PAUL SCHERRER INSTITUT

THE MERGE-ETL MODEL: MODEL DOCUMENTATION

Adriana Marcucci and Hal Turton

Energy Economics Group
Laboratory for Energy Analysis
The Energy Departments

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Paul Scherrer Institute
Laboratory for Energy System Analysis
Energy Economics Group

Tel. +41 56 310 4142
Villigen PSI, CH 5232
Switzerland

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Nomenclature / Abbreviations

AEEI .... Autonomous Energy Efficiency Improvements
BFS .... Swiss Federal Office of Statistics
bio .... Biomass
bio(CCS) .... Biomass with CCS
bio-FT .... Biomass to synthetic fuel
bio-FT(CCS) .... Biomass to synthetic fuel with CCS
bio-H2 .... Biomass to Hydrogen
bio-H2(CCS) ... Biomass to Hydrogen with CCS
CE .... Carbon equivalent
CES .... Constant elasticity of substitution
CF .... Capacity factor
CFC .... Chlorofluorocarbon
CHI .... China
coal-FT .... Coal to synthetic fuel
coal-H2 .... Coal to Hydrogen
coal-H2(CCS) .. Coal to Hydrogen with CCS
EAEEI .... AEEI rates for the electricity demand
eff .... Efficiency
EFR .... European Fast Reactor
EJ .... Exa-joule
ele-H2 .... Water to Hydrogen using electrolysis
EPR .... European Pressurized Reactor
EREF .... Electricity reference demand
EUP .... European Union region
FBR .... Fast breeder reactor
FOM .... Fixed operation and maintenance costs
FT .... Fischer-Tropsch
gas-FC .... Gas fuel cell
gas-H2 .... Gas to Hydrogen
gas-H2(CCS) ... Gas to Hydrogen with CCS
GJ .... Giga-joule
H_2 .... Hydrogen
HFC .... Hydrofluorocarbon
IEA .... International Energy Agency

IGCC .... Integrated Gasification Combined Cycle
IGCC(CCS) ..... Integrated Gasification Combined Cycle with CCS
IIASA .... International Institute for Applied Systems Analysis
IND .... India
JPN .... Japan
LBD .... Learning-by-doing
LBS .... Learning-by-searching
LLF .... Long-lived F-gases
LWR .... Light water reactor
MEA .... Middle East
NAEEI .... AEEI rates for the non-electric energy demand
NGCC .... Natural Gas Combined Cycle
NGCC(CCS) .... Natural Gas Combined Cycle with carbon capture and storage (CCS)
NREF .... Non-electric energy reference demand
nuc-H2 .... Nuclear to Hydrogen
OECD .... Organisation for Economic Co-operation and Development
PC .... Pulverized coal
PC(CCS) .... Pulverized coal with CCS
PEC .... Primary energy carrier
PFC .... Prefluorocarbons
ppt .... Part per trillion (volume)
RUS .... Russia
SEC .... Secondary energy carrier
SF_6 .... Sulfur Hexaflouride
SLF .... Short-lived F-gases
sth-H2 .... Solar thermal production of hydrogen
SWI .... Switzerland
ura .... Uranium
USD2000 .... US Dollars (2000)
VOM .... Variable operation and maintenance costs

List of symbols

Subindexes

g	Greenhouse gas
r	Region
t	Period
trd	Tradeable good
y	Technology

Economic submodel

a	Productivity factor
b	Productivity factor

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

Energy submodel

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

Nuclear cycle

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

u_o	Uranium ore
u_o^L	Uranium ore used by the LWR
u_o^F	Uranium ore used by the FBR
u_r^L	Reprocessed uranium from LWR spent fuel
u_{ri}^F	Reprocessed uranium used by FBR
u_{ro}^F	Reprocessed uranium from FBR spent fuel
ϵ	Ratio between enriched and depleted uranium

Endogenous technology learning

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

Climate submodel

A	Capacity fraction of atmospheric reservoirs
c	Atmospheric concentration
$catt$	Catastrophic temperature
hsk	Hockey-stick parameter
j	Atmospheric reservoirs
lg	Constant calibrating lag in the temperature increase
$nyper$	Number of years in a period
M	Magnitude of the impulse
S	climate sensitivity parameter
sul	Total sulfate emissions
T	Time constant for the absorption of the CO_2 by the ocean in each reservoir
x	Emission function
y	Atmospheric CO_2 response
y_δ	Atmospheric CO_2 response to an unitary impulse $\delta(t)$
τ	Mean lifetime of the gas
ΔAT	Actual temperature change
ΔF	Total radiative forcing
ΔF_{CFC}	Radiative forcing from CFCs
$\Delta F_{\mathrm{CH_4}}$	Radiative forcing from CH_4
$\Delta F_{\mathrm{CO_2}}$	Radiative forcing from CO_2
ΔF_{dir}	Direct radiative forcing from sulfate aerosols
ΔF_{indir}	Indirect radiative forcing from sulfate aerosols
$\Delta F_{\mathrm{N_2O}}$	Radiative forcing from N_2O
ΔQ	Change in heat flux absorbed by the ocean
ΔPT	Potential temperature change
ΔT	Temperature change

$\Delta T_{2\times CO_2}$	Equilibrium climate sensitivity

Chapter 1

The MERGE-ETL model

MERGE (Model for Evaluating Regional and Global Effects of GHG reductions policies) is an integrated assessment model originally developed by Manne et al. (1995). It divides the world in geopolitical regions, each one represented by two coupled submodels describing the energy and economic sectors, respectively. MERGE acts as a global social planner with perfect foresight and determines the economic equilibrium in each region that maximizes global welfare, defined as a linear combination of the current and future regional welfares. Besides these regional energy-economic submodels, and linked to them, MERGE includes global submodels of greenhouse gas emissions and the climate to allow the analysis of the effectiveness and impacts of climate policies and the role of technologies to realize climate targets. Figure 1.1 presents a simplified diagram of the structure of the model showing the inputs (highlighted in red), outputs and linkages between submodels.

