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The WITCH Model. Structure, Baseline, Solutions.

Valentina Bosetti

Fondazione Eni Enrico Mattei and Climate Impacts and Policy Division, CMCC

Emanuela Massetti

Fondazione Eni Enrico Mattei and Climate Impacts and Policy Division, CMCC

Massimo Tavoni

Fondazione Eni Enrico Mattei and Climate Impacts and Policy Division, CMCC

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Summary

WITCH – World Induced Technical Change Hybrid – is a regionally disaggregated hard link hybrid global model with a neoclassical optimal growth structure (top down) and a detailed energy input component (bottom up). The model endogenously accounts for technological change, both through learning curves that affect the prices of new vintages of capital and through R&D investments. The model features the main economic and environmental policies in each world region as the outcome of a dynamic game. WITCH belongs to the class of Integrated Assessment Models as it possesses a climate module that feeds climate changes back into the economy. Although the model's main features are discussed elsewhere (Bosetti et al., 2006), here we provide a more thorough discussion of the model's structure and baseline projections, to describe the model in greater detail. We report detailed information on the evolution of energy demand, technology and CO2 emissions. We also explain the procedure used to calibrate the model parameters. This report is therefore meant to provide effective support to those who intending to use the WITCH model or interpret its results.

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

JEL Classification: O33, O41, Q43

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Address for correspondence:
Valentina Bosetti
Divisione CIP, CMCC and
Fondazione Eni Enrico Mattei
Corso Magenta, 63
I- 20123 Milano
E-mail: valentina.bosetti@feem.it

1. Introduction

Climate change is a long run global phenomenon. Its impacts are felt over a long time horizon, with different adverse geographical and sectoral effects. Climate change negatively affects the welfare of present and future generations. It is an uncertain phenomenon and its control is likely to be difficult and costly. Because no one really believes, or is ready to accept, that the solution to the climate change problem is to reduce the pace of economic growth, policy analyses have often focused on changes in technology that could bring about the long sought de-coupling of economic growth from the generation of polluting emissions. It is indeed widely recognized that without drastic technological change, particularly in energy technologies, it will be difficult to control the dynamics of climate change and its impacts on ecosystems and economic systems.

The development of economy-climate models to analyze as many issues as possible of those relevant to the overall climate change problem, is an essential pre-requisite for a thorough understanding of the problem. Models mimicking some of these complex and interdisciplinary relationships have been widely used in academic literature to analyze various issues in climate change economics. However, contemporaneously accounting for economic intercourse about different environmental policies while portraying activities related to the energy sector, changes in technology and the effects on the climate is a difficult task. A model of technology development, adoption and diffusion should also take into account the long run dimension of the climate change problem, the interdependence of the needs of present and future generations, the linkages and externalities between different geographical regions and economic sectors, the dynamics of investments and population, and the uncertainty pervading the climate change phenomenon and its effects. The ideal model would feature all the above aspects and should be computationally manageable. Unfortunately, this ideal model does not yet exist. Existing classes of models stress or describe in detail some but not all the above aspects. Generally speaking, economists pay special attention to the economic dimension of climate change in their top-down (TD) models, whereas system analysts or engineers focus on the technological dimension of the problem in their bottom-up (BU) models.

In Bosetti *et al.* (2006) we present a new model called WITCH (World Induced Technical Change Hybrid) designed to at least partly bridge the gap among model classes. WITCH is a top-down neoclassical optimal growth model with an energy input specification that operates as a bottom-up model. It is designed to analyze optimal climate mitigation strategies within a game-theoretical framework, while portraying the evolution of energy technologies with adequate detail and allowing for endogenous technological progress. It is a "hard link hybrid" model in the sense that the energy sector is contained within the economy: capital and resources for energy generation are therefore allocated optimally with respect to the whole economy. As such, WITCH is in a good position – at least in principle – to appropriately describe the dynamics of the relevant variables of the problem (investments in energy technologies, final good and R&D, direct consumption of fuels). An integrated climate module makes it possible to track changes in atmospheric CO_2 concentrations and world mean temperatures as a consequence of the use of fossil fuels and feeds a damage function which in turn delivers the effect of climate changes on the economy. Thus, it is appropriate to define WITCH as a Integrated Assessment Hard-Link Hybrid model. Finally, the model dynamic and game theoretical features allow us to account for both the time and geographical dimensions of climate change.

This technical report is presented as a companion to Bosetti *et al.* (2006) and provides a more thorough discussion of model structure, baseline projections and calibrated parameters. Within a macroeconomic growth context, we report detailed information on the evolution of energy demand, technology and CO_2 emissions. Our goal is to give a comprehensive overview of the model so as to provide effective support to those who intend to use the WITCH model or interpret its results.

The paper is structured as follows. In the next section we present a careful review of the structure of the model and of the solution algorithm. In section three we give an inclusive account of the calibration procedure and an explanation of some key assumptions. Section four outlines the evolution of energy patterns, technology choices and CO_2 emissions as delivered by our baseline scenario. A few concluding remarks are contained in section five.

2. Model Description

2.1 General Features

WITCH is a Ramsey-type neoclassical optimal growth hybrid model defined for 12 macro regions of the world, as shown in Figure 1. For each of these regions a central planner chooses the optimal time paths of the control variables – investments in different capital stocks, in R&D, in energy technologies and consumption of fossil fuels – so as to maximize welfare, defined as the regional present value of log per capita consumption.[1] WITCH is a truly dynamic model in the sense that at each time step forward-looking agents simultaneously and strategically maximize with respect to the other decision makers. Therefore, the dynamic profile of optimal investments in different technologies is one of the outcomes of the model. These investment strategies are optimized by

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[1] Population is exogenous to the model. The full list of model equations together with the list of the model's variables can be found in the Appendix.

taking into account both economic and environmental externalities. The investment profile for each technology is the solution of an inter-temporal game between the 12 regions. More specifically, these 12 regions behave strategically with respect to all decision variables by playing an open-loop Nash game. From a top-down perspective this enables us to analyze both the geographical dimension (e.g. rich vs. poor regions) and the time dimension (e.g. present vs. future generations) of climate policy. All regions determine their optimal strategies by maximizing social welfare, while taking climate damage into account through feedback from an integrated climate module.

Optimization growth models are usually very limited in terms of technological detail. This severely constrains the analysis of climate change issues, which are closely related to the evolution of energy sector technologies. In WITCH this component is considerably richer in information than in most macro-growth models. It separates electric and non-electric uses of energy, features seven power generation technologies and includes the use of multiple fuels: oil, natural gas, coal, uranium, traditional biomass and biofuels. This kind of detail in the energy sector – although still much simpler than that of large scale energy system models – is a novelty for this class of models and enables us to reasonably portray future energy and technological scenarios and to assess their compatibility with the goal of stabilizing greenhouse gas concentrations. Also, by endogenously modelling fuel prices, as well as the cost of storing the captured CO_2, we are able to evaluate the implications of mitigation policies for all the components of the energy system.

Following recent research in climate modelling (see, for example, the 2006 special issue of the Energy Journal on the IMCP Project), technical change in WITCH is endogenous and can be induced by climate policy, international spillovers and other economic effects. Traditionally, BU models have modelled technological change through Learning-by-Doing, while TD ones have focused on investment in R&D, often reaching different conclusions (Clarke and Weyant, 2002). The hybrid nature of WITCH helps us to reconcile these distinct views. In the bottom up part of the model we encompass the Learning-by-Doing effects by bringing in experience curves for all energy technologies, while in the top down part we account for the accumulation of knowledge (via R&D) and for its effects on energy efficiency and the cost of advanced biofuels.

In comparison to other optimal growth models, WITCH shares a game-theoretic set-up with RICE (Nordhaus and Boyer, 2000), but departs from its stylized representation of the energy sector by working with richer technological detail, endogenous technical change, and natural resource depletion. MERGE (Manne *et al.* 1995) links a simple top-down model to a bottom-up component that returns the cost of energy; in contrast, WITCH is a single model that represents the energy sector within the economy, and therefore chooses the energy technology investment paths coherently with the optimal growth structure. Also, WITCH features a non-cooperative game among the regions. With respect to MIND (Edenhofer *et al.* 2005) – an optimal growth model with an energy component – WITCH takes advantage of richer technological detail, distinguishes between electric and non-electric energy uses and has a multi-region setup.

The model is solved numerically in GAMS/CONOPT for 30 5-year periods, although only 20 are retained as we do not impose terminal conditions. Solution time for the Baseline scenario is approximately 30 minutes on a standard Pentium PC. The code is available from the authors upon request.

2.2 Model Structure

Output is produced by aggregating factors via nested Constant Elasticity of Substitution (CES) functions as shown in Figure 2. Elasticity of substitution values are also reported. In particular, final good production *Y* of region *n* at time *t* is obtained by combining a Cobb-Douglas bundle of capital accumulated for final good production K_C and labour *L* with energy services *ES* in the following way:

$$Y(n,t) = \frac{TFP(n,t)\left[\alpha(n)\cdot\left(K_C^{\,1-\beta(n)}(n,t)L^{\beta(n)}(n,t)\right)^{\rho} + (1-\alpha(n))\cdot ES(n,t)^{\rho}\right]^{1/\rho}}{\Omega(n,t)} \tag{1}$$

where *TFP* represents total factor productivity which evolves exogenously over time and *Ω* is the damage that accounts for the feedback of temperature rise on production. Consumption of the single final good *C* is obtained via the economy budget constraint:

$$\begin{aligned} C(n,t) = {} & Y(n,t) - I_C(n,t) - \sum\nolimits_j I_{R\&D,j}(n,t) - \sum\nolimits_j I_j(n,t) - \sum\nolimits_j O\&M_j(n,t) \\ & - \sum\nolimits_f \left(P_f(n,t)\, X_{f,extr}(n,t) + P_f^{\text{int}}(t) X_{f,netimp}(n,t)\right) \\ & - P_{CCS}(n,t)CCS(n,t) \end{aligned} \tag{2}$$

i.e., from output *Y* we subtract investment in final good I_C , in energy R&Ds and in each energy technology – labelled by *j* – as well as expenditure for Operation and Maintenance, denoted with *O&M*. Expenditure on fuels – indexed by *f* – enter either as extraction costs, $X_{f,extr}$, or as net imports, $X_{f,imp}$. In particular if a country is a net oil exporter, this latter variable is negative and measures revenues from fuels exports. Finally, the cost of transporting and storing the captured CO_2

is deducted. The latter is endogenous and depends on the quantity captured and injected in each region.

The use of fossil fuels generates CO_2 emissions, which are computed by applying stoichiometric coefficients to energy use. The quantity of carbon captured with carbon-capture and sequestration (CCS) technologies is subtracted from the carbon balance. Emissions are fed into a stylized three-box climate module (the dynamics of this module is described in Nordhaus and Boyer, 2000) which yields the magnitude of temperature increases relative to pre-industrial levels. The increase in temperature creates a wedge between gross and net output of climate change effects through the region-specific quadratic damage function Ω.

2.3 Non-cooperative Solution

In WITCH policy decisions adopted in one region of the world affect what goes on in all the other regions. This implies that the equilibrium of the model, i.e. the optimal inter-temporal investment profiles, R&D strategies and direct consumption of natural resources, must be computed by solving a dynamic game. World regions interact through five channels.

