RECIPE

THE ECONOMICS OF DECARBONIZATION

Description of the RECIPE models

Working Paper

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Contents

Key Messages

- **This section introduces the three climate-energy-economy models used in the comparison exercise. It reviews the internal mechanisms describing the relationship between the macro-economy and energy consumption and gives a brief overview of data sources used for calibration of the models**
- **IMACLIM-R is a recursive CGE with a special focus on inertia in the development and deployment of new technologies, myopic behavior, and a special focus on modeling the transport sector**
- **REMIND-R is an optimal growth model featuring a highly flexible description of the macro-economy through inter-temporal trade among world regions and a high resolution of the energy sector**
- **WITCH also is an optimal growth model featuring induced technological change in terms of energy efficiency improvements and technological breakthroughs. Due to its game-theoretic structure, it is well-suited to analyze the non-cooperative nature of international relationships**
- **Conceptual differences in model structures and underlying assumptions result in differences in business-as-usual forecasts as well as optimal GHG mitigation strategies**
- **Analyzing how simulation results differ in the light of the above differences yields valuable information for building stabilization scenarios and is one of the main tasks of this report**

1 Introduction and Overview

This section introduces the three climate-energy-economy models used in this report (IMACLIM-R, REMIND-R, and WITCH) and gives a brief overview of crucial design elements of each model, which are summarized in Table 1-1. For more detailed information, comprehensive model descriptions can be found in the technical reports included in the appendix. All three models have in common that that they feature a representation of socio-economic processes, such as economic growth and the dynamics of consumption and investment. In this context final energy is regarded as a production factor, alongside capital and labor. Final energy, in turn, is generated through a conversion process from primary energy sources, such as fossil fuels, wind, solar radiation, hydropower, or biomass. To link energy use to climate impacts, carbon emissions from the combustion of fossil fuels are computed and their effects on atmospheric concentrations and temperatures are assessed using a coupled climate module. The three models used in this study follow different modeling approaches and embody different assumptions regarding future technological developments in the energy sector, inertia in the deployment new technologies, and economic agents' knowledge about the future, i.e. how expectations are formed. One major goal of this model comparison is to identify how these different assumptions impact on the resulting economic dynamics and in which way they have an influence on strategies to mitigate GHG emissions in the stabilisiation scenarios that were computed.

***IMACLIM-R** – Technological inertia and imperfect foresight.* **IMACLIM-R**, developed by CIRED (see Crassous et al., 2006), is a recursive computable general equilibrium model capturing explicitly the underlying mechanisms driving the dynamics of technical parameters, structural change in demand for goods and services and micro- as well as macro-economic behavioral parameters. The model considers open economies with international trade of all goods and CO_2 permits A major feature of IMACLIM-R is the partial use of production factors (underused capacities, unemployment) due to sub-optimal investment decisions resulting from the interplay between inertia, imperfect foresight and 'routine' behaviours. This allows distinguishing between potential and real economic growth, and, more specifically, to capture the transitory costs resulting from unexpected shocks affecting the economy. In **IMACLIM-R**, climate policies can be a means of remedying market failures and implement no-regret options which are profitable in the long term but which are not taken under normal conditions due to myopic behavior. This property can also result in some kind of 'bi-stability' in the sense that initially large efforts are required to move the system from its current path (i.e. fossil based) to an alternative one (i.e. low-carbon) but little extra effort is required once it is located on this new trajectory.

***REMIND-R** – Technology optimism, inter-temporal flexibility, and perfect foresight:* The global multi-region model **REMIND-R** as introduced by Leimbach et al. (2009) from PIK represents an inter-temporal energy-economy-environment model which maximizes global welfare based on nested regional macro-economic production functions. REMIND-R incorporates a detailed description of energy carriers and conversion technologies (including a wide range of carbon free energy sources), and allows for unrestricted inter-temporal trade relations and capital movements between regions. Mitigation costs estimates are based on technological opportunities and constraints in the development of new energy technologies. By embedding technological change in the energy sector into a representation of the macroeconomic environment, REMIND-R combines the major strengths of bottom-up and top-down models. Economic dynamics are calculated through inter-temporal optimization, assuming perfect foresight by economic actors. This implies that technological options requiring large up-front investments that have long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution.

***WITCH** – Induced technological change and perfect foresight.* The **WITCH** model developed by the climate change group at FEEM (Bosetti et al., 2006; Bosetti et al., 2007) is a regional model in which the non-cooperative nature of international relationships is explicitly accounted for. The regional and intertemporal dimension of the model make it possible to differentiate climate policies across regions and over time. In this way, several policy scenarios can be considered. WITCH is a truly intertemporal optimization model, in which perfect foresight prevails over a long term horizon covering the whole century. 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. Special emphasis is put on the emergence of carbon-free backstop energy technologies in the electricity as well as the non-electricity sector, and on endogenous improvements in energy efficiency triggered by dedicated R&D investments contributing to a stock of energy efficiency knowledge.

	IMACLIM-R	REMIND-R	WITCH
Model Type and Solution Concept	Recursive-dynamic Computable General Equilibrium	Intertemporal optimization (Negishi)	Intertemporal optimization (Open Loop Nash Equilibrium)
Expectation Formation	Myopic	Perfect Foresight	Perfect Foresight
Time Horizon, Steps	2000-2100, 1 year	2005-2100, 5 years	2005-2100, 5 years
Regions	12	11	12
Economic Sectors	12 (goods and services)	1 (composite, good)	1 (composite, good)
Trade	Oil, coal, gas, goods and services	Oil, coal, gas, uranium, composite good, emission permits	Emission permits
Primary Energy	Oil, Coal, Gas, Uranium, Wind, Solar, Hydro, Biomass	Oil, Coal, Gas, Uranium, Wind, Solar, Hydro, Biomass (quality grades for renewables)	Oil, Coal, Gas, Uranium, wind, solar, hydro, generic breakthrough backstop technologies in electricity and non-electricity
Final Energy Use	Industry, Services, Transport, Residential	Stationary, Transport	Electricity and non-electricity
Technical change	Endogenous change through worldwide learning curves	Learning-by-doing in the energy sector	Endogenous technological change through R&D investment and experience learning; international knowledge spillovers
Population	Exogenous	Exogenous	Exogenous
Economic growth	Exogenous improvements in labor productivity; investment rates determined by short-term market outlook	Exogenous improvements in efficiency parameters for capital, labor, and energy; endogenous investment rates	Exogenous improvements in total factor productivity; endogenous investment rates
Abatement technologies	CCS, nuclear, renewables for electricity; second generation biofuels and hybrid efficient cars in transportation	CCS, nuclear, renewables, biomass	CCS, nuclear, renewables, biofuels, two (emission free) backstop technologies