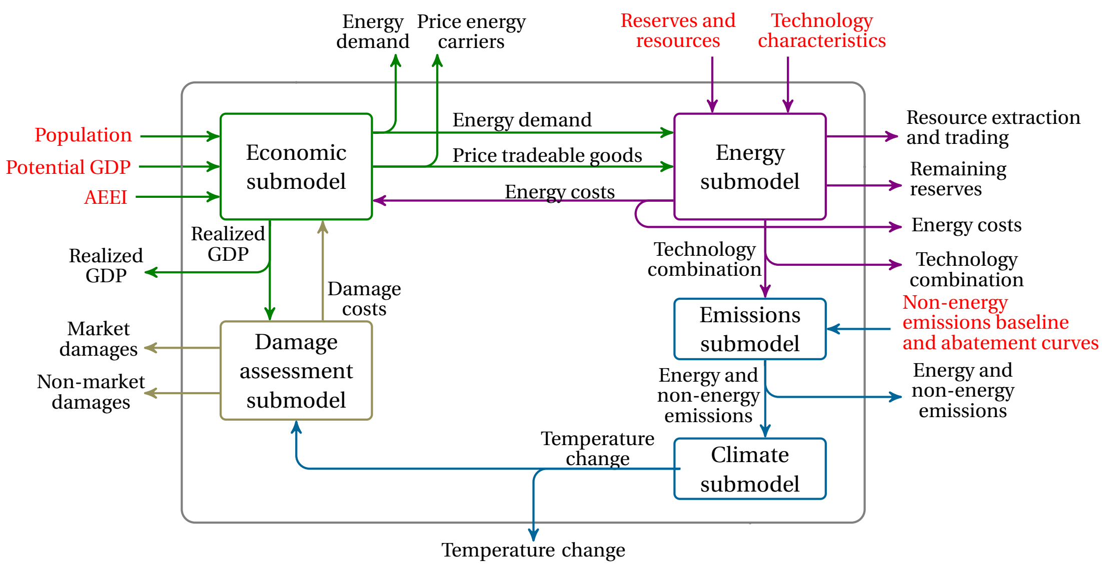


FIGURE 1.1: *MERGE-ETL model structure. Inputs to the model are highlighted in red, outputs are presented in black font coming from the different submodels.*

The economic submodel (see Chapter 2) is a top-down model that determines energy demand and prices as well as economic output (realized GDP) for each region. It is parametrized using exogenous inputs on population, potential GDP and autonomous energy efficiency improvements (AEEI);

and the energy costs obtained from the energy submodel. The energy submodel (see Chapter 3) is a bottom-up description of the energy sector that includes endogenous technology learning (ETL) to account for the effect that the accumulation of experience and knowledge might have on the technology development (Manne and Barreto, 2004). The energy submodel determines the technology combination; resource extraction and trading; and research and development expenditures that maximize the global welfare and satisfy energy demands given by the economic submodel and climate objectives (Manne et al., 1995). The main exogenous inputs comprise detailed technology characteristics (costs, efficiencies, lifetimes and load factors) and resource restrictions. The combination of these two submodels adds a value to MERGE compared to bottom-up or top-down models, since energy demands and prices are determined endogenously and at the same time technological options can be analyzed in detail in MERGE's bottom-up energy sector submodel.

The emissions submodel (see Chapter 4) determines energy and non-energy related emissions based on the technology combination obtained by the energy submodel and a non-energy emissions baseline assumed exogenously. With these emissions, the climate submodel determines global mean temperature changes. The damage assessment submodel (see Section 4.4) determines market and non-market damages using the temperature change.

This document is based on the PhD Thesis Marcucci (2012).

Chapter 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 and with the objective of maximizing global welfare. Supplies and demands are equilibrated every time period, through the prices of traded goods, which include energy commodities, an energy-intensive good and a numeraire good. The numeraire good represents the production of all goods but energy and it is assumed to be identical for all the regions (Manne et al., 1995).

2.1 Domestic supply and demand

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

$$Y_{r,t} = I_{r,t} + C_{r,t} + EC_{r,t}. \tag{2.1}$$

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

$$Y_{r,t} = YN_{r,t} + d \cdot Y_{r,t-1}. \tag{2.2}$$

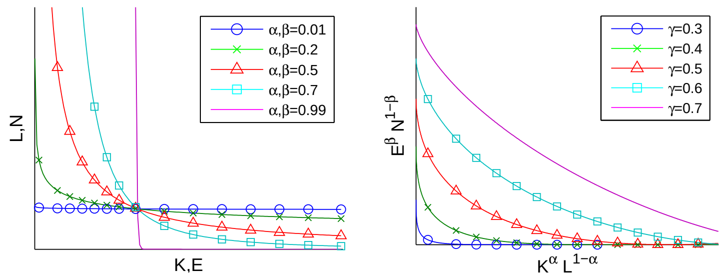
The new output in each region is represented through a nested CES (constant elasticity of substitution) production function (Manne and Richels, 2004). Production of new economic output ($YN_{r,t}$), for each region r, in each period t, is determined by four inputs governed by transition equations similar to the one used for total output (Equation 2.2): new capital ($KN_{r,t}$), new labour ($LN_{r,t}$), new electricity ($EN_{r,t}$) and new non-electric energy ($NN_{r,t}$), thus, based on Manne and Richels (2004),

$$YN_{r,t} = \left[a \left(KN_{r,t}^{\alpha} LN_{r,t}^{1-\alpha} \right)^{\gamma} + b \left(EN_{r,t}^{\beta} NN_{r,t}^{1-\beta} \right)^{\gamma} \right]^{1/\gamma} \tag{2.3}$$