First, at each time period, the prices of oil, coal, gas and uranium depend on the consumption in all regions of the world. Thus, investment decisions, consumption choices and R&D investment in any country at any time period indirectly affect all other countries' choices. Consider, for example, the impact of a massive reduction of oil consumption in the USA and in Europe alone, possibly stimulated by policies that promote the deployment of biofuels. The resulting lower oil prices would modify energy demand in the rest of the world, probably stimulating higher emissions that would reduce the innovative actions of first movers. We thus describe rebound effects not only inside a region but also across regions. Second, at any time period, CO_2 emissions from each region change the average world temperature and this affects the shadow value of carbon emissions in all other regions. Third, investment decisions in each electricity generation technology in each country at each time, affect other regions by changing the cumulative world installed capacity which in turns affects investment costs via Learning-by-Doing. The fourth channel of interaction derives from the international R&D spillovers that affect the costs of advanced biofuels. Finally, the fifth channel is at work if the model is used to analyze the effects of emissions trading. With an active emission permits market, regions interact via this channel. Marginal abatement costs are equalized across regions, with all the obvious consequences for R&D efforts and investment choices.

WITCH incorporates these channels of interaction to characterize the interdependency of all countries' climate, energy and technology policies. We model the interactions among world regions as a non-cooperative Nash game, which is solved recursively and yields an Open Loop Nash

Equilibrium. The solution algorithm works as follows. At each new iteration, the social planner in every region takes the behaviour of other players produced by the previous iteration as given and sets the optimal value of all choice variables; this newly computed level of variables is stored and then fed to the next round of optimizations. The process is iterated until each region's behaviour converges in the sense that each region's choice is the best response to all other regions' best responses to its behaviour. Convergence is rather fast (around fifty iterations) and the uniqueness of the solution has been tested using alternative starting conditions. The way in which the algorithm is constructed makes the solution invariant to different orderings of the regions.

2.4 Energy Sector

Figure 2 provides a diagrammatic description of the structure of the energy sector in WITCH and identifies the main technologies for the production of electric and non electric energy.

Energy services *ES*, an input of (1), combines energy with a variable, *HE*, that represents technological advances stemming from investment in energy R&D for improvements in energy efficiency. As in Popp (2004), an increase in energy R&D efforts improves the efficiency with which energy, *EN*, is translated into energy services, *ES* (e.g. more efficient car engines, trains, technical equipment or light bulbs).

EN is an aggregate of electric, *EL*, and non-electric energy, *NEL*. Contrary to what is specified in other top-down growth models – such as DEMETER (Gerlagh and van der Zwaan, 2004) and MIND (Edenhofer *et al.* 2005) – in WITCH energy demand is not exclusively defined by electricity consumption. We believe this is an important distinction as reducing emissions is traditionally more challenging in the non-electric sector, and its neglect would seriously over-estimate the potential GHG control achievements.

Non-electric energy is obtained by linearly adding coal and traditional biomass and an oil-gas-biofuels *(OGB)* aggregate. The use of coal in non-electric energy production *(COALnel)* is quite small and limited to a few world regions, and is thus assumed to decrease exogenously over time in the same fashion as traditional biomass (*TradBiom*). The oil-gas-biofuels aggregate combines oil *(OILnel*), biofuels (*Biofuels*) and natural gas (*GASnel*) sources. In WITCH, ethanol is produced from sugar cane, wheat or corn (*Trad Biofuel*), or from cellulosic rich biomass (*Advanced Biofuel*).[2] The two different qualities of ethanol add up linearly so that only the cheaper one is used.

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[2] Cellulosic feedstock comprises agricultural wastes (wheat straw, corn stover, rice straw and bagasse), forest residue (underutilized wood and logging residues, dead wood, excess saplings and small trees), energy crops (fast growing trees, shrubs, grasses such hybrid poplars, willows and switchgrass). For a description of the cellulosic ethanol production see IEA (2004b).

As for the use of energy for electricity production, nuclear power (*ELNUKE*) and renewable sources in the form of wind turbines and photovoltaic panels (*ELW&S*) are combined with fossil fuel-based electricity (*ELFF*), the output of thermoelectric plants using coal, oil and natural gas (*ELCOAL*, *ELOIL* and *ELGAS*). In this way, we are able to distinguish more interchangeable power generation technologies, such as the fossil-fuelled ones, from the others. Coal-based electricity is obtained by the linear aggregation of traditional pulverized coal technologies *(ELPC)* and integrated gasification combined cycle production with CCS *(ELIGCC).* Hydroelectric power (*ELHYDRO*) is added to the total electric composite; because of its constrained deployment due to limited site availability, we assume that it evolves exogenously, in accordance with full resource exploitation.

One might note that by using a CES function we aggregate the various forms of energy in a non-linear way. This kind of aggregation is commonly used in economic models, to represent a less than infinite substitutability among factors: moving away from an established energy mix costs more than it would in a least cost minimization framework. This is also in agreement with econometric studies on inter-fuel substitution, which find little connection between energy consumption and own and cross energy prices. CES function bundling allows for contemporaneous investments in different technologies which conform to base-year calibrated factor shares and chosen elasticity of substitution, in contrast to linear aggregation where exogenous constraints on single (or a combination of) technologies are needed to return a portfolio of several investments. Finally, one should keep in mind that in economic models such as WITCH energy itself is an intermediate input, an aggregation of factors of production (capital, resources etc).

For each technology *j* (wind and solar, hydroelectric, nuclear, traditional coal, integrated gasification combined cycle (IGCC) with CCS, oil and gas) at time *t* and in each region *n*, electricity is obtained by combining three factors in fixed proportions: (i) the installed power generation capacity (*K*) measured in power capacity units, (ii) operation and maintenance equipment (*O&M*) in final good units and (iii) fuel resource consumption (*X*) expressed in energy units, where appropriate. The resulting Leontief technology is as follows:

$$EL_j(n,t) = \min\{\mu_{n,j} K_j(n,t)\,; \tau_{n,j} O\&M_j(n,t); \varsigma_j X_{j,EL}(n,t)\} \qquad (3)$$

The parameters governing the production function take into account the technical features of each power production technology. Thus μ translates power capacity into electricity generation (i.e. from TW to TWh) through a plant utilization rate (hours per year) which allows us to take into consideration the fact that some technologies - noticeably new renewables such as wind and solar power - are penalized by comparatively lower utilization factors; τ differentiates operation and maintenance costs among technologies, i.e. nuclear power is more expensive to run and maintain than a natural gas combined cycle (NGCC); finally, ς measures (the reciprocal of) power plant fuel efficiencies and yields the quantity of fuels needed to produce a KWh of electricity. *ELHYDRO* and *ELW&S* are assumed to have efficiency equal to one, as they do not consume any fuel: the production process thus reduces to a two-factor Leontief production function.

It is important to stress the fact that power generation capacity is not equivalent to cumulated investment in that specific technology, as different plants have different investment costs in terms of final output. That is:

$$K_j(n,t+1) = K_j(n,t)\left(1-\delta_j\right) + \frac{I_j(n,t)}{SC_j(n,t)} \tag{4}$$

where δ_j is the rate of depreciation and SC_j is the final good cost of installing power generation capacity of type j, which is time and region-specific. It is worth noting that depreciation rates δ_j are set consistently with the power plants' lifetime, so that again we are able to take into account the technical specifications of each different electricity production technology.

In WITCH the cost of electricity generation is endogenously determined. WITCH calculates the cost of electricity generation as the sum of the cost of capital invested in plants and the expenditures for O&M and fuels. Since the cost of capital is equal to its marginal product, as capital is accumulated capital-intensive electricity generation technologies, such as nuclear or wind and solar, become more and more preferable to variable cost-intensive ones such as gas. Indeed, whereas at the beginning of the optimization period regions with high interest rates – such as the developing ones – disfavour capital-intensive power generation technologies, in the long run the model tends to prefer capital-intensive to fuel-intensive electricity production. Note that this feature is not shared by energy system models, as they are not able to ensure capital market equilibrium (see Bauer, 2005). Since investment costs, O&M costs, fuel efficiency for each technology and fuel prices are region-specific, we obtain a high degree of realism in constructing relative prices of different ways of producing electricity in the 12 regions considered.[3]

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[3] To our knowledge, the endogenous determination of electricity prices is a novelty in optimal growth integrated assessment models.

2.5 Exhaustible Resources

Four non renewable fuels are considered in the model – coal, crude oil, natural gas and uranium - whose cost follows a long-term trend that reflects their exhaustibility. We abstract from short-term fluctuations and model the time path of the resource *f* price starting from a reduced-form cost function that allows for non-linearity in the ratio of cumulative extraction to available resources.[4] Initial resource stocks are region specific and so are extraction cost curves. Thus, for each fuel *f* we have:

$$c_f(n,t) = q_f(n,t)\left(\chi_f(n) + \pi_f(n)\left[Q_f(n,t-1)/\overline{Q}_f(n,t)\right]^{\psi_f(n)}\right) \tag{5}$$

where *c* is the regional cost of resource *f*, depending on current extraction q_f as well as on cumulative extraction Q_f and on a region-specific markup, $\chi_f(n)$; $\overline{Q}_f$ is the amount of total resources at time *t* and $\pi_f(n)$ measures the relative importance of the depletion effect.[5] Assuming competitive markets, the regional price $P_f(n,t)$ is equal to the marginal cost:

$$\begin{gathered} P_f(n,t) = \chi_f(n) + \pi_f(n)\left[Q_f(n,t-1)/\overline{Q}_f(n,t)\right]^{\psi_f(n)} \\ Q_f(n,t-1) = Q_f(n,0) + \sum_0^{t-1} X_{f,extr}(n,s) \end{gathered} \tag{6}$$

The second expression represents cumulative extraction and $X_{f,extr}(n,t)$ is the amount of fuel *f* extracted in region *n* at time *t*. Fuels are traded among regions at an international market clearing price $P_f^{\text{int}}(t)$. Each region can thus opt for autarky or trade in the market, either as a net buyer or a net seller of fuels. The net import of fuels $X_{f,netimp}(n,t)$ takes on positive values when the region trades as a net buyer, and negative values when it trades as a net seller.[6]

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[4] Hansen, Epple and Roberds (1985) use a similar cost function that allows for non-linearity also in the rate of extraction.

[5] See Section 3 for more details.

[6] The results presented in this paper are obtained using a simplified version of the model where fuel trade is not endogenous; it simply keeps track of exogenously determined fuel trading and feeds it into the budget constraint. This "accounting" mechanism is more computationally tractable and, at the same time allows us to keep track of welfare effects due to trade in resources.

2.6 CO_2 Emissions

Since WITCH offers the possibility of tracking the consumption of fossil fuels, GHGs emissions that originate from their combustion are derived by applying the corresponding stoichiometric coefficients to total consumption. Even though we presently use a climate module that responds only to CO_2 emissions, a multi-gas climate module can easily be incorporated in WITCH thus allowing the introduction of gas-specific emissions ceilings.[7] For each region *n*, CO_2 emissions from the combustion of fossil fuels are derived as follows:

$$CO_2(n,t) = \sum_f \omega_{f,CO_2} X_f(n,t) - CCS(n,t) \tag{7}$$

where ω_{f,CO_2} is the stoichiometric coefficient for CO_2 emissions of fuel *f* and CCS stands for the amount of CO_2 captured and sequestered while producing electricity in the coal IGCC power plant. The stoichiometric coefficient is assumed to be positive for traditional biofuels and negative for advanced biofuels, in line with IEA (2004b). As noted above, when analyzing climate policy, regions and/or countries may be allowed to trade their emissions allowances in a global or regional carbon market.

Finally, WITCH's climate module delivers emissions from land use change that are added to emissions from combustion of fossil fuels to determine atmospheric concentrations as in Nordhaus and Boyer (2000).

2.7 Endogenous Technical Change

In WITCH, technical change is endogenous and is driven both by Learning-by-Doing (LbD) effects and by energy R&D investments. These two factors of technological improvements act through two different channels: LbD is specific to the power generation industry, while R&D affects the non-electric sector and the overall system energy efficiency.