Table 1-1: Overview of key model design features and data sources

2 Model Structures

2.1. General Framework

IMACLIM-R is a recursive computable general equilibrium model (CGE) based on an explicit description of the economy both in monetary values and in physical quantities linked by a price vector. It is structured as a succession of economic equilibria linked by reduced forms of bottom-up sub-modules capturing dynamics. For each static equilibrium in each of the included 12 world regions, characteristics of households' equipments and productive technologies are fixed to capture the short-term inelasticity of technical parameters. Production of goods and services, and the implied use of energy, are modeled for 12 economic sectors using input-output matrices encompassing engineering based analysis and expert information. Demand for goods and services then comes from micro- and macro-economic interactions between household consumption, government spending, investment and intermediate uses from other production sectors. In the specific case of energy markets, demand results from the sum of final demand to satisfy households' energy services and energy inputs for production (see Figure 2-1). Domestic and international markets for all goods and services clear by a unique set of relative prices that depend on the behavior of representative agents on the demand and supply sides.

IMACLIM-R generates an economic dynamic by solving successive static equilibria using dynamic modules in one year time steps for the period 2001-2100. Investment decisions are driven by profit maximization under imperfect expectations in non fully competitive markets, and structural change in the economy and energy system is driven by the interplay between consumption styles, technologies and localization patterns. Technical choices are flexible in each time period, but modify only at the margin the input-output coefficients and labor productivity embodied in the existing equipments resulting 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.

REMIND-R 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 2-2). Assuming perfect foresight and aiming at welfare maximization, REMIND-R simulates the world-economic dynamics over the time horizon 2005 to 2100 with a time step of five years. Macro-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. For this top CES nest, a low elasticity of substitution was assumed, located somewhere in the middle of the range given by Gerlagh and van der Zwaan (2004, p.49). The end use energy is calculated as a production function which comprises transportation energy and stationary energy with a very low elasticity of substitution. This implies that the transport sector's services can hardly be substituted and they are only supplied by a limited amount of energy carriers. Output is used for consumption, investments into the macroeconomic capital stock (for which a depreciation rate of 5% is assumed), all expenditures in the energy system (fuel costs, investment costs and operation and maintenance costs) and for the export of the composite good.

REMIND-R maximizes a global welfare function that results as a weighted sum of regional utility functions. Each region is modeled as a representative household with an inter-temporal utility function that depends on instantaneous utility in each time-step (discounted at a pure rate of time preference to amount to 3%), which is derived from consumption per capita. The individual regions are linked by trade relations. The present version of REMIND-R distinguishes 11 world regions, linked through trade in coal, gas, oil, uranium, goods, and emission permits. Trade and capital mobility (implied by trade in the composite final good) are driven by differences in factor endowments and technologies and modeled as exports in and imports from a common pool. The balance between exports and imports for each kind of good in each period is guaranteed by adequate trade balances. For individual regions, current account deficits and surpluses in any period are permitted as long as intertemporal trade is balanced. In fact, this feature of the model corresponds to the assumption of perfect capital markets in which countries are allowed to borrow against their future income.

WITCH is an optimal growth model of the world economy that integrates in a unified framework the sources and the consequence of climate change. As typically found in intertemporal optimal growth models, the production side of the economy is very aggregated. Each region's production of one single commodity (that can be used for consumption or investments) is described by a nested CES production function in which capital, labor, as well as energy services enter as production factors, as depicted in Figure 2-3. Energy services, in turn, are given by a combination of the physical energy input and a stock of energy efficiency knowledge. This way of modeling energy services allows for endogenous improvements in energy efficiency, as the stock of knowledge can 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. WITCH is a hard-link hybrid model because the energy sector is fully integrated with the rest of the economy[1] and therefore investments and the quantity of resources for energy generation are chosen optimally, together with the other macroeconomic variables. A detailed description of the values assigned to different elasticities of substitution can be found in the technical report (Bosetti et al. 2007).

The optimal path of consumption is determined by optimising the intertemporal social welfare function (defined as the utility of per capita consumption, weighted by regional population) from 2005 to 2100 with a time step of five years. 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. The world economy is disaggregated into twelve macro regions, grouping countries sharing similar economic, geographic, resource endowment and energy characteristics. Regions interact with each other through the presence of economic and

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[1] This stands in sharp contrast to soft-link hybrid models, which incorporate a reduced form model of the energy sector. As in this representation not all economic information is used optimally, soft-link models exclude certain economic effects and hence can not calculate the dynamics of optimal investment in the energy sector.

environmental global externalities. For each region a forward-looking agent maximizes her own intertemporal social welfare function, strategically and simultaneously to other regions, yielding the optimal dynamic path of the control variables (investments in different capital stocks, in R&D, in energy technologies and consumption of fossil fuels).