This production function implies three types of substitution:

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

  Figure 2.1A shows the isoquant curves for these first two types of substitution. When the share (α, β) tends to 0 or 1 (L-shape curves) the inputs are poor substitutes. In the intermediate values of β (or α for the K-L bundle) the inputs are considered better substitutes. In the current version, the share for the capital-labour bundle, α, changes across regions and it is assumed to be around 0.3 and the share for the energy bundle, β, is 0.45 in all the regions (Kypreos, 2007). This means that capital and labour, and electricity and non-electric energy are substitutable to some extent.
- between the two pairs of inputs, capital-labour and electricity-non electric energy. This is modeled with a constant elasticity substitution (CES), where $\gamma = (\sigma - 1)/\sigma$, σ being the constant elasticity of substitution. Thus, this formulation allows the substitution between the capital-labour ($K^\alpha L^{1-\alpha}$) and the energy ($E^\beta N^{1-\beta}$) bundles (Manne and Richels, 2004). Figure 2.1B presents the isoquant curves for the CES production function. When value σ tends to 0 the bundles are modeled as perfect compliments; and when it tends to 1 they are modeled as perfect substitutes. In MERGE-ETL, different values are assumed for different regions in the vicinity of 0.5 (Kypreos, 2007).



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

FIGURE 2.1: *MERGE production function*

The parameters a and b in Equation 2.3 represent productivity factors, i.e. they account for changes in output not caused by changes in the quantity of inputs in the production function. These productivity factors are estimated from an exogenous scenario of 'potential' GDP growth and autonomous energy efficiency improvements (AEEIs). The potential (or reference) GDP pathway can be interpreted as representing productivity improvements, economic output and energy demand at constant energy prices. In MERGE this reference GDP does not exclusively determine the realized GDP due to the energy-economic interactions. A climate policy, for example, will produce an increase in energy costs, leading in turn to a substitution between the energy bundle and the capital-labour bundle in production, and some reduction in economic output (Manne et al., 1995). The AEEI parameter accounts for changes in energy consumption not driven by prices, e.g. increases in the efficiency of electrical appliances, or structural changes to either more or less energy-intensive types of industry, etc. For more details on the estimation of the reference scenario see Appendix A.1.

2.2 Intertemporal optimization

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

$$\max \sum_r w_r u_r, \tag{2.4}$$

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

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

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

where $C_{r,t}$ and $\rho_{r,t}$ are the consumption and the social discount factor of region r in period t, respectively. Notice that in this case the utility is measured as the logarithm of the consumption adjusted by the $ELF_{r,t}$ parameter, which represents an economic loss factor due to the impact of climate change (see Section 4.4).

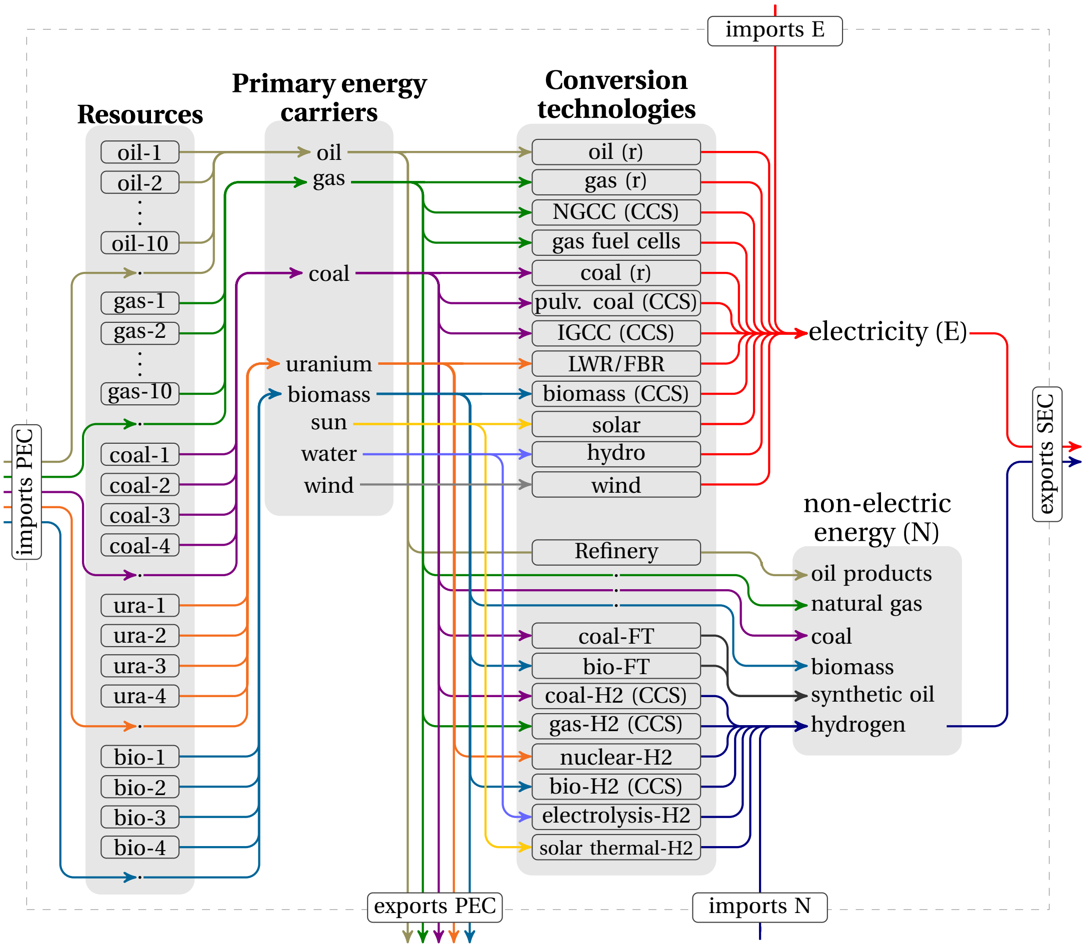
For a logarithmic utility function, the solution of the social planner maximizing problem (Equation 2.4) gives the following "optimal steady-state growth path" (Manne et al., 1995) (See Appendix A.2 for a proof of this optimal growth path),