By incorporating LbD effects in electricity generation, we are able to reproduce the observed empirical relation according to which the investment cost of a given technology decreases with the accumulation of installed capacity. This representation has proven important in areas such as the renewable energy sector where, for example, the installation costs of wind turbines have steadily declined at a constant rate. Learning rates depend on a variety of factors and vary considerably

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[7] As in Nordhaus and Boyer (2000) we take into account GHGs emissions other than CO_2 by including an exogenous radiative forcing when computing temperature deviations from pre-industrial levels. Thus, when we simulate GHG stabilization policies we consider this additional component and accordingly constrain CO_2 emissions to a global target.

across countries. In our framework we use world learning curves, where investment costs decline with the world installed capacity. In other words, we assume perfect technology spillovers and constant learning rates across countries, which is reasonable considering that any time step in the model corresponds to five years.[8]

In the description of learning curves, the cumulative (installed) world capacity is used as a proxy for the accrual of knowledge that affects the investment cost of a given technology *j*:

$$SC_j(n,t+1) = B_j(n) \cdot \sum_n K_j^*(n,t)^{-\log_2 PR_j} \tag{8}$$

where *PR* is the progress ratio that defines the speed of learning and K_j^* is the cumulative installed capacity in technology *j* (i.e. power generation capacity gross of depreciation). With every doubling of cumulative capacity the ratio of the new investment cost to its original value is constant and equal to *PR*, until a fixed floor level is reached. With several electricity production technologies, the model is flexibile enough to change the power production mix and invest in the more appropriate technology for each given policy measure, thus creating the conditions to foster the LbD effects associated with the clean but yet too pricey electricity production techniques.

We also model endogenous technical change through investments in energy R&D which serve different purposes. First, they increase energy efficiency. Following Popp (2004), technological advances are captured by a stock of knowledge combined with energy in a constant elasticity of substitution (CES) function, thus stimulating energy efficiency improvements:

$$ES(n,t) = \left[\alpha_H HE(n,t)^\rho + \alpha_{EN} EN(n,t)^\rho\right]^{1/\rho} \tag{9}$$

The stock of knowledge $HE(n,t)$ derives from energy R&D investments in each region through an innovation possibility frontier characterized by diminishing returns to research, a formulation proposed by Jones (1995) and empirically supported by Popp (2002) for energy-efficient innovations:

$$HE(n,t+1) = aI_{R\&D}(n,t)^b HE(n,t)^c + HE(n,t)(1-\delta_{R\&D}), \tag{10}$$

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[8] At the present stage of the model's development we have introduced learning effects only in wind and solar technologies.

with $\delta_{R\&D}$ being the depreciation rate of knowledge. As social returns from R&D are found to be higher than private ones in the case of energy R&D, the positive externality of knowledge creation is accounted for by assuming that the return on energy R&D investment is four times higher than the one on physical capital. At the same time, the opportunity cost of crowding out other forms of R&D is obtained by subtracting four dollars of private investment from the physical capital stock for each dollar of R&D crowded out by energy R&D, $\psi_{R\&D}$, so that the net capital stock for final good production becomes:

$$K_C(n,t+1) = K_C(n,t)(1-\delta_C)+(I_C(n,t)-4\psi_{R\&D}I_{R\&D}(n,t)) \tag{11}$$

where δ_C is the depreciation rate of the physical capital stock. We assume new energy R&D crowds out 50% of other R&D, as in Popp (2004). This way of capturing innovation market failures was also suggested by Nordhaus (2003).

A second set of energy R&D investments are devoted to lowering the costs of advanced biofuels. Conditional to research efforts, their cost may become lower than that of currently used fuels.

The cost of the cellulosic biofuels, $P_{ADVBIO}(n,t)$, is modelled as a decreasing function of investment in dedicated R&D via a power formulation:

$$P_{ADVBIO}(n,t)=P_{ADVBIO}(n,0)\left[TOT_{R\&D,ADVBIO}(n,t)\right]^{-\eta} \tag{12}$$

where η stands for the relationship between new knowledge and cost and:

$$TOT_{R\&D,ADVBIO}(n,t)=\sum_{n}K_{R\&D,ADVBIO}(n,t-2)+\sum_{\tau=t-1}^{t}I_{R\&D,ADVBIO}(n,\tau) \tag{13}$$

This represents the world R&D expenditure for advanced biofuels cumulated up to period *t-2,* to which only country *n*'s R&D investments from the two preceding periods are added. We thus assume that the effects of any region-cumulated R&D will influence other regions with a 10-year (2 model periods) delay. The time lag is meant to account for the advantage of first movers in innovation, thus introducing an incentive to R&D investments that reduces the usual free-riding incentives that derive from the positive externalities produced by R&D.

3. Base Year Calibration

This section carefully describes model calibration and the underlying assumptions. We comment on the assumptions concerning the dynamics and specific aspects of energy demand in the next section, where we illustrate the baseline.

The base year of calibration is 2002 for which we replicate GDP, energy demand, population, emissions and factor prices. Prices are expressed in constant 1995 USD. The basic input data are energy consumption and prices obtained from ENERDATA (2004, 2005) and IEA (2004a), output and population, adapted from the World Bank (2004) and the Common POLES IMAGE (CPI) baseline (van Vuuren *et al.* 2004), respectively.

Figure 1 illustrates how world countries have been grouped in 12 macro regions. We have grouped countries so as to maximize economic, geographic, resource endowment and energy supply homogeneity and to isolate major global players. The result is a rather standard classification with two special cases. South Africa has been separated from Sub-Saharan African countries because of its heavy reliance on coal use in its total primary energy supply — a unique case in this continent where coal is scarcely used — and because of strong differences in energy intensity, GDP per capita and other key economic and energy variables; energy supply and resource endowment are actually very similar to Australia's, another big coal-country. Despite evident economic differences between the two countries we have given priority to energy supply similarities and decided to grouped them; South Korea was added to this group (KOSAU), again because of heavy coal use and relatively high per capita income with respect to other neighbouring countries. Canada, Japan and New Zealand have been grouped mainly for similarities in income per capita. We recognize that a more disaggregated classification would better capture regional disparities but this would come at the cost of a more onerous calibration procedure and computational difficulties. We sometimes refer to the group of countries constituted by USA, OLDEUROPE, NEWEUROPE, KOSAU and CAJANZ as "rich" countries, the remaining ones being "poor" countries.

The values for elasticities of substitution for the CES production functions and other key parameters have been chosen on the basis of the existing empirical and modelling literature as detailed below. To calibrate the remaining parameters (factor shares and productivities) of the CES functions, we have computed the first order conditions with respect to all the choice variables and equated all the marginal products to their prices. This is crucially important to avoid "jumps" in the first optimization steps. Euler equations allowed us to calculate the prices of intermediate nests. This yields a system of 40 non-linear simultaneous equations that are solved with GAMS.

Final good is produced by aggregating a composite input made up of capital, labour and energy in a CES function with an elasticity of substitution equal to 0.5. This choice is in line with models that aggregate capital, labour and energy analogously: Manne *et al.* (1990) set the elasticity of substitution between the capital-labour and energy inputs at 0.4 for OECD countries and at 0.3 elsewhere; Whalley and Wigle (1990) set it equal to 0.5.

A survey of econometric estimates conducted by Burniaux *et al.* (1991) shows that capital-labour elasticities of substitution range from 0.5 and 1.5 in the USA, and between 0.5 and 0.7 in Europe and in the Pacific. We have chosen an elasticity of substitution equal to 1, which corresponds to a Cobb-Douglas aggregation of capital and labour; returns to scale are assumed to be constant.

The value of capital in the base year is calibrated so that its marginal product equates the gross interest rate, i.e. the prevailing interest rate in the economy plus the depreciation rate. The Cobb-Douglas exponent associated to the labour input is calibrated so that the labour share of gross output is equal to 0.7 in all regions. This choice is in contradiction with data from the United Nations National Account Statistics (1992), which show a high degree of variance among labour income shares across countries, ranging from 0.05 in Ghana to 0.77 in Ukraine, but it is in line with the interval between 0.65 and 0.8 computed by Gollin (2002) after correcting national statistics for income from self-employment. Across time, the labour income share has proven to be fairly constant, ranging from 0.65 to 0.7 in the United States and the United Kingdom since 1935 (U.S. Department of Commerce, 1986, 1990).

We calibrate energy R&D as in Popp (2004). Parameters of the CES function between energy and knowledge and of the innovation possibility frontier are chosen so as to be consistent with historical levels, to reproduce the elasticity of energy R&D with energy prices and to achieve a return four times the one of physical capital, thus taking into account the positive externality of knowledge creation.

The elasticity of substitution values for the energy sector are reported in Figure 2. Electric and non-electric energies are aggregated using an elasticity of 0.5. Econometric estimates of the elasticity of substitution between non-electric and electric energy are normally higher than the one we assume here. This is due to the fact that - as noted in Burniaux et al. (1991) - econometric analyses are frequently based on the assumption that energy and capital are weak substitutes in production. Firms first choose an optimal energy mix and then combine it with capital, assuming implicitly that multi energy technologies are available. Although possibilities for switching from direct energy to electricity exist in many sectors good examples are home heating and cooking systems - lock in investments from the past and large up-front costs reduce the substitutability between the two forms of energy. Other economic models generally use higher values: in an updated version of GREEN, Lee et al. (1994) choose 0.25 and 2 respectively for short term and long term elasticity of substitution between non electric energy and electricity. Babiker et al. (1997) choose an even higher value for short term elasticity, equal to 1.

As for the nonelectric energy nest, we have chosen an elasticity value of 0.5 when combining oil, biofuels and gas following Dahl (1993) in part. Coal is added linearly and is set exogenous, as its small share is expected to decline further in the next decades (IEA, 2004a).

For aggregating thermal electricity generation we use an elasticity of 2. This value best reflects the latest empirical estimates in the literature. Ko and Dahl (2001) and Soderholm (1998) summarize the econometric studies on inter-fuel substitution in fossil fuel powered generation: although results display considerable variability and the functional forms employed allow for greater flexibility than the CES does — i.e. elasticity values are allowed to vary between factors —the elasticity values of cross and own prices imply a substitution in the range of 1 to 3. GREEN, a global dynamic AGE model produced by the OECD uses an elasticity of substitution between energy inputs aggregated in a CES function equal to 0.25 and 2 for old and new capital respectively. We have chosen an intermediate value. As for the substitution between nuclear power, wind and solar and fossil fuel thermoelectricity, empirical evidence is lacking. We have assumed a value of 2 which allows for the complete displacement of any technology, though at a cost higher than the one in the linear aggregation. This way the electricity produced via different technologies is assumed to be substitutable, although imperfectly. Hydroelectric power is linearly added and is assumed to evolve exogenously. CES functions' elasticity of substitution values are set equal across all regions. Even if we recognize that this is a weak approximation of reality, to our knowledge there is neither empirical evidence nor enough confidence in expert judgment for most of the non-OECD countries, which makes it a challenging and risky endeavour to differentiate among regions.

At the bottom of the electricity sector we have electricity produced by aggregating power generation capacity, fuels and expenditure for 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 taken from NEA/IEA (1998, 2005), and are constant across regions and across time (see Table 1). Costs for new investments and maintenance in power generation (see Table 1) are our calculation from data contained in NEA/IEA (1998, 2005) and are different across world regions.

Investment costs decline with cumulated installed capacity at the rate set by the learning curve progress ratios. For the technology specification currently represented in the model, we have assumed that learning occurs for wind and solar electricity generation only, at the progress ratio of 0.87 — i.e. there is a 13% investment cost decrease for each doubling of world installed capacity.

Carbon transport and storage costs are region-specific and increase with the cumulative capture of CO_2. Hendriks (2002) provides regional cost curves for carbon dioxide transport and storage: we have fitted its estimates to each region using an exponential function form. The CO_2 capture rate is set at 90%. No after-storage leakage is considered.