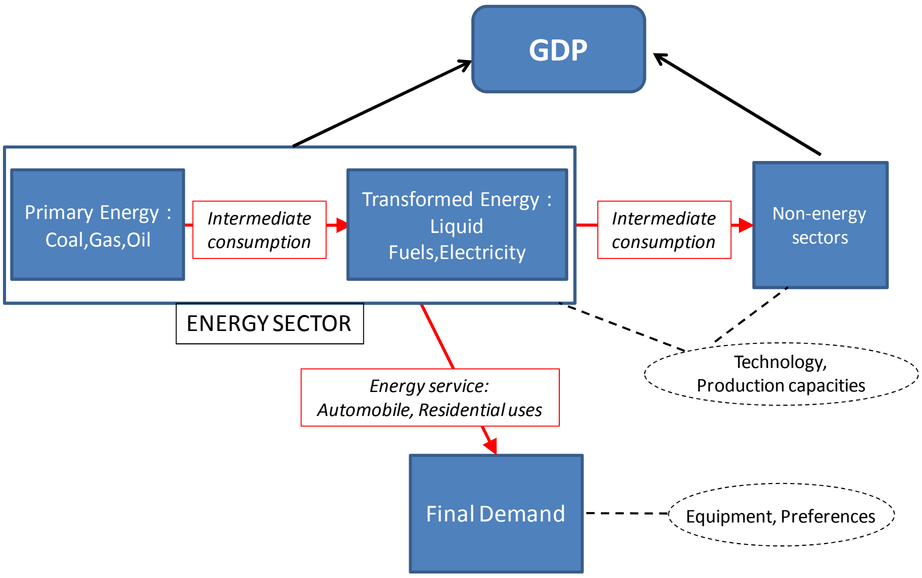

Figure 2-1: General Framework of the IMACLIM-R model

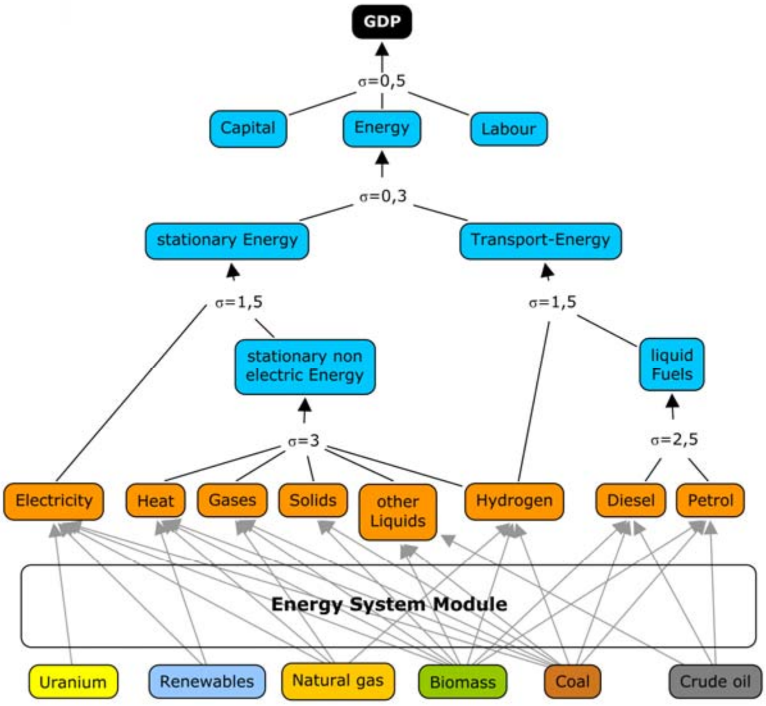

Figure 2-2: General Framework for REMIND-R

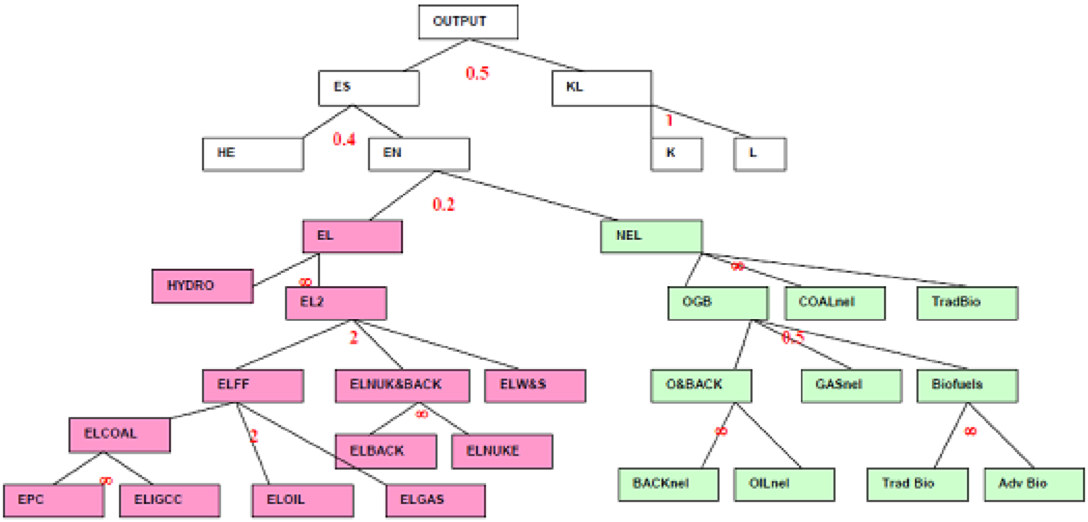

Figure 2-3: General Framework for WITCH

2.2. The energy sector

The energy sector in **IMACLIM-R** is described in physical quantities. Energy use is described through explicit technical coefficients informed by reduced forms of bottom-up models and experts' judgments. Energy consumption is determined by production and transportation.

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 the main mechanisms at the heart of transportation dynamics that are of crucial importance when analyzing the long-term dynamics of energy demand by transport. Transport is explicitly represented in physical quantities (passenger-km for passengers, and ton-km for freight) and enters agents' utility through the associated energy service it provides. This allows capturing endogenously the role of equipments and infrastructure on the mobility demand through utility maximization under both budget and time constraints. In particular, the rebound effect is explicitly accounted for though the decrease of unitary energy costs induced by efficiency measures on vehicles that makes an increase of mobility compatible with the budget constraint. Similarly, demand induction by infrastructure is captured through the influence of infrastructure on congestion, which ultimately acts on the average "speed" of transport modes and modifies the budget constraint. Moreover, the modal shift is explicitly represented through four alternative transport modes differentiated according to their unitary energy consumption and speed (automobile, air, public and non-motorized transport). Finally, stylized facts such as saturation effects on motorization rates and modal shifts with rising incomes are captured.

For electricity the so-called 'load curve' associated with an electrical grid and the evolution of electric generating capacities over time plays a central role in the choice of suitable technologies. Annual investment decisions within the electric sector endogenously emerge from producers' anticipations about the future demand for electricity and the optimal mix of electricity productive capacities to face this future demand at a 10-year horizon. More precisely, this optimal technology mix is defined as the one that minimizes production cost, given anticipated future fuel prices. The share of each technology in the optimal mix of producing capacities results from competition among available technologies depending on their mean production costs, differentiated whether the capacity is expected to meet peak or base load demand. Announced carbon policies explicitly influence these investment decisions through the associated expected increase of the cost of electricity production with fossil-fuel based technologies. This determines total capacity and its distribution among different power plant technologies (up to 15 conventional including coal-, gas- and oil fired, nuclear, hydro and renewables), calibrated on the POLES model (LEPII-EPE, 2006) . Once the optimal mix of productive equipment has been computed ten years ahead, the new capacity built 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 in the future. This minimization is run under the constraint of the actual amount of capital allocated to the electricity sector and repeated at every period with expectations adapted to changes in prices and demand.