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

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

Chapter 3

Energy submodel



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

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

The energy submodel determines the optimal combination of conversion technologies to supply electric and non-electric energy to the rest of the economy, i.e. E and N in Equation 2.3, subject to restrictions on resource availability and depletion. In MERGE-ETL, the energy sector in each region is represented by a reference energy system like that shown in Figure 3.1. In the first step, primary energy carriers (PEC) are either extracted from resources in the region or imported from another region. The extraction technologies cover oil, gas, coal, uranium and biomass. The primary energy carriers are then exported to other regions or processed by the conversion technologies to produce secondary energy carriers (SEC); that is, electricity and non-electric energy carriers. Non-electric energy carriers comprise oil products, natural gas, coal, biomass, synthetic oil and hydrogen.

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

3.1 Resource extraction technologies

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

3.2 Energy and electricity trading

MERGE-ETL models inter-regional trading (with a trading cost) of primary energy carriers (as shown in Figure 3.1); the numeraire good[1]; emission permits; and energy intensive products, such as steel and cement (Manne and Richels, 2004). Additionally, for this work, trading of electricity between regions has been included to better represent the geographic location of Switzerland and its access to the European network. This is of particular relevance for the analysis of the future Swiss energy system since Switzerland is integrated into the European electricity grid and future options to supply Swiss electricity demand can include a larger share of imports from neighboring countries.

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

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

where $X_{r,t,trd}$ corresponds to the exports minus imports of the region r, in the period t, for tradeable

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

good *trd*. Each of these balance equations has a price associated (shadow price of the restriction) that corresponds to the trading price of the tradeable good (Manne and Richels, 2004).

The economic output allocated to the production of net exports of the numeraire good is represented by adding a term to Equation 2.1, thus,

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

3.3 Conversion technologies

Conversion technologies transform primary energy carriers to either electricity or non-electric final energy carriers. Various characteristics of each conversion technology are represented in the model, such as efficiency, load factor, investment cost, and operation and maintenance expenditures. These determine the levelized cost of each energy carrier, along with fuel consumption and emissions. Future characteristics (and hence costs) of conversion technologies are highly uncertain.

TABLE 3.1: *Electricity technologies*

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

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

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

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

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

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

- Nuclear technologies included in MERGE comprise light water and fast breeder reactors. Section 3.5 presents a description of the nuclear fuel cycle included in MERGE.

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

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

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

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

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

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

TABLE 3.2: *Non-electric energy production technologies*

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

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

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

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

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

  - Hydrogen from natural gas (gas-H2) using steam reforming.
  - Production of hydrogen from coal (coal-H2) is based on a water shift reaction of the syngas produced from coal gasification (Hawkins and Joffe, 2005).
  - Hydrogen from biomass (bio-H2) can be produced using gasification and pyrolysis followed by a reforming process (Hawkins and Joffe, 2005).
  - Electrolysis (ele-H2) allows the use of electricity to produce hydrogen by splitting water into hydrogen and oxygen (Gül, 2008).

- The thermochemical production of hydrogen from nuclear energy (nuc-H2) consists on a sulphur-iodine cycle where the water is split and hydrogen is thermally produced (Nuclear Energy Agency, 2006).
- Solar-thermal hydrogen (sth-H2) is produced through a hydrolysis process that converts water into hydrogen and oxygen using zinc as catalyst (IEA, 2011).

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

3.4 Technology deployment and retirement

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

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

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

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

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

3.5 Nuclear cycle

Nuclear generation contributes an important share to current global electricity generation and it has a considerable potential to provide low-carbon electricity. However, the conversion from natural uranium to electricity is more complicated than the conversion process with fossil fuels. To represent this, MERGE-ETL includes a simplified model of the nuclear fuel cycle (see Figure 3.2). This nuclear cycle includes two types of reactors, a light water and a fast breeder, and models the flows of the different types of uranium, plutonium and wastes. It is based on Chakravorty et al. (2009).

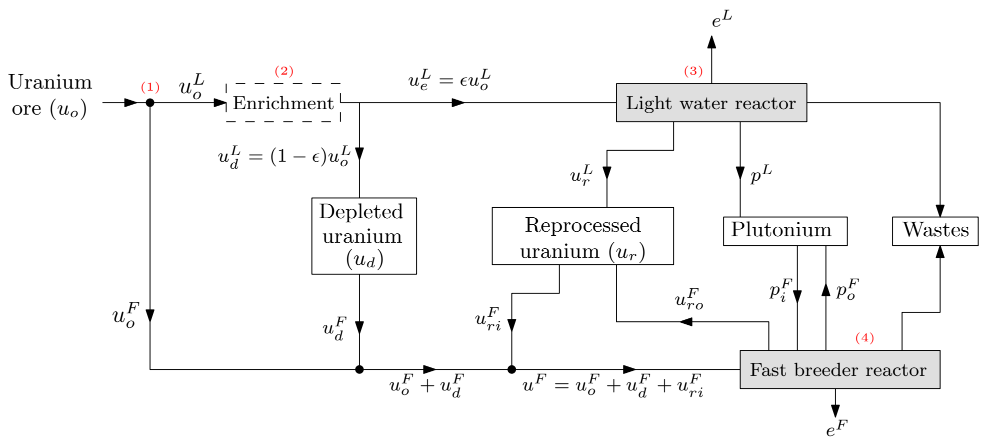


FIGURE 3.2: *Nuclear Cycle*

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

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

(3) The Light Water Reactor (LWR) uses enriched uranium, producing energy (e^L), reprocessed uranium (u_r^L), plutonium (p^L) and wastes. The light water reactor is modeled based on the European Pressurized Reactor (EPR), with the input-output relationship presented in Figure 3.3.