As for the non-electric energy nest, we have chosen an elasticity of 0.5 when combining oil, biofuels and gas following Dahl (1993) in part. Coal is added linearly and is set exogenous, as its small share is expected to further decline in the next decades, IEA (2004a). Babiker *et al.* (1997) have chosen a higher value, equal to 1, while Lee *et al.* (1994) use an elasticity of substitution of 0.25 in the short run and 2 in the long run.

Traditional biomass is used only in SSA, SASIA, CHINA, EASIA and LACA and it evolves exogenously over the century. Traditional biomass is not traded in the market and thus its price is equal to zero, with the cost measured by the shadow value of the time consumed in collecting raw materials. Since the calorific content of traditional biomass is low and the shadow value of time increases as economic growth proceeds, we use a negative relationship between income per capita and traditional biomass share over total energy supply to derive an exogenous demand path over the century. This relationship was estimated starting from data in IEA (2004a). For calibration purposes we set the cost of biomass slightly above zero and we keep it constant.

Biofuels consumption is currently low in all regions of the world. By far the biggest producers are Brazil and the United States. However, even in the United States biofuels cover only 2% of transport fuel; only Brazil has succeeded in substituting a considerable share of traditional fuels -30%- with ethanol from sugar cane (IEA, 2004b). In WITCH we distinguish between ethanol, which we label as "traditional biofuels", and "advanced biofuels", which are obtained from biomass transformation. They add up linearly so that only the less expensive source is employed. At present there is no industrial production of ethanol from cellulosic feedstock and the projected costs are far higher than for other traditional biofuels. However, IEA (2004b) shows that it is reasonable to expect an appreciable reduction of production costs in the near future so as to make the use of biofuels derived from advanced biomass a realistic option in the next two decades. For this reason we have introduced the possibility of specific R&D investment aimed at reducing advanced biofuel production cost. The learning parameter η that governs the speed at which costs decrease as investment in R&D cumulates is set equal to 0.1, which corresponds to a learning factor of 7%.

We assume that currently employed biofuels consist only of ethanol for two main reasons: (1) biodiesel is only produced and consumed in Europe, in very modest amounts and its share of global biofuel production will decline over the next few decades because (2) ethanol performs better than biodiesel in terms of CO_2 emissions, vehicle performance, transformation efficiency and agricultural production potential (IEA, 2004b). Biofuels were set at 1.4% of oil demand in USA, 10% in LACA, and 1% in EUROPE and NEWEUROPE. When data were not available we set biofuel consumption at 0.5% of transport fuel demand; MENA uses an even lower proportion, equal to 0.1%. Biofuel cost is set constant over the simulation time frame because sugar cane- wheat-ethanol production costs are not expected to decline in an appreciable way. Biofuels cost 0.32 cUSD and 0.17 cUSD per litre in USA and LACA, respectively, or 0.48 cUSD and 0.26 cUSD per gasoline equivalent litre. Other industrialized regions have the same costs as USA and other developing regions have a price that is an average between USA and LACA prices. Ethanol from cellulosic feedstock initially costs 0.40 cUSD per litre which corresponds to 59 cUSD per gasoline litre equivalent.[9]

Capital invested in final good and R&D depreciate at a rate of 10% and 5% per year respectively. Depreciation of investments in electricity production is set in agreement with plant lifetimes — see Table 1 — assuming that the end-life capital value is 10%. Interest rates on capital are initially set at 0.05 for industrialized regions (USA, OLDEURO, NEWEURO, KOSAU, CAJANZ) and at 0.07 for the others.

The climate module is adapted from Nordhaus and Boyer (2000). Figures have been adjusted for the different time step length and initial base year. Population is exogenous and follows the Common POLES IMAGE (CPI) baseline (van Vuuren *et al.* 2005), see Table 2 for more details. The inter-temporal discount rate is from Nordhaus and Boyer (2000), set equal to 3% in the base year, it declines at a constant rate of 0.25% per year. Total factor productivity is assumed to grow exogenously over time to reflect technological progress and all the other structural changes that are difficult to represent in a simplified Ramsey-type growth framework, especially in the case of developing countries. The exponential trend is calibrated to fit the output projection underlying the Common POLES IMAGE (CPI) baseline (van Vuuren *et al.* 2005).

We calibrate endogenous international extraction cost functions for coal, crude oil, natural gas and uranium ore.[10] We add two different mark-ups: the first is for differentiating between fuels used for electricity generation and fuels used for direct consumption, the second is for explaining regional differences in the price of natural resources. The international price of oil in 2002 was set at 20.9 USD per Barrel. We set total ultimately recoverable resources in 2002 equal to 3,345 billion barrels,

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[9] Costs are taken from IEA (2004b), which offers a thorough treatment of biofuels for transport.

[10] At the present stage of development region specific extraction cost curves have not yet been calibrated. Data on reserves and resources, as well as on production, consumption and net imports of oil and gas have been collected from ENERDATA (2005). The international trade of fuels has been tested on pseudo-curves and performs well. Currently, we are working to reproduce present data on the international trade of oil and gas with realistic dynamics.

as in IEA (2004a);[11] resource growth rate is 2.65% per year in 2002 and then declines, stabilizing at about 0.8% by the end of the century. By allowing that total resources not be finite, we stabilize prices of oil in the long run. The cumulative extraction component is assumed to be cubic, and scarcity becomes relevant when cumulative consumption reaches 2/3 of available resources at any point in time. The marginal extraction cost $\chi_{j,n}$ is set equal to 15.8 USD per barrel and is constant over time.

The coal extraction cost function is calibrated similarly. Total ultimately recoverable resources in 2002 are 16,907 billion tonnes, a figure obtained by combining data from IEA (2004a) and ENERDATA (2004). The cumulative extraction component is quadratic and scarcity becomes relevant when 3/4 of current resources have been depleted; resources grow at a constant exogenous rate of 0.1 % per year. We use a base year international price of 35 USD per tonne of coal.

Natural gas resources in 2002 are assumed to be equal to 405,944 billion cubic meters as in USGS (2000); resource growth rate is 11% per year in 2002 and then it declines, stabilizing at about 1% by the end of the century. The cumulative extraction component is quadratic and scarcity becomes relevant when 3/4 of current resources have been depleted. The import price of natural gas in 2002 is assumed to be 3.8 USD per MBtu for the USA, 3.4 for EUROPE and 3.9 for CAJANZ.[12]

The cost of uranium ore extraction in 2002 is set at 19 USD per Kg. Resources amount to 17.5 million tonnes according to IEA (2004a); unlike the way we treat other natural resources, we have assumed that the growth rate of uranium resources increases over time and that it obeys a logistic law, i.e. first the path is concave and then it becomes convex. In this way we account for the fact that, when uranium prices cross a certain level (around 300 $/kg), reprocessing spent fuel and fast-breeding reactors become convenient, and thus mitigate any further rise in cost. In 2002 the growth rate is about 0.6% per year and it reaches 2.5% per year by the end of the century. In order to be used as fissile fuel, uranium ore must undergo a process of conversion, enrichment and fabrication; we have set this cost at 222 USD per Kg of uranium ore on the basis of data in MIT (2003).

4. Baseline

In this section we illustrate the baseline scenario in which no constraint on CO_2 emissions is imposed and cooperation among countries towards GHG stabilization is not enforced. When

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[11] For a detailed discussion of the Hydrocarbon-Resource Classification see IEA (2004).

[12] The price of gas we use is the discounted average of import gas prices as reported by IEA (2005) for 2002 and 2001. If we used the spot price in 2002 alone, we could not respect the long-term relationship between US gas prices and European ones in which the latter are always inferior to the former (IEA, 2004).

countries are not committed to an international treaty they do not find it optimal to reduce CO_2 emissions unilaterally. Even if they perceive the damage caused by growing CO_2 concentrations in the atmosphere, they are not in control of the global public good and thus they correctly see their unilateral abatement effort as marginally ineffective and accordingly do not waste any resources on achieving that goal. This explains why our baseline foresees a continued carbon-based economy, slow penetration of carbon-free energy generation technologies like wind and solar and of new low-carbon technologies such as Carbon Capture and Sequestration and advanced biofuels. More rationale for this is provided in Section 5.

4.1 Economic Growth

We have calibrated the output growth dynamics so as to be in line with the output projections underlying the Common POLES IMAGE (CPI) baseline (van Vuuren *et al.* 2004).[13] Major drivers of growth in WITCH are population growth and total factor productivity, both exogenous in the model.

World population is expected to approach 9.5 billion by the end of the century; poor countries will host almost 90% of the total population. We have diverged from CPI population projections by mitigating the rather strong declining trend in industrialized countries to account for the probable migration of labourers attracted by high wages in labour-scarce countries.

World output is 34 trillion in 2002, it grows to 75 trillion in 2030 and reaches 234 trillion in 2100, almost a seven-fold increase; output is expected to grow at declining rates, with poor countries growing faster then rich ones (Table 3). Rich countries have mature economies that approach their steady state level: their share of world GDP decreases from 80% at 2002 to 60% in 2030 and finally reaches 38% in 2100. Fast growth is registered by all developing economies, especially the Middle East and North Africa (MENA), South East Asia (EASIA) and Latin America, Mexico and Caribbean (LACA).

The debate on convergence of income per capita has received wide attention in growth literature.[14] In the realm of global warming economics the debate on whether poor countries will eventually converge to the income per capita levels of rich ones has a substantial importance in shaping output projections because of the intimate link between the level of economic activity, energy supply and carbon emissions. Neoclassical growth models imply that, conditionally to the fact that two economies possess the same steady state, the poorer of the two will grow faster than the richer. This

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[13] We have assumed a slightly lower growth rate for CHINA than in Common POLES IMAGE (CPI).

[14] See Sala-i-Martin (1996a, 1996b) and Quah 1995; for the implications of the convergence debate on long run projections for climate change scenarios see McKibbin, Pearce and Stegman (2004).

is often defined as Beta convergence. Table 3b clearly shows that poor countries grow much faster than rich ones but the model does not show universal Beta convergence because regions differ in their underlying economic structure and thus move towards different steady states. The rapid growth of poor economies is in most cases however, insufficient to close the gap between them and rich economies as the speed of convergence is too slow. Thus our baseline features partial beta convergence and mild unconditional convergence across the century. This is substantially in line with the empirical literature on convergence as shown by Sala-i-Martin 1996b.

4.2 CO_2 Emissions

The model computes CO_2 emissions from the combustion of fossil fuels by applying the appropriate stoichiometric coefficients to total consumption. Biofuels are included (with a negative emission coefficient in the case of ethanol from cellulosic feedstock) while we adhere to the general convention of considering the traditional biomass carbon cycle as neutral. Total CO_2 emissions include those that arise from land use change, which evolve exogenously as in Nordhaus and Boyer (2000). Although we can compute in principle all GHGs emissions from combustion of fossil fuels, in this version of the model we keep track of CO_2 emissions only.

Emissions related to energy use are expected to grow steadily over time reaching 20 Gton C by 2100. This places our model in the highest range of B2 IPCC SRES scenarios. Emissions' growth primarily derives from developing countries' sustained economic activity and population increase. It is believed that poor countries will exceed OECD countries' emissions by 2025, and then take the lead, contributing to more than 12 Gton C in 2100. For a regional disaggregation of emissions see Figure 3. Despite this increase, emissions per capita remain higher in OECD countries throughout the century, mirroring the income per capita dynamics.

In Figure 4 we split world CO_2 emissions according to contributions from different fuels: oil — almost exclusively consumed in the non-electric sector — is the biggest source of emissions and remains such until the second half of the century when coal takes the lead, driven by its substantial deployment in electricity generation and because of its high carbon content per unit of energy. The contribution from natural gas is restrained by the low emission factor, and its share slowly declines over time.

