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THE 2008 WITCH MODEL: NEW MODEL FEATURES AND BASELINE

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SUMMARY WITCH is an energy-economy-climate model developed by the climate change group at FEEM. The model has been extensively used in the past 3 years for the economic analysis of climate change policies. WITCH is a hybrid top-down economic model with a representation of the energy sector of medium complexity. Two distinguishing features of the WITCH model are the representation of endogenous technological change and the game-theoretic set-up. Technological change is driven by innovation and diffusion processes, both of which feature international spillovers. World countries are grouped in 12 regions which interact with each other in a setting of strategic interdependence. This paper describes the updating of the base year data to 2005 and some new features: the inclusion of non-CO2 greenhouse gases and abatement options, the new specification of low carbon technologies and the inclusion of reducing emissions from deforestation and degradation.

Keywords: Climate Policy, Hybrid Modelling, Integrated Assessment, Technological Change

JEL: O33, O41, Q43

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OUTLINE

1. Introduction

The control of climate change is a challenging task, at least for three reasons. Climate change is a global problem which involves a large number of players, namely all countries in the world. Climate change is likely to have significant distributional implications, as the expected impacts of climate change, the costs to mitigate it or adapt to it are not equally distributed.

Secondly, it is a long-term phenomenon. Long-lived Greenhouse Gases (GHG) remain in the atmosphere from decades to centuries, increasing the concentrations for very long temporal horizons. As a consequence, mitigation efforts should be undertaken in advance, because today's abatement actions will only yield benefits in the distant future.

Thirdly, climate change is characterised by a high degree of uncertainty, both on the environmental and the economic side. Despite the increasing understanding of the scientific basis behind global warming, the climate remains a complex system. On the economic side, the future state of technology and innovation is hard to predict, and therefore the range of mitigation options to cope with climate change is uncertain. Global warming is an environmental externality and actions that deal with it respond to strategic incentives.

Sound economic analysis of climate policies should try to encompass the multifaceted dimension of climate change. The WITCH model, developed by the climate change group at FEEM (Bosetti et al., 2006; Bosetti et al., 2007), has been designed to explicitly deal with the main features of climate change. WITCH is a hybrid energy-economy of the world economy, with 12 representative macro-regions. It is an integrated assessment model (IAM), featuring a reduced form climate module and region-specific climate change damage functions that provide the climate feedback on the economic system. It is a forward-looking model, with perfect foresight, that optimises over a discounted stream of future consumption, over a long-term horizon covering all centuries until 2100. Two distinguishing features of the WITCH model are the representation of endogenous technological change and the game–theoretic set-up.

The intertemporal structure, the regional dimension and the game theoretical set-up make the WITCH model suitable for the assessment of long-term, geographic and strategic aspects of climate change policies.

The core structure of the model is described at length in the technical report (Bosetti et al., 2007). This paper briefly recalls its main characteristics, but the focus is on the new elements of the latest version, henceforth referred to as WITCH08[1].

The rest of the paper is structured as follows. Section 2 briefly describes the model structure. Section 3 reports the updating of the base year data to 2005 and the new dynamic calibration of the main driving forces behind economic growth. Section 4 describes the introduction of non-CO_2 greenhouse gases and of reducing emissions from deforestation and degradation (REDD). Section 5 illustrates the new specification of low carbon technologies and technological progress. Section 6 briefly summarises computational advancements. Section 7 provides an overview of the new baseline scenario.

[1] We refer to the latest version of the model with WITCH08. The first version instead is referred to as WITCH06.

Finally, Section 8 concludes the paper, summarising the key innovation of the model.

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 consequences of climate change. A climate module links 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. A damage function explicitly accounts for the effects of temperature increases on the economic system. Equations from (A19) to (A33) in the Appendix describe in detail the climate module.

WITCH08 can feature two different regional aggregations, which have both been calibrated to reproduce the same observed data.

The first one preserves the same regional grouping as WITCH06. The twelve macro-regions (US, WESTERN EUROPE, EASTERN EUROPE, KOSAU, CAJANZ, TE, MENA, SSA, SASIA, CHINA. EASIA, LACA) share similarities in terms of the structure of the economy, energy supply and demand and resource endowments.

The second regional aggregation is more suitable from the international policy standpoint. The regions CAJANZ (Canada, Japan, New Zealand), KOSAU (Australia, South Africa, Korea) and SSA (Sub-Saharan Africa without South Africa) have been changed into AUCANZ (Australia, Canada, New Zealand), JPNKOR (Korea, Japan) and SSA (Sub Saharan Africa, South Africa). Other regions have remained unchanged.

Regions interact with each other because of the presence of economic (technology, exhaustible natural resources) and environmental global externalities. For each region a forward-looking agent maximises its 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 (see section 2.5). More precisely, the Nash equilibrium is the outcome of a non-cooperative, simultaneous, open membership game with full information. Through the optimisation process regions choose the optimal dynamic path of a set of control variables, namely investments in key economic variables.

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 characterisation. 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.

2.2. The model

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), labour (L) and energy services (ES). In the first place capital and labour 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 Appendix. Climate damage (A20), which is a non-linear function of the gap between current and pre-industrial temperature, drives a wedge between net output and gross output.

The optimal path of consumption is determined by optimising 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 combination of the physical energy input and a stock of energy efficiency knowledge, as illustrated in equation (A6). This way of modelling 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 entails different fuels. Each region will choose the optimal intertemporal mix of technologies and R&D investments in a strategic way.

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 1). 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 by 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 pulverised coal (PC) power plants. Coal-based electricity can also be generated using integrated gasification combined cycle production with carbon capture and sequestration (CCS). Low carbon technologies include hydroelectric and nuclear power, renewable sources such as wind turbines and photovoltaic panels (Wind&Solar) and two breakthrough technologies.