On the supply-side, coal and gas extraction costs are depicted through reduced forms of the energy model POLES linking extraction costs to cumulated reserves. More precisely, production is simulated for each region using a full discovery-process model for the main producing that account for the estimate of Ultimate Recoverable Resources, the cumulative drilling and cumulative production since the beginning of field development and the evolution of reserves. Crude oil reserves are classified in 12 categories according to their nature (conventional vs. non-conventional) and the cost of putting a barrel at a producer's disposal. Available capacity of production is constrained not only by the amount of previous investments, but also by geological and technical factors imposing inertias on the deployment of oil production capacities. These latter determinants are captured by assuming an inverted-U shape for production at the field level to reproduce heuristically the long run dynamics of oil fields' production (initial increase followed by a decrease induced by depletion of reserves). This approach is often referred to as a 'Hubbert' production curve used to model the so-called Peak Oil.

The energy system module (ESM) of **REMIND-R** comprises a detailed description of energy carriers and conversion technologies. It is embedded into the macroeconomic growth model through the techno-economic characteristics and the system of balance equations that set up the energy system, i.e. all investment decisions (including those for energy technology capacities) are made simultaneously and have to respect the equilibrium conditions on the capital market (equalization of the return rates). The energy system can be considered as an economic sector with a heterogeneous capital stock that demands primary energy carriers and supplies secondary energy carriers. The structure of the capital stock is determined by the techno-economic characteristics of the technologies and the endogenously evolving prices of energy and CO_2 emissions. Hence, the energy sector develops according to an equilibrium relationship to the remaining economy with which it is interrelated through capital and energy markets.

Multiple primary energy sources are available in the ESM. There are renewable primary energy sources defined by region-specific and energy source-specific potentials, which are classified into different grades (e.g. a gradual potential of wind power is exhausted before the next - relatively less attractive - potential will be exploited). 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, which increase with cumulative extraction. Among the renewable energy sources, biomass has a special position since its fuel costs increase with the intensity of use. 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 as well as biomass and secondary energy carriers are non-tradable.

Final energy is demanded by the macro-economic sector for stationary and transport uses. All transformation technologies are considered by capacity stocks in the model with identical investment costs across region, except for wind turbines and solar photovoltaics, which are subject to the learning curve effect (i.e. decreasing investment costs with increasing cumulated capacities). For each transformation technology, each region starts with a vintage capital stock which meets the statistically given input-output relations. In general, the model has no exogenous restrictions on maximum growth rates or maximum shares for specific energy sources or technologies.

WITCH includes a wide range of technology options to describe the use of energy and the generation of electricity. 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. Carbon free technologies are hydroelectric and nuclear power and renewable sources such as wind turbines and photovoltaic panels (Wind&Solar).

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. 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. WITCH (as well as REMIND) is a normative model and therefore does not take into account policy constraints that exist in some regions of the world, but rather they represent a benchmark to which the costs of additional policy constraints can be compared.

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 food 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. In both the electric and non-electric sectors, a carbon free breakthrough technologies becomes available in the future if sufficient policy induced expenditure in innovation (R&D) is undertaken to lower their prices.

2.3. Technical change

Technological change is a key driver for economic growth. Without technological advances, economies would eventually reach their steady state in which capital is accumulated only to counter the effects of depreciation and population growth (i.e. the growth rate of output per capita is zero in the steady state). Competing theories trying to explain how technological change can take place on the macroeconomic level can be found in the economic literature. The models used in this study do not incorporate endogenous technological change but are driven by exogenous assumptions with regard to future developments of productivity parameters. However, all models feature a representation of endogenous technical change in the energy system, e.g. through learning curves, the emergence of backstop technologies, or dedicated investments in energy R&D.

Technical change in **IMACLIM-R** is induced by market conditions and is captured through the dynamics of different parameters according to the respective sectoral dynamic module considered. The model considers both autonomous energy efficiency gains and endogenous technical change captured through worldwide learning curves corresponding to the assumption of a perfect diffusion of innovation among different regions and important knowledge spillover effects. This is made completely explicit in the technology-rich sub-modules, mainly automobile and electricity production. Indeed, the dynamics of technical coefficients is related to an explicit choice of economic agents among a set of available technologies using “bottom-up” models of the energy sector to implement an explicitly endogenous technical change through worldwide learning curves (which depend on the sum of installed capacities). In other sectors, technical change in the energy sector is related to agents’ choices, which are, in turn, 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.

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 to occur for all production factors, i.e. capital, labor and the final energy types: electricity, heat, gases, solids, hydrogen, petrol, diesel and other liquids. Technological change in the energy sector, manifested in the diffusion and disappearance of single energy technologies, is an endogenous result which represents the optimal solution (for a given set of constraints) in each model run. In addition, some technologies are subject to learning effects, i.e. higher installed capacities resulting in reduced investment costs. This applies to the wind turbines technology and solar photovoltaics technology. This learning curve effect is implemented in such a way that investment costs can only be reduced to a certain fixed minimum level (so-called floor costs).

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. Both innovation and diffusion processes are modelled. Dedicated R&D investments for enhancing energy efficiency from investment enhance the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (backstops). R&D processes are subject to spillover 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 backstop technologies.

2.4. Climate module

In order to be able to simulate stabilization scenarios, all three models include a representation linking carbon emissions from the combustion of fossil fuels to atmospheric concentrations. As IMACLIM-R does not include a climate module, emission pathways yielding the desired atmospheric concentration are imposed exogenously. REMIND-R integrates a simple climate model (Petschel-Held et al., 1999) and WITCH uses the MAGICC 3-box layer climate model. Due to pronounced differences across climate models with regard to how atmospheric concentrations of GHGs impact on temperatures and the large inertia of the climate system, atmospheric concentrations instead of mean temperatures are used in this report as a target for climate policy.

