Appendix A: Model description IMACLIM-R

1. Introduction

IMACLIM-R was developed to analyze, amongst the drivers of baseline and policy scenarios, the relative role of *(i) technical parameters* in the supply side and in end-use equipments, *(ii) structural changes* in the final demand for goods and services (dematerialization of growth patterns), *(iii) micro and macroeconomic* behavioral parameters in open economies. This is critical to understand the mechanisms at play in a given transformation regarding economic cost and the widening or narrowing margins of freedom for mitigation or adaptation.

IMACLIM-R tries to reach this objective based on a twofold diagnosis about the design of baseline scenarios.

- The increasing recognition that endogenizing technical change to capture policy induced transformation of the set of available techniques should be broadened to the endogenization of *structural* change. As noted by Solow (1988), the rate and direction of technical progress depend not only on the efficiency of physical capital on the supply side but also on the structure of the final households' demand. Ultimately they depend on the interplay between consumption styles, technologies and localization patterns. The point is that drastic departures from current trends possibly required by sustainability targets cannot but alter the very functioning of the macroeconomic growth engine.
- Although computable general equilibrium models help to understand economic interdependences that are critical for the environment-economy interface, their limit is to study equilibrated growth pathways, often under perfect foresight assumptions. Nevertheless sustainability challenges result primarily from controversies about long term risks which can inhibit their internalization in due time and from the transition costs to adapt to unexpected hazards. This makes it necessary to describe an economy with disequilibrium mechanisms triggered by the interplay between inertia, imperfect foresight and 'routine' behaviours. For instance, an economy with structural debt or unemployment and submitted to volatile energy prices will not react in the same way to environmental shocks or policy intervention as an economy situated on a steady state growth pathway.

2. Model structure

2.1. General framework

IMACLIM-R is based on an explicit description of the economy both in money metric values and in physical quantities linked by a price vector. This dual vision of the economy is a precondition to guarantee that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and consistent sets of relative prices. For the very subject of climate change mitigation, which implies the necessity to account for physical energy flows, modelers use so-called 'hybrid matrices' including consistent economic input-output tables and physical energy balances (Sands et al., 2005). In the next versions of IMACLIM-R we aim at extending physical accounting to other non-energy relevant sectors such as transportation (passenger-kilometres, ton-kilometres) or industry (tons of steel, aluminium, cement). The existence of explicit physical variables allows a rigorous incorporation of sector based information about how final demand and technical systems are transformed by economic incentives, especially for very large variations from the reference scenario. This information encompasses (i) engineering based analysis about economies of scale, learning by doing mechanisms and saturation in efficiency progress (ii) expert views about the impact of incentive systems, market or institutional imperfections and the bounded rationality of economic behaviors.

But the full potential of this dual description could not be exploited without abandoning the conventional KLE[1] or KLEM[2] production functions. Regardless of questions about their empirical robustness, they are calibrated on cost-shares data through Shepard's lemma. The domain within which this systematic use of the envelope theorem provides a robust approximation of real technical sets is limited by (i) the assumption that economic data, at each point of time, result from an optimal response to the current price vector and (ii) the lack of technical realism of constant elasticities over the entire space of relative prices, production levels and time horizons under examination in sustainability issues. Even more important, the use of such production functions prevents models from addressing the path-dependency of technical change.

Conventionally, the growth engine is composed of exogenous demographic trends and labor productivity changes and is fuelled by regional net investment rates and investment allocation among sectors. But, given the intuition that a significant part of total discounted costs after a policy decision or an exogenous shock may be due to *transition* costs, we seek to capture the latter and we follow Solow's advice stating that more attention should be devoted to transition pathways, recognizing that economic cycles are not optimal responses to random shocks around an optimal steady state. This calls for a growth engine that permits the existence of endogenous departure from the steady state pathway. We thus adopted a "Kaleckian" dynamics in which investment decisions are driven by profit maximization under imperfect expectations in non fully competitive markets. Disequilibria are endogenously generated by the inertia in adapting to new economic conditions due to non flexible characteristics of equipment vintages available at each period. The inertia inhibits an automatic and costless come-back to the steady state equilibrium. In the short run the main available flexibility lies in the rate of utilization of capacities, which may induce excess or shortage of production factors, unemployment and unequal profitability of capital across sectors. Progress in computational capacity now allows us to run disequilibrium models that do not have the drawback of Harrod-Domar's knife-edged growth to generate structural (and unrealistic) crisis. In IMACLIM-R, we try to overcome this drawback without resorting to the "wrinkle" of the production function which tended to picture frictionless return to the steady state, by construction. Indeed, the growth pathways generated by IMACLIM-R always return to equilibrium in the absence of a new exogenous shock, but after 'some' transition.

2.2. The model

IMACLIM-R is thus based on the recognition that it is almost impossible to find functions with mathematical properties suited to cover large departures from a reference equilibrium over one century and flexible enough to encompass different scenarios of structural change resulting from the interplay between consumption styles, technologies and localization

---

[1] KLE: capital, labor and energy

[2] KLEM: capital, labor, energy and raw material

patterns (Hourcade, 1993). The absence of a formal production function is compensated for by a recursive structure (see Figure 1) that allows a systematic exchange of information between

- An annual static equilibrium module, in which the production function mimics the Leontief specification, with fixed equipment stocks and fixed intensity of labor, energy and other intermediary inputs, but with a flexible utilization rate. Solving this equilibrium for a given time (*t*) provides a snapshot of the economy at this date, a set of information about relative prices, levels of output, physical flows and profitability rates for each sector and allocation of investments among sectors;
- Dynamic modules, including demography, capital dynamics and sector-specific reduced forms of technology-rich models which take into account the economic values of the previous static equilibria, assess the reaction of technical systems and send back this information to the static module in the form of new input-output coefficients for calculating the equilibrium at *t+1*. Each year, technical choices are flexible but they modify only at the margin the input-output coefficients and labor productivity embodied in the existing equipments that result from past technical choices. This general putty-clay assumption is critical to represent the inertia in technical systems and the role of volatility in economic signals.

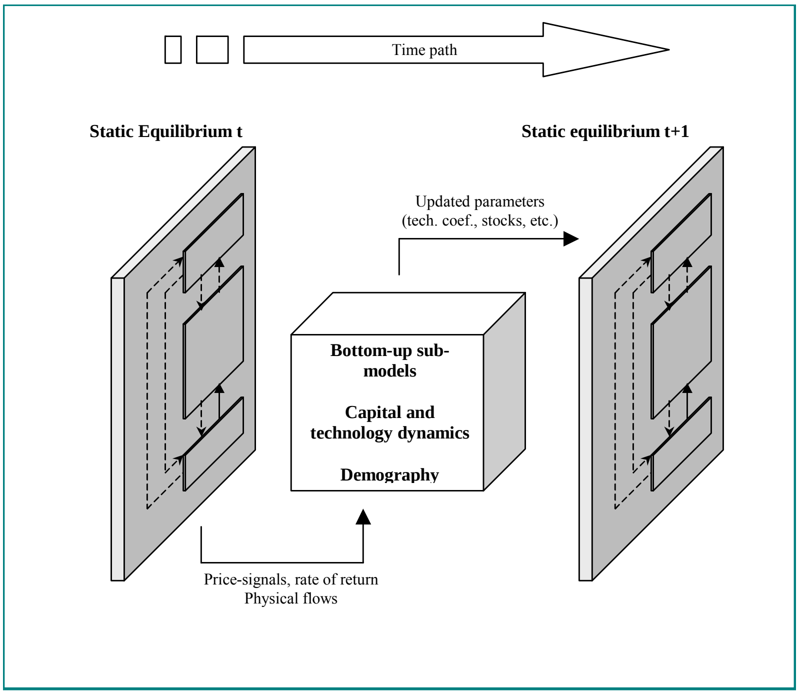


Figure 1: The recursive dynamic framework of Imaclim-R

Technically, the IMACLIM-R model generates an economic trajectory by solving successive yearly static equilibria of the economy interlinked by dynamic modules. Within the static equilibrium, in each region, the demand for each good comes from household consumption, government consumption, investment and intermediate uses from other production sectors. This demand can be provided either by domestic production or imports and all goods and services are traded on world markets. Domestic and international markets for all *goods* – not including *factors* such as capital and labor – are cleared by a unique set of relative prices that depend on the behaviors of representative agents on the demand and supply sides. The calculation of this equilibrium determines the following variables: relative prices, wages, labor, quantities of goods and services, value flows.

In its current version IMACLIM-R incorporates 12 regions - USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle East, Africa, Rest of Asia, Rest of Latin America – and 12 productive sectors – Coal, Crude Oil, Natural Gas, Refined products, Electricity, Construction, Agriculture and related industries, Energy-intensive Industries, Air Transport, Sea Transport, Other Transports, Other industries and Services. In addition IMACLIM-R includes transportation with personal vehicles and non-motorized transport. The time-horizon of the model is 2100 in a one-year step.

2.3. The energy sector

The energy sector is described in physical quantities (Mtoe), and both energy demand and supply are described through explicit technical coefficients informed by reduced forms of bottom-up models and experts' judgement. On the demand-side, we hereafter detail the drivers of energy consumption of transportation and production. Energy consumption in industrial and service sectors changes according to global energy efficiency improvements and shifts of the energy mix for new vintages of capital. Both are driven by relative prices of energy.

The transportation modeling in IMACLIM-R is an attempt to disentangle specific mechanisms of transportation dynamics. First, the transportation demand described inside the static equilibrium allows the representation of stylised facts such as the rebound effect or the demand induction by infrastructure that impacts both the total mobility and the underlying modal breakdown. Second, the transportation dynamic module alters the constraints applied to transportation demand formation in the static equilibrium: vehicles energy efficiency, households' car equipment, infrastructure policies and evolution of the freight content of economic activity. In practical terms, households' time dedicated to mobility evolves correlatively to the total population. The motorization rate is related to the evolution of per capita disposable income with a variable income-elasticity to capture the change from public and non-motorized modes to private motorized mobility with increasing income per capita. Finally, for higher per capita income level comparable to OECD's, saturation effects appear and the income elasticity of the motorization rate declines. The 'other transport' sector gathers road and rail freight transportation, therefore the evolution of its energy input-output coefficients, triggered by final energy prices variations, accounts for both energy efficiency gains and shifts between road and rail modes. This evolution is driven by a reaction function calibrated on bottom-up information from the POLES model. Eventually, the evolution of the freight content of the economic growth, which is represented by the transportation input-output coefficients of all the productive sectors in the economy, is an exogenous scenario variable.

On the supply-side, a convincing description of the evolution of coal, oil and gas prices is obviously central for long run energy-economy scenarios. In the current version of IMACLIM-R, coal and gas extraction costs are depicted through reduced forms of the energy model POLES linking extraction costs to cumulated reserves, while crude oil is subject to a detailed treatment which deserves more explanation. To capture the differentiated characteristics of oil sources (conventional vs. unconventional oil), oil reserves are classified in 6 categories according to the cost of putting a barrel at a producer's disposal (including prospecting and extraction). The decision to initiate the production of a given category of resources follows a simple profitability criterion, comparing its total production cost and the current world price of oil. The *profit rate* applied by producers depends on the short-run pressure on available production capacities as measured by the ratio of current output to total production capacity. A specificity of crude oil is that the availability of production capacity is not only constrained by the amount of previous investments, but also by geological and technical factors that cause intrinsic inertias in the increase of production. Indeed a reserve existing in the subsoil is not entirely and immediately available for extraction. Therefore for a given category of resource in a given region, the available capacity of production is assumed to follow a 'Hubbert' curve. Rehrl and Friedrich (2006) argue that this curve results from the interplay of two contradictory effects: the information effect (finding an oil reserve offers information about the probability of existence of other ones) and the depletion effect (the total quantity of oil in the subsoil is finite). Interestingly this physical interpretation of the 'Hubbert' curve at the 'field' level is not equivalent to empirically assuming the occurrence of a peak of world oil production sometime in the 21st century, which is still controversial. Moreover, we cannot neglect that the spatial localization of oil production capacities raises sharply the geopolitical stakes. IMACLIM-R is able to capture the impact of various geopolitical scenarios or behaviors: first, the unequal allocation of reserves is captured by an explicit description of available resources in each region; second, endogenous decision routines can mimic the decision to run or not new capacities in OPEC countries – that currently own between 40 % and 50 % of the world total production capacities – and the subsequent market power.

On the supply-side, the electricity sector cannot be represented in the same way as other producing sectors. Because electricity cannot be stored easily, the so-called 'load curve' associated with an electrical grid plays a central role in the choice of suitable technologies. The methodological issue is then to model realistically the production of electricity that mobilizes installed producing capacities according to a non-flat load curve. The electricity supply module in IMACLIM-R tries to tackle this issue of representing the evolution of electric generating capacities over time. When describing annual investment decisions within the electric sector, the model anticipates the potential future demand (for 10 years) for electricity, taking into account past trends of demand. The module then deduces an optimal mix of electricity productive capacities to face the future demand at the lowest cost given anticipated future fuel prices. The optimization process sets not only the total capacity of the plants' stock but also its distribution among 26 different power plant technologies (up to 15 conventional including coal-, gas- and oil fired, nuclear and hydro and 11 renewables) whose characteristics are calibrated on the POLES model. The share of each technology in the optimal mix of producing capacities results from a classical competition among available technologies depending on their mean production costs (see Table 1). Moreover, this competition is differentiated whether the capacity is expected to meet peak or base load demand. Technologies with high fixed costs and low variable costs such as nuclear power are more competitive for base load capacities whereas technologies with low fixed costs and high variable costs are likely to be chosen for peak production. Once the optimal mix of productive equipment for year *t+10* has been computed, the new capacity built at year *t* results from a minimization of the gap between the mix of capacity currently installed and the mix of capacity that is expected to be optimal to face the demand at year *t+10*. This minimization is run under the constraint of the actual amount of capital allocated to the electricity sector. This process of optimal planning with imperfect foresight is repeated at every period and expectations are adapted to changes in prices and demand.

2.4. Technical change

Technical change is induced by market conditions and is captured through the dynamics of different parameters according to the sectoral dynamic module considered. For automobile and electricity production, the dynamics of technical coefficients is related to an explicit choice of economic agents among a set of available technologies. In this case, IMACLIM-R includes the specificities of "bottom-up" models of the energy sector to implement an explicitly endogenous technical change.Capital cost of technologies depends on the sum of installed capacities through worldwide learning curves. In the electricity sector, the learning process induces both the decrease of capital costs and an improvement of the efficiency. Dynamic technical potentials of those two parameters are calibrated on the sectoral model POLES (LEPII-EPE, 2006).

In other sectors, technical change in the energy sector is related to agents' choices in terms of technology and equipment, which are dependent on economic signals. In the model, this is captured by reaction functions that are specific to each sector and relate the dynamics of technical coefficients to energy prices and carbon taxes. This specification is in particular used for technical coefficients of agricultural, industrial and services sectors as well as for energy consumption associated to residential end-uses. In those cases, technical change is captured by changes in the sectoral reaction functions modeled through learning curves. For agriculture, industry and services sectors, learning is captured by the minimum carbon tax that is necessary to induce the maximum additional annual gains. The decrease of this threshold is parameterized by assumptions on the learning rates, related to the sum of installed production capacities, and limited by a lowest value below which it cannot fall. For the residential sector, learning concerns the minimum carbon tax level that ensures the maximum diffusion of "Very Low Energy" buildings in new construction. This threshold is a decreasing function of the sum of already installed "Very Low Energy" surface.

2.5. Solution Concept

In the static equilibrium of IMACLIM-R domestic and international markets for all *goods* – not including *factors* such as capital and labor – are cleared by a unique set of relative prices that depend on the behaviors of representative agents on the demand and supply sides. Those behaviors derive from:

- the maximization of a households' representative utility function under budget constraints,
- the choice of the utilization rate of installed production capacities,
- the decision routines about government policies,
- the commercial and capital flows,
- the allocation of investments among domestic sectors.

The general structure of this equilibrium is thus a general equilibrium model which does not necessarily mean full markets equilibrium for all production factors. The calculation of this equilibrium determines the following variables: relative prices, wages, labor, quantities of goods and services, value flows.

Technically, the static equilibrium at date *t* consists in a system of equations derived from agents' behaviors and market clearing conditions that relates the above variables and fixed parameters capturing the dynamic constraints imposed by previous investments and embodied techniques (those parameters then evolve in the following dynamic modules). The numerical resolution of this equilibrium is carried out by using SCILAB.[3]

In its current version, IMACLIM-R is not integrated with a climate module. This means that the policy scenarios require an exogenous objective in terms of carbon emissions (provided by analysis from WITCH and REMIND-R in the RECIPE project). This objective is ultimately satisfied thanks to an iterative process leading to convergence of climate policy characteristics (carbon tax and "policy and measures") compatible with the constraint on emissions.

3. Database and calibration

3.1. Population

Exogenous assumptions for demographic trends are derived from UN scenarios corrected with migration flows capable to stabilize populations in low fertility regions, such as Europe. Both active and total populations are concerned: the former drives the available working force in the economy, the latter determines the level of consumption and equipment asymptotes, especially concerning per capita number of cars and square meters, available travel time and food consumption.

The default demographic projection used in IMACLIM-R corresponds to the median scenario of the United Nations (also used for the B2 SRES scenarios), that makes the assumption of a demographic transition towards stabilized population around ten billion people in 2100. Official UN statistics do not provide complete figures on active population, and we consider it as the working population (age 18-64 for developed countries, and 15-64 for developing countries). This approximation limits the interpretation of the results in terms of unemployment rates, but captures the role of active population in driving growth patterns.

3.2. Economic growth

The IMACLIM-R model is designed to represent potential gaps between *potential* and *real* growth, and the pace and direction of effective economic growth is endogenously determined by the interactions between:

- The growth engine (population, labor productivity) that determine the potential growth of the economy at each period,
- Induced structural change resulting from changes in households' preferences and productive capital,
- Technical change on energy demand and supply.

Labor productivity growth follows a constant long term rate for the most advanced economy and catching-up assumptions for other regions. More precisely, the baseline trajectory is based on the hypothesis that (i) the United States remain the world productivity leader and their mean labor productivity follows a steady growth of 1.65 % per year, (ii) other countries productivity dynamics are driven by a partial catch-up of productivity gaps, the parameters of

---

[3] SCILAB is free software developed by the SCILAB consortium. It can be downloaded at http://www.scilab.org

which are calibrated on historic trajectories (Maddison, 1995) and 'best guess' of long-term trends (Oliveira-Martins et al., 2005).

Besides these long-run drivers, both the availability of investments and their allocation are key elements controlling the effective growth. The amount of investment in each sector drives the pace of productive capacity expansion and the pace of embodied technical change. Productive capacity follows a usual law of capital accumulation with a constant depreciation rate, except electricity and industry sectors for which both vintages and equipment lifetimes are fully represented. Sub-sector allocation of investments among technologies is treated in a specific module for each sector, when relevant. Available financial resources for investment result from household's savings and the share of profits that are not redistributed. This division of value added between consumption and investment is determined, at each region level, by exogenous households' saving rates and firms' self-financing rates. The latter remains constant, whereas the former follows a decreasing trend informed by stylized facts from the macroeconomic model (INGENUE, 2006). The decreasing trend in IMACLIM-R reflects the ageing population, that determines the regional specific dynamics. The most important decrease concerns China, whose saving rates fall from 44 % in 2001 to 20 % in 2100. On the contrary, the United States face only a marginal decrease of their saving rates due to the low starting point.