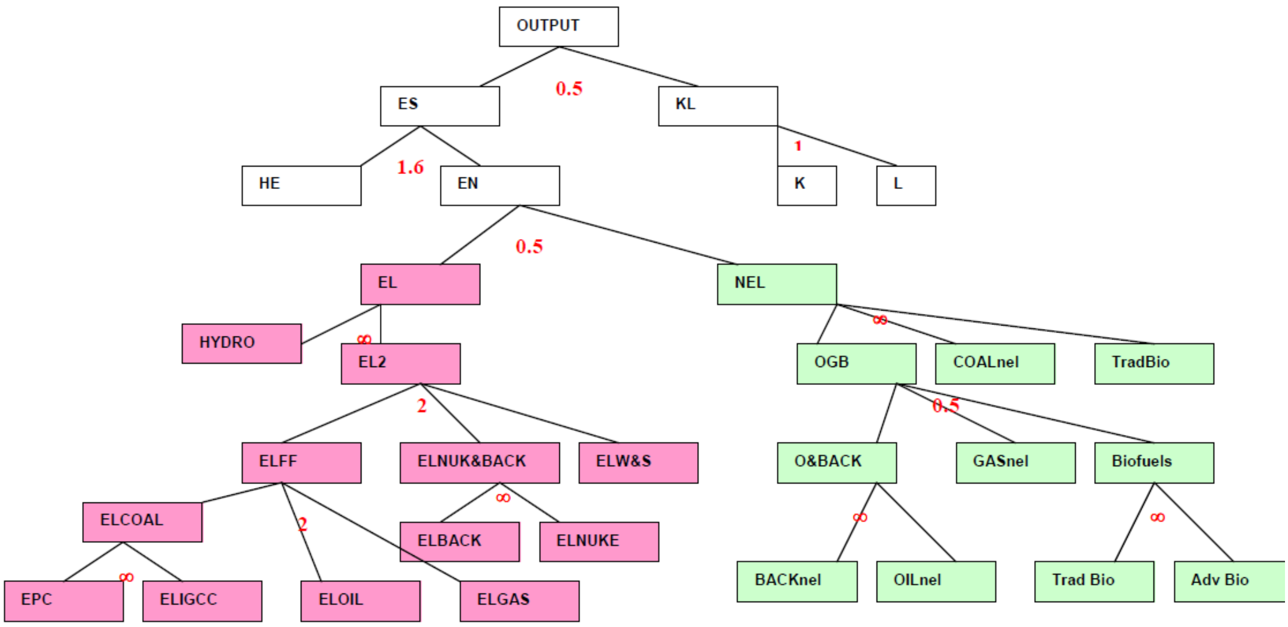


Figure 1: Production nest and the elasticity of substitution

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

All the main technology features are represented: yearly utilisation 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 which is replaced for a sufficiently high carbon price signal. For nuclear power, waste management costs are also modelled, but no exogenous constraint is assumed. Hydroelectric power is assumed to evolve exogenously to reflect limited site availability.

Breakthrough in power generation technologies is modelled 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 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. The use of fossil fuels generates CO_2 emissions, which are computed by applying stoichiometric coefficients to energy use.

2.4. Endogenous technical change

One of the main features of the WITCH model is the characterisation 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 modelled. We distinguish dedicated R&D investments for enhancing energy efficiency from investments aimed at facilitating the competitiveness of innovative low carbon technologies (backstops) in both the electric and non-electric sectors. R&D processes are subject to stand-on-shoulders as well on neighbours 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 behaviours 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 behaviours, both with respect to the environment (e.g. GHG emissions) and with respect to investments in knowledge and carbon-free but costly technologies.

Two different solutions can be produced: a co-operative one that is globally optimal and a decentralised, non-cooperative one that is strategically optimal for each given region (Nash equilibrium). In the cooperative solution all externalities are internalised and therefore it can be interpreted as a first-best solution. The Nash equilibrium instead can be seen as a second-best solution. Intermediate degree of cooperation, both in terms of externalities addressed and participation can also be simulated.

3. Database updating: new base year calibration

WITCH08 has been updated with more recent 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 are now available. We report on the main hypotheses on current and future trends on population, economic activity, energy consumption 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 update 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[2]. For the period 2050 to 2100, the updated data are 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. Similar techniques are used to project population trends beyond 2100.

Figure 2 compares global population figures in WITCH06 and WITCH08. 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.

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$[3]. We maintain the use of market exchange rates (MER)[4]. World GDP in 2005 equals to 44.2 Trillions US$.

Although part of the GDP dynamics is 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 3 shows the revised trajectories for Gross World Product over the century[5].

Economic growth rates and the level of convergence are strong determinants of energy demand and, therefore, GHG emissions. WITCH06 was largely based on the IPCC SRES B2 scenario, which assumed some relative convergence of income across countries. In this updated version of the model, we depart from existing IPCC scenarios, and base our projections for regional GDP growths on assumptions regarding labour productivity convergence[6].

OECD countries are assumed to reach a rather constant growth rate, higher than in the WITCH06 version, while the catch-up of non-OECD is driven by labour productivity which should bring most 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 4). 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

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

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

[4] 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.

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

[6] Such assumptions are consistent with a harmonisation process with two other prominent European models within the comparison project RECIPE. http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/externally-funded-projects/?searchterm=recipe

path consistent with these underlying assumptions on convergence and growth. Figure 4 shows the convergence of per capita income to the levels of the US. Figure 5 reports GPD growth rates.