3 Database and Calibration

3.1. Economic Growth

For all three models, economic growth is driven by the dynamics of technological progress and capital accumulation. Therefore, each model features a particular growth path reflecting its internal characteristics and assumptions. To facilitate the comparison of model results, assumptions concerning exogenous drivers of economic growth (e.g. improvements in factor productivities) have been chosen in a way such that the resulting GDP trajectories stay within close proximity to each other in the long run. As a starting point, GDP paths were obtained by running simulations with IMACLIM-R, experimenting with different sets of labor productivity and convergence parameters until a result consistent with the modeling teams' consensus view emerged, on which the other models were then calibrated. In this scenario, OECD countries are assumed to reach a rather constant growth rate, while convergence of income levels brings most developing countries (with the exception of Sub-Saharan Africa) close to the level of OECD countries by the end of the century. The resulting scenario (which is described in more detail in the chapter on baseline results) projects increases in GDP corresponding to average annual growth rates between 2.1% (for WITCH) and 2.4% (for REMIND-R) over the century.

The **IMACLIM-R** model is designed to represent gaps between potential and real growth. The pace and direction of effective economic growth is endogenously determined by the interactions between the growth engine (population, labor productivity), and structural and technical change on energy demand and supply. In particular, structural change results from investment decisions that modify the distribution of productive capital across sectors, and changes in households' preferences capturing some empirical evidence on the evolution of consumption patterns (manufacturing goods' consumption per capita features some asymptotes and the share of income devoted to agricultural goods decreases with increasing income). Labor productivity growth follows a constant long term rate for the most advanced economy and catching-up assumptions for other regions, assuming that the United States remain the world productivity leader and their mean labor productivity follows a steady growth of 1.65% per year. Other countries' productivity dynamics are driven by a partial catch-up of productivity gaps, the parameters of which are calibrated on historic trajectories. Besides these long-run drivers, both the availability of investments and their allocation are key elements controlling effective growth.

Economic growth in **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 a constant efficiency of capital is assumed, labor productivity growth is adjusted to reproduce the regional GDP baselines harmonized for the three models. Efficiency growth of the different final energy types is in constant relation to changes of labor productivity. For all energy production factors, efficiency change rates are defined in relation to labor productivity changes. 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 well as possible the given GDP path. The transition from the initial to the final growth also differs between regions and contributes to matching the given GDP path.

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. Economic growth rates and the level of convergence are strong determinants of energy demand and, therefore, GHG emissions. Projections for regional GDP growth is based on assumptions regarding labor productivity convergence. OECD countries are assumed to reach a rather constant growth rate, while catch-up 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, with Sub-Saharan Africa experiencing delays in catch-up and Eastern Europe showing the highest convergence rate.

3.2. Population

Identical exogenous time paths for population change were assumed for all three models. Population forecasts come from the UN Department of Economic and Social Affairs, Population Division[2]. Population data up to 2050 are available at 5 year intervals, while for later periods, only the forecast for the year 2100 is available, but not for years between 2050 and 2100 (UN, 2004). The differences in the two datasets were thus reconciled by extrapolating levels at 5 year periods in 2050-2100 using average 2050-2100 growth rates. The scenario employed in here assumes a continued upward trend in global population, albeit at steadily decreasing rates of growth, reaching 9 billion in 2050, 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.

3.3. Regions

In their standalone version, each model features a particular aggregation scheme which defines how country-level data are represented on the basis of world regions. These schemes are listed in Table 3-1. As each model builds on a specifically gathered set of parameters (such as technological coefficients, capital stocks, renewable energy potentials, etc.), which are often not available on a country level, full harmonization of regions is clearly not a feasible option. However, to make the results of the model runs comparable, model-specific regions have been aggregated into 6 macro-regions, which are fairly similar across models. These are: USA, Europe, Rest of Annex I, China, India, and Rest of non-Annex I. The aggregation scheme is given in Table 3-2. The main differences between models are that for IMACLIM-R and WITCH, the ‘Europe’ macro-region includes non-EU East-Europe and EFTA (plus Turkey for IMACLIM-R), while for REMIND-R it is only the EU27. In REMIND-R South Africa is part of the ROW region, and this region (which also includes Australia and New Zealand) is treated as being part of ‘Rest of Annex I’. In WITCH India is included in the South Asia region, which is treated as the macro-region ‘India’. Therefore, for WITCH, the macro-region ‘India’ also contains additional countries such as Pakistan, Bangladesh, and Sri-Lanka. Finally, countries that used to be part of the former Soviet Union are treated differently in all three models: In IMACLIM-R, they belong, together with Russia, to the region ‘FSU’, which is included in the macro-region ‘Rest of Annex I’. In REMIND, these countries are divided between the regions ‘MEA’ and ‘ROW’ – the former is part of the macro-region ‘Rest of

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

non-Annex I', the latter of 'Rest of Annex I'. In WITCH, they are included in 'TE', which, according to the aggregation scheme, is treated as 'Rest of non-Annex I'.

	Original Regions
IMACLIM-R	**AFR** (Africa), **BRA** (Brazil), **CAN** (Canada), **CHN** (China), **EUR** (Europe, including non-EU EFTA and Eastern Europe, including Turkey), **FSU** (Russian Federation, Rest of Former Soviet Union), **IND** (India), **ME** (Middle East), **OECD Pacific** (Japan, Korea, Australia, New Zealand), **RAL** (Rest of Latin America and the Caribbean), **RAS** (Rest of Asia)
REMIND-R	**AFR** (Sub-Saharan Africa), **CHN** (China), **EUR** (EU27), **IND** (India), **JAP** (Japan), **LAM** (Latin America and the Caribbean), **MEA** (Middle East and Northern Africa), **OAS** (Other Asia), **ROW** (Rest of the World), **RUS** (Russia), **USA** (USA)
WITCH	**CAJAZ** (Canada, Japan, and New Zealand), **CHINA** (China), **EASIA** (East Asia, excluding China Japan, and Korea), **KOSAU** (Australia, Korea, South Africa), **LACA** (Latin America and Caribbean), **MENA** (Middle East and Northern Africa), **NEW EUROPE** (recent accessions to EU), **OLD EUROPE** (EU15), **SASIA** (South Asia), **TE** (non-EU East-Europe and Central Asia), **US** (USA)

Table 3-1: Definition of Regions for the three models

RECIPE	USA	Europe	Rest of Annex I	China	India	Rest of non-Annex I
IMACLIM-R	USA	EUR	Canada, FSU, OECD Pacific	CHN	IND	AFR, BRA, ME, RAL, RAS
REMIND-R	USA	EUR	JAP, RUS, ROW	CHN	IND	AFR, LAM, MEA, OAS,
WITCH	US	Old Europe, New Europe	CAJAZ, KOSAU	China	SASIA	EASIA, LACA, MENA, SSA, TE