Structural and technical change will be described in more detail for the most important sectors.

3.3. Energy and emissions data

The representation in explicit physical quantities creates some important constraints on calibration. Indeed, it is necessary to build a social accounting matrix that is dual in money and physical quantities. To do that, tables providing macroeconomic flows in money values are combined with energy balances in physical quantities to result in composed hybrid matrix. In the IMACLIM-R model, the database used are GTAP 6 providing macroeconomic flows for the year 2001, energy balances from ENERDATA 4.1 and the International Energy Agency (IEA), and data on passenger transport from (Schäfer and Victor, 2000). In the next sub-sections, we describe the most important modules of the IMACLIM-R in more detail, and the data used when relevant.

3.3.1. Power generation model

Description of technologies in the electricity sector relies on a discrete set of 13 explicit technologies, including both currently available ones and those which are expected to become mature in the future (among which technologies using carbon capture and sequestration). Each technology is characterized by a set of technico-economic parameters used to compute the mean cost of discounted production costs. They are capital costs (dollars per kilowatt installed), energy efficiency (in percent, for fossil fuel technologies), constant and variable operation and maintenance costs, (in dollars per kilowatt and dollars per kilowatt-hour, respectively) and a discounting factor that accounts both the opportunity cost of capital and a technology-specific risk factor (including objective evaluation of risk, and social acceptability for nuclear and CCS technologies). Technico-economic parameters associated to each technology are either calibrated on sectoral technology-rich models (like the POLES model) or taken from the literature (Grübler et al., 2002; Rao et al., 2006; Sims et al., 2007). Table 1 gives calibration values for the United States of the technico-economic parameters for the 13 available technologies. Last four lines give results of the different components of the average discounted production cost for a yearly use of 8760 hours. Technologies that are currently non-mature or in quick evolution can be represented either through autonomous trends or endogenous learning mechanisms. For example, the efficiency of electricity production from coal can be greatly improved thanks to advanced technologies like supercritical cycles or gasification. Data given in Table 1 correspond to characteristics of technologies at the calibration date (or maturation date for currently non-mature technologies). They differ from the average characteristics of installed capacities, since they include older capital vintages. Similarly, in the future, average characteristics of production capacities will be a weighted average of technical characteristics of the different capital vintages still in operation.

			Natural Gas			Coal						Renewables		
	Unit	Fioul	Conventional thermal	Combined Cycle	Combined Cycle with CCS	Thermal	Super critical	Super critical with CCS	Coal Gasification and Combined Cycle	Coal Gasification and Combined Cycle with CCS	**Nuclear**	Hydro	Wind onshore	Wind offshore
Available at calibration date		yes	yes	Yes	No	Yes	no	no	no	No	Yes	Yes	yes	no
Investment cost	$ 2001/kW	1000	400	500	1120	1050	1600	2700	1500	2400	2600	2000	1400	1800
Fixed O&M costs	$ 2001/kW	15	26	10	50	53	35	60	37	70	58	20	50	50
Lifetime	Years	30	30	30	30	30	30	30	30	30	30	45	20	20
Discount rate	%	10	10	10	10	10	10	10	10	10	10	10	10	10
Variable O&M costs	$ 2001/kWh	0.0017	0.0014	0.0014	0.0022	0.0024	0.0028	0.0034	0.0024	0.0029	0.0012			
Fuel cost	$ 2001/Toe	237	160	160	160	71	71	71	71	71				
Energy efficiency	%	36	35	53	47	35	45	35	42	36				
Availability rate	%	100	100	100	100	100	100	100	100	100	100	100	20	24
Discounted investment cost	$ 2001/MWh	12.1	4.8	6.1	13.6	12.7	19.4	32.7	18.2	29.1	31.5	23.1	93.9	100.6
Disc. fuel cost	$ 2001/MWh	56.6	39.3	26.0	29.3	17.4	13.6	17.4	14.5	17.0	5.0	0.0	0.0	0.0
Disc. O&M cost	$ 2001/MWh	5.3	3.0	1.5	6.1	6.1	4.0	14.1	4.2	17.0	7.8	2.3	28.5	23.8
Disc. production cost	$ 2001/MWh	**74.0**	**47.1**	**33.5**	**48.9**	**36.2**	**36.9**	**64.2**	**36.9**	**63.0**	**44.3**	**25.4**	**122.4**	**124.3**

Table 1: Technico-economic parameters for electricity production technologies in USA in 2001. Discounted average costs are computed for an utilization of 8760 hours. Some technologies are available with and without Carbon Capture and Storage (CCS)

3.3.2. Non-electricity sector

The other main sources of energy demand and emissions are transport activities (passenger and freight) and productive sectors.

For passenger transport, two main dimensions are driving energy demand: motorization rate and efficiency of vehicles. As demonstrated by Storchmann (2005), the former is closely related to average income per capita and distribution of revenue, but hardly to energy prices. In IMACLIM-R, the motorization rate is dependent on revenue through an income-elasticity. Calibration of this elasticity embarks national disparities in terms of historical and geographical characteristics. In particular, the saturation level is different across regions. Efficiency of the vehicles results from households' technological choices and technical progress. The automobile fleet is differentiated according to the type of vehicle (conventional or hybrid, with a distinction between standard and advanced technologies) and its vintage. Characteristics of each type of vehicle – capital cost, energy efficiency, operation and maintenance costs – are calibrated on data from the IEA (IEA, 2006) and dynamically evolve with technical change. Hybrid technology is assumed to potentially reach 1.5 liter per 100 kilometers, and can therefore be interpreted as a mix of electric vehicles and plug-in hybrid. At each date, the composition of the vehicle fleet results from agents' choices among the four technologies, accounting for both fixed and variable costs based on myopic anticipations about future energy prices.

For other transport modes, intermediate energy consumption is described through simple reduced forms:

- Air transport features an autonomous trend of 0.7 % of annual efficiency gains corresponding to both technological progress and organizational methods affecting the average occupancy rate.
- In sea transport, unitary intermediate energy consumption is constant.
- For other transport (including freight and non-automobile passenger transport), technical progress is captured by a price-elasticity at -0.3 with an asymptote set at 25 % of initial values. This aggregated transport sector corresponds to the sectoral disaggregation of the GTAP database. The dynamics of unitary energy consumption captures technical progress on vehicles, modal shift (in particular, for freight from road to rail) and structural change among sub-sectors.

Another important driver of energy consumption in the transport sector is the transport intensity of production. In IMACLIM-R, it is related to the intermediate demand of transport by productive sectors. In baseline scenarios, it is kept constant, whereas policy scenarios include underlying assumption of reorganization of the production/distribution network and of urban forms inducing a decoupling of economic activity and transport demand.

Productive sectors are aggregated in "meta-sectors" (agriculture, industry and services), which include a large variety of sub-sectors (for example, aluminium, cement and steel are all contained in the industry sector). As a consequence, the cost structure cannot be explicitly related to a decision among a given set of technologies. Instead, the average technology parameters represent the mix of specific technologies used in all sub-sectors. Technical coefficients are derived from the hybridization process, which results in intermediate consumption of energy (and transport demand) for production in money values and physical quantities

3.3.3. Carbon emissions from fossil fuels

Only CO_2 emissions from fossil fuels are accounted for in IMACLIM-R. Sources of emissions considered are the three final energy sources (coal, gas, and liquid fuels) associated to the three primary fossil energies (coal, gas, oil). Emissions are counted when fossil energies are actually burned, either in final consumption or intermediate consumption in the production or energy production process. We assume that all the carbon included in one unit of energy is released in the atmosphere.

3.3.4. Prices of fossil fuels and exhaustible resources

The price of fossil fuels is calibrated by the combination of money flows provided by the social accounting matrix and physical flows in Mtoe. The ratio of those two quantities directly gives the price of the associated energy for the use considered. The dynamics of prices is endogenous in the model, as a result of market interactions between demand and constrained supply. This latter dimension is described differently according to sectors, with an explicit Hubbert-like description for oil, and a relation between price and cumulated extraction for coal and gas.

3.3.5. Carbon emission coefficients of fossil fuels

As described previously, coefficients relating energy consumption to carbon missions are fixed during the simulation, as an intrinsic chemical characteristic of the energy considered. Two exceptions are worth being noted:

- Certain sectors (especially electricity) can use CCS technologies that lower the emission actually released in the atmosphere.
- A share of liquid fuels can be provided by biofuels or Coal-To-Liquid. In the former case, the unitary emission coefficient associated to liquid fuels’ consumption is decreased to account only for the emissions related to growing process of culture and transformation. Symmetrically, emissions related to the production of Coal-To-Liquid must account for the lower efficiency of this production process.

4. Specific features in abatement technologies

4.1. Innovative carbon-free technologies

In IMACLIM-R, five main types of carbon-free technologies are described:

- Carbon Capture and Storage. The role of this technology is crucial in the abatement efforts of the electricity sector. Three of such technologies are explicitly included in the technology portfolio. Two of them concern electricity production from coal (Super critical with CCS and Coal Gasification and Combined Cycle with CCS), the third one being based on gas (Combined Cycle with CCS). Those technologies are available both with and without CCS, and the CCS technology becomes economically profitable when the carbon price is high enough to compensate for the additional fixed costs required for building and operating production units with CCS.
- Nuclear. This technology is also included in the technology portfolio for electricity production. In addition to purely economic factors, intangible costs are included in

the computation of the global production costs, so as to capture obstacles related to social acceptability.

- Renewable energies for electricity production. Their specificity is the intermittent production, which prevents those technologies from exceeding a certain share of total production (the maximum is set at 40 % of total electricity production). In the current version of the IMACLIM-R model, the proportion of electricity production ensured by renewable is related to the ratio of total production costs with wind energy (the only renewable technology explicitly accounted for in the portfolio) and with the least expensive conventional technology. This structure accounts for public intervention (subsidies, quotas) designed to foster the diffusion of renewable even if their current average production is higher than for other technologies. In addition, solar energy is assumed to be used only as an integrated source of energy in buildings that permits reaching very low energy buildings (50 kWh/ m^2/year).
- Second generation biofuels. The production of this energy is constrained by a global limitation related to the availability of agricultural land. The IMACLIM-R framework contains a compact land-use module that is, in the current version of the model, captured through supply curves calibrated on results from sectoral analysis (IEA, 2006). Diffusion of this technology is submitted to competitiveness (with respect to the traditional oil-based production process) and availability (captured by a threshold on production depending on the date).
- Hybrid efficient cars. As described previously, hybrid efficient cars are one of the stylized classes of vehicles at households' disposal.

4.2. International spillovers of knowledge and experience

Worldwide learning curves are introduced in the model to describe the way endogenous technical change spreads from one region to others. The choice of worldwide learning curves implicitly assumes a perfect diffusion of innovation among different regions and important knowledge spillover effects. This concerns in particular the technology-explicit modules, namely electricity and private transportation.

5. Conclusion

Besides other attempts to bridge the gap between top-down and bottom-up approaches by adapting pre-existing models, the development of the IMACLIM-R framework was conceived in a search for an integrative framework able to simulate long-term growth, to represent short-run inertias and to incorporate pieces of expertise about economic behavior, technical systems or development pathways. As a policy-oriented model, IMACLIM-R aims at facilitating the dialog between economists, engineers and decision-makers. As a scientific tool, it tries to reinforce the consistency of long-term scenarios, by including the main feedbacks between technology deployment, macroeconomic conditions, and the behavior of agents with bounded rationality. In its current state of development, the model now deserves a comparison with other simulation tools to assess how its alternative features modify the evaluation of development, climate and energy policies. It also needs further complementary developments. Some of them are already on track, as a land-use dynamic module – crucial to deliver insights about the competition between food and biofuels for example – and the correction of actual data to take into account the informal economy. Others will be launched in the near future to address current scientific and policy challenges: the adaptation of the IMACLIM-R framework to the aggregation level of a country or a big town and, simultaneously, a spatial description of economic activities, especially to deal with the high policy stakes that arise from the intricate dynamics of housing, transportation and material flows.

6. References

Grübler A., Nakićenović N., Nordhaus W. D. (Eds.), 2002, Technological Change and the Environment, Washington, DC, Resources for the Future.

Hourcade J.C. (1993): Modelling long-run scenarios. Methodology lessons from a prospective study on a low CO2 intensive country, Energy Policy 21(3): pp 309-326.

IEA (2006) Energy Technology Perspectives: Scenarios and Strategies to 2050, OECD/IEA, Paris, France.

LEPII-EPE (2006) : The POLES model, Institut d'Économie et de Politique de l'Énergie, Grenoble, France, 12 pp. http://webu2.upmf-grenoble.fr/iepe/textes/POLES12p_Jan06.pdf (accédé le 12/04/2008)

Maddison, A. (1995): Monitoring the World Economy: 1820 – 1992, OECD Development Center, 260 p.

Oliveira Martins, J., F. Gonand, P. Antolin, Ch. de la Maisonneuve, Y. Kwang-Yeol (2005): The impact of ageing on demand, factor markets and growth, OECD Economics Department Working Papers, #420, OECD Economics Department.

Rehrl T., R. Friedrich (2006): Modelling long-term oil price and extraction with a Hubbert approach: The LOPEX model, Energy Policy, 34(15) , pp. 2413-2428.

Sands, R.D., S. Miller, M.-K. Kim (2005) The Second Generation Model: Comparison of SGM and GTAP Approaches to Data Development, Pacific Northwest National Laboratory, PNNL-15467, 2005.

Schäfer A., D.G. Victor (2000): The future mobility of future population, Transportation Research Part A, 34, pp 171-205.

Solow, R.M. (1988) Growth theory and after, The American Economic Review, 78:3, pp 307-317.

Rao S., I. Keppo, K. Riahi (2006): Importance of technological change and spillovers in long term climate policy, The Energy Journal, (Special issue on Endogenous Technological Change and the Economics of Atmospheric Stabilisation), pp 55–72.

Sims, R.E.H., R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martínez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang (2007): Energy supply, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Storchmann, K. (2005): Long-run gasoline demand for passenger cars: the role of income distribution, Energy Economics 27, pp. 25-58.

Appendix B: Model description REMIND-R

Authors: Marian Leimbach, Nico Bauer, Lavinia Baumstark

1. Introduction

The global multi-region model REMIND-R represents an intertemporal optimizing energy-economy-environment model which maximizes global welfare subject to equilibrium conditions on different markets. A distinguished pareto-optimal solution, which in the absence of externalities also corresponds to the market equilibrium, is obtained using the Negishi algorithm. In this respect, REMIND-R resembles well-known energy-economy-climate models like RICE (Nordhaus and Yang, 1996) and MERGE (Manne et al., 1995; Kypreos and Bahn, 2003). REMIND-R is distinguished from these models and from other hybrid models like WITCH (Bossetti et al., 2006) and Imaclim (Crassous et al., 2006) by a high technological resolution of the energy system and intertemporal trade relations between regions. This expands the range of mitigation options which are mainly based on a switch between energy technologies and compensates for a restricted representation of technological learning.

In REMIND-R, mitigation costs estimates are based on technological opportunities in the development of new energy technologies. Most essential, technological change in the energy sector (as represented in bottom-up models) is embedded in a macroeconomic environment (as represented by top-down models) that by means of investment and trade decisions governs regional development. Altogether, this provides a high level of climate policy decision support and a basis for assessing future climate policy regimes.

This model description is based on the introduction of the REMIND-R model in Leimbach et al. (2009) and the technical description in Bauer et al. (2008a) on our website[4]. Here, we focus on a non-technical description.

2. Model structure

2.1. General frame work

REMIND-R as introduced by Leimbach et al. (2009) is a multi-regional hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model (see Figure 2). The hard-link between the energy system and the macroeconomic system follows the method by Bauer et al. (2008). Assuming perfect foresight and aiming at welfare maximization, REMIND-R simulates the world-economic dynamics over the time horizon 2005 to 2150 with a time step of five years.

The individual regions are linked by trade relations. The present version of REMIND-R distinguishes 11 world regions:

---

[4] At http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1 the technical description of REMIND-R is available. REMIND-R is programmed in GAMS. The code is available from the authors on request.

- UCA - USA
- EUR - EU27
- JAP - Japan
- CHN - China
- IND - India
- RUS - Russia
- AFR - Sub-Saharan Africa (excl. Republic of South Africa)
- MEA - Middle East and North Africa
- OAS - Other Asia
- LAM - Latin America
- ROW - Rest of the World (Canada, Australia, New Zealand, Republic of South Africa, Rest of Europe).

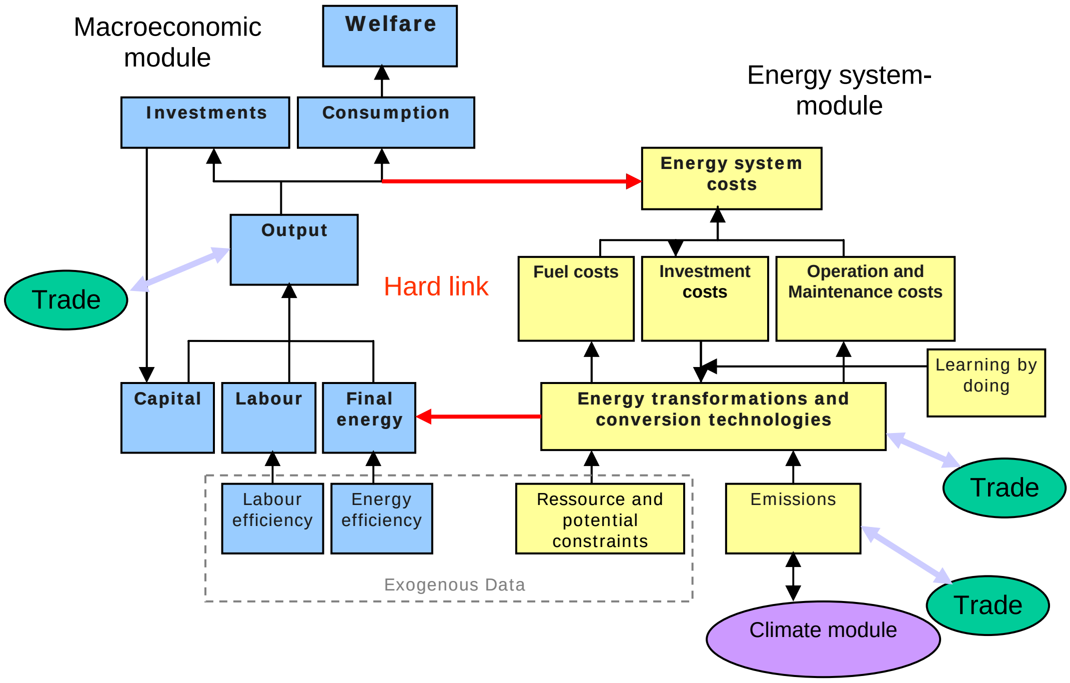


Figure 2: Structure of REMIND-R

REMIND-R is run in the cost-effectiveness mode when it is used for climate policy simulations, i.e. climate policy targets are integrated into the model by an additional constraint (e.g. upper bound for temperature increase or CO_2 concentration). The model generates a first-best solution which in particular means that regions, in general, co-operate in achieving the climate policy target.

2.2. The macroeconomic model

Each region is modeled as a representative household with a utility function that depends upon per capita consumption. It is the target of REMIND-R to maximize a global welfare function that results as a weighted sum of the regional utility functions. Utility calculation is subject to discounting. We assume the pure rate of time preference to amount to 3 %.