4.3 The Energy Sector

4.3.1 Primary Energy Supply

The growth rate for world energy supply is 2.5% per year in the first 20-25 years of the century, it declines to 1% by 2050 and it stabilizes at 0.4% by 2100. At the end of the century energy demand is expected to reach almost 27,000 MToe (1,140 EJ). Figure 5 represents total primary energy supply over the century. We anticipate an increasing energy demand share for developing countries, especially in Asia. OECD countries — which now total 60% of the world demand — by 2030 will be surpassed by NON-OECD countries and their role will continue to diminish with their share stabilizing at about 30% at the end of the century.

In Table 4 we disaggregate the demand for fossil fuels in 2002, 2030 and 2100. Oil covers 44% of total primary supply in 2002, almost entirely directed to non-electric energy use. Its share is predicted to decline to 37% in 2100, though it never declines in absolute values. Sustained oil supply is possible thanks to an increasing penetration of non-conventional oil — for more on this see the next paragraph. Coal is expected to be stable till 2030 and to significantly increase afterwards due to its wide use in electricity generation. Coal use in the non-electric sector is assumed to decline over time. The contribution from natural gas increases in 2030 from 26% to 32%, mainly because of more extensive use in electricity generation. It then returns to the base year share at the end of the century. Fossil fuel demand increases faster in the electric sector than in the non-electric one: the electrification-induced switch is mainly driven by a substitution of non-electric fuels with coal-generated electricity.

Despite the substantial increase in the use of fossil fuel, energy intensities decline over time in all regions and progressively converge towards a common world average — see Figure 6. The main driving force behind this result is the increasing cost of fossil fuels over the whole century.

Biofuel penetration remains modest over the century and consists exclusively of ethanol from corn, wheat and sugar cane. Its share of total primary energy supply increases from an average of 1.7%, in energy equivalent terms, to 2% in 2030 and to 3.6% in 2100. At this penetration rate there is no conflict between biofuel crops and traditional land use.[15] This is equivalent to a two-fold expansion by 2030 and a five-fold expansion at the end of the century. Advanced biofuels are not employed at all. Without concerns for GHGs emissions traditional and advanced biofuels produced from cellulosic biomass sources remain too pricey for substituting traditional oil-based fuels.

The traditional biomass share of total primary energy supply declines from 8% in 2002 to 5% in 2030 and still further to 3% in 2100. Strong population growth in SSA, where traditional biomass is the primary component of total primary energy demand, prevents this figure from declining any faster over the century.

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[15] Estimates of the long run potential production of biofuels are contained in IEA (2004b).

4.3.2 Fossil Fuel Availability and Prices

WITCH's baseline is characterized by a continued use of fossil fuels throughout the century. Such a projection depends on the underlying assumptions about fuel resource availability and prices, which we discuss in this paragraph.

In WITCH fossil fuel costs have two components: a marginal extraction cost and a part that measures pressure on resources, as a fraction of cumulative extraction on total resources. Marginal extraction cost is assumed to be constant. Resources grow over time and mitigate the exhaustibility effect.

Fossil fuel prices are reported in Figure 7. The price of oil rises from 21.6 USD per barrel in 2002 to 32.5 USD in 2030 and to 85 USD in 2100, in real terms this is a four-fold increase over the century. According to the latest estimates from the USGS (2000), initial stocks of conventional oil resources amount to 3,345 billion barrels;[16] non-conventional oil resources (tar sands, shale oil, etc.) are estimated to be 7,000 billion barrels (IEA, 2004a). At this stage of the model's development we do not distinguish between conventional and non-conventional oil. As the extraction cost of conventional oil increases, it is assumed that non-conventional oil will start to penetrate the market and will act as stabilizer of world oil prices.[17] In order to include this effect we have set the growth rate of the conventional resource base above 1% per year up to 2050 and then we let it stabilize at about 0.8%. It is thus possible to admit a three-fold increase of oil resources over the simulation interval. Even without considering the contribution of non-conventional oil, we believe that our assumption about oil resource base growth is not excessive: total ultimately recoverable conventional oil resource estimates have steadily increased during the last twenty years at an average annual rate of 3.4% (USGS, 2000); the production to resources ratio declined from 26% in 1981 to 21% in 2000. Another indicator of oil scarcity, the production years to reserves ratio, remained quite stable at around 40% from 1994 to 2004.

As for natural gas, remaining conventional reserves are similar to conventional oil in calorific content. They amount to 359 billion cubic meters, according to the most recent USGS (2000) survey. Gas resource growth rate is initially assumed to be 11% per year; it subsequently declines to 2.6% per year in 2030 and finally stabilizes at 1% by the end of the century. We intentionally overestimate the rate of natural reserves' growth for the first two decades because this is the easiest way to capture the expected decline in natural gas prices from now to 2010 (IEA, 2004a) with our cost function. It is as if spare capacity would grow at a faster rate than demand in the next two

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[16] We follow IEA (2004a) by considering the reserves of natural gas liquids (NGL) as a part of oil reserves.

[17] For example, extraction of non-conventional oil from tar sands in the Canadian province of Alberta and in Venezuela is believed to be economically viable at a price of around 30-35 USD per barrel of conventional oil.

decades. The result is that, in the baseline, natural gas prices decline by about 10% up to 2010 and then start to rise slightly above the 2002 level in 2030; at the end of the century they increase three-fold with respect to 2002. Our assumption about resource growth amplifies, but does not contradict, recent trends in natural gas exploration. It is important to stress the fact that knowledge of natural gas resources is still limited and resource estimates undergo continuous upward corrections. According to USGS (1985, 1990, 1993, 2000) reserves have more than doubled in fifteen years, at an average annual growth rate of almost 8%; resources have grown at an increasing rate, totalling an average yearly growth rate of 4.4%. As in the case of oil, there exist large amounts of non-conventional gas. The volume of carbon contained in methane hydrates worldwide is estimated to be twice the amount contained in all fossil fuels on Earth, including coal (Collett, 2001). Even if at this time it is still uncertain how much of this enormous potential can be extracted at economically viable costs, it is reasonable to expect that natural gas will not be exhausted in the foreseeable future.

Coal is the most abundant fossil energy source, with reserves that amount to about 17,000 billion tonnes. In equivalent energy content they are twenty times and ten times greater than conventional and non-conventional oil resources, respectively. We assume that coal resources are will grow at a constant rate of 0.5% and that its price will slowly increase from 30 USD per tonne in 2002 to almost 60 USD per tonne at the end of the century.[18]

We are optimistic about the future availability of fossil fuels. In line with Lackner and Sachs (2005), we project the energy resource base to be sufficient to feed the energy demand of a fast-growing world economy in the XXIst century. We believe that the real threat is not the exhaustibility of fossil fuels but rather the fact that without the wide deployment of carbon-free technologies it will not be possible to meet the rapidly increasing world energy demand without severely compromising climate stability and without seriously harming the environment.

4.3.3 Power Generation Mix and Investments

In Figure 8 we show the world electricity mix as it evolves over time. Exact figures and shares are reported in Table 5. Electricity generation is expected to expand by a factor of 4 in this century, from 16,000 to almost 60,000 TWh by 2100. The power mix is not foreseen to change dramatically over time. Coal remains the largest provider of electricity, though its share first declines from 38% in 2002 to 33% in 2030, and then substantially increases to 47% by 2100. A substantial deployment of coal is expected in Asian countries such as India and China, but also in some industrialized ones,

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[18] Potentially, one can produce other fuels from coal. Synthetic gasoline, for example, can be obtained from coal at around 30 USD per barrel. It is important to consider that the abundance of coal resources places an upper bound to oil prices.

such as the US for example. IGCC with Carbon Capture and Sequestration is not included the power generation mix because the baseline regions do not take any steps towards emission reduction. Electricity generated from natural gas increases from 19% in 2002 to 28% in 2030 and then it declines to 15% by 2100 due to increasing fuel costs. Nuclear power's share is constant at 17% until 2060 and then its penetration increases slightly until the end of the century when it covers 21% of total electricity generation. Wind and solar power grow significantly in absolute terms but their proportion remains small and by 2100 they represent only 3% of the power generation mix. Oil-based electricity generation gradually declines due to increasing fuel costs and low efficiency. Hydroelectric is assumed to remain stable in real terms and so its share will diminish.

4.3.4 Endogenous Electricity Prices

In WITCH the cost of electricity generation is equal to the sum of the remuneration of capital invested in power capacity and the expenditure for fuels and operation and maintenance. As in optimal growth models, capital in WITCH is paid its marginal product plus the depreciation rate. Without technical progress capital productivity diminishes as accumulation proceeds. This causes the gross interest rate to decline over time, though technical progress may counteract this process by increasing the productivity of capital.[19] Thus, over time more capital intensive technologies — such as coal and nuclear — gain a comparative advantage to less capital intensive ones, and tend to be preferred. This does not happen in the same way in each region of the world: countries with high interest rates such as the developing countries find capital-intensive electricity generation technologies more expensive than industrialized countries.

In Table 6 we show the electricity costs of the technologies that enter the power mix in 2002, 2030 and 2100. In Table 7 we decompose electricity generation costs into their main components. We look at the main aspects of each electricity generation technology in the next sections.

4.3.5 Hydroelectric

Hydropower's share in total electricity demand is 18% in the base year and then declines to 15% in 2030 and to 8% in 2100. As pointed out when outlining the model structure, hydroelectricity is added exogenously to total electricity, as its deployment is constrained by the availability of sites and is thus easily predictable. Few sites remain to be exploited in OECD countries and thus almost all of the new installed capacity will be in developing countries.[20] Hydropower is a capital-intensive technology in all regions: in 2002, 75% of electricity generation costs, which range from 4.2 to 5.6

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[19] Here we assume that labor augments technical progress.

[20] We are not considering the potential diffusion of small hydroelectric plants.

cUSD/kWh, is due to the remuneration of invested capital and 25% to O&M expenditure. This feature explains why fast-growing regions, which have rising or non-declining interest rates in the first decades, experience an increase in hydropower generation costs between 2002 and 2030. However, from 2030 onward, when interest rates begin to decline in all countries, the cost of hydropower generation diminishes and ranges between 3.2 and 4.2 cUSD/kWh.

4.3.6 Fossil Fuel Electricity

In our baseline the electricity generated using coal, oil and natural gas covers 65% of world demand in 2002 and this share slightly increases to 68% in 2030 and then remains stable over the century.

Electricity generated using coal is 6,127 TWh in 2002 and grows at an average growth rate of 1.5% per year during the century to reach 9,535 TWh in 2030 and 27,389 TWh in 2100. However, its share in world electricity demand declines during the first three decades from 38% to 33% due to the expansion of gas-fired power plants. From 2030 onward, this share begins to rise and reaches 47% of total demand by 2100. We have assumed that new investments are all in “clean coal” technologies, i.e. with desulphurization and de-NOx, and with higher investment and O&M costs than traditional plants. We also progressively introduce an environmental tax that takes into account local negative externalities as quantified by ExternE at about 1 cUSD per kWh. Coal generation is, along with gas, the least expensive electricity generation technology in all countries. It is cheaper than gas in all regions rich in coal reserves, such as KOSAU, CHINA, NEWEURO, SASIA, it is equivalent to gas in USA and more expensive in the others. In 2002 cost per kWh ranges from 2.4 cUSD/kWh in KOSAU to 4.6 cUSD/kWh in Japan, with about 60% of expenditure due to capital remuneration, and from 8 to 30% due to fuel costs. The cost of coal-generated electricity does not grow remarkably. Two factors contribute to this result: first, coal is a much more capital-intensive technology than oil and gas and so the use of coal benefits in greater proportion from the reduction of interest rates experienced by regions across the century and, secondly, the price of coal grows less than price of oil and gas. It is important to note that even when a local pollutant tax is computed coal remains competitive. IGCC coal is never economically attractive in the baseline scenario. We devote the next section to a more detailed description of IGCC assumptions.