Table 3-2: Aggregation of model regions to RECIPE macro-regions

3.4. Energy and Emissions Data

For **IMACLIM-R**, a social accounting matrix combines flows in monetary values with energy balances in physical quantities. The composed hybrid matrix is constructed based on GTAP 6 (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). Technico-economic parameters in the electricity sector associated with each of 13 explicitly modeled technologies are either calibrated on sectoral technology-rich models (like the POLES model) or taken from the literature (Grübler et la., 2002 ; Rao et al., 2006 ; Sims et al., 2007). Technologies that are currently non mature or in quick evolution can be represented either through autonomous trends or endogenous learning mechanisms. For passenger transport, the automobile fleet is detailed according to the type of vehicle and its vintage, and different technologies (including hybrid vehicles) are explicitly represented for a bottom-up representation of households' decisions on vehicle purchases. Capital costs, energy efficiency, as well as operation and maintenance costs are calibrated on data from 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. 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, while for sea transport, unitary intermediate energy consumption is constant and for other 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. Productive sectors are aggregated in "meta-sectors", which include a large variety of sub-sectors. The average technology parameters represent the mix of specific technologies used in all sub-sectors. Technical coefficients are derived from the hybridization process, which gives intermediate consumption of energy (and transport) for production in money values and physical quantities.

The price of fossil fuels is calibrated by the combination of money flows provided by the social accounting matrix and physical flows. 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.

Only CO_2 emissions from fossil fuels are accounted for in IMACLIM-R. Sources of emissions considered are the 3 final energy sources (coal, gas, and liquid fuels) associated to the three primary fossil energies (coal, gas, oil). Coefficients relating energy consumption to carbon emissions are fixed as an intrinsic chemical characteristic of the energy considered. However, certain sectors (especially electricity) can use CCS technologies that lower the emission actually released in the atmosphere and a share of liquid fuels can be provided by biofuels or Coal-To-Liquid.

REMIND-R features a large variety of conventional as well as carbon-free energy technologies. Techno-economic characteristics of these technologies (i.e. conversion efficiencies, investment as well as operation and maintenance costs, and capture rates if the technology can be equipped with CCS) are taken from the respective literature[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. Electricity is the secondary energy carrier that can be produced in REMIND-R out of all primary energy carriers. The production of liquid fuels and hydrogen used in the transport sector can either be produced from fossil energy carriers or biomass. Biomass plays an important role in the transport sector either for the generation of liquid fuels or of hydrogen and a fairly smooth transition from traditional to modern forms of biomass utilization is assumed for developing countries. The model contains three types of biomass (of which potentials and associated costs vary

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[3] Bauer (2005), Gül et al. (2008), Hamelinck (2004), Iwasaki (2003), Rageletti (2007), Schulz et al. (2007), Takeschita and Yaaij (2008)

significantly with the type) and a number of technologies that are available to transform the raw material into useful energy carriers. Heating plants exhibit a range of conversion efficiencies. The investment costs are relatively low; the data is taken from Schulz (2007, p. 140). Ranges for CHP technologies are chosen 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).

Reserve endowments of exhaustible primary energy carriers are based on data from Enerdata (2008), which assumes abundant and widely available coal but scarce oil, gas, and uranium. Initial extraction costs and extraction costs at the reserve limit are connected by a quadratic cost curve. This leads to initial extraction costs of 1.8 US$ per GJ for coal, 8 US$ for oil, 5.5 US$ for natural gas and 30 US$ per kg of uranium.

With regards to GHG emissions, REMIND considers energy-related CO_2 only. As in the other models, CO_2 emissions from the combustion of fossil fuels (oil, gas, and coal) and biomass are calculated using physical identities in the form of stochiometric coefficients. For certain forms of energy, release of the associated emissions can be avoided by using carbon capture and sequestration (CCS).

The energy sector in **WITCH** is composed by electricity generation and a non-electric sector, which consumes energy of different sources. WITCH08 maintains the same underlying structure as the previous version of the model, but the data is updated using Enerdata (2008). Despite the detailed description of the power generation sub-sector, not all types of power plants are modelled explicitly in WITCH (for instance, the model does not distinguish gas with no combined cycle). Therefore the standard use of factors for new power plants is assumed to avoid accounting difficulties for multi-fuel and marginal power plants. The efficiency of fuel consumption in power generation plants are close to the implied values in the new Enerdata database. Following recent debates over the technical feasibility, the investment costs for Integrated Gasification Combined Cycle (IGCC) technologies were increased from 2000 1995US$/kW to 2500 1995US$/kW. The same increase is applied to nuclear power generation. It is assumed that 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. For the non-electric sector, updated figures from the Enerdata 2008 database are derived by subtracting energy consumptions in the electricity sector from total consumption figures.

Following the sharp increases in the market prices between 2002 and 2005, the prices of fossil fuels and exhaustible resources have been revised upwards compared to earlier versions of WITCH. Base year prices have been calibrated following Enerdata (2008), IEA (2007) and EIA (2008). The year 2005 international prices for exhaustible resources are set at 55 US$/bbl for oil, or roughly 8US$/GJ, 7.14 US$/GJ for natural gas, and 60 US$/ton for coal, equivalent to 2 US$/GJ. In order to match the large difference in price increases shown in the Enerdata database, the mark-up prices were adjust upwards to account for the tripling of uranium ore price from 2002 to 2005. The cost of conversion was increased from 5 US$/kg to 11 US$/kg, while enrichment costs stayed roughly constant, thus slightly increasing the cost of conversion and enrichment from 221 to 230 1995 US$/kg. Country specific mark ups are set to reproduce regional figures from IEA (2007).

In order to differentiate the higher emission content of non-conventional oil as opposed to conventional ones, WITCH links the carbon emission coefficient for oil to its availability. Specifically, the stochiometric 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).