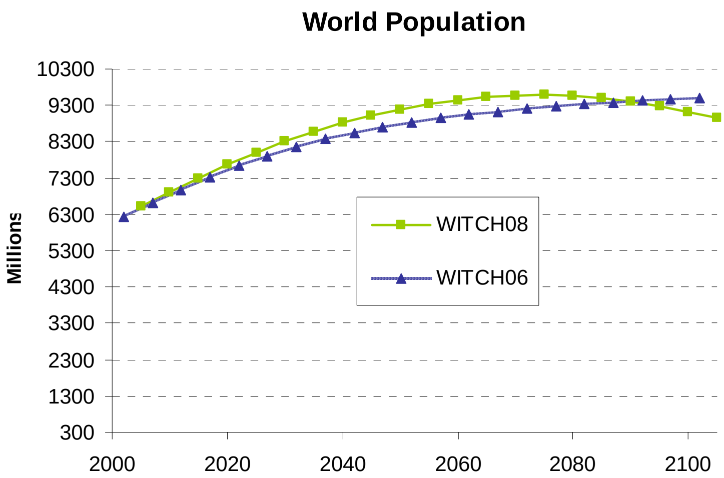


Figure 2: Population dynamics

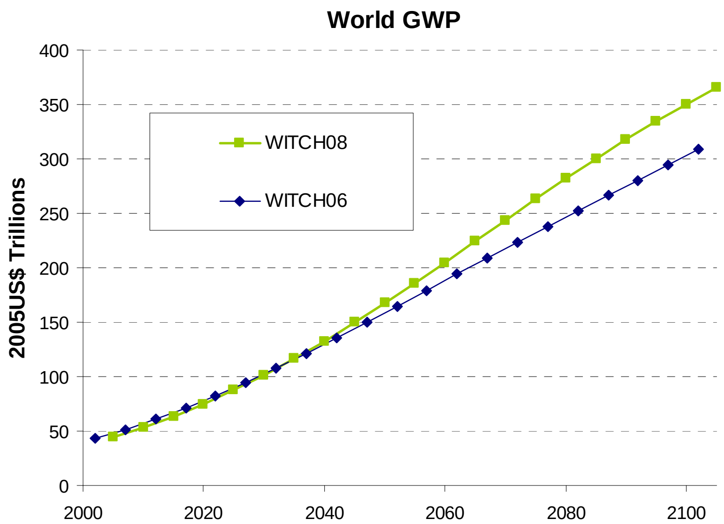


Figure 3: GWP trajectories

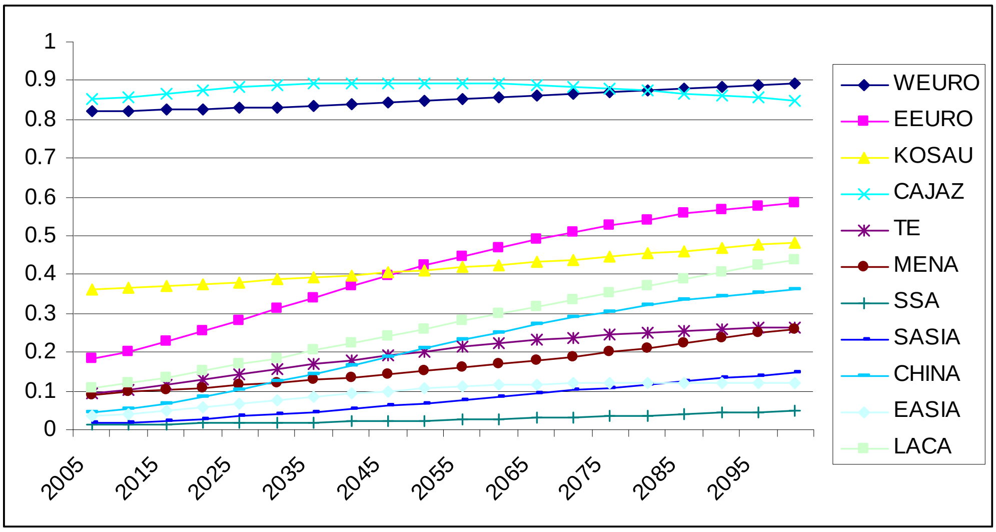


Figure 4: Convergence of GDP per capita to US levels

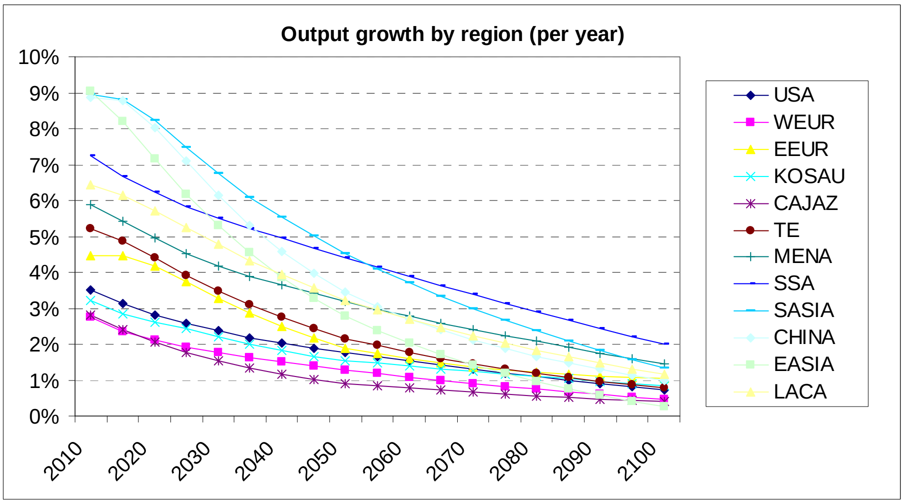


Figure 5: Output growth rates

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 the substitution of fossil fuel use is particularly challenging.

WITCH08 maintains the same underlying structure of the previous version of the model as described in Section 2.3, but the data is updated using Enerdata (2008).

3.3.1. Power generation sector

We maintain the same specification as in WITCH06 for the capacity factors, specified by type of power generation plant. 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). 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. We maintain the same specification as in WITCH06 for the efficiency of fuel consumption in power generation plants, since they are close to the implied values in the new Enerdata database. 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 utilisation factor of Wind&Solar is assumed to increase from 2500 to 3500 hours per year within a 30-year time frame.

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 greater detail 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 equal to 0.87 — i.e. there is a 13% investment cost reduction 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 1 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 utilisation factor of renewables, the higher costs of running and maintaining IGCC-CCS and nuclear plants.

	Investment costs World average USD$_{2005}$/KW	**O&M** World average USD$_{2005}$/KW	**Fuel Efficiency** %	**Load factor %**	**Lifetime** years	**Depreciation %**
Renewables (W&S)	1904	30	100%	30%	30	7.40%
Nuclear	2540	176	35%	85%	40	5.60%
Hydropower	1780	70	100%	50%	45	5%
Coal	1530	47	45%	85%	40	5.60%
Oil	1010	36	40%	85%	25	8.80%
Gas	810	30	60%	85%	25	8.80%
IGCC-CCS	3170	47	40%	85%	40	5.60%

Table 1: Initial investment costs and O&M costs of electricity generation technologies

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.

For the non-electric sector, we derive the updated figures from the Enerdata 2008 database, by subtracting energy consumptions in the electricity sector from total consumption figures.

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 (2008). The 2005 international prices for exhaustible resources are set at:

- 55 US$/bbl for oil, or roughly 8US$/GJ
- 7.14 US$/GJ for natural gas
- 60 US$/ton for coal, equivalent to 2 US$/GJ. In order to match the large difference in price increases shown in the Enerdata database, we adjust the mark-up prices
- Uranium ore price tripled from 2002 to 2005[7], and we thus update to this new level. The cost of conversion was increased from 5 US$/kg to 11 US$/kg[8], while enrichment costs stayed roughly constant[9]. We thus slightly increased the cost of conversion and enrichment from 221 to 230 1995 US$/kg.