Electricity produced by burning oil accounts for 7% of total demand in 2002 and this share remains stable up to 2030 when it begins to decline, stabilizing at 5% in 2100. Oil-based electricity generation is concentrated almost exclusively in MENA countries where almost all the investment in new capacity is concentrated; in other regions there is virtually no investment in oil power plants and this technology is displaced by natural gas and coal.

Natural gas power grows faster than any other electricity generation technology from 2002 to 2030. Electricity generation more than doubles from 3,129 TWh in 2002 to 8,224 TWh in 2030, expanding its share of total demand from 19% to 28%. However, this sudden increade quickly turns into decline as gas electricity generation loses ground in favour of coal from 2030 to 2100. By the end of the century electricity generated with gas is at 8,578 TWh, 15% of total demand, and less than the 2002 share. The reason for this is that natural gas becomes expensive given its exhaustibility, so that without high carbon prices coal becomes more economic. As mentioned above, natural gas rivals coal as the least expensive electricity generation technology in 2002: costs are as low as 2.8 cUSD/kWh in MENA countries and 3-4 cUSD/kWh in all other regions. In 2030 they are slightly below the 2002 level in almost all regions, due to the converging effect of the constant price of gas and the decline of expenditure for capital. However, gas-based electricity generation is a fuel-intensive technology: expenditure for natural gas accounts for 50% of the electricity generation cost. Once gas prices increase and there are no environmental concerns, coal power plants supply electricity at a lower cost and displace natural gas.

Summarizing, in WITCH's baseline fossil fuels play a major role in electricity supply throughout the century. Switching from this scenario to a low carbon one will thus be a serious challenge that should not be underestimated. If climate change is considered a serious menace, as we do consider it to be, decisive action must be taken to draw the world away from tempting, but dangerous, carbon-intensive energy paths.

4.3.7 IGCC Coal with CCS

IGCC is a generating technology involving the gasification of coal, its combustion in a Combined Cycle Gas Turbine and the sequestration of the carbon dioxide produced in the process. However, IGCC with CCS is penalized by higher investment costs, energy efficiency loss and the cost of transporting and storing the CO_2 that is captured. We assume that 90% of the CO_2 produced is captured. Since IGCC is modelled as a direct substitute for coal-fired power plants, it comes in only when its costs are lower than the cost of traditional coal. In this baseline that does not entail significant emission reductions, as CO_2 is not valued enough to make CCS an economically competitive technology.

4.3.8 Nuclear Power

Nuclear power accounts for 17% of world electricity demand in 2002, which corresponds to 2,713 TWh of electricity generated each year. Its share of the mix is equivalent to gas and hydropower. During the first three decades nuclear power grows at an average rate of 2% but its share of electricity supply remains constant. From 2030 onward nuclear electricity's share grows to reach

21% of total supply, the second most important electricity generation technology after coal. The cost of electricity generation is between 5.3 and 6.4 cUSD/kWh in 2002, considerably higher than coal and gas because of high investment and O&M costs in particular. Since nuclear power is a capital-intensive technology, generation costs slightly increase in the first three decades for fast-growing regions, such as CHINA and SASIA, while they decline in mature economies. After 2030 prices converge in almost all regions at 5.0 cUSD/kWh, and then remain stable thanks to their low sensitivity to fuel cost.

This characteristic, together with the fact that is does not emit CO_2, makes nuclear power an interesting option for the 21st century. 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, but a major expansion might revive the Fast Breeding Reactors (FBR), which reprocess the spent fuel to feed the nuclear reactor again, and thus produce less waste. However, present designs are economically unattractive and increase proliferation risk as they separate plutonium from spent fuel. A number of unconventional schemes — such as the "intrinsically safe" reactors and the High Temperature Gas-Cooled Reactors — are under study, but the innovation process will require time and R&D investments. Although many believe a major expansion will not happen without the FBRs, for instance see Beck (1999), here we take the view of Bunn *et al.* (2005) and MIT (2003) by assuming that all nuclear power will be based on a once-through fuel cycle. 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.

We have separated the cost of natural uranium from the costs of conversion, enrichment and fuel fabrication that are necessary to transform the mineral ore into fuel bars that are used in the fission process. Conversion, enrichment and fuel fabrication costs are set at 222 USD per Kg of uranium ore processed, which is equivalent to 0.5 cUSD/kWh, and are kept constant over the century.

Due to a rising cost in waste management, O&M expenditures grow over the century to become the most expensive component of the cost of electricity generation; at the same time the price of uranium ore increases but has almost no repercussion on electricity generation costs due to the limited weight of this component. The price of uranium ore depends on the quantity extracted, and in our baseline scenario it increases from 20 to 130 $/kg by the end of the century. Increased use might push prices even higher, but one should keep in mind that prices are essentially capped by the recycling options — via reprocessing and fast breeding reactors — at a level between 250 and 300

$/kg, see Bunn *et al.* (2005). Also, almost infinite amounts of uranium are available from oceans at an extraction cost above 200 USD/Kg. Given that only 1% of nuclear electricity generation cost per kWh is due to uranium ore, even a twenty-fold increase of uranium price would not affect the economic competitiveness of this technological option.

4.3.9 Wind and Solar

In 2002 53 TWh of electricity are generated with wind turbines and solar power plants worldwide, i.e. 0.3% of world electricity demand. Installed capacity is concentrated in a few regions, mainly in the USA and EUROPE. Even in these areas the share of electricity demand covered by wind and solar is limited, with only EUROPE recording more than 1%. Wind and solar is projected to be the fastest growing electricity generation technology, both worldwide and at regional level: the electricity generated grows by 180% from 2002 and 2030 and over the century it increases 28-fold.[21]

Electricity from wind and solar is generated using only capital and O&M expenditures. The initial investment cost is 1,500 USD per kWe. The rapid development of wind and solar power technologies in recent years has led to a reduction in investment costs; beneficial effects from learning-by-doing are expected to decrease investment costs even further in the next few years. We model this effect by letting the investment cost follow a learning curve. As world-installed capacity in wind and solar doubles, investment cost diminishes by 13% as dictated by the learning factor which is equal to 0.87.

Thanks to the learning-by-doing effect, the cost of wind and solar power capacity decreases to 1,180 USD/kWe by 2030 and then to 667 USD/kWe by 2100. Although this cost reduction is outweighed by the low utilization factor, the electricity generation cost from wind and solar decreases from 8-9 cUSD/kWh in 2002 to 3.5 cUSD/kWh in 2100, thus becoming the least expensive electricity generation technology together with hydroelectric power.[22] However, this breakeven point occurs too late to allow wind and solar gain a significant share in power generation.

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.

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[21] Simulation results for policies for the stabilization of CO_2 concentrations at 550ppmv and 450 ppmv show that wind and solar electricity generation plays a major role in containing emissions. We record even higher penetration rates.

[22] We have not included the cost of installing backup capacity for renewable power plants, which would substantially increase investment costs.

4.4 Technological Change

In WITCH it is possible to invest in energy saving R&D and in R&D aimed at reducing the cost of advanced biofuels; technical progress in the form of learning-by-doing reduces the investment costs of power generation technologies (see Figure 9 for data on energy saving R&D and the LdB effect). At this stage of the model's development, we have activated the LbD effect for wind and solar power generation only because this is the sector in which technological improvements and price reductions are thought to be most significant over the next few decades. It is our intention however to extend LbD to other technologies in their early stages of development and penetration.

Investment in energy-saving R&D grows worldwide by 80% between 2002 and 2030, increasing from 16 billion USD to 29 billion USD per year; over a time horizon of 100 years it increases four-fold and reaches 80 billion USD per year.

As installed capacity in wind and solar grows in each time period, beneficial effects due to increasing expertise reduce investment costs in the following periods. Learning-by-doing spillovers are assumed to occur at the international level, as cumulated world installed capacity grows over time. The five-year time steps in which the model is simulated allow for a sufficient lag to let technology know-how, human capital and best practices flow across firms that have worldwide operations in the sector. The effect of LbD on investment cost is significant: from 2002 to 2030 we record a reduction from 1,500 to 1,180 USD/kWe and from 2030 to 2100 there is a further reduction to 667 USD/kWe. The introduction of international spillovers in our non-cooperative setting creates a wedge between regional and world benefit from investment in wind and solar electricity generation that causes underinvestment in this technology option. Thus, there is margin for policy action to reduce this market failure.

The presence of learning-by-doing (LbD) introduces increasing returns to capital invested in wind and solar electricity production since the reduction of investment costs can be assimilated to an increase of capital productivity. However, the decreasing marginal product of electricity generated with wind and solar power plants more than compensates the increasing marginal product of capital and eliminates a potential source of disequilibrium.

5. Cooperative versus Non-cooperative Solutions

WITCH incorporates a climate module adapted from Nordhaus and Boyer (2000) that delivers atmospheric concentrations of CO_2 and shows how they affect average world temperature. Temperature levels are fed into a region-specific quadratic damage function that has an effect on gross output. During the first time periods some regions experience positive feedback from increasing average world temperature but the positive effect quickly vanishes as temperature rises and the retroaction turns out to be negative worldwide.

In the baseline CO_2 emissions from the combustion of fossil fuels rise during the 21st century from 6.75 to 19.8 GTC, thus increasing concentrations and then pushing average world temperature 2.6°C above pre-industrial levels by 2100. If we compare this result with the one obtained by switching off the damage function, we see that temperature rise is assumed to be responsible for a global loss of 60 billion USD by 2030 and a loos of up to 6 trillion by 2100, 0.1% and 2.5% of global GDP, respectively. Why then does our baseline allow for such a strong increase of coal electricity generation, especially in the second part of the century when damage costs are higher? There are two main explanations for this result.

First, costs and benefits of emissions reductions have different timing: regions have to bear costs for adopting more virtuous technologies first, and they will benefit from lower temperatures only later. This time discrepancy —which we might also define as an intergenerational conflict — is governed by how much the present generation values future streams of consumption, i.e. via the inter-temporal discount factor. Discounting has been a very much debated issue in economics and especially in environmental economics; here we have chosen a discount factor of 3% which declines over time towards 2% by 2100, in line with Nordhaus and Boyer (2000). With this profile, the effect of distant benefits is not strong enough to induce significant emission reductions. In Figure 10 we compare emission profiles in the baseline when the climate module is switched on/off: clearly, emission paths are very similar, with the climate module inducing a reduction of only 0.5 Gton C by 2100.

In the same Figure we also show the emission profile assuming a cooperative behaviour among world regions, i.e. assuming that a social planner maximizes world welfare. In this case emissions would be reduced to almost half the level of the non-cooperative case. As described in Section 2.1, in WITCH the twelve regions interact strategically in a non-cooperative way, and this is the second main explanation for the high emissions baseline. Each social planner optimizes regional welfare without taking into account the effect of that behaviour on other regions' welfare, this results in free-riding on CO_2 emissions, a typical global pollutant. The internalization of the externality through the climate damage component doesn't provide enough incentive to moderate pollution considerably, since any effort is dampened by the non-cooperative behaviour of other players. This is confirmed by a very low carbon shadow price, which never exceeds 16 USD/Ton C throughout the century, and remains much lower in most regions. On the contrary, the cooperative solution yields a scenario that is significantly lower in carbon intensity: for example, the power generation mix in the cooperative case — reported in Figure 11 — assigns a substantial role to low-CO_2

technologies. Coal-fierd IGCC plants with carbon capture and sequestration enter the electricity mix in 2040, and gradually replace the no-CCS coal-fired plants; wind and solar and nuclear noticeably increase their relative shares.

This result is in line with predictions of non-cooperative games and stresses the point that a major task of international agreements on climate control should be the specific promotion of cooperation among countries to avoid free-riding. Cooperation should be a major target of climate change policy and not an initial condition. With our baseline we stress this fact and we show that in the absence of an international agreement all regions will pursue a least-cost energy portfolio in which carbon-rich fuels will play a major role.