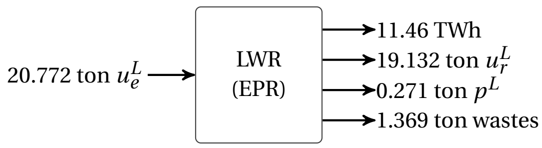


FIGURE 3.3: *Inputs and outputs of the LWR*

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

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

(4) The Fast Breeder Reactor (FBR) uses a combination of uranium from uranium ore (u_o^F), depleted uranium from the enrichment process (u_d^F), and reprocessed uranium (u_{ri}^F). These different

types of uranium are assumed to be substitutes, thus: $u^F = u_o^F + u_{ri}^F + u_d^F$. Besides uranium, the FBR uses plutonium (p_i^F). The uranium and plutonium inputs are assumed to be used in a fixed proportion, $\frac{u^F}{p_i^F} = k$. The FBR produces energy (e^F), reprocessed uranium (u_{ro}^F), plutonium (p_o^F) and wastes. The ratio between uranium input and reprocessed uranium output is assumed to be a fixed proportion, $\frac{u^F}{u_{ro}^F} = k_u$. The Fast Breeder Reactor is modeled based on the European Fast Reactor (EFR), with the input-output relationship presented in Figure 3.4.

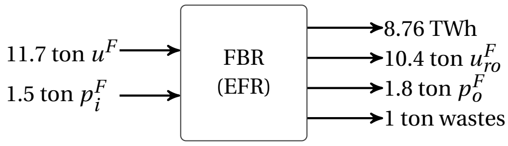


FIGURE 3.4: *Inputs and outputs of the FBR*

3.6 Endogenous technology learning

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

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

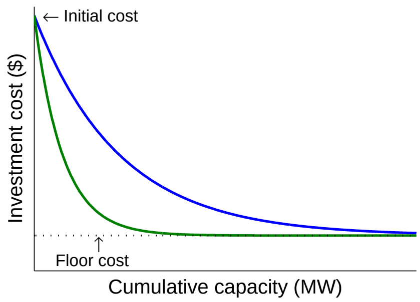


FIGURE 3.5: *Endogenous technology learning*

The first learning factor, often called "learning-by-doing" (LBD), models the possibility of achieving declining investment costs with the accumulation of experience on the production of a technology. The accumulation of experience is assumed to be reflected by the cumulative installations of a technology, and therefore, as shown in Figure 3.5, the learning curve describes investment cost as a function of the cumulative capacity (Magne et al., 2010). For this factor, the investment cost for the y-technology declines with the installed capacity until it reaches a floor cost, thus,

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

where A_y is a constant calibrated with the initial cost and capacity; CC_y is the cumulative capacity; b_y is the learning index, which reflects the effectiveness of the learning process for the y-technology; and l_y is the floor cost of the y-technology. The two different learning curves presented in Figure 3.5 illustrate an example of two technologies with the same initial investment cost, the same floor cost but different learning indices.

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

$$inv_y = \begin{cases} A_y \cdot CC_y^{-b_y} CRD_y^{-c_y} & \text{if } inv_y \geq l_y, \\ l_y & \text{otherwise,} \end{cases} \tag{3.2}$$

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

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

Accordingly, the two factor learning represented in Equation 3.2 is applied at the level of key components. The key components included in MERGE-ETL and their relationships with the conversion technologies are presented in Table 3.3.

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

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

Chapter 4

Emissions, climate and damage assessment submodels

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

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

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

4.1 Emissions and abatement

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

Non-energy emissions are specified with an exogenous baseline . The model allows the abatement of these emissions using abatement cost curves (also given exogenously, based on Manne and Richels (2004)).

4.2 Climate submodel

The climate submodel represents carbon and non-CO_2 gases cycles to estimate atmospheric concentration of GHGs, and then calculates the radiative forcing and global temperature change. This section presents in detail the climate submodel, assumed to have fixed physical constants and presents an additional comparison with other integrated assessment models.

4.2.1 Carbon cycle

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

$$y(t) = \int_0^{\tau} (A_0 + \sum_{j=1}^{4} A_j e^{-(t-\tau)/T_j}) x(\tau) d\tau \tag{4.1}$$

where A_0 represents the emitted CO_2 that remains in the atmosphere after many thousand of years. Maier-Reimer and Hasselman (1987) estimated A_0 around 0.15, consistent with more recent studies that estimate this fraction to 19±4% (Solomon et al., 2010). The other 4 terms (indexed with j) can be interpreted as independent atmospheric reservoirs, with A_j capacity fraction and T_j being the time constant for the absorption of the CO_2 by the ocean[1]. Using equation 4.1, the atmospheric CO_2 response $y_\delta(t)$ to an unitary impulse $\delta(t)$ is given by,