Country specific mark-ups are set to reproduce regional figures from IEA (2007).

3.3.4. Carbon emission coefficients of fossil fuels

In WITCH08 we maintain the same initial stoichiometric coefficients as in WITCH06. However, 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. 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 4th Assessment Report (2007). Other parameters governing the climate equations have been adjusted following Nordhaus

[7] http://www.uxc.com/review/uxc_g_price.html
[8] http://www.uxc.com/review/uxc_g_ind-c.html
[9] http://www.uxc.com/review/uxc_g_ind-s.html

(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. The damage function of climate change on the economic activity is left unchanged.

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]. WITCH06 only considers explicitly industrial CO_2 emissions, while other GHGs, together with aerosols, enter the model in an exogenous and aggregated manner, as a single radiative forcing component.

In WITCH08, we take a step forward and specify non-CO_2 gases, modelling explicitly 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 SF6). We also distinguish SO_2 aerosols, which have a 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], which has underlying 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 Appendix). 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 the IPCC 4th Assessment Report, Working Group I. The simplified equation translating CO_2 concentrations into radiative forcing has been modified from WITCH06 and is now in line with IPCC[14].

We introduce end-of-pipe type of abatement possibilities via marginal abatement curves (MAC) 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. MAC 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

[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

[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

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 emission 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, with a subsequent gradual decline. This path is similar to what is found in the CCSP report[16], as well as in MESSAGE stabilisation scenarios. Nonetheless, the scarce evidence on technology improvements potential in non-CO_2 GHG sectors indicates that a sensitivity analysis should be performed to verify the impact on policy costs.

4.2. Forestry

Forestry is an important contributor of CO_2 emissions and, similarly to non-CO_2 gases, it might provide relatively convenient abatement opportunities. Forestry sector models differ substantially from energy-economy ones, so that normally the interaction is solved via soft link (e.g. iterative) coupling. For example, WITCH06 has been coupled with a global timber model to assess the potential of carbon sinks in a climate stabilisation policy (Tavoni et al. 2007). However, the model did not include this option in the standard simulation exercises.

WITCH08 is enhanced with baseline emissions and supply mitigation curves for reduced deforestation. The focus is on REDD[17] given its predominant role in CO_2 emissions and the policy importance of this option as stressed in the 2007 Bali Action Plan.

Baseline emissions are provided by the Brent Sohngen GTM model. REDD supply mitigation cost curves have been built and made suitable to be incorporated in the WITCH model.

Two versions of abatement cost curves have been incorporated in the model representing two extreme cases. The first version includes abatement curves for the whole century for the Brazilian tropical forest only and have been developed using Brazil's data from the Woods Hole Research Center (Nepstad et al. 2008)[18]. A second version includes abatement curves for all world tropical forests, based on the Global Timber Model of Brent Sohngen, Ohio State University, used within the Energy Modeling Forum 21 (2006) and data from the IIASA cluster model (Eliasch 2008). Bosetti et a. (2009) describes in depth the results from this analysis.

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 possible development of innovative technologies with low or zero carbon emissions. These technologies, which are currently far from being commercial, are usually referred to in the literature as backstop technologies, and are characterised as being available in large supplies. For the purpose of modelling, 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

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

[17] Reducing emissions from deforestation and degradation.

[18] http://whrc.org/BaliReports/

decades. This representation has the 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 modelling characterisation do not exist.

WITCH06 features a series of mitigation options in both the electric and non-electric sectors, such as nuclear power, CCS, renewables, biofuels etc. However, limited deployment potential of controversial technologies, such as nuclear, and resource constrained ones such as bioenergy, suggests that the possibility to invest towards the commercialisation of innovative technologies should be a desirable feature of models that evaluate long-term policies.

To this extent, WITCH08 is enhanced by the inclusion of 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 characterisation in the technology and climate change literature, modelling 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 tec 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). $P_{tec,t}$, the unit cost of technology tec at time t is a function of deployment, $CC_{tec,t}$ and dedicated R&D stock, $R\&D_{tec,t}$ as described in equation [1]

$$\frac{P_{tec,T}}{P_{tec,0}} = \left(\frac{R\&D_{tec,T-2}}{R\&D_{tec,0}}\right)^{-c} * \left(\frac{CC_{tec,T}}{CC_{tec,0}}\right)^{-b} \qquad [1]$$

where the R&D stock ($R\&D_{tec}$) accumulates with the perpetual rule and is also augmented by the stock of R&D accumulated in other regions through a spillover effect, *SPILL*

$$R\&D_{tec,T+1} = R\&D_{tec,T} \cdot (1-\delta) + IR\&D^{\alpha}{}_{tec,T} SPILL_{tec,T}{}^{\beta} \qquad [2]$$

and *CC* is the cumulative installed capacity (or consumption) of the technology. The specification of the spillover component, *SPILL*, is described in equation (A9) in the Appendix. We assume a two-period time interval (i.e. 10 years) between R&D knowledge and its effect on the price of the backstop technologies to account for time lags between research and commercialisation.

The two exponents are the Learning-by-Doing index ($-b$) and the Learning-by-Researching index ($-c$). They define the speed of learning and are derived from the learning ratios. The learning ratio *lr* is the rate at which the generating cost declines each time the cumulative capacity doubles, while *lrs* is the rate at which the cost declines each time the knowledge stock doubles. The relation between *b*, *c*, *lr*, and *lrs* can be expressed as in [3]

$$1 - lr = 2^{-b} \text{ and } 1 - lrs = 2^{-c} \qquad [3]$$

We set the initial prices of the backstop technologies 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 1,000twh and 1,000EJ, 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.

This formulation has received significant attention from the empirical and modelling literature in the most recent past (Criqui et al, 2000; Barreto and Kypreos, 2004; Klassens et al, 2005; Kypreos, 2007; Jamasab, 2007; Söderholm and Klassens, 2007). Estimates of parameters controlling the learning processes vary significantly across studies, see Table 2. They also primarily focus on power generation. For WITCH08 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 criticised for being too optimistic and leading to excessively low costs of transition towards low carbon economies.