WITCH succeeds at combining an Integrated Assessment framework with a non-cooperative interaction structure among players, in a world in which there are several technology options for supplying energy. It is thus possible to work with all these dimensions when studying climate change control policy options.

6. Conclusions

This paper presents the main characteristics and properties of a new model designed for climate policy analysis: WITCH (World Induced Technical Change Hybrid). It integrates a previously published, shorter description of the model, to discuss calibration details and to carefully illustrate baseline results along with relevant underlying assumptions.

WITCH, is a top-down macro model where different regions of the world strategically interact in determining their optimal energy investments. Optimal investments are the outcome of a dynamic open-loop Nash game with perfect foresight. Investments depend on the dynamics of technical change, which is itself endogenous and depends on investment paths as well as on prices and other economic and climatic variables (including climate policy). Investment decisions in one country depend on those in the other countries, given the several interdependency channels specified in the model.

The model is carefully calibrated using the information available in the empirical literature. Section 3 is devoted to illustrating the calibration procedure, data sources and main assumptions that drive the choice of key parameters.

In Section 4 we extensively report the figures that define WITCH's baseline scenario. We show that substantial emissions are projected for this century, driven by sustained population and economic growth, especially in the developing world. We also project the continuous use of fossil fuels, and especially an expansion of coal usage in the second half of the century; the energy resource base seems to be sufficient to provide for the energy demand of a fast-growing world economy in the

XXIst century. This result is derived despite the fact that the model accounts for climate damages and endogenously determines the optimal level of emission mitigation. The appearance of climate damage far in the future, assumptions about its magnitude and non-cooperative interaction among regions lead us to believe that a shift to less carbon-intensive technologies would be a sub-optimal strategy. Indeed, new low-carbon technologies such as Carbon Capture and Sequestration and advanced bio-fuel do not turn out to be economically competitive, and thus do not enter the energy mix.

In Section 5 we compare our baseline to a case in which world welfare is maximized: cooperation is shown to yield substantial emission reductions and greater promotion of low-carbon intensity technologies with respect to the non-cooperative optimum. Thus strong mitigation efforts and international cooperation agreements are not likely to emerge naturally. Conversely, they should be explicitly imposed, if one believes in the need for a conservative approach to the uncertainty surrounding climatic responses and climate damage.

Under what conditions can climate policy achieve the goal of stabilizing GHG concentrations? What are the features of an optimal climate policy? To what extent would it be technology-based? These are all questions that WITCH is designed to address. They will be the subject of future model applications. With this technical report we have worked to achieve a high level of transparency in order to offer a solid grounding to all those who wish to interpret WITCH results or plan to use the model to perform policy analysis.

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Appendix

Model Equations

In this Appendix we reproduce the model's main equations. The list of variables is reported at the end. In each region, indexed by *n*, a social planner maximizes the following utility function:

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

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

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

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:

$$\begin{aligned}C(n,t)=&\,Y(n,t)-I_C(n,t)-\sum\nolimits_j I_{R\&D,j}(n,t)-\sum\nolimits_j I_j(n,t)-\sum\nolimits_j O\&M_j(n,t)\\&-\sum\nolimits_f\left(P_f(n,t)\,X_{f,extr}(n,t)+P_f^{\text{int}}(t)X_{f,netimp}(n,t)\right)\\&-P_{CCS}(n,t)CCS(n,t)\end{aligned} \tag{A3}$$

Output is produced via a nested CES function that combines a capital-labour aggregate and energy; capital and labour are obtained from a Cobb-Douglas function. Climate damage Ω reduces gross output: to obtain net output we subtract the costs of the natural resources and *CC*S (*j* indexes technologies):

$$Y(n,t)=\frac{TFP(n,t)\left[\alpha(n)\cdot\left(K_C{}^{1-\beta(n)}(n,t)L^{\beta(n)}(n,t)\right)^{\rho}+(1-\alpha(n))\cdot ES(n,t)^{\rho}\right]^{1/\rho}}{\Omega(n,t)}\,. \tag{A4}$$

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:

$$K_C(n,t+1)\;=\;K_C(n,t)(1-\delta_C)+I_C(n,t)-4\psi_{R\&D}I_{R\&D}(n,t)\,. \tag{A5}$$

Labour is assumed to be equal to population and evolves exogenously. Energy services are an aggregate of energy and a stock of knowledge combined with a CES function:

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

The stock of knowledge $HE(n,t)$ derives from energy R&D investment:

$$HE(n,t+1)\ =\ aI_{R\&D}(n,t)^b\, HE(n,t)^c+HE(n,t)(1-\delta_{R\&D})\,. \tag{A7}$$

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

$$EN(n,t)=\left[\alpha_{EL}EL(n,t)^{\rho_{EN}}+\alpha_{NEL}NEL(n,t)^{\rho_{EN}}\right]^{1/\rho_{EN}}\ . \tag{A8}$$

Each factor is further decomposed into several sub-components. Figure 2 portrays a graphical illustration of the energy sector. 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:

$$EL_j(n,t)=\min\left\{\mu_{n,j}K_j(n,t)\,;\tau_{n,j}O\&M_j(n,t);\varsigma_j X_{j,EL}(n,t)\right\}. \tag{A10}$$

Capital for electricity production technology accumulates in the usual way:

$$K_j(n,t+1)=K_j(n,t)\left(1-\delta_j\right)+\frac{I_j(n,t)}{SC_j(n,t)}\,, \tag{A11}$$

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

$$SC_j(n,t+1)=B_j(n)\cdot\sum\nolimits_n K_j^*(n,t)^{-\log_2 PR_j} \tag{A12}$$

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

$$P_f(n,t)=\chi_f(n)+\pi_f(n)\left[Q_f(n,t-1)/\overline{Q}_f(n,t)\right]^{\psi_f(n)} \tag{A13}$$

where Q_f is the cumulative extraction of fuel f:

$$Q_f(n,t-1)=Q_f(n,0)+\sum\nolimits_{s=0}^{t-1}X_{f,extr}(n,s)\,. \tag{A14}$$

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.

$$X_f(n,t) = X_{f,extr}(n,t) + X_{f,netimp}(n,t) \tag{A15}$$

Climate Module

GHGs emissions from the combustion of fossil fuels are derived by applying stoichiometric coefficients to the total amount of fossil fuels utilized minus the amount of CO_2 sequestered:

$$CO_2(n,t) = \sum_f \omega_{f,CO_2} X_f(n,t) - CCS(n,t). \tag{A16}$$

The damage function impacting output varies with global temperature:

$$\Omega(n,t) = \frac{1}{1+\left(\theta_{1,n}T(t)+\theta_{2,n}T(t)^2\right)}. \tag{A17}$$

Temperature increases through augmented radiating forcing *F(t)*:

$$T(t+1) = T(t) + \sigma_1\left\{F(t+1) - \lambda T(t) - \sigma_2\left[T(t) - T_{LO}(t)\right]\right\} \tag{A18}$$

which in turn depends on CO_2 concentrations:

$$F(t) = \eta\left\{\log\left[M_{AT}(t)/M_{AT}^{PI}\right] - \log(2)\right\} + O(t), \tag{A19}$$

caused by emissions from fuel combustion and land use change:

$$M_{AT}(t+1) = \sum_n \left[CO_2(n,t) + LU_j(t)\right] + \phi_{11}M_{AT}(t) + \phi_{21}M_{UP}(t), \tag{A20}$$

$$M_{UP}(t+1) = \phi_{22}M_{UP}(t) + \phi_{12}M_{AT}(t) + \phi_{32}M_{LO}(t), \tag{A21}$$

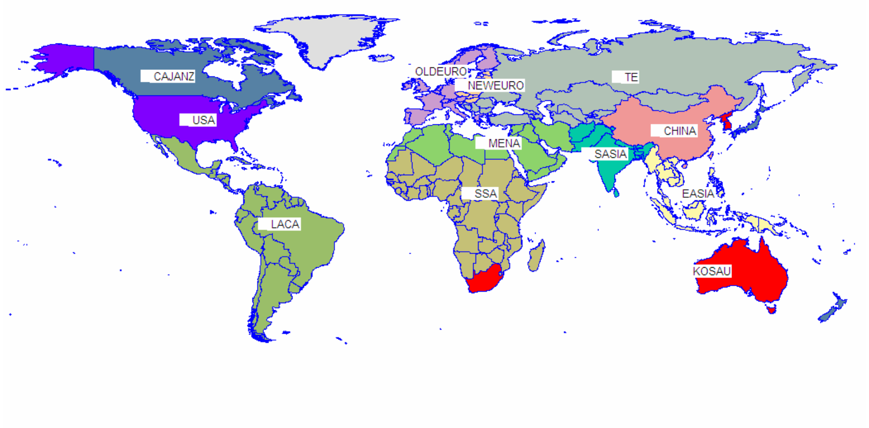
$$M_{LO}(t+1) = \phi_{33}M_{LO}(t) + \phi_{23}M_{UP}(t). \tag{A22}$$

Model variables are denoted with the following symbols:

W = welfare
U = instantaneous utility
C = consumption
c = per-capita consumption
L = population
R = discount factor
Y = production
I_c=investment in final good
$I_{R\&D}$=investment in energy R&D
I_j=investment in technology j
$O\&M$=investment in operation and maintenance
TFP=total factor productivity
K_c=final good stock of capital
ES=energy services
Ω = damage
P_j= fossil fuel prices
X_j= fuel resources
P_{CCS}= price of CCS
CCS= sequestered CO_2
HE=energy knowledge
EN=energy
EL=electric energy
NEL=non-electric energy
K_j= capital stock for technology j
SC_j=investment cost
CO_2= emissions from combustion of fossil fuels
M_{AT} = atmospheric CO_2 concentrations
LU = land-use carbon emissions
M_{UP} = upper oceans/biosphere CO_2 concentrations
M_{LO} = lower oceans CO_2 concentrations
F = radiative forcing
T= temperature level

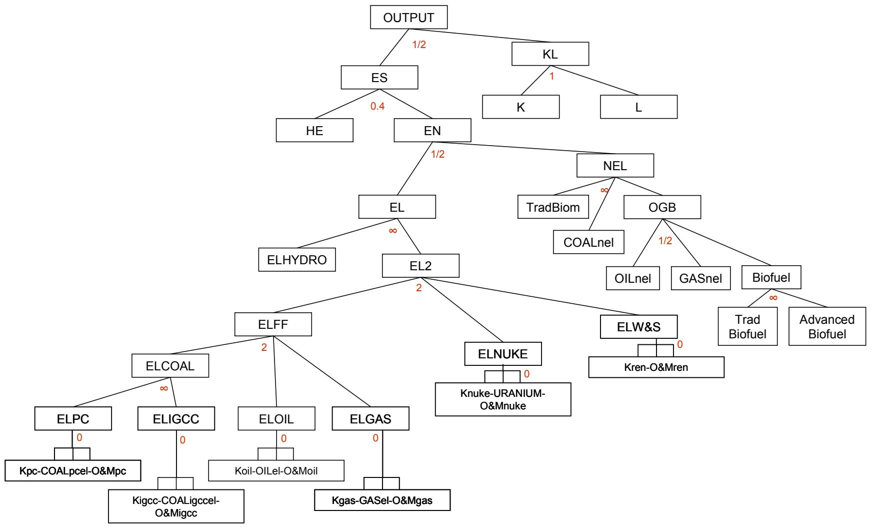
Figures and Tables.