Marco-economic output, i.e. gross domestic product (GDP), is determined by a "constant elasticity of substitution" (CES) function of the production factors labor, capital and end use energy. The end use energy of the upper production level is calculated as a production function which comprises transportation energy and stationary used energy. Both are connected by a substitution elasticity of 0.3. These two energy types are in turn determined by means of nested CES functions of more specific final energy types (see Figure 3). Substitution elasticities between 2.5 and 3 hold for the lower levels of the CES nest. An efficiency parameter is assigned to each production factor in the various macroeconomic CES functions. Changes in the efficiency of the individual production factors for each region are given by exogenous scenarios.

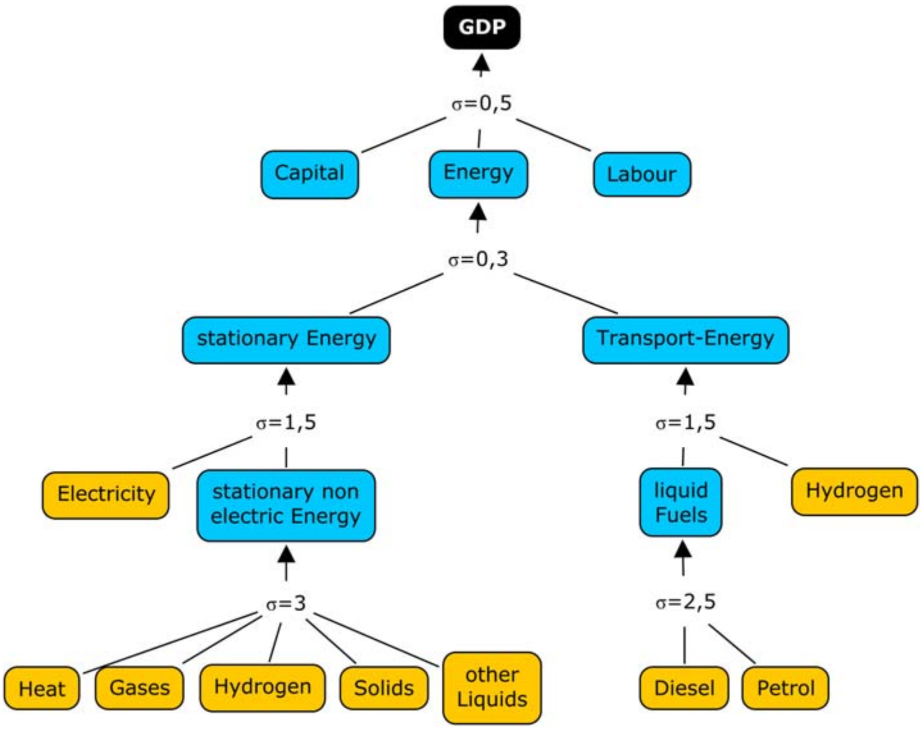


Figure 3: CES production structure in the macroeconomic module

In each region, produced GDP $Y(t)$ is used for consumption $C(t)$, investments into the macroeconomic capital stock $I(t)$, all expenditures in the energy system and for the export of composite goods X_G. Energy system expenditure consist of fuel costs $G_F(t)$, investment costs $G_I(t)$ and operation & maintenance costs $G_O(t)$. Imports of the composite good M_G increase the available GDP:

$$Y(t) - X_G(t) + M_G(t) \geq C(t) + I(t) + G_F(t,r) + G_I(t) + G_O(t).$$

This balance of GDP distribution forms the budget constraint each region is subjected to. Macroeconomic investments enter a conventional capital stock equation with an assumed depreciation rate of 5 %.

In following the classical Heckscher-Ohlin and Ricardian models (Flam and Flanders, 1991), trade between regions is induced by differences in factor endowments and technologies. In

REMIND-R, this is supplemented by the possibility of intertemporal trade. However, there is no bilateral trade, but exports in and imports from a common pool. Trade is modeled in the following goods:

- Coal
- Gas
- Oil
- Uranium
- Composite good (aggregated output of the macro-economic system)
- Permits (emission rights)

Intertemporal trade and capital mobility, implied by trade in the composite good, cause factor price equalization and provide the basis for an intertemporal and interregional equilibrium.

In REMIND-R, the balance between exports and imports for each kind of goods in each period is guaranteed by adequate trade balance equations. However, the question whether a chosen trade structure is intertemporally balanced and optimal depends on how the welfare weights are adjusted. A distinguished pareto-optimal solution, which in the case of missing externalities also corresponds to a market solution, can be obtained by adjusting the welfare weights according to the intertemporal trade balances.

The trade pattern that will result from model runs is highly impacted by the intertemporal budget constraint each region is additionally subjected to. Each composite goods export qualifies the exporting region for a future import (of the same present value), but implies for the current period a loss of consumption. Trade with emission permits works in a similar way. Emission rights are distributed free of charge according to the given allocation rule. The revenues from the sale of emission rights represent entitlements to future re-exports of permits or goods. A permit constraint equation ensures that each unit of CO_2 emitted by combusting fossil fuels is covered by emission certificates.

The representative households in REMIND-R are indifferent regarding domestic and foreign goods as well as indifferent among foreign goods of different origin. This can potentially lead to a strong specialization and, related to the cooperative approach to solution, to rather optimistic results. For climate policy assessments this is less critical as it applies to both baseline and policy scenarios.

2.3. The energy sector

The energy system module (ESM) of REMIND-R comprises a detailed description of energy carriers and conversion technologies. The ESM is embedded into the macroeconomic growth model: the techno-economic characteristics and the system of balance equations that set up the energy system are constraints to the welfare maximization problem of the macroeconomic module.

The energy system can be considered as an economic sector with a heterogenous capital stock that demands primary energy carriers and supplies secondary energy carriers. The structure of the capital stock determines the energy related demand-supply structure. The sector demands financial means at the capital market that are allocated among a portfolio of alternative energy conversion technologies. The techno-economic characteristics of the technologies and the endogenously evolving prices of energy and CO_2 emissions determine the size and structure of the energy sector capital stock. Hence, the energy sector develops according to an equilibrium relationship to the remaining economy with which it is interrelated through capital and energy markets.

Table 2 shows the technologies of transforming energy carriers available in the model. Table 2 presents the primary energy carriers in the columns and the secondary energy carriers in the rows. The conversion technologies indicate possible routes of converting the primary energy carriers into the secondary energy carriers.

Secondary energy types	**Primary energy types**						
	Exhaustable				Renewable		
	Coal	Crude oil	Natural gas	Uranium	Solar Wind Hydro	Geo- thermal	Biomass
Electricity	PC*	DOT	GT	LWR	SPV**	HDR	BioCHP
	IGCC*		NGCC*		WT**		
	CoalCHP		GasCHP		Hydro		
Hydrogen	C2H2*		SMR*				B2H2*
Gases	C2G		GasTR				B2G
Heat	CoalHP		GasHP			GeoHP	BioHP
	CoalCHP		GasCHP				BioCHP
Transport fuels	C2L*	Refinery					B2L*
							BioEthanol
Other liquids		Refinery					
Solids	CoalTR						BioTR

Abbreviations: PC - conventional coal power plant, IGCC - integrated coal gasification combined cycle power plant, CoalCHP - coal combined heat and power, C2H2 - coal to hydrogen, C2G – coal to gas, CoalHP - coal heating plant, C2L coal to liquids, CoalTR - coal transformation, DOT - diesel oil turbine, GT - gas turbine, NGCC – Natural gas combined cycle power plant, GasCHP – Gas combined heat and power, SMR - steam methane reforming, GasTR - gas transformation, GasHP - gas heating plant, LWR - light water reactor, SPV – solar photovoltaics, WT - wind turbine, Hydro - hydroelectric power plant, HDR - hot dry rock, GeoHP - heat pump, BioCHP – biomass combined heat and power, B2H2 - biomass to hydrogen, B2G – biogas plant, BioHP - biomass heating plant, B2L - biomass to liquid, BioEthanol - biomass to ethanol, BioTR - biomass transformation.

* this technology is also available with carbon capture and sequestration (CCS)

** this technology is characterized by endogenous technological learning.

Table 2: Overview on primary and secondary energy carriers and the available conversion technologies

Multiple primary energy sources are available in the ESM. There are renewable primary energy sources that can be used in each period without changing the costs of utilization in subsequent periods. However, they cannot be used unboundedly. Region-specific and energy source-specific potentials are presented here. In addition, the potentials are classified into different grades which, as a result of optimization, leads to a gradual extension of the use of renewable energy sources. This means that e.g. a gradual potential of wind power is exhausted before the next – relatively less attractive – potential will be exploited as the electricity price crosses a critical value.

Besides, there are exhaustible primary energy sources. The exhaustible energy carriers (coal, oil, gas, and uranium) are tradable and characterized by region-specific and energy source-specific extraction cost functions. These functions catch the idea that exhaustible resources should be exploited in an optimal sequence, which implies that the cheapest deposits are exploited first. The result is a function in which the marginal extraction costs increase with cumulative extraction.

As for exhaustible primary energy sources, the use of fossil energy leads to CO_2 emissions, while the application of carbon capture technologies can contribute to a strong decrease of CO_2 emissions. Transformation technologies which use biomass can also be complemented by CO_2 capturing provided that they are used to produce fuels or hydrogen. Among the renewable energy sources, biomass has a special position since its fuel costs increase with the intensity of use. This complies with a biomass supply curve which, however, is only defined up to a maximum possible potential. It should be noted that the use of fossil energy sources and biomass will lead to further emissions that will, however, not be considered in the model, except for the emissions of sulfate aerosols. In contrast to the CO_2 emissions, SO_2 emissions are not calculated technology-specifically.

Coal and biomass are highly flexible primary energy carriers since all secondary energy carriers could be produced out of them. Crude oil and natural gas are mainly used to produce liquids and gases. Renewable energy carriers other than biomass are well suited for the production of electricity, but they are less suited to produce other secondary energy carriers. Renewable energy sources including biomass are non-tradable.

Secondary energy carriers are assumed to be non-tradable across regions. Statistics indicate that liquid fuels are globally traded. However, the relative magnitude is not that significant and since the REMIND model considers crude oil to be tradable the bias is limited. Secondary energy carriers are converted into final energy carriers by considering mark-ups for transmission and distribution. Final energy is demanded by the macro-economic sector and rewarded with equilibrium prices. Note that in this REMIND-R version, the end use sectors household and industry are aggregated to the stationary sector. Hence, we distinguish the stationary and the transport sector as final energy demanding sectors.

All technologies are considered by capacity stocks in the model. The possibility of investing in different capital stocks provides a high flexibility of technological evolution. Nevertheless, every additional energy production (either based on existing or new technologies) needs investments in capacities in advance. Furthermore, the model does not allow for idle capacities. The lifetime of capacities differs between various types of technologies, but amount to around 40 years on average. Depreciation rates are quite low in the first two decades.

Each region starts with a vintage capital stock which meets the statistically given input-output relations. The technical transformation coefficients for new vintages are the same for all regions and assumed to be constant. However, the following modifications apply: the transformation efficiency is improved over time for fossil power generation technologies and different technology grades are considered when renewable energy sources are used. The by-production coefficients of the combined power-heat technologies (CHP) have been region-specifically adjusted to the empirical conditions of the base year.

Taking into account that older generations of fossil power plants have a lower transformation efficiency than more new power plants implies higher specific CO_2 emissions of the former. Furthermore, the model considers that captured CO_2 needs to be transported and compressed prior to injection. Storage is assumed to be in geological formations only. There is leakage in the process of capturing, but no leakage from sequestered CO_2. Space in geological formations is generously measured for all regions.

The investment costs for each technology are the same in each region and constant over time with two exceptions. Wind turbines (WT) and solar photovoltaics (SPV) are subject to the learning curve effect. "Learning" technologies are characterized by the fact that their investment costs decrease by a certain percentage (the learning rate) with each doubling of the cumulated capacities

In general, the model has no exogenous restrictions that limit maximum growth rates or maximum shares in the energy mix for energy sources or technologies. Hence the model is flexible in technology choice and maintains the capital market equilibrium for all technologies. It is difficult to find reasonable justification for setting limits on capacity extension variables; e.g. wind turbine capacity grew over ten years by more than 15 % p.a. globally (IEA, 2007). One single exogenous restriction is implemented in REMIND: For nuclear power plants, the increase of investment costs depends on the actual capacity expansion. There is an exogenous critical value - starting at 5 GW in 2005 and increasing at 1 GW per year. Exceeding this value by 10 % increases investment costs by 5 %; i.e. the elasticity is 0.5 %.

2.4. Technical change

REMIND-R distinguishes between exogenous and endogenous technical change. The former is part of the dynamics of the macroeconomic system, the latter drives technological evolution in the energy system.

Exogenous efficiency growth is assumed for all production factors, i.e. capital, labour and the final energy types: electricity, heat, gases, solids, hydrogen, petrol, diesel and other liquids (see Figure 3). This type of efficiency growth is autonomous and free of charge. No particular measures are assigned.

Technological change in the energy sector is the result of model simulations and is manifested in the diffusion and disappearance of single energy technologies. In addition, some technologies are subject to learning effects. This applies to the Wind turbines (WT) technology and solar photovoltaics (SPV) technology. The learning curve effect is implemented in such a way that only some part of the investment costs can be reduced. Another part of costs - the floor costs - is fixed (cf. Section 3.3.2).

2.5. Climate model

The present version of REMIND-R integrates a simple climate model (Petschel-Held et al., 1999). For basic model equations as well as for parameter values and initial values see Kriegler and Bruckner (2004). The climate module determines the atmospheric CO_2 concentration and considers the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature. The emission of sulphates is directly linked to the combustion of fossil fuels in the energy sector. The radiative forcing of both the non-CO_2 greenhouse gases and the CO_2 emissions from land use change is taken into account by exogenous scenarios. The climate sensitivity - as the most important parameter of the climate module – is set to 2.8°C.

2.6. *Solution Concept*

REMIND-R forms a multi-region optimization problem with a single objective function. Solving this non-linear optimization problem results in a pareto-optimal solution that corresponds with a global planner solution. A distinguished pareto-optimal solution that represents a general equilibrium solution is obtained by using the Negishi approach (cf. Manne and Rutherford, 1994; Leimbach and Toth, 2003). In this iterative approach, the welfare weights, which merge regional utility functions of to a global objective function, are adjusted according to the intertemporal trade balances. The higher the intertemporal trade balance deficit of a region, the more the welfare weight needs be lowered to induce exports from this region to other regions. In the calculation of the intertemporal trade balances, shadow price information from the model solution of the current iteration is used. The shadow prices of the market clearing equations and/or trade balances represent the respective prices of the goods in present values. The intertemporal trade balance has to be leveled off in the equilibrium point.

The convergence of the Negishi algorithm is guaranteed for convex models. While REMIND-R comprises non-convexities by modeling learning curve effects, experiences from a multitude of model runs provide evidence that the convergence behavior is quite robust.

REMIND-R is a normative model that comes up with a first best solution. Perfect foresight and co-operative behavior of all agents is assumed as default. For particular scenarios (fragmented climate policy regimes, delayed action), we ease these assumptions.

While the optimization approach allows to determine a distinguished solution that meets a given climate target with lowest welfare losses, the variety of nearly equal solutions (in welfare terms) can be huge. Moreover, with respect to the technological evolution (e.g. energy mix), these solutions can be quite different. Running scenarios with different assumptions on the availability and/or diffusion of technologies, helps to identify their importance (i.e. the option value of technologies).

3. Database and calibration

3.1. *Population*

For the purpose of the model comparison exercise we employ population forecast from the UN Department of Economic and Social Affairs, Population Division (see Figure 4). This scenario assumes a continued upward trend in global population, albeit at steadily decreasing rates of growth, reaching 9 billion in 2050. Around this date, a number of major demographic transitions are expected to set in, followed by a peak of world population at roughly 9.5 billion people in 2070 and a subsequent decline to roughly 9 billion at the end of the century.

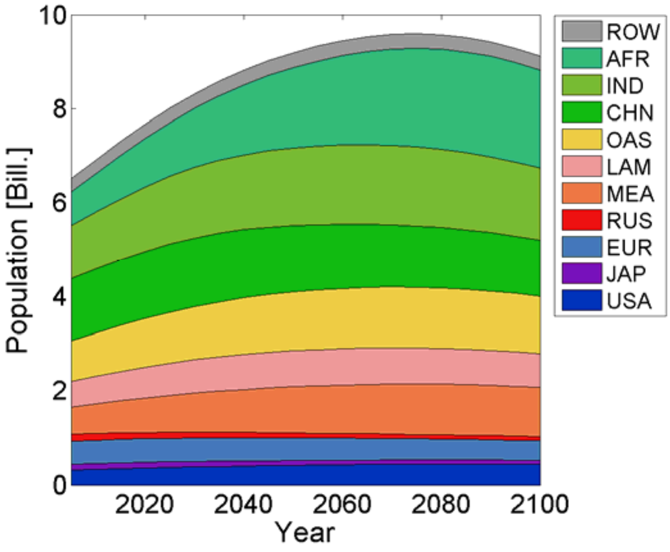
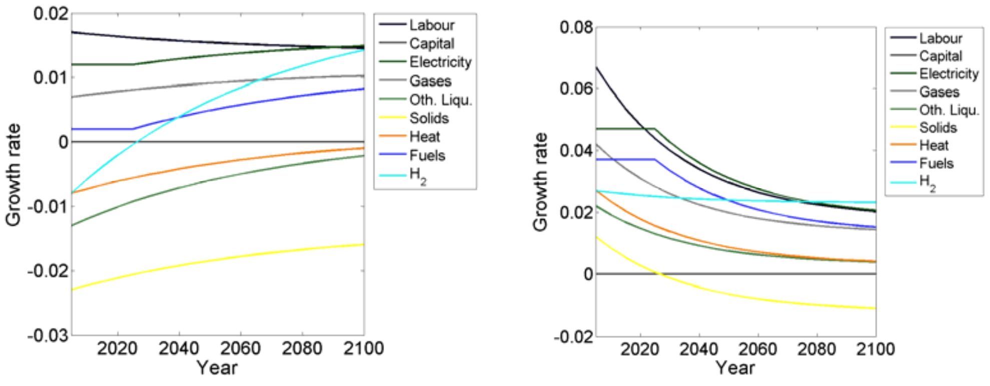


Figure 4: Population dynamics

3.2. Economic growth

Economic growth as simulated by REMIND-R is mainly triggered by the efficiency parameters of all production factors and their changes over time. Changes in the efficiency of the individual production factors are given by exogenous scenarios. While we assume a constant efficiency of capital, labor productivity growth is adjusted to reproduce the regional GDP baselines as harmonized within RECIPE. For all energy production factors, efficiency change rates are defined in constant relation to labor productivity changes, assuming e.g. that efficiency improvement for the production factor hydrogen and electricity is higher than labor productivity growth, but for solids and heat it is lower. The rate of labor productivity change itself is based on a time profile which starts on a level which is in accordance to empirical data (PWT, 2007) and ends at a level which is chosen to fit as good as possible the GDP path given in the RECIPE project. The transition from the initial to the final growth rate level also differs between regions and contributes to matching the given GDP path.

Figure 5 shows exemplary the growth rates of the efficiency parameters for the individual production factors in the region EUR and CHN.



Europe

China

Figure 5: Efficiency growth of production factors

The initial efficiency levels are computed as part of the pre-processing calibration routine which is based on the base year factor inputs and income shares.