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

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

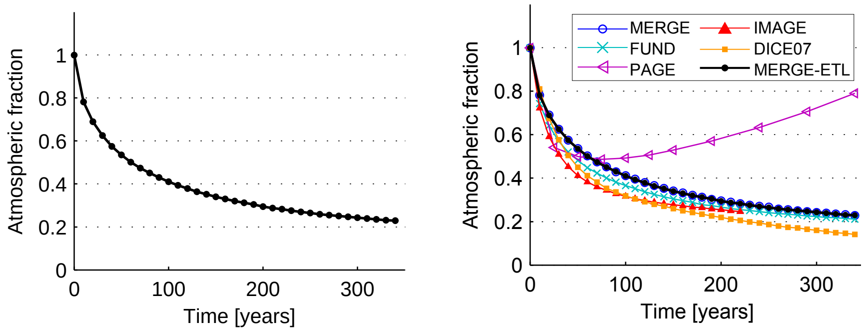
	Reservoir				
	0	1	2	3	4
A_j	0.142	0.241	0.323	0.206	0.088
T_j [years]	∞	313.8	79.8	18.8	1.7

Figure 4.1A presents the unitary impulse response of the carbon cycle in MERGE-ETL. After 100 years 40% of the emitted CO_2 remains in the atmosphere and after 300 years the atmospheric fraction is reduced to around 20%. When comparing with other integrated assessment models[2] (see Figure 4.1B)

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

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

and other climate models[3]presented in van Vuuren et al. (2011), MERGE-ETL has a relatively slow decay in the first 200 years but an overall picture consistent with the behavior of all the models.



(A) *MERGE-ETL*

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

FIGURE 4.1: *Impulse response carbon cycle. Compared to DICE99 (Nordhaus, 1999), DICE07 (Nordhaus, 2008), FUND 2.8 (Tol, 2006), IMAGE (Bowman et al., 2006), MAGICC (Wigley), MERGE (Manne and Richels, 2004) and PAGE2002 (Hope, 2006).*

4.2.2 Non-CO_2 gases

The behavior in the atmosphere of the other greenhouse gases is modeled using a single reservoir representation, based on Intergovernmental Panel in Climate Change (IPCC) (1997, App. 1), thus, for the gas g,

$$\frac{dc_g(t)}{dt} + \frac{1}{\tau_g} c_g(t) = x_g(t), \tag{4.2}$$

where $c_g(t)$ represents the concentration, $x_g(t)$ is an arbitrary emission function and τ_g is the mean lifetime of each gas [4].

The atmospheric concentration for the other greenhouse gases is calculated using the impulse response in Equation 4.2, thus,

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

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

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

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

4.3 Temperature increase

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

For the greenhouse gases, the change in radiative forcing is calculated using the simplified expressions presented in Table 4.1 based on the IPCC Third Assessment Report (Intergovernmental Panel in Climate Change (IPCC), 2001b, Table 6.2). These expressions depend on the current concentration of each greenhouse gas: CO_2 [ppm], CH_4 [ppb], N_2O [ppb], SLF [ppb] and LLF [ppb]; and the pre-industrial concentration indicated with the subindex o. The concentrations of CO_2, CH_4, N_2O, SLF and LLF are estimated endogenously in the model. For the chlorofluorocarbons, we assume that their effect on the world radiative forcing does not change among scenarios because they are regulated under the Montreal Protocol, thus their production ended in 1996 and 2010 for developed and developing regions, respectively (Fahey and Hegglin, 2011).

TABLE 4.1: *Radiative forcing for each greenhouse gas. Based on Intergovernmental Panel in Climate Change (IPCC) (2001b, p. 358)*

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

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

[†]Corresponds to the HFC-134a value

[‡]Corresponds to the SF_6 value

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

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

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

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

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

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

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

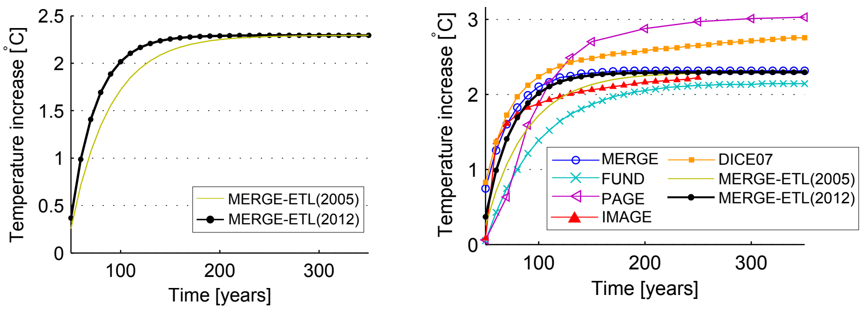
The equilibrium climate sensitivity ($\Delta T_{2\times CO_2}$) is the global average temperature change produced by a doubling in the CO_2 concentration (Knutti and Hegerl, 2008), $\Delta T_{2\times CO_2} = S \cdot 5.35 \ln(2)$ (see Table 4.1). In the version of MERGE-ETL, we define the climate sensitivity $\Delta T_{2\times CO_2} = 2.3$°C, consistent with the ranges presented in Knutti and Hegerl (2008) and Intergovernmental Panel in Climate Change (IPCC) (2007), thus $S = \Delta T_{2\times CO_2}/5.35 \ln(2)$. The potential temperature change (ΔPT), defined as the long-run temperature that will occur if forcing level is kept constant indefinitely, is calculated as,

$$\Delta PT = \frac{\Delta T_{2\times CO_2}}{5.35 \ln(2)} \Delta F. \tag{4.3}$$

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

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

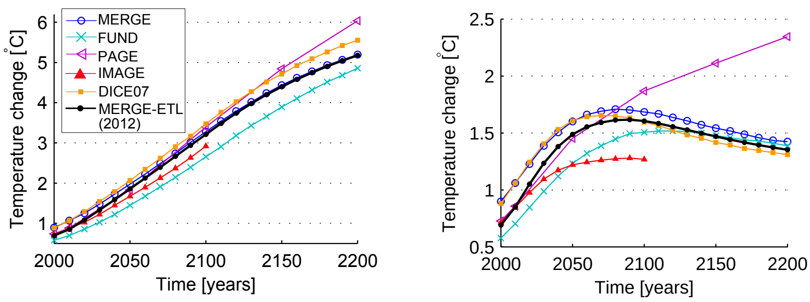
where ΔAT_t represents the actual temperature change in the period t compared to the base year; $nyper_t$ represents the number of years of the period t; and $(1 - lg)$ represents the yearly decay of the actual temperature increase with lg being a constant. This constant was calibrated to reduce the lag between the potential and the actual temperature increase. Figure 4.2A presents the actual temperature increase resulting by a doubling in CO_2 concentration (modeled by a step in radiative forcing of 3.7 m^2/W) for the previous version of MERGE-ETL (Kypreos, 2005) and this version. Comparing with the response of other IAMs (see Figure 4.2B) the new calibrated MERGE-ETL has a delay in the actual temperature change closer to most of the other models.