Finally, it must be highlighted that modelling 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%
WITCH08		*10%*	*13%*

Table 2: Learning ratios for diffusion (LbD) and innovation (LbR) processes

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-organisation 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 processes via knowledge investments and experience are not likely to remain within the boundaries of single countries, but to spill to other regions too. The effect of international spillovers is deemed to be 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.

WITCH06 featured 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. An enhanced version was developed to include spillovers in knowledge for energy efficiency improvements (Bosetti et al. 2008), which are retained also in this WITCH08. As mentioned in section 2.3, 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. In WITCH08 we continue along this strand of research and model spillovers of both experience and knowledge in the newly featured backstop technologies. 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 parameterisation follows Bosetti et al. (2008) and it is recalled in the Appendix, equation (A9).

5.3. Key mitigation options

The WITCH model features a series of mitigation options in both the power generation sector and the other usages of energy carriers, 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 decarbonised 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 mUSD/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.

The limited deployment of controversial technologies such as nuclear calls for other alternative mitigation options. One technology that has received particular attention in the recent past is carbon capture and sequestration (CCS). In the WITCH model this option can be applied only to integrated coal gasification combined cycle power plants (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 by 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 1. 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 WICTH 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.

Other two important mitigation options are the endogenous improvement of overall energy efficiency with dedicated energy R&D (section 5.2) and reducing emissions from deforestation and degradation (section 4.2).

6. Computational issues

The WITCH model is solved numerically using GAMS – General Algebraic Modelling System[19]. GAMS is a high-level modelling system for mathematical programming problems, designed to provide a convenient tool to represent large and complex models in algebraic form, allowing a simple updating of the model and flexibility in representation, and modular construction.

WITCH features two different solution concepts, a cooperative concept that optimises jointly all regions, and a non-cooperative decentralised one that is achieved iteratively via an open loop Nash algorithm in which each region is optimised separately. This second solution was implemented sequentially in WITCH06.

In WITCH08, the regional maximisation 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

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

optimisation exercise. The solutions of each region's maximisation 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 an 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.

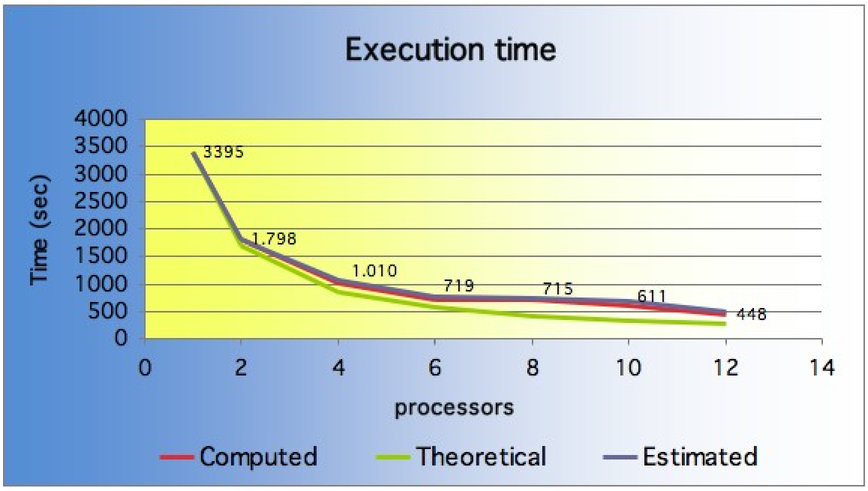


Figure 6: Execution time

Several tests have been performed for evaluating the scalability and performance of the parallel algorithm (Figure 6). The execution tests have been made on the SPACI's HP-XC6000 cluster ranging from 1 up to 12 CPUs, see Figure 6. 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 parallelisation produces a decreasing efficiency starting from 6 processors. The reason can be found in the imperfect balance of the workload.[20]

[20] 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).

7. Baseline scenario

This section outlines the main output of the WITCH08 baseline scenario which is the non cooperative, market solution of the model, without stabilisation constraints on GHG concentrations. 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. Components of emission growth

Figure 7 distinguishes the different drivers of GHG emissions, following Kaya's decomposition of total emissions (EMI) into carbon intensity of energy (EMI/EN), energy intensity (EN/GDP), per capita GDP (GDP/POP) and population. The left panel reproduces the historical components of GHG emissions observed over the past thirty years *vis-à-vis* the short-term WITCH baseline projections, whereas the right panel depicts the long-term trends produced by the model. Historically, per capita GDP and population have been the major determinants of emissions growth, whereas improvements in carbon intensity had the opposing effect of reducing emissions. The long-term scenario is still characterised by a preponderant role of economic growth, whereas the role of population fades over time. Economic growth, measured in terms of per capita GDP, is the major driver of GHG emissions over the whole century whereas population growth contributes to the increase in GHG emissions up to 2075, when population starts to follow a slightly negative trend. A decrease in energy intensity has a positive effect on emission reductions, which is however not sufficiently large to compensate for the pressure of economic and population growth. The carbon content of energy remains rather constant over time, with a slight carbonisation of energy due to an increase in coal consumption in fast-growing countries like China and India.

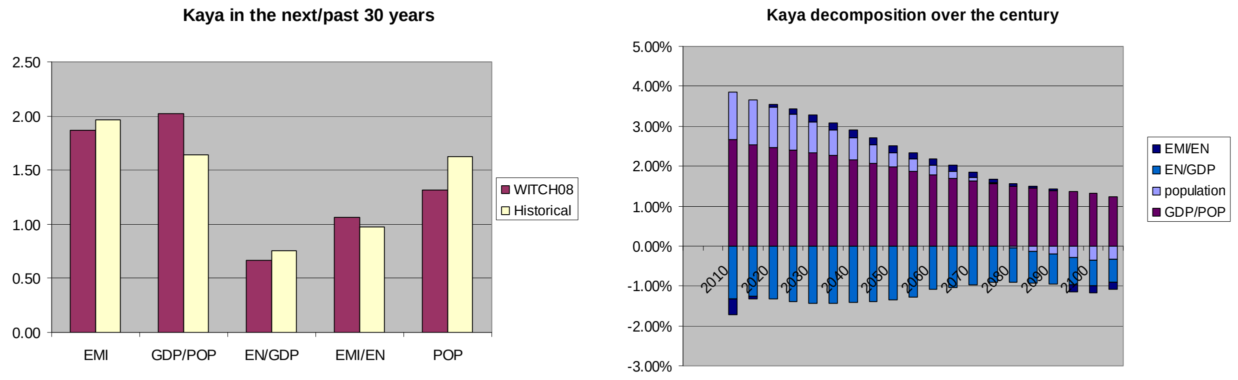
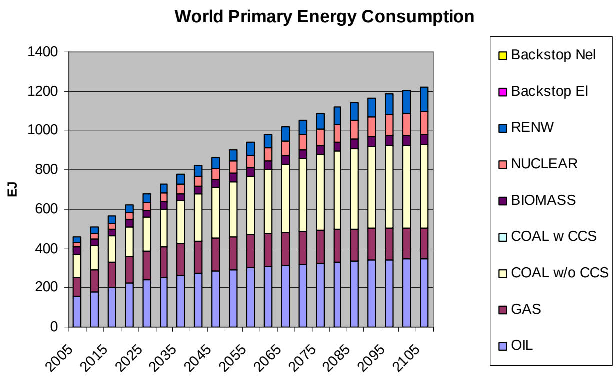