In result of the exogenous efficiency growth scenario and the above population scenario, REMIND-R simulates economic growth from 2005 to 2100 for all regions as shown in Figure 6. The world-wide GDP of about 48 trillion $US in 2005 increases to 441 trillion $US in 2100. A large part of the GDP growth occurs in the regions CHN, OAS and LAM.

The GDP of all regions is growing faster than its population. On the world-wide average, the GDP per capita will increase between 2005 and 2100 from approx. 7300 $US to approx. 48300 $US.

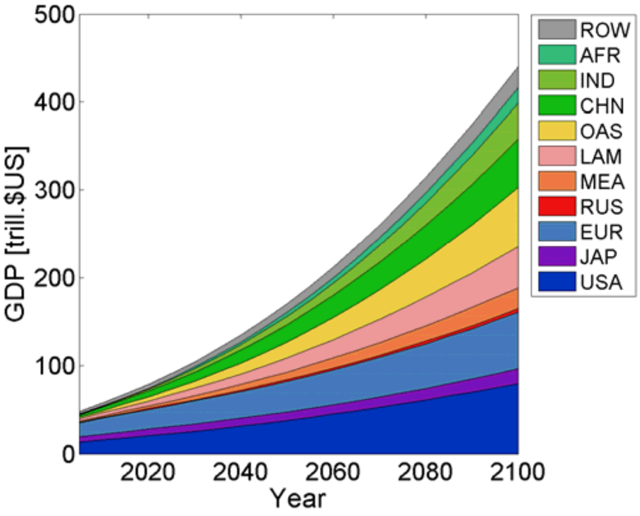


Figure 6: Global GDP

3.3. *Energy and emissions data*

3.3.1. Extraction sector

Figure 7 shows the reserve endowments of exhaustible primary energy carriers based on data from ENERDATA. In contrast to the other three energy carriers, coal is abundant and widely available. However, the highly populated regions China, India and Africa have only relatively small endowments. USA, Russia and the aggregate ROW are well endowed especially with coal, though the population is relatively small.

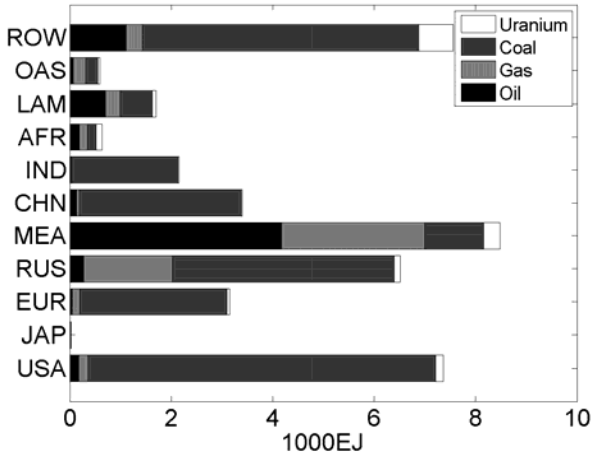


Figure 7: Overview on reserve endowments of exhaustible primary energy carriers

Table 3 relates the reserves to the extraction cost functions. The initial extraction costs refer to the assumption in the year 2005. The extraction costs at reserve limit are reached as the cumulative extraction equals the available reserve. The extraction can go beyond the reserve limit, but extraction costs will increase. The initial assumption and the extraction cost at the reserve limit are connected by a quadratic function, which is the extraction cost curve.

	coal	Oil	natural gas	uranium
Initial extraction costs [$US per GJ]	1.8	8	5.5	30 $US/kg
Extraction costs at reserve limit [$US per GJ]	4	10.5	8	80 $US/kg

Table 3: Overview on cost parameters of exhaustible primary energy carriers

Renewable energy sources are subject to constraints of potentials that are in turn differentiated in grades. The harvest costs of biomass are increasing from 1.2 to 4 $US per GJ. For renewables other than biomass the grades differ in the availability factor. The two most important renewables are wind and solar, that have global maximum potentials of 140 EJ and 750 EJ with maximum availability factors of 31 % and 25 %, respectively (see e.g. Hoogwijk, 2004; WBGU, 2003).

3.3.2. Stationary sector

Key techno-economic assumptions of both stationary and transport technologies are summarized in Table 3. The investment costs for each technology are the same in each region and constant over time with two exceptions. Wind turbines (WT) and solar photovoltaics (SPV) are subject to the learning curve effect. With respect to CCS technologies there are some empirical studies that provide estimates for investment costs (cf. Table 4), but there is hardly any foundation on the cost dynamics based on learning curve effects.

Electricity is the secondary energy carrier that can be produced out of all primary energy carriers. Whereas the fossil fueled power stations could be augmented by CCS, the option of biomass power production with CCS is not included into the model.

The electricity generation technologies wind and solar PV are characterized by endogenous technology learning. The learning rate (i.e. the rate at which the investment costs decrease with doubling of installed capacities) are assumed to be 10 % and 20 %, respectively (see e.g. Neij et al., 2003; Junginger et al., 2004; Junginger et al., 2005; McDonald and Schrattenholzer, 2001). Investment costs can be reduced to the floor cost limit of 700 $US per kW for wind and 1000 $US per kW for solar PV. The effect of learning is limited to a region; no spillovers are considered. The initially installed capacities and the initial investment costs vary across regions. Regions like Europe already have installed much capacities and therefore have lower investment costs compared to regions that have not yet installed notable capacities. In average, initial investment costs for wind and solar PV technologies amount to 1100 $US per kW and 4500 $US per kW, respectively.

Regarding nuclear power the model only considers Light Water Reactors. The investment costs for these facilities are highly uncertain. The assumption for this study is 2500 $US per kW. Within the model framework undesired side-effects regarding proliferation, dismantling, waste treatment and safety are not considered explicitly.

		Techno-economic Parameters							
		Lifetime	Investment costs		O&M costs		Conversion eff.		Capture rate
		years	$US/kW		$US/GJ		%		%
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS
Coal	PC	55	1150	1900	1.64	2.58	42	35	90
	Oxyfuel	55		1700		2.86		34	99
	IGCC	45	1500	1800	1.89	2.93	48	42	90
	C2H2*	45	756	712	0.61	0.58	57	57	90
	C2L*	45	1000	1040	1.47	1.66	40	40	70
Gas	NGCC	45	650	1350	1.02	1.78	55	47	90
	SMR	45	300	380	0.57	0.8	75	70	90
Biomass	B2H2*	45	1400	1700	2.02	2.44	61	55	90
	B2L*	45	2500	3000	2.87	3.94	41	41	50
	B2G	45	1000		1.35		55		
Nuclear	LWR	35	2500				33~		
Renewables	Hydro	80	3000				45		
	WT**	35	1100				35		
	SPV**	35	4500				12		

*) these technologies represent joint processes; Capturing does not necessarily result in higher investment costs and lower efficiency in producing the main product

**) regional investment cost vary around the listed value

Abbreviations: PC - conventional coal power plant, Oxyfuel – coal power plant with oxyfuel capture, IGCC - integrated coal gasification combined cycle power plant, C2H2 - coal to hydrogen, C2L coal to liquids, NGCC – Natural gas combined cycle power plant, SMR - steam methane reforming, B2H2 - biomass to hydrogen, B2G – biogas plant, B2L - biomass to liquid, LWR - light water reactor, SPV – solar photovoltaics, WT - wind turbine, Hydro - hydroelectric power plant.

Note: technologies marked with a * are joint production processes; for these technologies, capturing does not necessarily result in higher investment costs and lower efficiency in producing the main product.

Table 4: Techno-economic characteristics of technologies that could be augmented with CCS equipement (cf. Bauer ,2005; Gül et al., 2008; Hamelinck, 2004; Iwasaki, 2003; Ragettli, 2007; Schulz et al., 2007; Takeschita and Yamaij, 2008).

3.3.3. Transport sector

The production of liquid fuels and hydrogen used in the transport sector can either be produced from fossil energy carriers or biomass (see also Section 4.1). Liquid fuels and hydrogen production could also be equipped with CCS; also for the case of biomass fueled facilities. Note that the investment costs for both biomass technologies (B2H2 and B2L) with and without CCS is quite high (see Table 4). An important difference in the case of CCS technologies is that the capture rate for the liquid fuel production is considerably lower than for hydrogen and electricity. Overall, there are plenty of options to decarbonize the production of electricity and hydrogen, but relatively few options for the production of liquid fuels and gases. However, only hydrogen is an alternative in the transport sector, as the electrification of the transport sector is not yet implemented in REMIND.

3.3.4. Prices of fossil fuels and exhaustible resources

Prices of fossil fuels and exhaustabile resources are determined endogenously. A major price factor are the extraction costs which are derived based on the assumed Rogner curve (see above). By adjusting the parameter of the Rogner curve, different price paths of fossil fuels can be generated. However, due to the internal dependency of the fossil fuel prices, it is not possible to combine a low coal price path with a high oil and gas price path over the long run.

3.3.5. Carbon emission coefficients of fossil fuels

CO_2 is emitted in the process of burning fossil fuels. In REMIND-R, this applies exclusively to the process of converting primary energy into secondary energy. This means that emissions in the transport sector are already occur when petrol or diesel is produced in the refinery. This is no problem from the perspective of assigning emissions regionally as there is no trade in secondary energy.

Emissions are derived based on the emission coefficients as shown in Table 5. The emission coefficients are equal for all regions.

	coal	**Oil**	**natural gas**
Emission coefficient [kgC per GJ]	26.1	20.0	15.3

Table 5: Carbon emission coefficients (cf. IPCC TAR WGIII, p. 236)

4. Specific features in abatement technologies

4.1. Biomass technologies

Currently most biomass is used in developing countries to satisfy basic needs like cooking and heating applying traditional methods and equipment. However, a fairly smooth transition from traditional to modern forms of biomass utilization is assumed.

The model contains three types of biomass and a number of technologies that are available to transform the raw material into useful energy carriers. Table 6 introduces the biomass types (columns), the types of secondary energy (rows) and the transformation technologies (matrix fields). Starch and oil biomass are suited to produce liquid fuels, but ligno-cellulosic biomass is a multipurpose primary energy carrier that can be flexibly allocated to a variety of transformation technologies. We do not consider third generation biomass from industrial scale algae production.

We assume biomass supply functions with an upper limit for the supply. The biomass potentials and associated costs vary significantly with the type of biomass. This also comes with the problem that the biomass types compete for the same land. However, the concept of multiple marginal cost curves for supplying biomass does not consider this trade-off since supply functions are assumed to be separable. Analysis showed that sugar and oil based biomass are less attractive than ligno-cellulosic biomass. Hence, ligno-cellulosic biomass is favored over both alternatives by assuming very limited supplies for the inferior alternatives. This choice also solves two other problems of biomass production from sugar and oil based biomass. First, ligno-cellulosic biomass needs much less nitrogen fertilizers which would cause N_2O emissions. Second, in turn the energy need for producing the fertilizer is not required; see e.g. Farrell et al. (2006). Hence the linkages from biomass supply to energy needs and N_2O emissions are ignored.

		Biomass types		
		Ligno-cellulosic	**Starch, sugar**	**Oil**
Secondary energy	**Solids**	Transformation; traditional use		
	Heat	Heating plant CHP plant		
	Electricity	CHP plant Power plant		
	Diesel	FT-Synthesis		Biodiesel
	Ethanol	Ethanol refinery	Ethanol refinery	
	Gas	Biogasification		
	H2	B2H		

Table 6: Alternative conversion technologies using biomass.

Table 7 documents essential techno-economic data of the technologies fueled with ligno-cellulosic biomass. The data is taken from the relevant literature. The figures need some qualification to put them into perspective.

	Efficiency	Investment costs	Availability
	%	$US per kW	%
Traditional biomass	90	150	90
Heat	60-97	400	46
CHP	9-33 (heat. 4-54)	1375	40
Biogasification	55	1000	91
Bioethanol	36.1 (elec. 15)	2383	90.4
BTL	40 (elec. 16)	2500	91
BTL with CCS	41 (elec. 14)	3000	91
H_2	61	1404	90
H_2 with CCS	55	1700	90

Table 7: Techno-economic data of technologies using lingo-cellulosic biomass. (Intervals represent the range to be found in energy statistics; notes in parenthesis indicate the joint product, where the number reads as x joint output for every unit of main output.)

Traditional biomass is the most commonly used technology of using biomass deployed today. It summarizes a great set of technology alternatives. Though it represents a great variety of different entities we did not disaggregate the technology because it is a highly problematic field. Instead we assume that the solid energy carriers that are produced of biomass are of low value and the demand growth is the slowest of all energy carriers. The figures given in the table represent the idea that a low value energy carrier is produced.

Heating plants exhibit a range of conversion efficiencies. The figures refer to the conversion efficiencies implied by the IEA data on energy balances. The investment costs are relatively low, which is due to the low value energy carrier produced; the data is taken from Schulz (2007, p. 140). A comparison with FNR (2002, p. 84) shows that investment costs are 560 $US per kW (280 $US per kW) for a small (huge) heating plant. The applied number is a compromise between these two values.

CHP technologies are more difficult to assess. The ranges are again in correspondence with the IEA energy balances. The investment costs are in line with the costs reported in Junginger et al. (2006, p. 4031) and Schulz (2007, p. 140). However, we did not assume learning for this technology, though the former study found a learning rate nearly 10 % (p. 4038). Heinrich and Jahraus (2000, p. 37-8) report investment costs for various technologies and differing capacities. The assumption applied in the model is in line with the reference for huge CHP plants. The availability factor is assumed in line with Schulz.

Biogasification plants produce synthetic natural gas from biomass. The efficiency is taken from Schulz, but we did not take into account the joint production of heat, which lead us to a discount for the investment costs that is used in that study.

Bioethanol indicates the production of ethanol from ligno-cellulosic biomass as a substitute for petroleum in transportation. The assumption for investment costs is quite high. The literature reports lower values between 1123 and 2145 $US per kW. Also the efficiency is usually rated at 44 %; see Aden et al. (2002), Yamashita and Barreto (2007), and Raggetli (2007).

Hydrogen production from biomass is available with and without carbon capture and sequestration. The efficiencies to be found in the literature range from 45 to 68 % for the case without CCS. We assumed investment costs much higher than in the literature, where the reported figures are usually assessed to be lower than 1000 $US per kW in the case without CCS; see Yamashita and Barreto (2007), Takeshita and Yamaij (2008, p.2795), and Iwasaki (2003).

Diesel from ligno-cellulosic biomass can be produced via Fischer-Tropsch synthesis with or without the option to capture and sequester part of the CO_2. The assumptions used here are less optimistic than those found in the literature. Schulz reported investment costs of about 1500 $US per kW with an efficiency of 45 % and additional 0.2 GJ electricity for every GJ of produced diesel. Takeshita and Yamaij (2008) assumed 2250 $US per kW and an efficiency of 46 %; however in this case electricity is an input to the production process.

In summary, it can be concluded that the assumptions in the REMIND model are not overly optimistic. For various technologies that are not already available we deviated from the literature assuming less optimistic parameter values. Moreover, the combination of biomass with CCS is only considered within the transport sector, but not for CHP technologies and biomass power plants.

4.2. *Key mitigation options*

Six major mitigation options, applied in REMIND-R, can be summarized:

- Lowering energy consumption
- Modernizing the output structure of secondary energy carriers
- Reduction of fossil fuel based transportation fuels and gases (mainly by the use of biomass)
- Use of renewable primary energy sources
- Use of nuclear energy
- Application of CCS technologies for the use of gas, coal and biomass.

Technological and economic characteristics of the single technologies underlying these options are discussed in Section 2.3, 3.3 and 4.1.

Which of the mitigation options are chosen (when and where) is part of the endogenous decision process simulated by the model. The cost of different mitigation options is an essential decision criteria. Energy efficiency is increased (beyond the improvements that are autonomously happen already in the baseline scenario) by the first two options. The output structure of secondary energies is modernized by installing capacities of new transformation technologies.

The CCS option and the renewable energy option play the most important role in cost-efficient mitigation policies. Biomass is intensively used already in the baseline scenario. Biomass in combination would gain additional importance if negative emissions hast to be achieved. If CCS technologies will not be available, renewable energies technologies (mainly solar) will fill the gap. In the short and mid term also the share of nuclear energy would be increased. Total energy consumption would be lowered. Nuclear energy plays some role in mitigation policies. Its option value, however, is much lower than for renewable and CCS mitigation option, i.e. nuclear energy technologies can be substituted with quite low costs.

5. Baseline scenario

This section aims not at providing a comprehensive overview on results from the baseline scenario. Here we will briefly discuss separate details that will help to understand why some probably counter-intuitive results occur.

First, it should be emphasized that in our definition of the baseline scenario any form of climate policy is disregarded. The baseline scenario is not meant to describe a highly reasonable scenario, but only to form a reference point, against the background of which the results of the policy scenario can be evaluated.

Nevertheless, initial data may reflect consequences from first climate policies (e.g. installation of solar energy technologies), leading to results that seem to be surprising at a first glance: decreasing energy production from solar energy technologies and missing cost degradation of investment costs in the first decades. Even more surprisingly, the same phenomenon applies to the policy scenario. What happens here, is that the initially existing capital stock of this technology is used according to its life time, but not any new capacity will be built up. Without any subsidy these technologies are not competitive. REMIND does not take market imperfections of this kind into account, but looks for a solution in a first-best world.

Another surprising result is the drastic reduction in the consumption of gas in the first decades. Gas is in direct competition with coal as both energy carriers are used for the same type of conversion technologies (see Table 2). In a world without carbon constraint and a coal price that is sustainably below the gas price, coal-based technologies are dominant and gas consumption is reduced to the account of coal consumption (see Figure 8). This trend is intensified by unobstructed trade in coal.

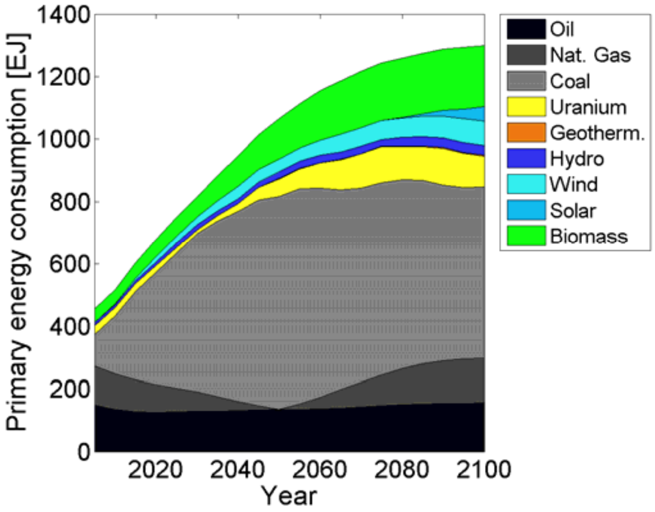


Figure 8: Primary energy consumption

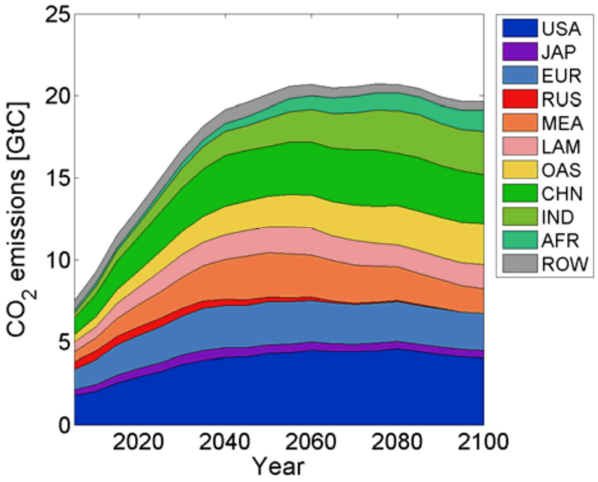


Figure 9: Global emissions

Both the absence of any climate policy and the shift towards a massive use of coal leads to an increase of emissions which in particular in the first decades is remarkable and well above of the projections of the IEA and the WEO.