(A) *MERGE-ETL* (B) *Comparison with other IAMs. Modified from van Vuuren et al. (2011)*

FIGURE 4.2: *Temperature change produced by a doubling in CO_2 concentration*

Two additional experiments were developed to analyze the response of the climate submodel and then compared to the response of other IAMs presented in van Vuuren et al. (2011). These experiments considered high and low CO_2 emissions scenarios, corresponding to the IPCC's A2 scenario (Nakicenovic, 2000) and a 450ppm CO_2e scenario, respectively. Figure 4.3 presents the temperature change for the two experiments. The behavior of the new calibrated climate submodel in MERGE-ETL in both experiments is comparable to the other IAM's and the climate models shown in van Vuuren et al. (2011).



(A) *IPCC's A2 scenario* (B) *450ppm CO_2e*

FIGURE 4.3: *Climate submodel response. Modified from van Vuuren et al. (2011)*

4.4 Damages

Manne and Richels (2004) included the assessment of market and non-market damages of climate change in MERGE. The market damages are estimated assuming that a rise in temperature of 2.5°C would lead to GDP losses of 0.25% in the high income nations and 0.5% in the low-income ones (Manne and Richels, 2004). At higher or lower temperatures than 2.5°C the losses are estimated proportionally to the temperature increase. Market damages are subtracted from the economic output

(Y_t) shown in Equation 2.1. For non-market damages, the expected losses are assumed to increase quadratically with the temperature increase. This was modeled by Manne and Richels (2004) using an "economic loss factor" (*ELF*), that is given by:

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

where *catt* is the catastrophic temperature and *hsk* is the hockey-stick parameter. The catastrophic temperature is the temperature after which the economic output of the region will be 0. The catastrophic temperature parameter is specified such that 5.5°C warming corresponds to a loss in GDP of 10% when *hsk*=1. The hockey-stick parameter determines how sensitive the losses are to a change in the actual temperature, e.g. if *hsk*=1, the loss is quadratic with ΔAT (Manne and Richels, 2004). In MERGE-ETL the hockey-stick parameter changes among regions and periods. Figure 4.4 presents the economic loss factor (*ELF*) for the different possible values of *hsk*. Less developed regions have lower *hsk*.

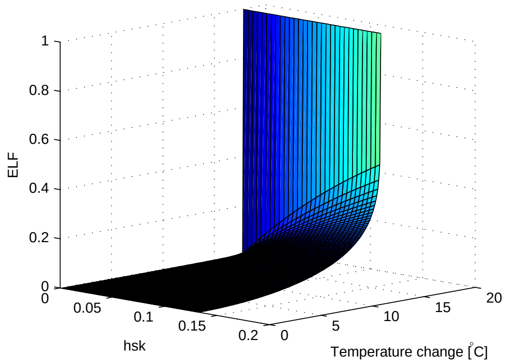


FIGURE 4.4: *Economic loss factor*

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

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Appendices

Appendix A

Economic submodel

A.1 Reference scenario

The reference scenario comprises an important set of assumptions for the parametrization of MERGE and, therefore, the development of the future energy system. This appendix shows the assumptions and calculation of this reference scenario. It is calculated using as an input a scenario of potential (or reference) GDP and autonomous energy efficiency improvements (AEEI). The potential GDP pathway can be interpreted as representing economic output at constant energy prices. The AEEI measures changes in energy consumption not driven by prices, e.g. increase in the efficiency of electrical appliances, or changes to either more or less energy intensive types of industry, etc. (Manne et al., 1995)[1]. From this potential (or reference) GDP scenario and AEEIs the following can be calculated:

- A reference energy demand: This is the energy demand implied by the scenario of potential GDP growth (g) and the non-price AEEIs, in a hypothetical case with constant prices. It can be calculated as follows:

$$
\begin{aligned}
E_{ref,t+1} &= E_{ref,t}\left(1+g_t\right)\left(1-EAEEI_t\right) \\
N_{ref,t+1} &= N_{ref,t}\left(1+g_t\right)\left(1-NAEEI_t\right),
\end{aligned}
$$

  where $E_{ref,t}$ and $N_{ref,t}$ correspond to the electricity and non-electric reference demand in the period t; and *EAEEI* and *NAEEI* are the assumed autonomous energy efficiencies for the electricity demand and the non-electric energy carrier consumption, respectively.

