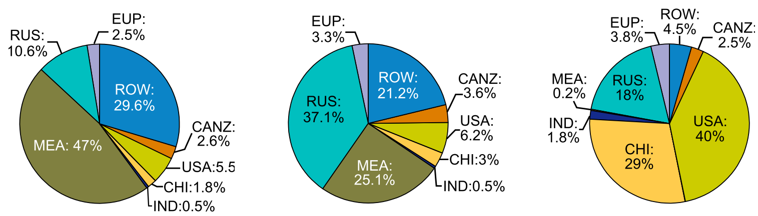
3.2.1 Fossil fuels

Table 3.1 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 3.1: *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 3.4A and 3.4B), while coal is mostly located in USA, China and Russia (see Figure 3.4C).

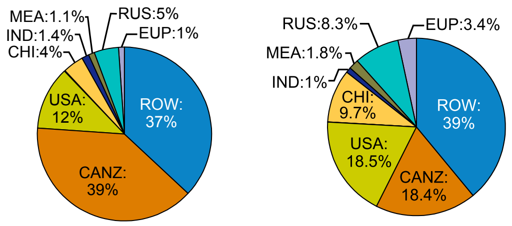


(A) *Oil* (B) *Gas* (C) *Coal*

FIGURE 3.4: *Fossil fuels: Proven reserves + Undiscovered Resources*

3.2.2 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 estimate 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 3.5 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 3.5: *Uranium resources*

3.2.3 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, 2005). 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 3.2 presents the estimated potential by region.

TABLE 3.2: *Regional biomass potentials by 2050 [EJ/a]. Based on IEA (2005) 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

The distribution among the cost categories (2, 4, 7 and 10 US$/GJ) is based on Ragettli (2007). These costs include the cost of truck transport from the place of harvest to the processing location (estimated to be a distance of 50 km).

3.2.4 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[1] 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 3.3: *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

3.2.5 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 studies estimate different potentials in the range from 2 to 4 TWh in 2050 (see Table 3.4).

  The wind potential in Switzerland for the reference scenario 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 3.5 presents the estimated solar PV potential of different studies in Switzerland.

[1] 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).

TABLE 3.4: *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

TABLE 3.5: *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 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.

3.3 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 3.6 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 A. MERGE-ETL represents different resources categories with different extraction costs. The estimates in Table 3.6 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 3.6: *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 3.8.

†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 3.6 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%. All the learning components have a floor cost, which corresponds to 20% to 50% of the initial investment cost.

3.3.1 CO_2-emissions coefficients

Table 3.7 presents the CO_2-emissions coefficients used in this version of MERGE-ETL for current and future technologies.

3.3.2 Nuclear cycle costs

The unit costs of the nuclear cycle are based on Chakravorty et al. (2009) and are presented in Table 3.8. Fabrication and reprocessing of the fuel account for the largest part of the costs, which are highly dependent on the type of reactor.

TABLE 3.7: *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. 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.

TABLE 3.8: *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

3.3.3 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 were estimated based on the work of Ecofys (Hendriks et al., 2004). Table 3.9 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).

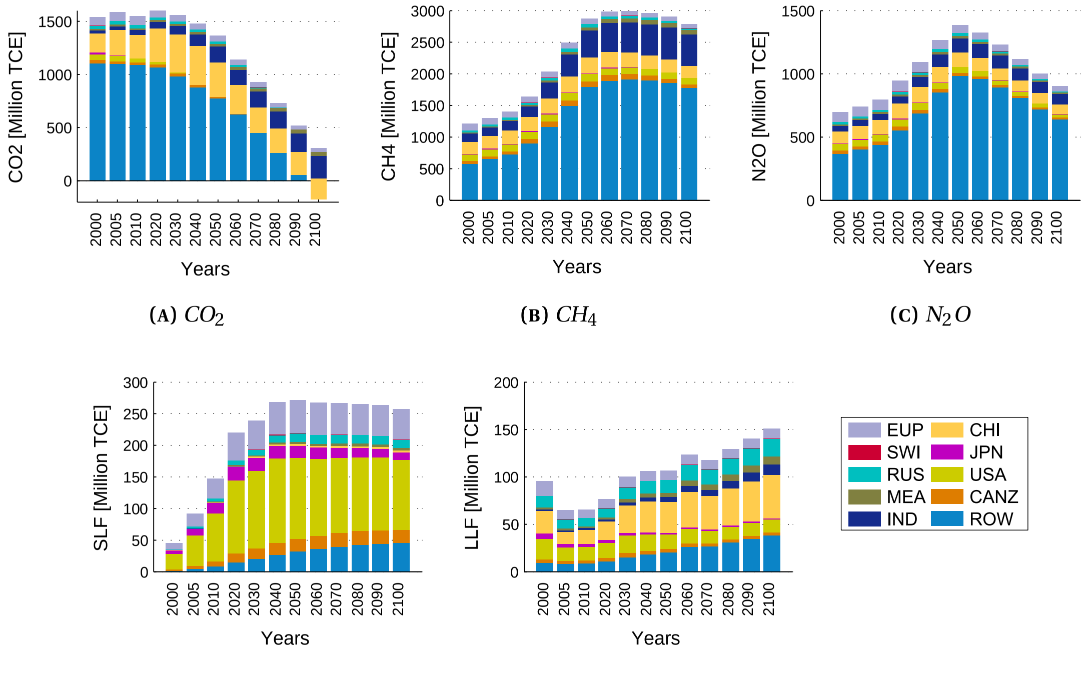
TABLE 3.9: *Carbon storage potential [GtCO$_2$]. Based on Hendriks et al. (2004)*

	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, which 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.

3.4 Non-energy emissions

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 3.6 shows the baseline of the different GHGs.



(A) CO_2 (B) CH_4 (C) N_2O (D) *SLF* (E) *LLF*

FIGURE 3.6: *Baseline non-energy related emissions. These emissions are an exogenous input for the emissions and climate submodel*

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Appendices

Appendix A

Technology characteristics in the Reference scenario

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.

TABLE A.1: *Studies included in the technology analysis*

2001-2011	EIA	Annual Energy Outlook 2001-2011 (EIA, 2001, 2002, 2003, 2004, 2005, 2006, 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 and NEA, 2005)
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, 2010)
	IEA/NEA	2010 Projected costs of generating electricity (IEA and NEA, 2010)

Table A.2 presents the electricity technology characteristics for the reference scenario. These values are based on the studies are presented in Table A.1.

TABLE A.2: *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.

The characteristics of the non-electric energy technologies are presented in Table A.3. 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 A.3: *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

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