References

Aden, A. , M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace (2002): Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis forCorn Stover. Report of the NREL, No. 510-32438.

Bauer, N., O. Edenhofer, S. Kypreos (2008): Linking Energy System and Macroeconomic Growth Models. Journal of Computational Management Science 5, 95-117.

Bauer, N. (2005): Carbon Capture and Sequestration-An Option to Buy Time? Ph.D. thesis, Faculty of Economic and Social Sciences, University Potsdam, Germany.

Bosetti, V., C. Carraro, M. Galeotti. E. Massetti, M. Tavoni (2006), WITCH: A World Induced Technical Change Hybrid Model. The Energy Journal, Special Issue 2006, 13-38.

Crassous, R., J.-C. Hourcade, O. Sassi (2006): Endogenous Structural Change and Climate Targets. Modeling experiments with Imaclim-R. The Energy Journal, Special Issue Endogenous Technological Change and the Economics of Atmospheric Stabilisation, 259-276.

Farrell, A.E., R.J. Plevin, B.T. Turner, A.T. Jones, M. O'Hare, D.M. Kammen (2006): Ethanol Can Contribute to Energy and Environmental Goals, Science, 311(5760): 506-8.

Flam, H. and M.J. Flanders (eds.) (1991): Heckscher-Ohlin Trade Theory, Cambridge, Massachusetts: MIT Press.

FNR (2002): Energie aus Biomasse. Fachagentur Nachwachsende Rohstoffe. Gülzow, Germany. http://www.fnr-server.de/ftp/pdf/literatur/pdf_40lehrmaterial.pdf

Gül, T., S. Kypreos, L. Barreto (2008): Hydrogen and Biofuels - A Modeling Analysis of Competing Energy Carriers for Western Europe. In: Proceedings of the World Energy Congress "Energy Future in an Interdependent World", 11-15 November 2007, Rome, Italy.

Hamelinck, C. (2004): Outlook for advanced biofuels. Ph.D. thesis, University of Utrecht, The Netherlands.

Heinrich, P. and B. Jahraus (2000): Stromerzeugung aus Biomasse. Contribution to Gülzower Fachgespräche: „Energetische Nutzung von Biomasse durch Kraft-Wärme-Kopplung“, p. 25-39. Fachagentur Nachwachsende Rohstoffe (FNR), Gülzow.

Hoogwijk, M.M. (2004): On the Global and Regional Potential of Renewable Energy Sources. Ph.D. thesis, University of Utrecht.

IEA (2007): Electricity Information, CD IEA Statistics; Paris , France.

IPCC (2001): W.R. Moomwa and J.R. Moreira. Technological and Economic Potential of Greenhouse Gas Emissions Reductions. In B. Metz, editor, Climate Change 2001: Mitigation: Contribution of Working Group IIII to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp. 167. Cambridge University Press, Cambridge, UK, 2001.

Iwasaki, W. (2003): A consideration of the economic efficiency of hydrogen production from biomass. Int. Jour. of Hydrogen Energy 28, 939-944.

Junginger, M., A. Faaji, W. Turkenburg (2005): Global Experience Curves for Wind Farms. Energy Policy 33, 133-150.

Junginger, M., A. Faaij, W. Turkenburg (2004): Cost reduction prospects for off-shore wind farms. Wind Engineering 28 (1), 97_118.

Junginger, M., E. Visser, K. Hjort-Gregersen, J. Koornneef, R. Raven, A. Faaij, W. Turkenburg (2006): Technological Learning in Bioenergy Systems. Energy Policy 34, 4024-41.

Kriegler, E., T. Bruckner (2004): Sensitivity of emissions corridors for the 21st century. Climatic Change 66, 345-387.

Kypreos, S., O. Bahn (2003): A MERGE model with endogenous technological progress. Environmental Modeling and Assessment 19, 333-358.

Leimbach, M., N. Bauer, L. Baumstark, O. Edenhofer (2009): Mitigation costs in a globalized world: climate policy analysis with REMIND-R, submitted to Environmental Modeling and Assessment.

Leimbach, M., F. Toth (2003): Economic development and emission control over the long term: The ICLIPS aggregated economic model. Climatic Change, 56, 139-165.

Manne, A.S., M. Mendelsohn, R. Richels (1995): MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Energy Policy 23, 17-34.

Manne, A. S., T. Rutherford (1994): International trade, capital flows and sectoral analysis: formulation and solution of intertemporal equilibrium models. In: Cooper, W. W. and Whinston, A. B. (eds.), New directions in computational economics, Kluwer Academic Publishers, Dordrecht, The Netherlands, 191-205.

Neij, L., P.D. Andersen, M. Durstewitz, P. Helby, M. Hoppe-Klipper, P.E. Morthorst (2003): Experience Curves: A Tool for Energy Policy Assessment. Environmental and Energy Systems Studies Lund University Gerdagatan 13 SE-223 63 Lund Sweden. Extool final report.

McDonald, A., L. Schrattenholzer (2001): Learning Rates for Energy Technologies. Energy Policy 29, 255-261.

Nordhaus, W.D., Z. Yang (1996): A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. American Economic Review 86, 741-765.

Petschel-Held, G., H.J. Schellnhuber, T. Bruckner, F.L. Toth, K. Hasselmann.(1999): The tolerable windows approach: theoretical and methodological foundations. Climatic Change 41, 303-331.

Penn World Tables (2007): Version 6.2, http://pwt.econ.upenn.edu/php-site/pwt-index.php

Ragettli, M. (2007): Cost Outlook for the Production of Biofuels. Ph. D. thesis, ETH Zurich, Switzerland.

Schulz, T.F., L. Barreto, S. Kypreos, S. Stucki (2007): Assessing wood-based synthetic natural gas technologies using the SWISS-MARKAL model. Energy 32, Issue 10, Pages 1948-1959,

Takeshita, T., K. Yamaij (2008): Important roles of Fischer-Tropsch synfuels in the global energy future. Energy Policy 36, 2773_2784.

Yamashita, K., L. Barreto (2007): Biomass Gasification for Co-production of Fischer-Tropsch Liquids and Electricity. IIASA, Interim Report IR-04-047, Laxenburg, Austria. http://www.iiasa.ac.at/Publications/Documents/IR-04-047.doc

WBGU (2003): Welt im Wandel: Energiewende zur Nachhaltigkeit. Springer.

Appendix C: Model description WITCH

1. Introduction

Although economic attempts aimed at quantifying the costs of climate policies have been increasing in the recent years, the economic analysis of climate change remains a complex task. Sound economic analysis should be based on climate-economy models that encompass all possible features characterizing climate change and its relationship with human activities.

Climate change is a difficult issue, essentially for three reasons. First of all, it is a global problem with an international dimension, which involves a very large number of players, namely all countries in the world. Furthermore, the expected impacts of climate change, potential costs to mitigate it or adapt to it, and the ensuing benefits, are not spread equally. Secondly, it is a long-term phenomenon because of the inertia of the climate system: abatement actions taken today will only yield benefits in the distant future. Thirdly, climate change is characterized by a high degree of uncertainty, under several aspects: although the scientific basis behind global warming has become more robust, the climate remains a complex system, difficult to understand; it is difficult to know the future development of technologies, which may broaden the options available for slowing down climate change; Moreover, in the international arena countries respond to strategic incentives and therefore it is not easy to foresee the action of different regions.

To provide reliable results, climate-economy models used for the economic analysis of climate change policies should attempt at representing all these features.

The WITCH model developed by the climate change group at FEEM (Bosetti et al., 2006; Bosetti et al., 2007) is an energy-economy-climate model designed to explicitly deal with the main features of climate change. It is a regional model in which the non-cooperative nature of international relationships is explicitly accounted for. It is a truly intertemporal optimization model, with a long term horizon covering all century until 2100. Moreover, the regional and intertemporal dimension of the model makes it possible to differentiate climate policies across regions and over time. In this way, several policy scenarios can be considered. Finally, the model includes a wide range of energy technology options, with different assumptions on their future development, which is also related to the level of innovation effort undertaken by countries.

The core structure of the model is described at length in the technical report (Bosetti et al., 2007). This chapter recalls the main characteristics of the model version used for the RECIPE project.

2. Model structure

2.1. General framework

WITCH – World Induced Technical Change Hybrid – is an optimal growth model of the world economy that integrates in a unified framework the sources and the consequence of climate change. A climate module links greenhouse gas (GHG) emissions produced by economic activities to their accumulation in the atmosphere and the oceans. The effect of these GHG concentrations on the global mean temperature is derived.

The world economy is disaggregated into twelve macro regions:

- USA: United States
- OLDEURO: Western Europe
- NEWEURO: Eastern Europe
- KOSAU: Korea, South Africa, Australia
- CAJAZ: Canada, Japan, New Zealand
- TE: Transition Economies
- MENA: Middle East and North Africa
- SSA: Sub-Saharan Africa
- SASIA: South Asia
- CHINA: China and Taiwan
- EASIA: South East Asia
- LACA: Latin America, Mexico and Caribbean

Countries have been grouped according to economic, geographic, resource endowment and energy characteristics. Regions interact with each other through the presence of economic and environmental global externalities. For each region a forward-looking agent maximizes her own intertemporal social welfare function, strategically and simultaneously to other regions. The intertemporal equilibrium is calculated as an open-loop Nash equilibrium, but a cooperative solution can also be implemented. Through the optimization process regions choose the optimal dynamic path of the control variables, namely investments in different capital stocks, in R&D, in energy technologies and consumption of fossil fuels.

WITCH is a hard-link hybrid model because the energy sector is fully integrated with the rest of the economy and therefore investments and the quantity of resources for energy generation are chosen optimally, together with the other macroeconomic variables. The model can be defined hybrid because the energy sector features a bottom-up characterization. A broad range of different fuels and technologies can be used in the generation of energy. The energy sector endogenously accounts for technological change, with considerations for the positive externalities stemming from learning by doing and learning by researching. Overall, the economy of each region consists of eight sectors: one final good, which can be used for consumption or investments, and seven energy sectors (or technologies): coal, oil, gas, wind & solar, nuclear, electricity, and biofuels.

The length of the time horizon (from 2005 to 2100 with a five-years step), the regional dimension and the game theoretical setup make the WITCH model suitable for the assessment of intertemporal, geographic and strategic aspects of climate change policies.

2.2. The model

As typically found in intertemporal optimal growth models, the production side of the economy is very aggregated. Each region produces one single commodity that can be used for consumption or investments. The final good (Y) is produced using capital (K_C), labor (L) and energy services (ES). In the first place capital and labor are aggregated using a Cobb-Douglas production function. This nest is then aggregated with energy services with a

Constant Elasticity of Substitution production function (CES). Production of net output is described in equation (A4) in the last chapter.

The optimal path of consumption is determined by optimizing the intertemporal social welfare function, which is defined as the log utility of per capita consumption, weighted by regional population, as described in equation (A1). The pure rate of time preference declines from 3 % to 2 % at the end of the century, and it has been chosen to reflect historical values of the interest rate.

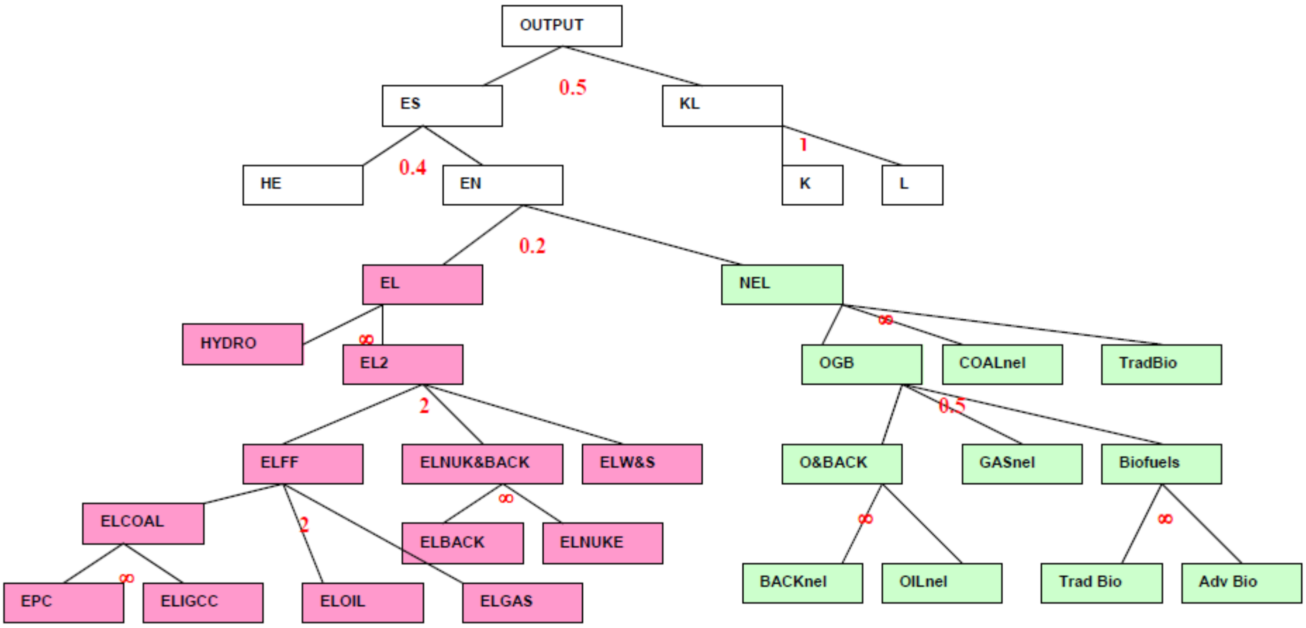
Energy services, in turn, are given by a CES combination of the physical energy input and a stock of energy efficiency knowledge, as illustrated in equation (A6). This way of modeling energy services allows for endogenous improvements in energy efficiency. Energy efficiency increases with investments in dedicated energy R&D, which build up the stock of knowledge. The stock of knowledge can then replace (or substitute) physical energy in the production of energy services.

Energy used in final production is a combination of electric and non electric energy. Electric energy can be generated using a set of different technology options and non electric energy also consists of different fuels. Fuel consumption and investments in different technologies are the result of each region’s optimization. In other words, each region will choose the optimal intertemporal mix of technologies and R&D investments in a strategic way. The next section describes in detail the energy sector.

2.3. The energy sector

Despite being a top-down model, WITCH includes quite a wide range of technology options to describe the use of energy and the generation of electricity (see a schematic representation of the energy sector and its role within the economic module of the model in Figure 10). Energy is described by a production function that aggregates factors at various levels and with different elasticities of substitution. The main distinction is among electric generation and non-electric consumption of energy.

Electricity is generated from a series of traditional fossil fuel-based technologies and carbon free options. Fossil fuel-based technologies include natural gas combined cycle (NGCC), fuel oil and pulverized coal (PC) power plants. Coal-based electricity can also be generated using integrated gasification combined cycle production with CCS (IGCC-CCS). Low carbon technologies are hydroelectric and nuclear power and renewable sources such as wind turbines and photovoltaic panels (Wind&Solar).



Legenda: KL= Capital-labour aggregate; K = Capital invested in the production of final good; L = Labour; ES = Energy services; HE = Energy R&D capital; EN = Energy; EL = Electric energy; NEL = Non-electric energy; OGB = Oil, Backstop, Gas and Biofuel nest; ELFF = Fossil fuel electricity nest; W&S= Wind and Solar; ELj = Electricity generated with technology j (IGCC plus CCS, Oil, Coal, Gas, Backstop, Nuclear, Wind plus Solar); TradBiom= Traditional Biomass; TradBio= Traditional Biofuels; AdvBio= Advanced Biofuels

Figure 10: Production nest and the elasticity of substitution

All the main technology features are represented: yearly utilization factors, fuel efficiencies, investment, and operation and maintenance costs. For CCS, supply costs of injection and sequestration reflect sites availability at the regional level, as well as energy penalty, capture and leakage rates. IGCC-CCS competes with traditional coal, so that it replaces it for a sufficient carbon price signal. For nuclear power, waste management costs are also modeled, but no exogenous constraint is assumed, contrary to most models. Hydroelectric power is assumed to evolve exogenously to reflect limited site availability.

Breakthrough in power generation technologies is modeled by introducing a backstop technology, that can be better thought of as a compact representation of a portfolio of advanced technologies that can substitute nuclear power.

Energy consumption in the non-electric sector is based on traditional fuels (traditional biomass, oil, gas and coal) and biofuels. In order to account for land use security concerns, overall penetration of biofuels is assumed to remain modest over the century. The consumption of oil can be substituted with a carbon free backstop technology, which could be thought of as next generation biofuels or carbon free hydrogen. As a consequence, the backstop technology is mostly conceived as an abatement option for the transport sector.

The cost of electricity generation is endogenous and it combines capital costs, O&M expenditure and the expenditure for fuels. The price of fossil fuels and exhaustible resources (oil, gas, coal and uranium) is also endogenously determined by the marginal cost of extraction, which in turn depends on current and cumulative extraction, plus a regional mark up to mimic different regional costs.

2.4. *Endogenous technical change*

One of the main features of the WITCH model is the characterization of endogenous technical change. Albeit difficult to model, technological innovation is key to the decoupling of economic activity from environmental degradation, and the ability to induce it using appropriate policy instruments is essential for a successful climate agreement, as highlighted also in the Bali Action Plan.

Both innovation and diffusion processes are modeled. We distinguish dedicated R&D investments for enhancing energy efficiency from investment aimed at facilitating the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (backstops). R&D processes are subject to stand on shoulders as well on neighbors effects. Specifically, international spillovers of knowledge are accounted for to mimic the flow of ideas and knowledge across countries.

Finally, experience processes via Learning by Doing are accounted for in the development of niche technologies such as renewable energy (Wind&Solar) and the backstops.

2.5. *Non cooperative solution*

The game theoretic setup makes it possible to capture the non-cooperative nature of international relationships. Free riding behaviors and strategic inaction induced by the presence of a global externality are explicitly accounted for in the model. Climate change is the major global externality, as GHG emissions produced by each region indirectly impact on all other regions through the effect on global concentrations and thus global average temperature. The model features other economic externalities that provide additional channels of interaction. Energy prices depend on the extraction of fossil fuels, which in turn is affected by consumption patterns of all regions in the world. International knowledge and experience spillovers are two additional sources of externalities. By investing in energy R&D, each region accumulates a stock of knowledge that augments energy efficiency and reduces the cost of specific energy technologies. The effect of knowledge is not confined to the inventor region but it can spread to other regions. Finally, the diffusion of knowledge embodied in wind&solar experience is represented by learning curves linking investment costs with world, and not regional, cumulative capacity. Increasing capacity thus reduces investment costs for all regions.

These externalities provide incentives to adopt strategic behaviors, both with respect to the environment (e.g. GHG emissions) and with respect to investments in knowledge and carbon free but costly technologies. In order to represent strategic behaviors, the model is solved as a non-cooperative game. The solution is found when all regions' strategies are a best response to other regions' best responses. An iterative algorithm solved recursively is used, yielding an Open Loop Nash Equilibrium.