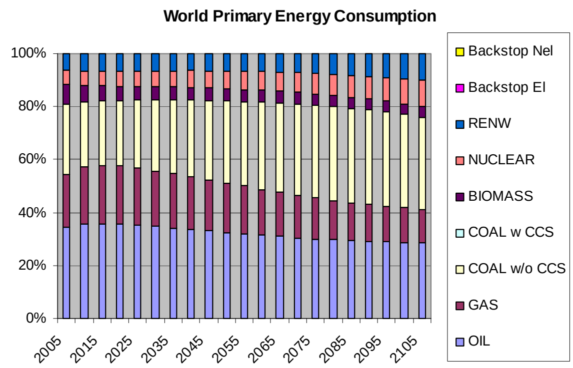
Figure 7: Components of GHG emissions: historical data and future path

7.2. Energy supply and prices

The growth rate of the world's 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 1,220 EJ. Figure 8 represents, on the left hand side, the energy mix over time at the global level, whereas in the right hand side panel the same information is translated into percentage shares. 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 3 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 a rate three times higher 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 the population. Looking at per capita figures (right panel), an average OECD resident currently consumes six times more energy than a non-OECD one; such a gap is expected to narrow over time, but it will 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)		
	OECD	**NON OECD**
2005	258	203
2050	374	529
2100	435	767
Average annual change		
2005-2050	0.9%	3.2%
2100-2050	0.3%	0.9%

Per capita energy consumption (TJ/person)		
	OECD	**NON OECD**
2005	0.24	0.04
2050	0.32	0.07
2100	0.41	0.10
Average annual change		
2005-2050	0.7%	1.5%
2100-2050	0.5%	1.0%

Table 3: 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 it can be seen from the right hand side panel on Figure 9, 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, loses market share over time because its production is limited by the availability of suitable sites and it is thus assumed to remain constant.

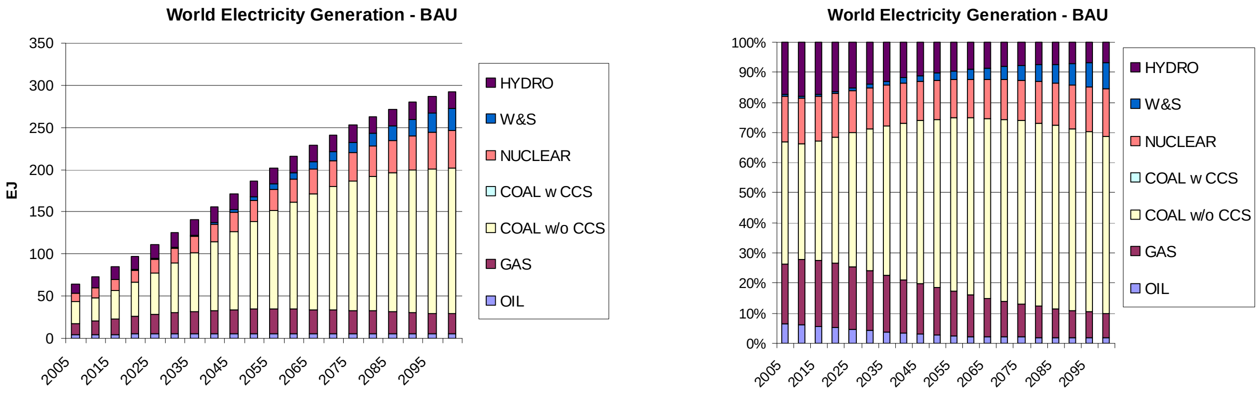


Figure 9: World electricity generation – levels and shares

As for fossil fuel prices, we project a general increase in the medium term, in line with IEA projections (see Table 4 and Figure 10). 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 tonne 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 4: International energy prices

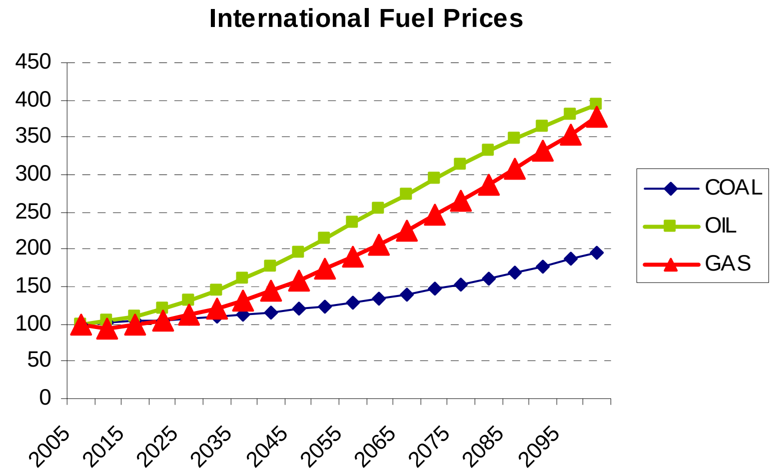


Figure 10: International fuel prices (2005 =100)

7.3. Technological change

Learning-by-Doing and Learning-by-Researching are the two major engines of endogenous technical change in the energy sector. Experience or Learning-By-Doing in wind and solar, as 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 9). Figure 11 – left hand side panel – depicts the downward path of investments costs, which decrease from 1,906US$/kW in 2005 to 1010 by 2050 and 649 by 2100, with an overall reduction of about 67%.