	IMACLIM-R	**REMIND-R**	**WITCH**
Oil	Hubbert Curve for 12 varieties of crude oil distinguished according to production costs and type (conventional vs. non conventional)	Rogner curve: extraction costs increase quadratically with cumulatively extracted quantity	Extraction costs related to cumulative extracted quantity and discovery of new reserves. Regional mark-ups
Coal	Extraction costs determined by a reduced form of the POLES model	Rogner curve linking extraction costs to cumulatively extracted quantity	Extraction costs related to cumulative extracted quantity and discovery of new reserves. Regional mark-ups
Gas	Extraction costs determined by a reduced form of the POLES model, partial indexation on oil price	Rogner curve linking extraction costs to cumulatively extracted quantity	Extraction costs related to cumulative extracted quantity and discovery of new reserves. Regional mark-ups
Uranium	No explicit description (exogenous price)	Rogner curve linking extraction costs to cumulatively extracted quantity	Extraction costs related to cumulative extracted quantity and discovery of new reserves. Regional mark-ups
Biomass	Dynamic supply curves distinguished between first and second generation biofuels.	Grades, price rises with increasing harvest	Conservative assumption on availability due to land competitions issues

Table 3-3: Summary of description of primary energy carriers in the three models

3.5. Specific Features of Abatement Technologies

In the **IMACLIM-R** model, several carbon-free technologies are described. For electricity production, these are CCS, nuclear (which entails intangible costs related to social acceptability) and renewable energies. The latter's 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, which is a conservative assumption capturing slow progress in storage and grid management. The proportion of electricity production ensured by renewables 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 renewables 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). For transportation, IMACLIM-R features second generation biofuels (for which production is constrained by a global limitation related to the availability of agricultural land simulated by a compact land-use module calibrated on results from sectoral analysis) as well as hybrid efficient cars.

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.

REMIND-R includes nuclear, renewable energies and biomass as carbon-free energy sources. In addition, emissions from fossil fuels can be avoided by using CCS. Furthermore, it is also possible to use CCS in combination with biomass. For nuclear power REMIND-R only considers Light Water Reactors, for which investment costs are assumed to be 2500$US per kW. Concerning renewables, REMIND-R distinguishes different grades with maximum production constraints. The grades differ with respect to the maximum capital utilization rate. Since the production technology is linear of the Leontieff type a decreasing capital utilization rate captures the idea of decreasing quality of different locations. A power storage technology is included in REMIND-R to account for the need to balance fluctuation arising from an increasing share of wind and solar PV in electricity production. Electricity production from wind turbines and photovoltaics are characterized by learning-by-doing, with learning rates (for each individual regional) of 10% and 20%, respectively. In this way, cumulative production of these technologies lowers required investment costs to a minimum (so-called floor costs) of 890 US$/kW for wind and 700 US$/kW for solar PV. With an increasing penetration of fluctuating renewables, the additional investment costs for storage amount to 110-280 USD/kW (wind) and 310-530 USD/kW (solar), depending on the share in regional electricity mixes. Wind and solar, have global maximum potentials of 140EJ and 750EJ with maximum availability factors of 31% and 25%, respectively (see e.g. Hoogwijk, 2004; WBGU, 2003). Biomass plays an important role among the mitigation technologies, largely because of the option to combine it with CCS. As harvest costs of biomass are increasing with increased use, they range from an initial value of 1.2 to 4$US per GJ at the point of maximum production. REMIND-R further includes production of synthetic natural gas from biomass in biogasification plants, ethanol production from ligno-cellulosic biomass, hydrogen production from biomass and diesel from ligno-cellulosic biomass via Fischer-Tropsch synthesis. For the transport sector, petroleum products can be substituted with hydrogen or fuels derived from biomass; the electrification of the transport sector is not yet implemented in REMIND-R.

WITCH features a series of mitigation options in both the electric and non-electric sectors, such as nuclear power, CCS, renewables, biofuels and two backstop technologies that necessitate dedicated innovation investments to become economically competitive, even in a scenario with a climate policy. These latter technologies are modeled with a two-factor learning curve in which their price declines both with investments in dedicated R&D and with technology diffusion. 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. Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. It is assumed 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 reflecting the inertia in the system.

Learning processes via knowledge investments and experience are likely to spill to other regions. WITCH features spillovers of experience for wind and solar in that the Learning by Doing effect depends on world cumulative installed capacity as well as spillovers in knowledge for energy efficiency improvements and spillovers of both experience and knowledge in the backstop technologies. 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 the domestic knowledge stock and investments and thus contributes to the production of new technologies at home. The WITCH model provides an appropriate framework to implement second best features such as knowledge externalities. When solved as a non-cooperative game, regions can play strategically not only on GHG emissions, but also on knowledge investments.

	IMACLIM-R	REMIND-R	WITCH
CCS	For Super Critical Coal, Coal Gasification, and Gas Combined Cycle	For some fossil fuel based technologies in the power sector and for some transformation technologies using biomass	For Coal Integrated Gas Combined Cycle
Nuclear	For electricity generation; takes into account intangible costs	Light Water Reactors for electricity generation	Light Water Reactors for electricity generation; accounts for waste management costs
Renewables	Wind for electricity production, solar for residential	Wind Turbines, Photovoltaics, Hydro, Geothermal	Wind, PV, and Solar Thermal plus two generic backstop technologies
Biomass	Second generation biofuels	Ligno-cellulosic, starch, sugar, and oil for electricity, biofuel, and hydrogen production	Traditional biomass and biofuels. Low penetration assumed because of land use security concerns
Energy Efficiency	Energy efficiency improvements through new vintages of capital in the energy sector	Exogenous energy efficiency improvements and through new vintages of capital in the energy sector	R&D investments to increase energy efficiency

Table 3-4: Summary of characteristics of abatement technologies in the three models

4 Key differences in modeling approaches

As can be seen from the model descriptions above, the models incorporate different perspectives with regards to economic behavior, the representation of the energy sector, and development of new technologies.

With regard **formation of expectations**, REMIND-R and WITCH are designed as optimal growth models, in which decisions are taken with perfect foresight. IMACLIM-R, on the other hand, features a recursive CGE structure, in which actors' decisions are based on imperfect expectations about the future resulting from observations of past and current values of state variables. For this reason, the former two models can be expected to feature a considerably higher inter-temporal flexibility when it comes to anticipating the necessity of long-term changes, such as engaging in learning-by-doing or investing in R&D, early on. However, in recursive models with imperfect foresight, such as IMACLIM-R, it might be the case that non-regret options (e.g. investing in energy efficiency) that have long pay-back times or whose benefits materialize only in the far future are not undertaken in the business-as-usual case. Therefore, for this type of model, climate measures can be a means of remedying these market failures and might result in lower (or even negative) mitigation costs over the century. This property can also result in some kind of 'bi-stability' in the sense that initially large efforts are required to move the system from its current path (i.e. fossil based) to an alternative one (i.e. low-carbon) but little extra effort is required once it is located on this new trajectory.