As a consequence, such equilibrium represents a second-best solution that, differently from models that maximize a global social welfare function and thus do not internalize international externalities on the environment and on the diffusion of new technologies.

3. Database and calibration

The WITCH model has recently been updated with latest data and revised estimates for future projection of the main exogenous drivers. The base calibration year has been set at 2005, for which socio-economic, energy and environmental variables data is now available. We report on the main hypotheses on current and future trends on population, economic activity, energy consumptions and climate variables.

3.1. Population

An important driver for the emissions of greenhouse gases is the rate at which population grows. In the WITCH model, population growth is exogenous. We updated the model base year to 2005, and use the most recent estimates of population growth. The annual estimates and projections produced by the UN Population Division are used for the first 50 years[5]. For the period 2050 to 2100, the updated data is not available, and less recent long term projections, also produced by the UN Population Division (UN, 2004) are adopted instead. The differences in the two datasets are smoothed by extrapolating population levels at 5 year periods for 2050-2100, using average 2050-2100 growth rates.

Population in 2005 equals roughly 6.5 Billions, and peaks in 2070 at almost 9.6 Billions, slightly decreasing thereafter to reach 9.1 in 2100 (Figure 11), following a similar pattern as in REMIND-R and IMACLIM. Almost half of world population is located in Sub-Saharan Africa and South Asia.

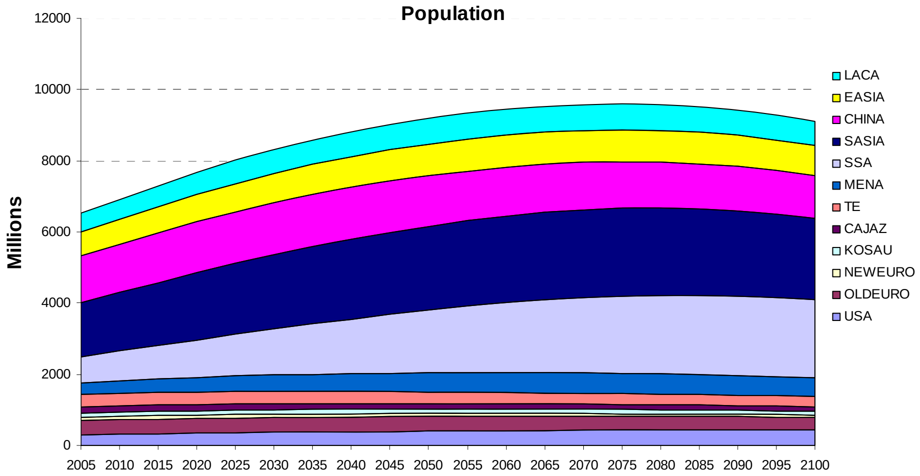


Figure 11: Population dynamics

---

[5] Data is available from http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple.

3.2. Economic growth

The GDP data for the new base year are from the World Bank Development Indicators 2007, and are reported in 2005 US$[6]. We maintain the use of market exchange rates (MER)[7]. World GDP in 2005 equals to 44.2 Trillions US$.

Although GDP dynamics is partly endogenously determined in the WITCH model, it is possible to calibrate growth of different countries by adjusting the growth rate of total factor productivity, the main engine of macroeconomic growth. Figure 12 shows the revised trajectories for Gross World Product over the century[8]. We project a continued economic growth, with a global GWP in 2050 3.9 times higher than current levels. Growth rates start at around 4 %/yr, declining to 2.5 %/yr towards mid-century. Even with substantial income convergence across countries, per capita differences remain substantial.

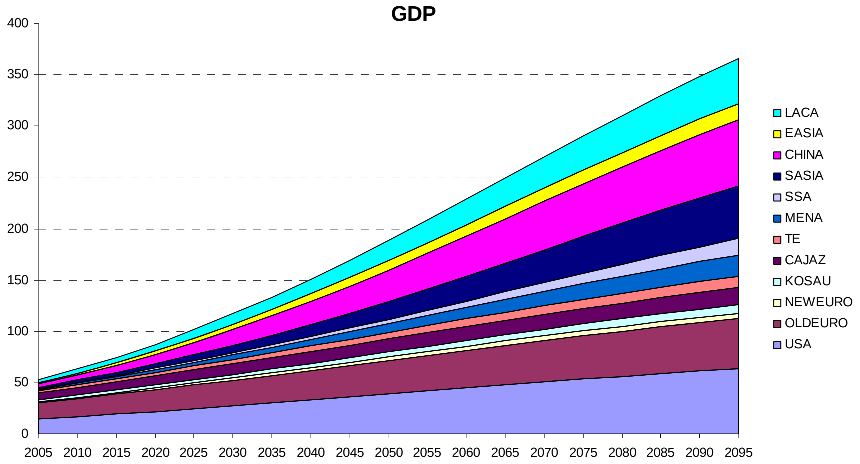


Figure 12: GDP trajectories

Economic growth rates and the level of convergence are strong determinants of energy demand and, therefore, GHG emissions. Projections for regional GDP growth have been

---

[6] http://go.worldbank.org/U0FSM7AQ40

[7] This is in line with the most common practice in energy-economic-environment modelling. There has been a recent intense debate on the use of MER vs. purchasing power parity (PPP) exchange rate, in particular in relation to the implications for greenhouse gases emission trajectories. MER might underestimate current relative output levels of low-income countries by a factor of around three relative to high-income countries, because tradable goods are currently relatively more expensive in low income countries than in high income countries (the Harrod–Balassa–Samuelson effect). However, output data is more readily available and reliable in MER, and allows for better comparison of both output growth and carbon intensities with historical empirical studies, that mostly rely on the MER metric, as well as short term projections of economic and energy variables. Furthermore, the lower carbon efficiency of developing countries implicit in MER calculations does not necessarily translate in higher emission projections: income elasticity of energy demand is higher when using PPP, so that lower autonomous efficiency improvements should be assumed for PPP projection. The final effect on emissions is unclear, and might not be significant.

[8] We report all US$ in 2005US$. All figures have been adjusted using the 1995->2005 conversion factor of 0.788.

harmonized with the other two models, REMIND-R and IMACLIM, so as to yield some degree of convergence in labor productivity.

OECD countries are assumed to reach a rather constant growth rate, while the catch-up of non-OECD is driven by labor productivity which should bring most of developing countries closer to the level of OECD countries by the end of the century. The convergence is nonetheless slow in per capita terms given the higher population growth of developing countries (Figure 13). Sub-Saharan Africa, in particular, experiences delays in catch-up. Eastern Europe shows the highest convergence rate. We therefore calibrate the model dynamically to match a growth path consistent with these underlying assumptions on convergence and growth. Figure 13 shows the convergence of income per capita to the levels of the US. Figure 14 reports GPD growth rates.

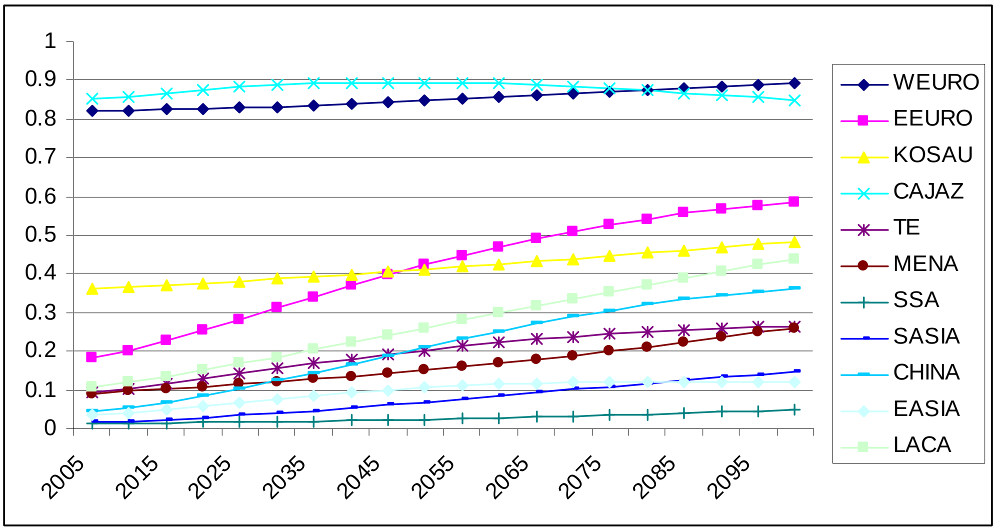


Figure 13: Convergence of GDP per capita to US levels

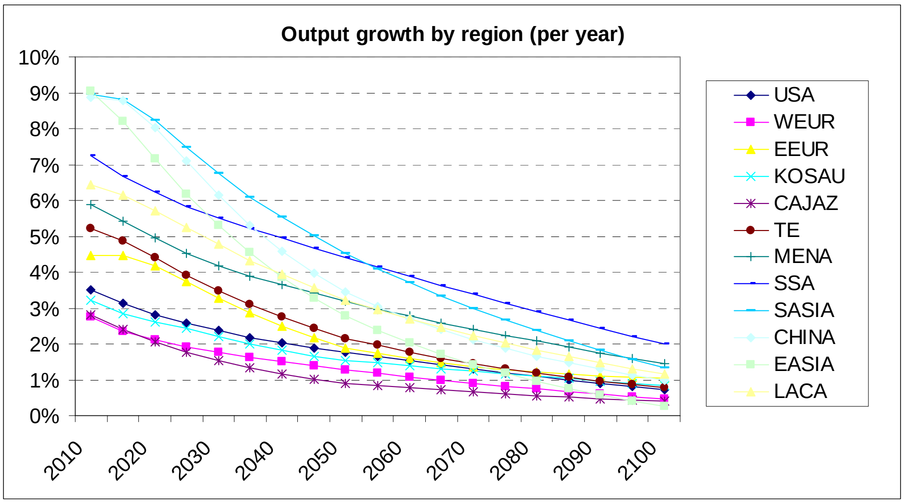


Figure 14: Output growth rates

3.3. Energy data

The WITCH model distinguishes the end use of energy between power generation (electricity sector) and other alternative usages, also referred to as non electric usages or non electric sector. This distinction makes it possible to account for emissions reduction from the non electric sector, where substitution of fossil fuel use is particularly challenging.

3.3.1. Power generation sector

Despite the detailed description of the power generation sub-sector, not all types of power plants are modeled explicitly in WITCH (for instance, the model does not distinguish gas with no combined cycle). We therefore assume the standard use of factors for new power plants. This assumption helps us to avoid accounting difficulties for multi-fuel and marginal power plants. Following recent debates over the technical feasibility, we increase the investment costs for Integrated Gasification Combined Cycle (IGCC) technologies from 2540 US$\$_{2005}$/kW to 3170 US$\$_{2005}$/kW. The same increase is applied to nuclear power generation.

We assume the average efficiency of gas and coal power plants improves autonomously to 60 % and 45 % respectively over the next decades. Similarly, the utilization factor of Wind&Solar is assumed to increase from 2500 to 3500 hours per year within a 30 years time frame. Hydroelectric and renewables are assumed to have efficiency equal to 100 % as they do not use primary energy carriers. Waste management costs for nuclear start at 0.1 c$/KWh (MIT, 2003) and grow with global nuclear electricity. Other key techno-economic assumptions of technologies used in the power sector are described in Table 8.

Costs for new investments and maintenance in power generation are region specific and constant over time, but for renewables and backstop technologies, which are discussed in more detailed in Section 5.1. Investment costs in renewable energy decline with cumulated installed capacity at the rate set by the learning curve progress ratios, which is set equal to 0.87 — i.e. there is a 13 % investment cost decrease for each doubling of world installed capacity.

Electricity production is described by a Leontief production function that combines generation capacity, fuels and expenditure for operation and maintenance (O&M) in a Leontief production function. The fixed proportions used to combine the three inputs (two in the case of wind and solar electricity generation which does not need any fuel input) have been derived by plant operating hours, fuel efficiencies and O&M costs described in Table 8 and are constant across regions and across time. The parameters governing the production function take into account the technical features of each power production technology, such as the low utilization factor of renewables, the higher costs of running and maintain IGCC-CCS and nuclear plants.

	Investment costs	**O&M**	**Fuel Efficiency**	**Load factor**	**Lifetime**	**Deprecia-tion**
	World average USD_{2005}/KW	World average USD_{2005}/KW	%	**%**	years	**%**
Renewables (W&S)	1904	30	100 %	30 %	30	7.4 %
Nuclear	2540	176	35 %	85 %	40	5.6 %
Hydropower	1780	70	100 %	50 %	45	5 %
Coal	1530	47	45 %	85 %	40	5.6 %
Oil	1010	36	40 %	85 %	25	8.8 %
Gas	810	30	60 %	85 %	25	8.8 %
IGCC-CCS	3170	47	40 %	85 %	40	5.6 %

Table 8: Technical parameters for electricity generation

3.3.2. Non electricity sector

The energy carriers that are used for usages other than power generation are traditional biomass, biofuels, coal, gas and oil. In addition, a backstop technology, representing potential breakthrough options that could substitute oil in the non electric sector, pending sufficient R&D investments, is also considered. Oil and gas together account for more than 70 % of energy consumption in the non electric sector. Instead the use of coal is limited to some developing regions and it is assumed to decrease exogenously. Traditional biomass as well is used mostly in non-OECD regions and its share declines over time, from 11 % in 2005 to 7 % in 2030, as rural population in developing countries progressively gains access to standard forms of energy. In WITCH we distinguish between ethanol, which we label as “traditional biofuels”, and “advanced biofuels”, which are obtained from biomass transformation. Biofuels consumption is currently low in all regions of the world and the overall penetration remains modest over time given the conservative assumptions on their large scale deployment.

3.3.3. Prices of fossil fuels and exhaustible resources

The prices of fossil fuels and exhaustible resources have been revised upwards, following the sharp increases in the market prices between 2002 and 2005. Base year prices have been calibrated following Enerdata (2008), IEA (2007) and EIA (2008a). The 2005 international prices for exhaustible resources are set at:

- 55 US$/bbl for oil, or roughly 8 US$/GJ
- 7.14 US$/GJ for natural gas
- 60 US$/ton for coal, equivalent to 2 US$/GJ. In order to match the large difference in price increases shown in the Enerdata database, we adjust the mark-up prices

- Uranium ore price are set at 2005[9] level. The cost of uranium conversion and enrichment is set at 230 US$$_{1995}$/kg of ore.

As mentioned in section 2.3, country specific mark ups are set to reproduce regional figures from IEA (2007).

3.3.4. Carbon emission coefficients of fossil fuels

The use of fossil fuels generates CO_2 emissions, which are computed by applying stoichiometric coefficients to energy use. In order to differentiate the higher emission content of non-conventional oil as opposed to conventional ones, we link the carbon emission coefficient for oil to its availability. Specifically, the stoichiometric coefficient for oil increases with the cumulative oil consumed so that it increases by 25 % when 2000 Billions Barrels are reached. An upper bound of 50 % is assumed. The 2000 figure is calibrated on IEA (2005) estimates on conventional oil resource availability. The 25 % increase is chosen given that estimates range between 14 % and 39 % (Farrell and Brandt, 2006).

3.4. Climate data and feedback

We continue to use the MAGICC 3-box layer climate model as described in Nordhaus and Boyer (2000). CO_2 concentrations in the atmosphere have been updated to 2005 at roughly 385ppm and temperature increase above pre-industrial at 0.76 °C, in accordance with IPCC Fourth Assessment Report (2007). Other parameters governing the climate equations have been adjusted following Nordhaus (2007)[10]. We have replaced the exogenous non-CO_2 radiative forcing in equation (A22), *O*, with specific representation of other GHGs and sulphates, see Section 4. Climate sensitivity, a key parameter, is set equal to 3.

4. Additional sources of GHGs

4.1. Non-CO_2 GHGs

Non-CO_2 GHGs are important contributors to global warming, and might offer economically attractive ways of mitigating it[11]. For this reason, the WITCH model explicitly models non-CO_2 gases, namely emissions of CH_4, N_2O, SLF (short lived fluorinated gases, i.e. HFCs with lifetimes under 100 years) and LLF (long lived fluorinated, i.e. HFC with long lifetime, PFCs, and SF_6). SO_2 aerosols are also accounted for through their cooling effect on temperature (see equation A21).

Since most of these gases are determined by agricultural practices, we rely on estimates for reference emissions and a top-down approach for mitigation supply curves. For the baseline projections of non-CO_2 GHGs, we use EPA regional estimates (EPA, 2006). The regional estimates and projections are available until 2020 only: beyond that date, we use growth rates for each gas as specified in the IIASA-MESSAGE-B2 scenario[12], that has underlying

---

[9] http://www.uxc.com/review/uxc_g_price.html

[10] http://nordhaus.econ.yale.edu/DICE2007.htm

[11] See the Energy Journal Special Issue (2006) (EMF-21), Multi-Greenhouse Gas Mitigation and Climate Policy - Special Issue n°. 3 and the IPCC 4th AR WG III (IPCC, 2007b)

[12] Available at http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=regions

assumptions similar to the WITCH ones. SO_2 emissions are taken from MERGE v.5[13] and MESSAGE B2: given the very large uncertainty associated with aerosols, they are translated directly into the temperature effect (cooling), so that we only report the radiative forcing deriving from GHGs. In any case, sulphates are expected to be gradually phased out over the next decades, so that eventually the two radiative forcing measures will converge to similar values.

The equations translating non-CO_2 emissions into radiative forcing are taken from MERGE v.5 (see equations A24 to A27 in the last section). The global warming potential (GWP) methodology is employed, and figures for GWP as well as base year stock of the various GHGs are taken from IPCC Fourth Assessment Report, Working Group I. The simplified equation translating CO_2 concentrations into radiative forcing is in line with IPCC[14].

We introduce end-of-pipe type of abatement possibilities via marginal abatement curves (MACs) for non-CO_2 GHG mitigation. We use MAC provided by EPA for the EMF 21 project[15], aggregated for the WITCH regions. MAC are available for 11 cost categories ranging from 10 to 200 US$/tC. We have ruled out zero or negative cost abatement options. MACs are static projections for 2010 and 2020, and for many regions they show very low upper values, such that even at maximum abatement, emissions would keep growing over time. We thus introduce exogenous technological improvements: for the highest cost category only (the 200 US$/tC) we assume a technical progress factor that reaches 2 in 2050 and the upper bound of 3 in 2075. We however set an upper bound to the amount of emissions which can be abated, assuming that no more than 90 % of each gas emissions can be mitigated. Such a framework enables us to keep non-CO_2 GHG emissions somewhat stable in a stringent mitigation scenario (530e) in the first half of the century, and subsequently decline gradually. This path is similar to what is found in the CCSP report[16], as well as in MESSAGE stabilization scenarios. Nonetheless, the very little evidence on technology improvements potential in non-CO_2 GHG sectors indicates that sensitivity analysis should be performed to verify the impact on policy costs.

5. Specific Features in Abatement Technologies

5.1. *Innovative carbon free technologies*

In the short to mid term, energy savings, fuel switching mainly in the power sector, as well as non fossil fuel mitigation, are believed to be the most convenient mitigation options. In the longer term, however, one could envisage the possibility that innovative technologies, currently far from being commercial, will be developed, with low or zero carbon emissions. These technologies are usually referred to in the literature as backstop technologies, and are characterized as being available in large supplies. For the purpose of modeling, a backstop technology can be better thought of as a compact representation of a portfolio of advanced technologies, that would ease the mitigation burden away from currently commercial options, though it would become available not before a few decades. This representation has the

---

[13] http://www.stanford.edu/group/MERGE/m5ccsp.html

[14] http://www.grida.no/climate/ipcc_tar/wg1/222.htm, Table 6.2, first row.