- Reference prices: The reference scenario is estimated by solving the production problem in each region, that is,

$$
\max Y_t - \left(pk_t K_t + pl_t L_t + pe_t E_t + pn_t N_t\right),
$$

  where $Y_t = \left[a\left(K_t^{\alpha} L_t^{1-\alpha}\right)^{\gamma} + b\left(E_t^{\beta} N_t^{1-\beta}\right)^{\gamma}\right]^{1/\gamma}$ (see Equation 2.2); and pk_t, pl_t, pe_t and pn_t are the prices of capital, labor, electricity and non-electric energy in the period t. The relationship be-

[1] Note, although MERGE is a multiregional model, for simplicity equations below are presented without a region index.

tween the price of electricity and non-electric energy is obtained from the first-order optimality conditions, thus,

$$\begin{aligned} pe_t &= b\beta \cdot Y_t^{1-\gamma} \cdot E_t^{\beta\gamma-1} N_t^{(1-\beta)\gamma} \\ pn_t &= b(1-\beta) \cdot Y_t^{1-\gamma} \cdot E_t^{\beta\gamma} N_t^{(1-\beta)\gamma-1}. \end{aligned} \tag{A.1}$$

Therefore, for the reference case,

$$pe_{ref,t} = \frac{\beta \cdot pn_{ref,t} \cdot N_{ref,t}}{(1-\beta) \cdot E_{ref,t}}.$$

- Reference gross output: The gross output corresponds to the net output (GDP) plus the intermediate consumption, thus, the gross output in the reference scenario ($Y_{ref,t}$) is estimated as,

$$Y_{ref,t} = \text{GDP}_{pot,t} + pe_{ref,t} \cdot E_{ref,t} + pn_{ref,t} \cdot N_{ref,t}.$$

- Reference labour ($L_{ref,t}$): The reference labour is measured in "efficiency units" (Manne, 1991); it is assumed to be 1 in the base year and to grow with the growth rate of the potential GDP.
- Reference capital: The reference capital ($K_{ref,t}$) corresponds to:

$$K_{ref,t} = kgdp \cdot \text{GDP}_{pot,t},$$

where *kgdp* is the capital-GDP ratio assumed exogenously (based on (Manne et al., 1995)) .

- Productivity factors. Using Equations 2.2 and A.1, and the previously presented reference case, the parameters a_t and b_t are calibrated, thus,

$$b_t = \frac{pn_{ref,t} \cdot Y_{ref,t}^{\gamma-1}}{(1-\beta) \cdot E_{ref,t}^{\beta\gamma} N_{ref,t}^{(1-\beta)\gamma-1}} \quad \text{and} \quad a_t = \frac{Y_{ref,t}^{\gamma} - b_t \left(E_{ref,t}^{\beta} N_{ref,t}^{1-\beta}\right)^{\gamma}}{\left(K_{ref,t}^{\alpha} L_{ref,t}^{1-\alpha}\right)^{\gamma}}$$

A.2 Discount rate

Following Manne (1995), let's assume we have a single agent economy that acts as consumer, producer, investor and saver. Without depreciation, the capital formation for this economy is given by,

$$K_{t+1} = K_t + I_t \tag{A.2}$$

where K_t and I_t are, respectively, capital and investments in period t. Additionally, from equation 2.1, we know that the economy output (Y_t) can be allocated between consumption (C_t), investment and energy costs (EC_t), thus,

$$Y_t = I_t + C_t + EC_t. \tag{A.3}$$

Therefore, the social planner aims to maximize the discounted utility subject to Equations A.2 and A.3, thus,

$$\begin{aligned} &\max \sum_{t=1}^{T} \frac{1}{\left(1+\rho\right)^{t}} \log\left(C_t\right) \\ &\text{s.t. } K_{t+1} = K_t + I_t \\ &\qquad Y_t = I_t + C_t + EC_t. \end{aligned}$$

The restrictions of this problem can be combined into one, thus,

$$\begin{aligned} &\max \sum_{t=1}^{T} \frac{1}{\left(1+\rho\right)^{t}} \log\left(C_t\right) \\ &\text{s.t. } Y_t = K_{t+1} - K_t + C_t + EC_t. \end{aligned} \tag{A.4}$$

The Lagrangian for this optimization problem corresponds to:

$$\mathscr{L} = \sum_{t=1}^{T} \frac{1}{\left(1+\rho\right)^{t}} \log\left(C_t\right) + \sum_{t=1}^{T} \lambda_t \left(Y_t - K_{t+1} + K_t - C_t - EC_t\right)$$

The first order optimality conditions for this problem are:

$$\begin{aligned} \frac{\partial \mathscr{L}}{\partial C_t} &= \frac{1}{\left(1+\rho\right)^{t}} \frac{1}{C_t} - \lambda_t = 0 \\ \frac{\partial \mathscr{L}}{\partial C_{t-1}} &= \frac{1}{\left(1+\rho\right)^{t-1}} \frac{1}{C_{t-1}} - \lambda_{t-1} = 0 \\ \frac{\partial \mathscr{L}}{\partial K_t} &= -\lambda_{t-1} + \lambda_t \left(\frac{\partial Y_t}{\partial K_t} + 1\right) \end{aligned} \tag{A.5}$$

From the three first order conditions in Equation A.5 we obtain:

$$\begin{aligned} \frac{\partial Y_t}{\partial K_t} + 1 &= \left(1+\rho\right) \frac{C_t}{C_{t-1}} \\ mpc_t + 1 &= \left(1+\rho_t\right)\left(1+g_t\right) \end{aligned}$$

where $\frac{\partial Y_t}{\partial K_t} = mpc_t$ is the marginal productivity of capital in period t and corresponds to the discount rate rate of goods and services; and g_t is the growth rate in period t of consumption, which for the optimal path equals the growth rate of output. Using the approximation $\left(1+\rho\right)\left(1+g\right)^{\epsilon} = 1+\rho+\epsilon g$, where $\epsilon \in \mathbb{Z}^{+}$ and equals 1 in this case, we obtain,

$$mpc_t = \rho_t + g_t.$$

The approach used in the calibration of the model is to choose a marginal productivity of consumption exogenously and a scenario of potential GDP (see Appendix A.1). This scenario has a specific growth rate g_t and implies a certain utility discount factor that represents a choice between consumption by current and future generations.