The second source of endogenous technical change is energy research and development (R&D). In WITCH08 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 11 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 US$ billions 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.

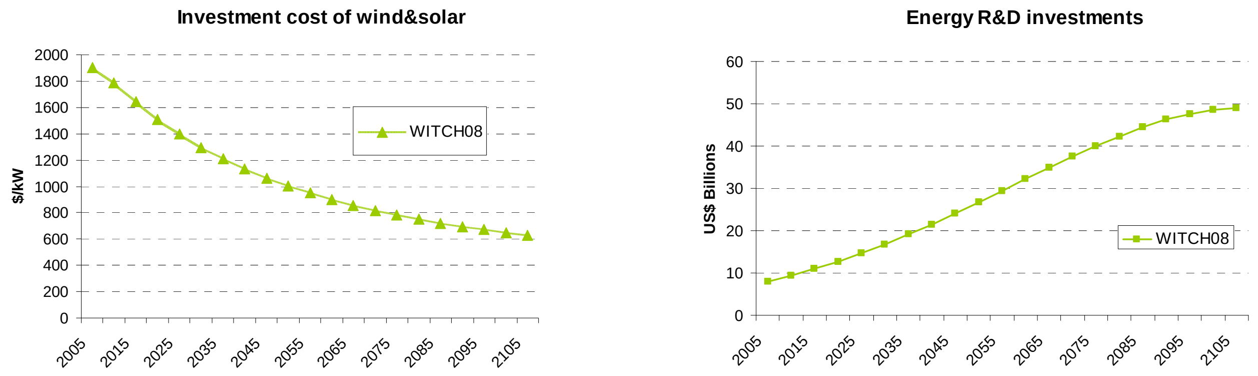


Figure 11: Learning-by-Doing and Learning-by-Researching

7.4. GHG Emissions

The growing energy demand reported in the previous section is expected to be met mainly by fossil fuel consumption, especially coal, with the obvious repercussions for the evolution of greenhouse gases, as shown in Figure 12. CO_2 emissions grow over the century, albeit at a declining rate, from the current 8 GtC to over 23 GtC per year in 2100. This marked increase is due especially to fast- growing and fossil fuel endowed non-OECD countries, especially China and India, but also the Middle East and the transition economies. China has a particularly important role, as it has been the main cause of the rapid surge of emissions experienced after the year 2000 (left panel). In the short-term, we foresee a period of emission growth consistent with the one recently occurred, and somewhat above the latest projections of the Energy Information Agency (EIA, 2008b).

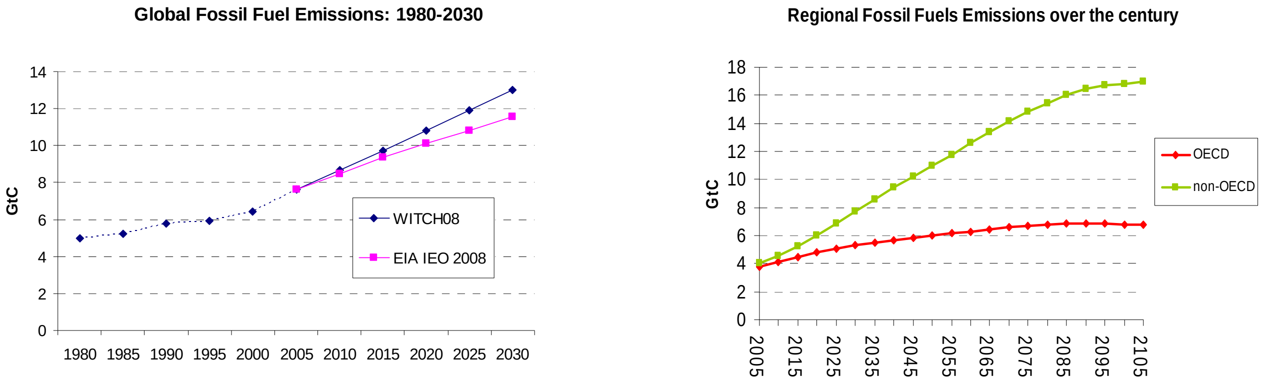


Figure 12: World CO_2 emissions from fossil fuel combustion

As far as the other GHGs are concerned, Figure 13 shows that CH_4 is the major non-CO_2 gas, followed by N_2O and then fluorinated gases. Total non-CO_2 GHG emissions increase and eventually stabilise in the second part of the century at around 5 GtCe (as opposed to about 23GtC from fossil fuel combustion).

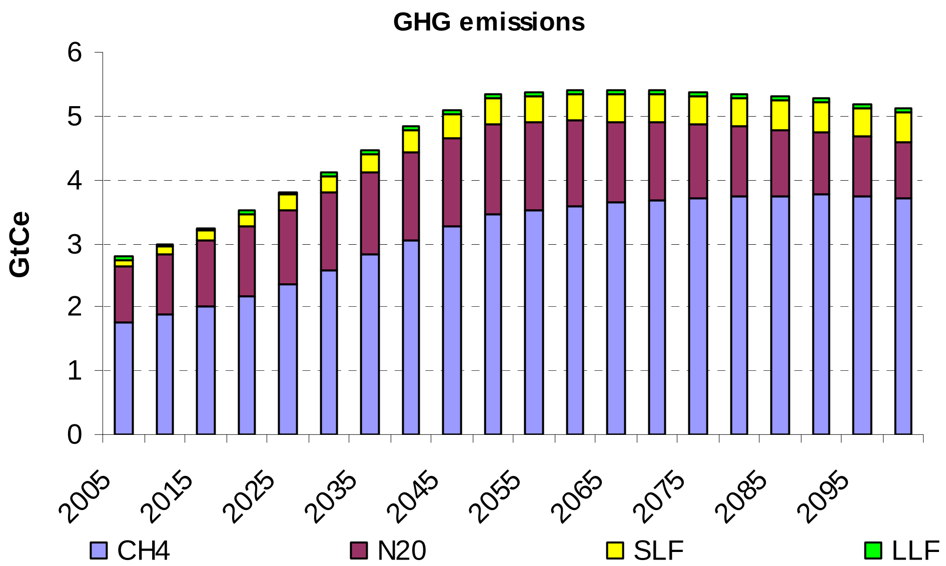


Figure 13: World emissions of non-CO_2 gases

Table 5 summarises the information regarding the regional contribution to world GHG emissions, at three different points in time. Non-OECD countries are the major emitters of all types of GHG emissions, especially CH_4, as a major source of methane is agriculture, the main economic activity in non-OECD countries.