[15] http://www.stanford.edu/group/EMF/projects/projectemf21.htm

[16] http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm

advantage of maintaining simplicity in the model by limiting the array of future energy technologies and thus the dimensionality of techno-economic parameters for which reliable estimates and meaningful modeling characterization do not exist.

The WITCH model includes two backstop technologies that necessitate dedicated innovation investments to become economically competitive, even in a scenario with a climate policy. We follow the most recent characterization in the technology and climate change literature, modeling the costs of the backstop technologies with a two-factor learning curve in which their price declines both with investments in dedicated R&D and with technology diffusion. This improved formulation is meant to overcome the main criticism of the single factor experience curves (Nemet, 2006) by providing a more structural – R&D investment led – approach to the penetration of new technologies, and thus to ultimately better inform policy makers on the innovation needs in the energy sector.

More specifically, we model the investment cost in a backstop technology as being influenced by a Learning by Researching process (main driving force before adoption) and by Learning by Doing (main driving force after adoption), the so called 2 factor learning curve formulation (Kouvaritakis et al., 2000).

We assume a two-period time (i.e. 10 years) interval between R&D knowledge and its effect on the price of the backstop technologies to account for time lags between research and commercialization.

The initial prices of the backstop technologies is set at roughly 10 times the 2005 price of commercial equivalents (16,000 US$/kW for electric, and 550 US$/bbl for non-electric). The cumulative deployment of the technology is initiated at 1000 TWh and 1000 EJ respectively for the electric and non-electric, an arbitrarily low value (Kypreos, 2007). The backstop technologies are assumed to be renewable in the sense that the fuel cost component is negligible. For power generation, it is assumed to operate at load factors comparable with those of baseload power generation.

Estimates of parameters controlling the learning processes vary significantly across studies, see Table 9. They also primarily focus on power generation. For WITCH we take averages of the values in the literature, as reported in the last row of the table. Note that the value chosen for the Learning by Doing parameter is lower than those normally estimated in single factor experience curves, since part of the technology advancement is now led by specific investments. This more conservative approach reduces the role of black box autonomous learning, which has been criticized for being too optimistic and leading to excessively low costs of transition towards low carbon economies.

Finally, it must be highlighted that modeling of long term and uncertain phenomena such as technological evolution calls for caution in the interpretation of exact quantitative figures, and for accurate sensitivity analysis. The model parsimony allows for tractable sensitivity studies, as stressed above. One should nonetheless keep in mind that the economic implications of climate policies as well as carbon price signals are influenced by innovative technologies availability only after 2030.

Technology	**Author**	**LbD**	**LbR**
Wind	Criqui et al., 2000	16 %	7 %
	Jamasab, 2007	13 %	26 %
	Soderholm and Klassens, 2007	3.1 %	13.2 %
	Klassens et al., 2005		12.6 %
PV	Criqui et al., 2000	20 %	10 %
Solar Thermal	Jamasab, 2007	2.2 %	5.3 %
Nuclear Power (LWR)	Jamasab, 2007	37 %	24 %
CCGT (1980-89)	Jamasab, 2007	0.7 %	18 %
CCGT (1990-98)	Jamasab, 2007	2.2 %	2.4 %
WITCH		*10 %*	*13 %*

Table 9: Learning ratios for diffusion (LbD) and innovation (LbR) process

Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. We assume that once the backstop technologies become competitive thanks to dedicated R&D investment and pilot deployments, their uptake will not be immediate and complete, but rather there will be a transition/adjustment period. These penetration limits are a reflection of inertia in the system, as presumably the large deployment of backstops will require investment in infrastructures and the re-organization of the economic system. The upper limit on penetration is set equivalent to 5 % of the consumption in the previous period of energy produced by technologies other than the backstop, plus the energy produced by the backstop itself.

5.2. International spillovers of knowledge and experience

Learning process via knowledge investments and experience are likely not to remain within the boundaries of single countries, but to spill to other regions too. The effect of international spillovers is deemed to be very important, and its inclusion in integrated assessment models desirable, since it allows for a better representation of the innovation market failures and for specific policy exercises. The WITCH model is particularly suited to perform this type of analysis, since its game theoretic structure allows distinguishing first and second best strategies, and thus to quantify optimal portfolios of policies to resolve all the externalities arising in global problems such as climate change.

The WITCH model features spillovers of experience for Wind&Solar in that the Learning by Doing effect depended on world cumulative installed capacity, so that single regions could benefit from investments in virtuous countries, thus leading to strategic incentives. The model also includes spillovers in knowledge for energy efficiency improvements (Bosetti et al., 2008).

As mentioned in Section 2.2, energy services are a CES nest of physical energy and energy knowledge. Energy knowledge depends not only on regional investments in energy R&D, but also on the knowledge stock that has been accumulated in other regions. Similarly to the learning by doing for Wind&Solar, we assume experience accrues with the diffusion of technologies at the global level. We also assume knowledge spills internationally. The amount of spillovers entering each world region depends on a pool of freely available knowledge and on the ability of each country to benefit from it, i.e. on its absorption capacity. Knowledge acquired from abroad combines with domestic knowledge stock and investments and thus contributes to the production of new technologies at home. The parameterization follows Bosetti et al. (2008) and is recalled in the last section, equations (A8) and (A9).

5.3. Key Mitigation Options

The WITCH model features a series of mitigation options in both in the power generation sector and in the other usages of energy carries, e.g in the non-electric sector.

Mitigation options in the power sector include nuclear, hydroelectric, IGCC-CCS, renewables and a backstop option that can substitute nuclear.

Nuclear power is an interesting option for decarbonized economies. However, fission still faces controversial difficulties such as long-term waste disposal and proliferation risks. Light Water Reactors (LWR) – the most common nuclear technology today – are the most reliable and relatively least expensive solution. In order to account for the waste management and proliferation costs, we have included an additional O&M burden in the model. Initially set at 1 mUS$/kWh, which is the charge currently paid to the US depository at Yucca Mountain, this fee is assumed to grow linearly with the quantity of nuclear power generated, to reflect the scarcity of repositories and the proliferation challenge.

Hydroelectric is also a carbon free option, but it is assumed to evolve exogenously to reflect limited site availability.

Limited deployment of controversial technologies such as nuclear calls for other alternative mitigation options. One technology that has received particular attentions in the recent past is carbon capture and storage (CCS). In the WITCH model this option can be applied only to integrated coal gasification combined cycle power plant (IGCC-CCS). In fact, CCS is a promising technology but still far from large scale deployment. CCS transport and storage cost functions are region specific and they have been calibrated following Hendriks et al. (2004). Costs increase exponentially with the capacity accumulated of this technology. The CO_2 capture rate is set at 90 % and no after-storage leakage is considered. Other technological parameters such as efficiency, load factor, investment and O&M costs are described in Table 8. In the case of CCS there is no learning process or research activity that can either reduce investment costs or increase the capture rate.

Electricity from wind and solar is another important carbon free technology. The rapid development of wind and solar power technologies in recent years has led to a reduction in investment costs. In fact, beneficial effects from learning-by-doing are expected to decrease investment costs even further in the next few years. This effect is captured in the WITCH model by letting the investment cost follow a learning curve. As world-installed capacity in wind and solar doubles, investment cost diminishes by 13 %. International spillovers in learning-by-doing are present because we believe it is realistic to assume that information and best practices quickly circulate in cutting-edge technological sectors dominated by a few major world investors. This is particularly true if we consider that the model is constructed on five-year time steps, a time lag that we consider sufficient for a complete flow of technology know-how, human capital and best practices, across firms that operate in the sector.

Less flexible is the non-electric sector. Two are the major mitigation options: the use of biomass and the deployment of the breakthrough technology. The breakthrough technology can substitute oil and it can be thought of as next generation biofuels or carbon free hydrogen to be used in the transport sector. The overall penetration of traditional (e.g. sugar cane or corn) biofuels remains modest over time and therefore the mitigation potential coming from this option is quite limited.

Another important mitigation option in the WITCH model is the endogenous improvement of overall energy efficiency with dedicated energy R&D, as described in more detail in Section 5.1.

6. Computational issues

The WITCH model is solved numerically using GAMS – General Algebraic Modeling System[17]. GAMS is a high-level modeling system for mathematical programming problems, designed to provide a convenient tool to represent large and complex model in algebraic form, allowing a simple updating of the model and flexibility in representation, and modular construction.

The non-cooperative decentralized solution is achieved iteratively via an open loop Nash algorithm in which each region is optimized separately. Originally, this solution concept was implemented sequentially. In the WITCH model used in the last year and in the version used for this project as well, the regional maximization problems for the non-cooperative solution are solved in parallel, exploiting new computing power afforded by multiple-core hardware, and thus allowing for a much more rapid solution of the overall optimization exercise. The solutions of each region's maximization problem are combined in a single step following each iteration – the total number of parallel solves is therefore equal to the number of regions (twelve in the case of WITCH). The speed of the solution is thus determined by the slowest region.

The model also runs in batch mode for remote solution, using SSH interface and a system of shared files, stored in the remote host computer. The use of Globus Toolkit 4 allows the submission of the solve jobs to more than one cluster, thus further reducing the execution time needed to find a solution.

Several tests have been performed for evaluating the scalability and performance of the parallel algorithm (Figure 15). The execution tests have been made on the SPACI's HP-XC6000 cluster ranging from 1 up to 12 CPUs, see Figure 15. Since the GAMS executable is not available for the considered architecture, an emulator for x86_32 processors has been used. The analytic model of the parallel execution time highlights how the coarse grained

---

[17] http://www.gams.com/

parallelization produces a decreasing efficiency starting from 6 processors. The reason can be found in the not well balancing of the workload.[18]

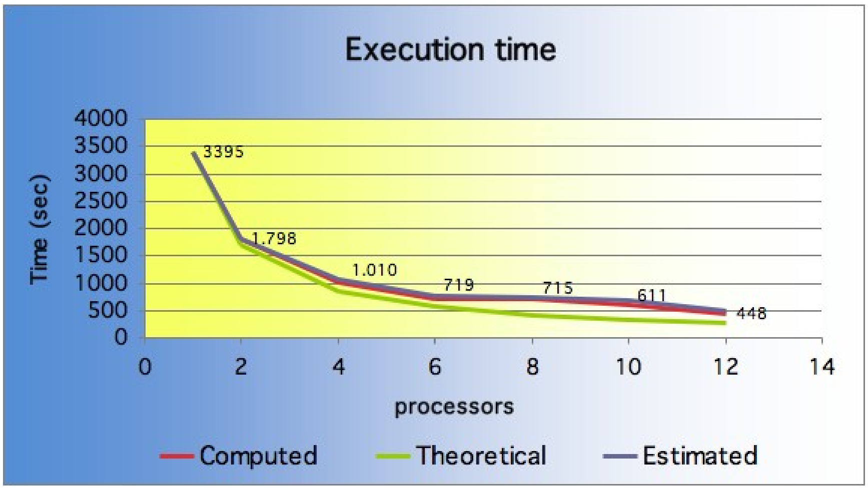


Figure 15: Execution time

7. Baseline scenario

This section does not aim at providing a comprehensive description of the baseline scenario, but instead it illustrates some of the aspects that can help to better understand results from policy scenarios. In all exercises carried out for this project, the feedback effect of climate change into the economic system is turned off, so that regions' strategies are not affected by the sensitivity to climate damage.

7.1. Energy supply and prices

The growth rate of world primary energy supply is about 1.8 % per year over the first half of the century and declines to 0.6 % by the end of the century, reaching the figure of 1220 EJ. Energy supply will be heavily based on fossil fuels throughout the century, given the assumption of sufficient resources of conventional and non-conventional fossil fuel. Renewables and nuclear slightly increase their share in total energy supply. Backstop technologies are not deployed in the baseline scenario; despite the rising prices of fossil fuels, the incentives are not strong enough to induce the large up-front R&D investments needed to make these technologies economically competitive.

Table 10 reports on the distribution of energy demand. Today, OECD countries consume more than the non-OECD, but the latter are expected to take the lead in the near future, since they are projected to grow at rate three times the one of developed countries (left panel). That is, as expected, the growth engine of developing regions will require a large inflow of energy resources, that will slow down only late in the century. The growing dominant position of non-OECD is also due to the different size and growth rate of population. Looking at per capita figures (right panel), an average OECD resident currently consumes six times more energy than a non-OECD one; such gap is expected to narrow over time, but it will

---

[18] More on this can be found in Epicoco, I., S. Mocavero, G. Aloisio (2008): Analisi e sviluppo del modello parallelo per l'applicazione WITCH, presented at Italian e-Science 2008 (IES08).

nonetheless remain significant (a 4-fold ratio) until the end of the century. The growth rate in non-OECD regions is only twice the one for OECD due to a higher relative increase in population.

	Primary energy consumption (EJ)		**Per capita energy consumption (TJ/person)**	
	OECD	NON OECD	OECD	NON OECD
2005	258	203	0.24	0.04
2050	374	529	0.32	0.07
2100	435	767	0.41	0.10
	Average annual change		Average annual change	
2005-2050	0.9 %	3.2 %	0.7 %	1.5 %
2100-2050	0.3 %	0.9 %	0.5 %	1.0 %

Table 10: Distribution of energy consumption – absolute (left) and per-capita (right)

Electricity generation will expand from 65 EJ in 2005 to 292 EJ by 2100. As can be seen from the right hand side panel on Figure 16, the power mix remains quite stable over the century, mostly dominated by traditional coal, driven by a significant expansion in the developing countries. The share of electricity generated by wind and solar increases significantly from 0.6 % to 9 % by 2100, but still covers only a small fraction of total supply. Nuclear energy maintains its share constant, providing 50 EJ of electricity at the end of the century. Hydroelectric power generation, on the other hand, looses market share over time, since its production is limited by the availability of suitable sites, and is thus assumed to remain constant.

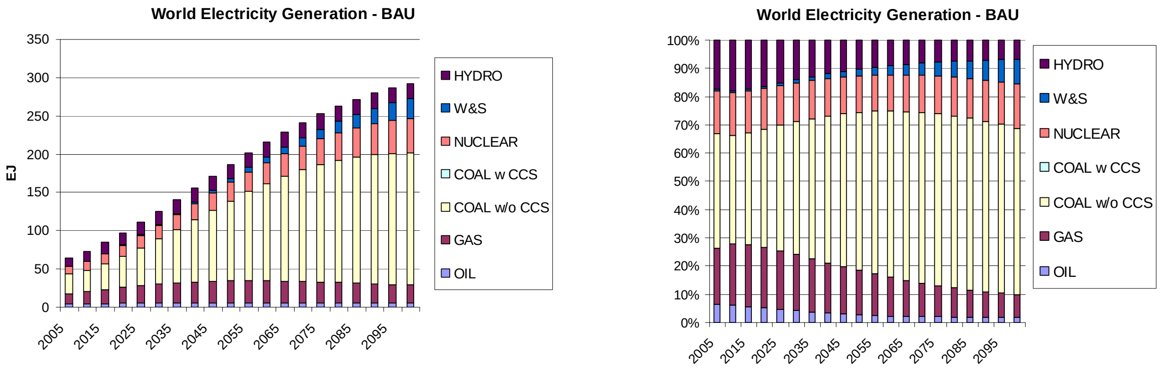


Figure 16: World electricity generation – levels and shares

As for fossil fuel prices, we project a general increase in the medium term, in line with IEA projections (see Table 11). Oil price (including non-conventional) rises from 55 to 219 US$ per barrel in 2100, in real terms, whereas gas price goes from 7.14 to 27 US$/GJ. Coal price is the most stable, increasing over the century from 60 in 2005 to 118 US$ per ton in 2100.

	Oil (US$/bbl)	Coal (US$/ton)	Gas (US$/GJ)
2005	55.65	60.02	7.14
2050	119.68	74.18	12.39
2100	219.13	118.02	26.92

Table 11: International energy prices

7.2. Sources of endogenous technical change

Learning by Doing and Learning by Researching are the two major engine of endogenous technical change in the energy sector. Experience or learning by doing in wind and solar, as it can be represented by world installed capacity, reduces investments costs in these technologies. Over time wind and solar become progressively more competitive, as suggested by the increased share in electricity generation (Figure 16). Figure 17 – left hand side panel – depicts the downward path of investments costs, which decreases from 1906 US$/kW in 2005 to 1010 US$/kW by 2050 and 649 US$/kW by 2100, with an overall reduction of about 67 %. The second source of endogenous technical change is energy research and development. Energy R&D plays a twofold role: it is targeted at improving overall energy efficiency in final production and it also reduces the unit cost of the two backstop technologies. The right hand side panel of Figure 17 shows an upward trend in energy R&D, though only related to efficiency improvements as noted previously. A five-fold expansion brings energy R&D investments from 8 to 49 billions US$ by 2100; this increase is however smaller than the one for output, so that energy R&D slightly decreases as a share of GDP from 0.02 % to 0.015 % over the century.

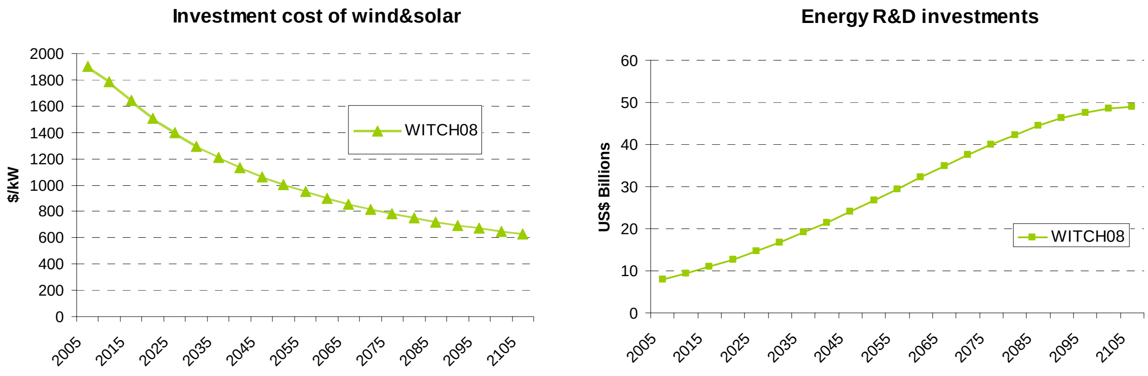


Figure 17: Learning by Doing and Learning by Researching

7.3. Climate variables

As shown in the last paragraph, the WITCH baseline foresees a continued use of fossil fuels that leads to a growth of greenhouse gases throughout the century. This has important implications for climate related variables and ultimately for global warming.

Figure 9 shows the radiative forcing by GHGs over time; it grows quite rapidly to reach 6.6 w/m^2 by 2100: even though total non-CO_2 GHG emissions stabilize in the second part of the century at around 5 GtCe, concentrations in the atmosphere and therefore radiative forcing continue to increase. As expected, carbon dioxide is the dominant contributor to the higher forcing, though methane and nitrous oxide play an important part in the first decades.