In the **energy sector**, decarbonization can take place by fuel switch or the introduction of novel technologies, such as renewables, biomass, or CCS. Therefore, one should expect the flexibility and potential costs of mitigation options included in the representation of a model's energy sector to be a major determinant of mitigation costs. For this aspect, REMIND-R presents the most optimistic outlook for the production of carbon-free energy, featuring a large variety of options that allow substituting away from fossil fuels in the stationary as well as the transport sector and apply CCS in the power sector as well as for transformation technologies in the transport sector. WITCH, on the other hand, is less optimistic when it comes to decarbonising energy production, in particular in the non-electric sector where the alternatives to fossil fuels are costly and need innovation expenditures to trigger the diffusion process. IMACLIM-R lies somewhere in between REMIND-R and WITCH as it includes ample scope for abating GHG emissions in the power sector as well in transportation (such as second generation biofuels and hybrid vehicles), but explicitly accounts for the technological and behavioral inertias likely to affect their diffusion.

All three models feature **endogenous technological change** in the form of learning-by-doing (i.e. decreasing investment costs with increasing cumulatively installed capacity) for some of the carbon-free sources of energy. In addition, in WITCH investments in innovations, which increases energy efficiency and decreases the costs of breakthroughs in technology, play an important role which is not considered in the other models. Therefore, it can be expected that in WITCH increasingly investing into energy efficiency in addition (or even as a substitute) to decarbonizing the production of energy could turn out as a viable option to abate carbon emissions, especially if switching to low-carbon or carbon-free energy sources involves relatively high costs.

5 The Model Comparison Framework

The economic analysis of climate change is concerned with two types of major uncertainties: firstly, parameter uncertainty (i.e. incomplete knowledge with regards to economic and technology parameters used to calibrate the models), and, secondly, model uncertainty (i.e. having several plausible model structures without a clear indication to prefer one structure over the others). Carrying out model comparisons in order to reduce model uncertainty is an often used concept in climate economics (see e.g. The Energy Journal Special Issue, 2006). In this context, one should be clearly aware that models are not intended to predict the future, but to generate plausible, self-consistent scenarios. These scenarios, in turn, constitute useful tools for scientists and policymakers to explore the scope of possible developments, discuss the plausibility of underlying assumptions, and derive appropriate courses of action.

The three models employed in this model comparison represent very similar assumptions with regards to socio-economic developments (i.e. population growth and world GDP) but different visions of development and diffusion of new technologies as well as of economic mechanisms. Comparing the results obtained for the baseline as well as stabilization scenarios with these three models will hence help to shed some light on how different assumptions on technologies and economic dynamics translate into differences in mitigation costs, investment patterns, and optimal emissions reduction trajectories.

For these reason, various scenarios were generated. The baseline scenario represents the business-as-usual development (i.e. projections of future emissions if no climate policy measures beyond those already in place are implemented), against which all stabilization scenarios are evaluated. The policy scenarios assess the costs of stabilizing GHG concentrations at 450 ppm CO_2 only, a target that is a minimum requirement to avoid dangerous climate change. In an additional scenario, the case in which more stringent cuts - that would ensure a higher likelihood of achieving the EU's target of limiting global warming to no more than 2°C - is assessed. For this low stabilization scenario an atmospheric concentration of 410 ppm CO_2 only was used as policy target. The analysis pays considerable attention to the regional dimension of climate policy (i.e. feasibility of reaching the target and the implied increases in mitigation costs if certain regions do not participate in a cooperative agreement, as well as the distributional impact of different rules how permits are allocated across regions), the technology dimension (i.e. option values of including certain technologies in the portfolio), and timing of action (i.e. if climate measures are taken at a later date).

6 Lessons learned

During the process of carrying out the model comparison for this study, important lessons, that can be useful for future exercises conducted in a similar way, emerged. In order to allow other modeling teams to benefit from the efforts undertaken within RECIPE, these key lessons will be discussed below. Not all of these messages follow directly from the insights gained in this chapter; rather this section should be regarded as a synthesis of the lessons learned while compiling the model descriptions, baseline results, and stabilization scenarios.

Firstly, it is of crucial importance to establish a clear picture which features and assumptions should be harmonized, and which ones should be allowed to differ across models. In this context, it should also be clearly stated which values are chosen endogenously within a certain model, and which ones are determined by exogenous parameters. To ensure the comparability of results on a regional scale, modeling teams should strive to apply identical definitions of world regions.

Secondly, key differences in modeling approaches have to be identified and explained in detail such that a clear understanding what drives the model results is possible. This implies a transparent description of key characteristics and parameter values (e.g. investment and O&M costs as well as learning rates and floor costs for energy technologies) in combination with an evaluation of their importance, supported by sensitivity analysis. Special attention should be paid to highlighting the technological visions represented by each model, i.e. which technologies are included, which future development are projected, and how these impact on energy systems as well as patterns of production and consumption.

Thirdly, modelers should be explicit about which policy messages can (and which cannot) be derived within the setup of their respective models. This applies especially for the question which kinds of regulative instruments, such as cap-and-trade, carbon taxes, feed-in-tariffs, etc., can be simulated.

Fourthly, sectoral detail should be included, especially when it comes to the description of mitigation strategies. Instead of focusing exclusively on aggregate variables on the macro-scale (such as overall mitigation costs), increased attention should be paid to processes taking place at a higher resolution to gain a better understanding of the mechanics underlying different mitigation strategies and provide estimates of the associated investment flows required. However, when including sectoral detail, it should be ensured that sectors are defined comparably by different modeling teams.

Fifthly, investments in the energy system are not only an important for policy advice, but their analysis is also highly insightful for an in-depth understanding of model characteristics with respect to economic flexibility and decarbonization strategies.

Finally, on the technical side, establishing a harmonized structure for reporting output data is crucial. This should be as comprehensive as possible, in order to allow for in-depth cross-comparisons of models and for attributing differences across in model results to structural differences across models. For instance, the detailed reporting of energy consumption by end-use sector proved highly valuable in the context of RECIPE.

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