The major contribution of OECD countries is in terms of fossil fuels CO_2 emissions. However, also for this greenhouse gas non-OECD countries account for the larger share of global emissions already from 2030, and the gap widens over time.

	Fossil fuels CO_2			CH_4			N_20		
	World (GtC)	OECD	non-OECD	World (GtCe)	OECD	non-OECD	World (GtCe)	OECD	Non-OECD
2030	13.01	40.7%	59.3%	2.57	14.4%	85.6%	1.23	22.0%	78.0%
2050	16.99	35.3%	64.7%	3.45	10.2%	89.8%	1.42	15.3%	84.7%
2100	23.60	28.7%	71.3%	3.71	8.0%	92.0%	0.88	14.1%	85.9%

Table 5: World GHG emissions and regional distribution

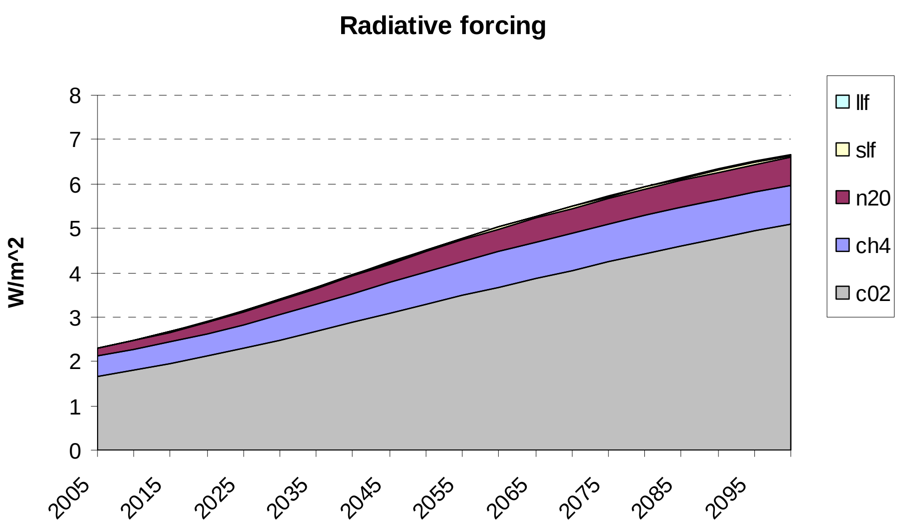


Figure 14: Radiative forcing of GHGs

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

Table 6: Temperature increase above pre-industrial levels

7.5. Climate variables

As shown in the last paragraph, the WITCH08 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 14 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-CO2 GHG emissions stabilise 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.

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 between GHG stocks and temperature increase, and could be considerably higher in the case that parameters such as climate sensitivity are higher than expected[21]. Leaving aside these uncertainties, according to IPCC 4th 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 realisation.

8. Conclusions

Climate change is a complex issue whose analysis requires models that are able to capture the international, intertemporal and strategic dimension of climate change. With this regard, the WITCH model can be considered a successful modelling tool.

WITCH08 improves several aspects of the first version WITCH06. Particular attention has been paid to improve the evolution of technological change in the energy sector. The possibility of investing in the commercialisation of innovative technologies is a desirable feature for models evaluating long-term scenarios. WITCH08 has broadened the set of technology options by including two backstop technologies, which can be thought of as a compact representation of technologies that have not yet been commercialised. Special attention is given to the international dimension of knowledge and experience diffusion.

The second important feature of WITCH08 is the inclusion of non-CO2 greenhouse gases. Other GHGs are important contributors to global warming and they offer additional mitigation options, increasing the model flexibility in responding to climate policies.

Reducing emissions from deforestation and degradation (REDD) offers another sizeable, low-cost abatement option. WITCH08 can include a new baseline projection of land use CO_2 emissions and estimates of the global potential and costs for reducing emissions from deforestation.

The base year data has been updated to 2005 and new data on economic growth, energy prices and technology costs have been used to re-calibrate the main exogenous drivers of the model, yielding an updated future socio-economic baseline scenario. The main differences of the new baseline scenario are driven by the upward revision of long-term world economic growth and mid-term international energy prices.

[21] For climate sensitivity, we assume a central value of 3.

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10. Appendix: equations and variables

This Appendix describes the main equations of the model. The complete list of variables is reported at the end. In each region, indexed by *n*, a social planner maximises 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-labour aggregate and energy services $ES(n,t)$ capital and labour 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:

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

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:

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

Labour 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:

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

The stock of knowledge evolves according to the perpetual rule:

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

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*:

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

The contribution of foreign knowledge to 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):

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

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

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

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

Capital for electricity production technology accumulates as follows:

$$K_j(n,t+1) = K_j(n,t)(1-\delta_j) + \frac{I_j(n,t)}{SC_j(n,t)} \quad \text{(A12)}$$

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:

$$SC_j(n,t+1) = B_j(n) \cdot \sum_n K_j(n,t)^{-\log_2 PR_j} \quad \text{(A13)}$$

Operation and maintenance are 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:

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

where Q_f is the cumulative extraction of fuel *f* :

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

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

$$X_f(n,t) = X_{f,extr}(n,t) + X_{f,netimp}(n,t) \quad \text{(A16)}$$

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

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

(A17)

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

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

(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:

$$CO_2(n,t) = \sum_f \omega_{f,CO_2} X_f(n,t) - CCS(n,t) \quad \text{(A19)}$$

The damage function impacting output varies with global temperature:

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

Temperature relative to pre-industrial levels increases through augmented radiating forcing *F(t)*, moderated by the cooling effects of SO_2 aerosol, $cool(t)$:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where *dec2* and *dec1* describes the yearly retention factor and the one period retention factor for non-CO_2 gases, respectively. 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

$□_C$ = investment in final good

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

$□_j$ = investment in technology j

O&M = investment in operation and maintenance

□*FP* = total factor productivity

$□_C$ = final good stock of capital

ES = energy services

□ = climate feedback

P_i^{int} = international fuels' 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

$□_j$= 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