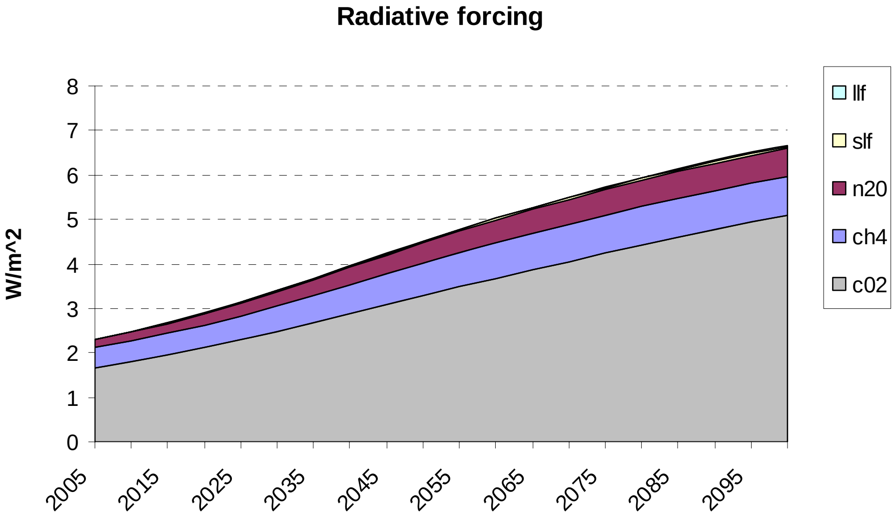


Figure 18: Radiative forcing of GHGs

In terms of climate change, the growing stock of gases translates into a steady temperature increase over time, from 0.7 °C above pre-industrial levels today up to 3.7 °C in 2100. These figures should be taken with caution, given the considerable uncertainty that surrounds the relation of GHG stocks to temperature increase, and could be considerably higher in the case that parameters such as climate sensitivity are higher than expected[19]. Leaving aside these uncertainties, according to IPCC Fourth Assessment Report (IPCC, 2007) estimates, this warming could lead to severe damages to natural and socio-economic systems, and call for action to prevent its realization.

	Global mean temperature increase (in °C) with respect to pre-industrial
2030	1.4
2050	2.0
2100	3.7

Table 12: Temperature increase above pre-industrial levels

8. Conclusions

Climate change is a complex issue whose analysis requires models that are able to capture the main features characterizing the international and long-term dimension of climate change. The peculiarity of the WITCH model compared to the other two modeling tools used in the RECIPE project is the comprehensive representation of endogenous, and thus

---

[19] We assume a central value of 3.

exogenous technical change. In fact, the possibility of investing in the commercialization of innovative technologies is a desirable feature of model evaluating long-term scenarios. The WITCH model gives special attention to the international dimension of knowledge and experience diffusion, following the modeling approach used in Bosetti et al. (2008).

The baseline scenario of the WITCH model has been updated so as to yielding an updated future socio-economic baseline scenario that is harmonized with the baseline scenarios of the other two models used within the RECIPE project.

9. Model equations and variables

This chapter describes the main equations of the model. At the end, the list of all variables is reported. In each region, indexed by *n*, a social planner maximizes the following utility function:

$$W(n) = \sum_t U\left[C(n,t), L(n,t)\right] R(t) = \sum_t L(n,t)\left\{\log\left[c(n,t)\right]\right\} R(t) \qquad \text{(A1)}$$

where *t* are 5-year time spans and the pure time preference discount factor is given by:

$$R(t) = \prod_{v=0}^{t} \left[1+\rho(v)\right]^{-5} \qquad \text{(A2)}$$

where the pure rate of time preference $\rho(v)$ is assumed to decline over time. Moreover, $c(n,t) = \dfrac{C(n,t)}{L(n,t)}$ is per capita consumption.

Economic module

The budget constraint defines consumption as net output less investments:

$$C(n,t) = Y(n,t) - I_C(n,t) - \sum_j I_{R\&D,j}(n,t) - \sum_j I_j(n,t) - \sum_j O\&M_j(n,t) \qquad \text{(A3)}$$

Where *j* denotes energy technologies. Output is produced via a nested CES function that combines a capital-labor aggregate and energy services $ES(n,t)$ capital and labor are obtained from a Cobb-Douglas function. The climate damage $\Omega(n,t)$ affects gross output; to obtain net output we subtract the costs of the fuels *f* and of CCS:

$$\begin{aligned} Ynet(n,t) = {} & \frac{TFP(n,t)\left[\alpha(n)\cdot\left(K_C^{\,1-\beta(n)}(n,t)L^{\beta(n)}(n,t)\right)^{\rho} + (1-\alpha(n))\cdot ES(n,t)^{\rho}\right]^{1/\rho}}{\Omega(n,t)} \\ & - \sum_f \left(P_f(n,t)X_{f,extr}(n,t) + P_f^{\text{int}}(t)X_{f,netimp}(n,t)\right) \\ & - P_{CCS}(n,t)CCS(n,t) \end{aligned} \quad . \qquad \text{(A4)}$$

P_f is the domestic fuel *f* extraction cost, P_f^{int} is instead the international market clearing price for fuel *f*.

Total factor productivity $TFP(n,t)$ evolves exogenously with time. Final good capital accumulates following the standard perpetual rule, but four dollars of private investments are subtracted from it for each dollar of R&D crowded out by energy R&D:

$$K_C(n,t+1) = K_C(n,t)(1-\delta_C) + I_C(n,t) - 4\psi_{R\&D}\sum_j I_{R\&D,j}(n,t) \qquad \text{(A5)}$$

Labor is assumed to be equal to population and evolves exogenously. Energy services are an aggregate of energy, $EN(n,t)$, and a stock of knowledge, $HE(n,t)$, combined with a CES function:

$$ES(n,t) = \left[\alpha_H HE(n,t)^{\rho_{ES}} + \alpha_{EN} EN(n,t)^{\rho_{ES}}\right]^{1/\rho_{ES}} \tag{A6}$$

The stock of knowledge evolves according to the perpetual rule:

$$HE(n,t+1) = Z(n,t) + HE(n,t)(1-\delta_{R\&D}) \tag{A7}$$

At each point in time new ideas are produced using a Cobb-Douglas combination between domestic investments, $I_{R\&D}$, the existing stock of knowledge, *HE,* and the knowledge of other countries, *SPILL*:

$$Z(n,t) = a\, I_{R\&D}(n,t)^{b}\, HE(n,t)^{c}\, SPILL(n,t)^{d} \tag{A8}$$

The contribution of foreign knowledge on the production of new domestic ideas depends on the interaction between two terms: the first describes the absorptive capacity whereas the second captures the distance from the technology frontier, which is represented by the stock of knowledge in rich countries (USA, OLDEURO, NEWEURO, CAJANZ and KOSAU):

$$SPILL(n,t) = \frac{HE(n,t)}{\sum_{HI} HE(n,t)}\left(\sum_{HI} HE(n,t) - HE(n,t)\right) \tag{A9}$$

Energy is a combination of electric and non-electric energy:

$$EN(n,t) = \left[\alpha_{EL} EL(n,t)^{\rho_{EN}} + \alpha_{NEL} NEL(n,t)^{\rho_{EN}}\right]^{1/\rho_{EN}} \tag{A10}$$

Each factor is further decomposed into several sub-components. Factors are aggregated using CES, linear and Leontief production functions. For illustrative purposes, we show how electricity is produced via capital, operation and maintenance and resource use through a zero-elasticity Leontief aggregate:

$$EL_j(n,t) = \min\left\{\mu_j(n) K_j(n,t);\, \tau_j(n) O\&M_j(n,t);\, \varsigma_j X_{j,EL}(n,t)\right\} \tag{A11}$$

Capital for electricity production technology accumulates as follows:

$$K_j(n,t+1) = K_j(n,t)\left(1-\delta_j\right) + \frac{I_j(n,t)}{SC_j(n,t)} \tag{A12}$$

where, for selected technologies j, the new capital investment cost $SC(n,t)$ decreases with the world cumulated installed capacity by means of Learning-by-Doing:

$$SC_j(n,t+1) = B_j(n) \cdot \sum\nolimits_n K_j(n,t)^{-\log_2 PR_j} \tag{A13}$$

Operation and maintenance is treated like an investment that fully depreciates every year. The resources employed in electricity production are subtracted from output in equation (A4). Their prices are calculated endogenously using a reduced-form cost function that allows for non-linearity in both the depletion effect and in the rate of extraction:

$$P_f(n,t) = \chi_f(n) + \pi_f(n)\left[Q_f(n,t-1)/\overline{Q}_f(n,t)\right]^{\psi_f(n)} \tag{A14}$$

where Q_f is the cumulative extraction of fuel f:

$$Q_f\left(n,t-1\right)=Q_f\left(n,0\right)+\sum_{s=0}^{t-1}X_{f,extr}\left(n,s\right) \tag{A15}$$

Each country covers consumption of fuel *f*, $X_f\left(n,t\right)$, by either domestic extraction or imports, $X_{f,netimp}\left(n,t\right)$, or by a combination of both. If the country is a net exporter, $X_{f,netimp}\left(n,t\right)$ is negative.

$$X_f\left(n,t\right)=X_{f,extr}\left(n,t\right)+X_{f,netimp}\left(n,t\right) \tag{A16}$$

The unit cost of each backstop technology, $P_{tec,t}$, is a function of deployment, $CC_{tec,t}$ and dedicated R&D stock, $R\&D_{tec,t}$:

$$\frac{P_{tec,T}}{P_{tec,0}}=\left(\frac{R\&D_{tec,T-2}}{R\&D_{tec,0}}\right)^{-c}*\left(\frac{CC_{tec,T}}{CC_{tec,0}}\right)^{-b} \tag{A17}$$

R&D stock accumulates with the perpetual rule and with the contribution of international knowledge spillovers, *SPILL*:

$$R\&D_{tec,T+1}=R\&D_{tec,T}\cdot(1-\delta)+IR\&D^{\alpha}{}_{tec,T}SPILL_{tec,T}{}^{\beta} \tag{A18}$$

<u>*Climate Module*</u>

GHGs emissions from the combustion of fossil fuels are derived by applying the CO_2 stoichiometric coefficients, ω_{f,CO_2} to total consumption of fossil fuels, minus the amount of CO_2 sequestered:

$$CO_2\left(n,t\right)=\sum_f\omega_{f,CO_2}X_f\left(n,t\right)-CCS\left(n,t\right) \tag{A19}$$

The damage function impacting output varies with global temperature:

$$\Omega(n,t)=\frac{1}{1+\left(\theta_{1,n}T(t)+\theta_{2,n}T(t)^2\right)} \tag{A20}$$

The damage function can be switched off. Temperature relative to pre-industrial levels increases through augmented radiating forcing *F(t)*, moderated by the cooling effects of SO_2 aerosol, $cool(t)$:

$$T(t+1)=T(t)+\sigma_1\left\{F(t+1)-\lambda T(t)-\sigma_2\left[T(t)-T_{LO}(t)\right]\right\}-cool(t+1) \tag{A21}$$

Radiative forcing in turn depends on CO_2 atmospheric concentrations $M_{AT}\left(t\right)$, combined linearly with the radiative forcing of other GHGs, $O(t)$:

$$F(t)=\eta\left\{\log\left[M_{AT}(t)/M_{AT}^{PI}\right]-\log(2)\right\}+O(t) \tag{A22}$$

$$O(t)=F_{CH4}(t)+F_{N20}(t)+F_{SLF}(t)+F_{LLF}(t) \tag{A23}$$

$$F_{CH4}(t)=\gamma_{1,CH4}\,0.036\,[\gamma_{2,CH4}M_{ATCH4}(t)^{0.5}-\gamma_{3,CH4}M^{PI}{}_{ATCH4}(t)^{0.5}] \tag{A24}$$

$$F_{N20}(t)=\gamma_{1,N20}\,0.12\,[\gamma_{2,N20}M_{ATN20}(t)^{0.5}-\gamma_{3,N20}M^{PI}{}_{ATN2O}(t)^{0.5}] \tag{A25}$$

$$F_{SLF}(t) = 2.571\ [\gamma_{2,SLF} M_{ATSLF}(t) - \gamma_{3,SLF} M^{PI}{}_{ATSLF}(t)] \quad \text{(A26)}$$

$$F_{LLF}(t) = 13.026\ [\gamma_{2,LLF} M_{ATLLF}(t) - \gamma_{3,LLF} M^{PI}{}_{ATLLF}(t)] \quad \text{(A27)}$$

CO_2 atmospheric concentrations are caused by emissions from fuel combustion and land use change; a three box-climate module accounts for the interaction between the atmosphere and oceans:

$$M_{AT}(t+1) = \sum_n \left[CO_2(n,t) + LU_j(t)\right] + \phi_{11} M_{AT}(t) + \phi_{21} M_{UP}(t), \quad \text{(A28)}$$

$$M_{UP}(t+1) = \phi_{22} M_{UP}(t) + \phi_{12} M_{AT}(t) + \phi_{32} M_{LO}(t), \quad \text{(A29)}$$

$$M_{LO}(t+1) = \phi_{33} M_{LO}(t) + \phi_{23} M_{UP}(t). \quad \text{(A30)}$$

Other GHGs accumulate in the atmosphere according to the following equations:

$$M_{ATCH4}(t+1) - dec2_{CH4}(t)*0.5*Wo(t+1) = M_{ATCH4}(t)\ dec1_{CH4}{}^{nyper(t)} + dec2_{CH4}(t)*0.5*Wo(t) \quad \text{(A31)}$$

$$M_{ATN20}(t+1) - dec2_{N2O}(t)*0.5*Wo(t+1) = M_{ATN2O}(t)\ dec1_{N2O}{}^{nyper(t)} + dec2_{N2O}(t)*0.5*Wo(t) \quad \text{(A32)}$$

$$M_{ATSLF}(t+1) - dec2_{SLF}(t)*0.5*Wo(t+1) = M_{ATSLF}(t)\ dec1_{SLF}{}^{nyper(t)} + dec2_{SLF}(t)*0.5*Wo(t) \quad \text{(A32)}$$

$$M_{ATLLF}(t+1) - dec2_{LLF}(t)*0.5*Wo(t+1) = M_{ATLLF}(t)\ dec1_{LLF}{}^{nyper(t)} + dec2_{LLF}(t)*0.5*Wo(t) \quad \text{(A33)}$$

where *dec2* and *dec1* describes respectively the yearly retention factor and the one period retention factor for non-CO_2 gases. The time step in WITCH is of 5 years and the parameter *nyper(t)* accounts for the number of years in each period. *Wo* are world emissions of non-CO_2 GHGs.

W = welfare

U = instantaneous utility

C = consumption

c = per-capita consumption

L = population

R = discount factor

Y = net output

I_c = investment in final good

$I_{R\&D,EN}$ = investment in energy R&D

I_j = investment in technology j

$O\&M$ = investment in operation and maintenance

TFP = total factor productivity

K_c = final good stock of capital

ES = energy services

Ω = climate feedback

P_i^{int} = internationalfuels' prices

P_j = fuels' prices

$X_{f,\,extr}$ = extracted fuel resources

$X_{f,\,netimp}$ fuel resources, net imports

P_{CCS} = price of CCS

CCS = sequestered CO_2

HE = energy knowledge

EN = energy

EL = electric energy

NEL = non-electric energy

K_C = capital for final good production

K_j= capital stock for technology j

SC_j = investment cost

CO_2 = emissions from combustion of fossil fuels

M_{AT} = atmospheric CO_2 concentrations

M_{ATCH4} = atmospheric CH_4 concentrations

M_{ATN20} = atmospheric N_20 concentrations

M_{ATSLF} = atmospheric concentrations of short lived fluorinated gases

M_{ATLLF} = atmospheric concentrations of long lived fluorinated gases

LU = land-use carbon emissions

M_{UP} = upper oceans/biosphere CO_2 concentrations

M_{LO} = lower oceans CO_2 concentrations

F = radiative forcing

F_{CH4} = radiative forcing of CH_4

F_{N20} = radiative forcing of N_20

F_{SLF} = radiative forcing of short lived fluorinated gases

F_{LLF} = radiative forcing of long lived fluorinated gases

O = radiative forcing from other gases

T = temperature

References

Anderson, D. (2006): Costs and finance of carbon abatement in the energy sector. Paper for the Stern Review.

Barreto, L.; S. Kypreos (2004): Endogenizing R&D and market experience in the "bottom-up" energy-systems ERIS model. Technovation 2: 615-629.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, M. Tavoni (2006): WITCH: A World Induced Technical Change Hybrid Model. The Energy Journal. Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down: 13-38.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, M. Tavoni (2007): The WITCH model: Structure, Baseline and Solution, FEEM Working Paper N. 10.2007, Milan.

Bosetti, V., C. Carraro, E. Massetti, M. Tavoni (2008): International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization, Energy Economics, 30 (6) Pages 2912-2929.

Criqui, P., G. Klassen, L. Schrattenholzer (2000): The efficiency of energy R&D expenditures. Economic modeling of environmental policy and endogenous technical change, Amsterdam, November 16-17, 2000.

Eliasch J. (2008): Climate Change: Financing Global Forests. The Eliasch Review, available at http://www.occ.gov.uk/activities/eliasch.htm

EIA (2008a): Annual Energy Outlook. Energy Information Administration, Washington, DC.

EIA (2008b): International Energy Outlook. Energy Information Administration, Washington, DC.

ENERDATA (2008): Energy Statistics.

EPA (2006): Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases 1990-2020. Report 430-R-06-003, June 2006. The report is available at http://www.epa.gov/climatechange/economics/mitigation.html.

Farrell A.E., A.R. Brandt (2006): Risks of the oil transition. Environmental Research Letters, 1 (1).

IEA (2005): Resources to Reserves – Oil & Gas Technologies for the Energy Markets of the Future. OECD/IEA, Paris.

IEA (2007): World Energy Outlook 2007. OECD/IEA, Paris.

IPCC (2007): Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment.

Jamasab, T. (2007): Technical change theory and learning curves: patterns of progress in electric generation technologies. The Energy Journal 28(3).

Junginger, M., A. Faaij, W. C. Turkenburg (2005): Global experience curves for wind farms. Energy Policy 33: 133-150.

Kahouli-Brahmi, S. (2008): Technological learning in energy-environment-economy modelling: a survey. Energy Policy 36: 138-162.

Klassen, G., A. Miketa, K. Larsen, T. Sundqvist (2005): The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics 54(2-3): 227-240.

Kouvaritakis, N., A. Soria and S. Isoard (2000): Endogenous Learning in World Post-Kyoto Scenarios: Application of the POLES Model under Adaptive Expectations. International Journal of Global Energy Issues 14(1-4): 228-248.

Kypreos, S. (2007): A MERGE model with endogenous technical change and the cost of carbon stabilisation. Energy Policy 35: 5327-5336.

McDonald, A., L. Schrattenholzer (2001): Learning rates for energy technologies. Energy Policy 29(4): 255-261.

Nordhaus, W., J. Boyer (2000): Warming the World: Economic Models of Global Warming, MIT Press

Nemet, G. F. (2006): Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34(17): 3218-3232.

Nemet, G. F., D. M. Kammen (2007): U.S. energy research and development: declining investment, increasing need, and the feasibility of expansion. Energy Policy 35(1): 746-755.

Schock, R. N., W. Fulkerson, M. L. Brown, R. L. San Martin, D. L. Greene, J. Edmonds (1999): How much is energy research & development worth as insurance? Annual Review of Energy and the Environment 24: 487-512.

Söderholm, P., G. Klassen (2007): Wind power in Europe: a simultaneous innovation-diffusion model. Environmental and Resource Economics 36(2): 163-190.

Tavoni, M., B. Sohngen, V. Bosetti (2007): Forestry and the carbon market response to stabilise climate, Energy Policy , 35: 5346–5353.

UN (2004): World Population to 2300, Report No. ST/ESA/SER.A/236, Department of Economic and Social Affairs, Population Division, New York