Figure 1: World Regions in the WITCH Model



Regions:
1)CAJANZ (Canada, Japan, New Zealand)
2)USA
3)LACA (Latin America, Mexico and Caribbean)
4)OLDEURO (Old Europe)
5)NEWEURO (New Europe)
6)MENA (Middle East and North Africa)
7)SSA (Sub-Saharan Africa excl. South Africa)
8)TE (Transition Economies)
9)SASIA (South Asia)
10) CHINA (including Taiwan)
11) EASIA (South East Asia)
12) KOSAU (Korea, South Africa, Australia)

Figure 2: Production Nest and the Elasticity of Substitution values



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 use
NEL = Non-electric energy use
OGB = Oil, Gas and Biofuel nest
ELFF = Fossil fuel electricity nest
W&S= Wind and Solar
ELj = Electricity generated with the technology j
TradBiom= Traditional Biomass
Kj = Capital for generation of electricity with technology j
O&Mj = Operation and Maintenance costs for generation of electricity with technology j
‘FUELj’el = Fuel use for generation of electricity with technology j
‘FUELj’nel = Direct fuel use in the non-electric energy use

Figure 3: CO_2 Emissions

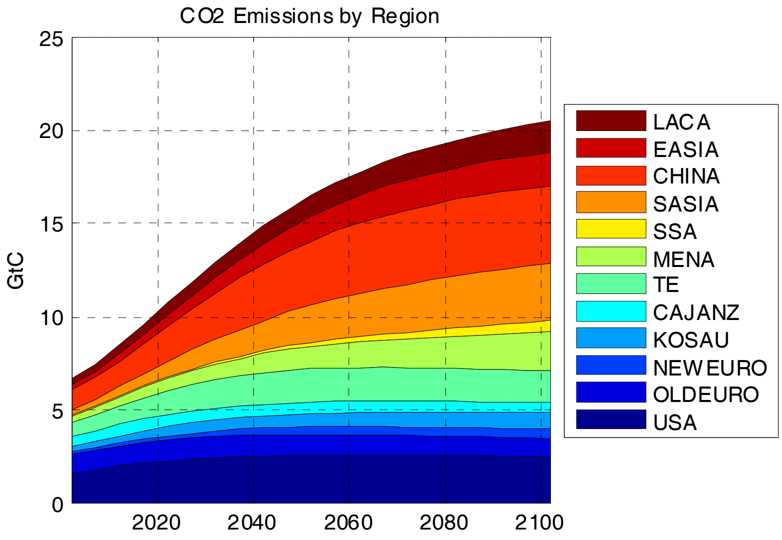


Figure 4: CO_2 Emissions by Fuel (Gton of Carbon)

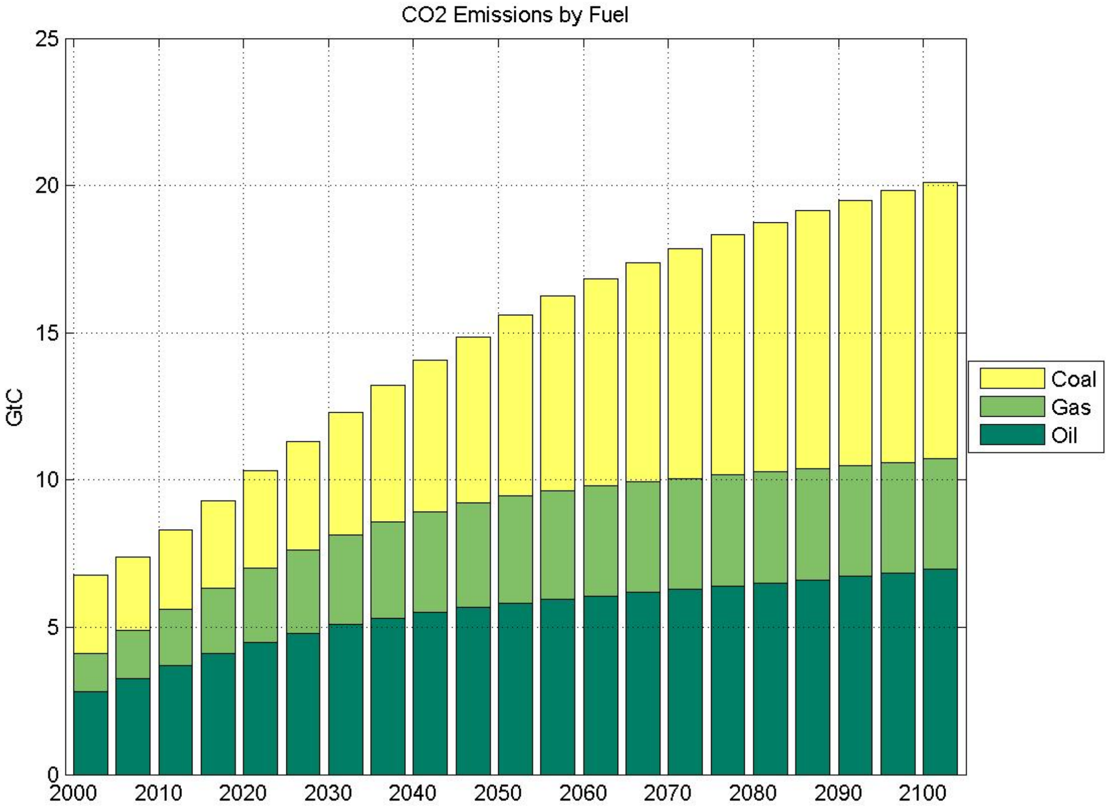


Figure 5: Total Primary Energy Supply

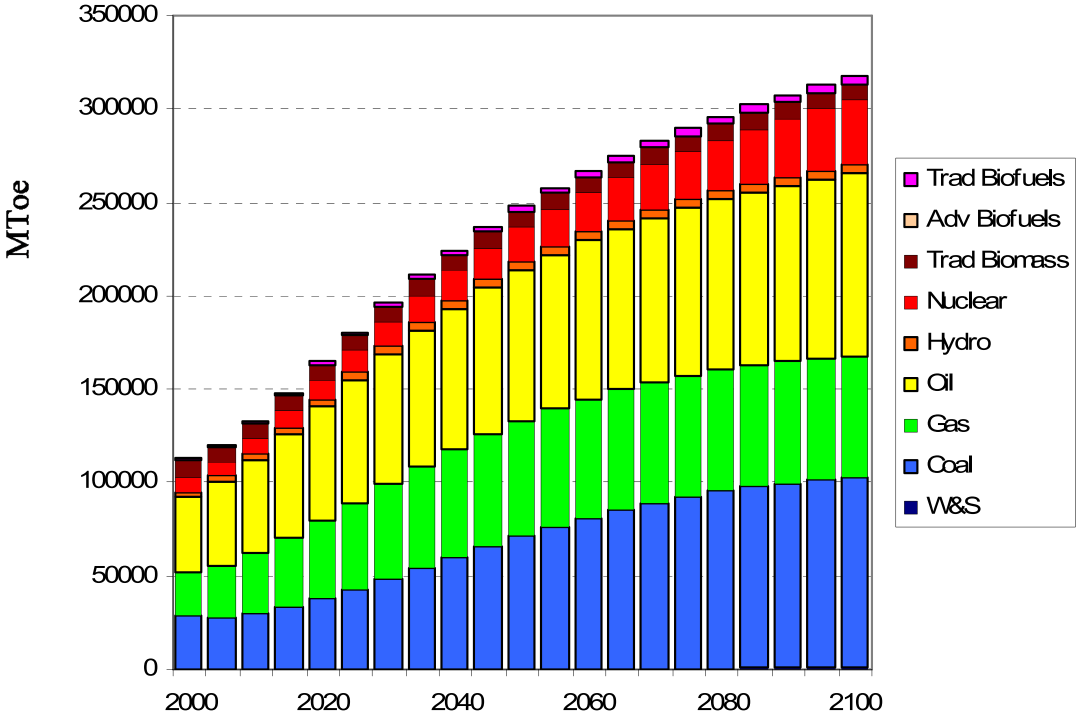


Figure 6: Energy Intensities by Region

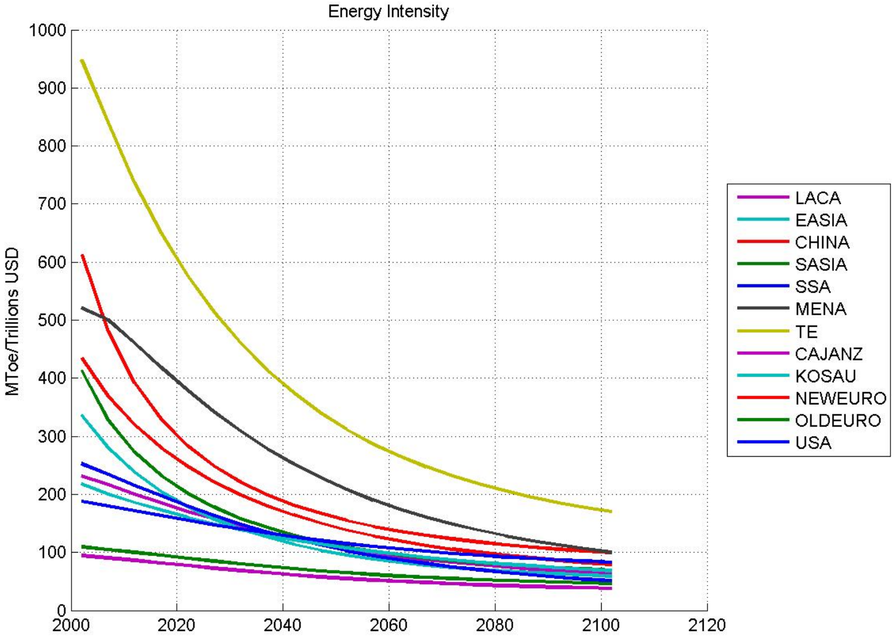


Figure 7: Fuel prices

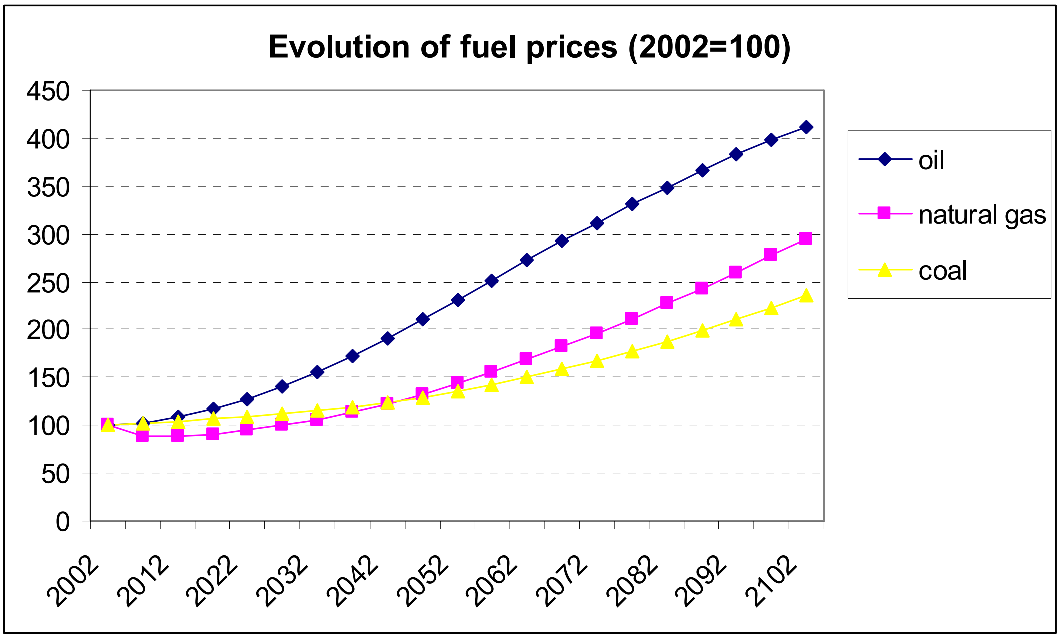


Figure 8: Power Generation Mix

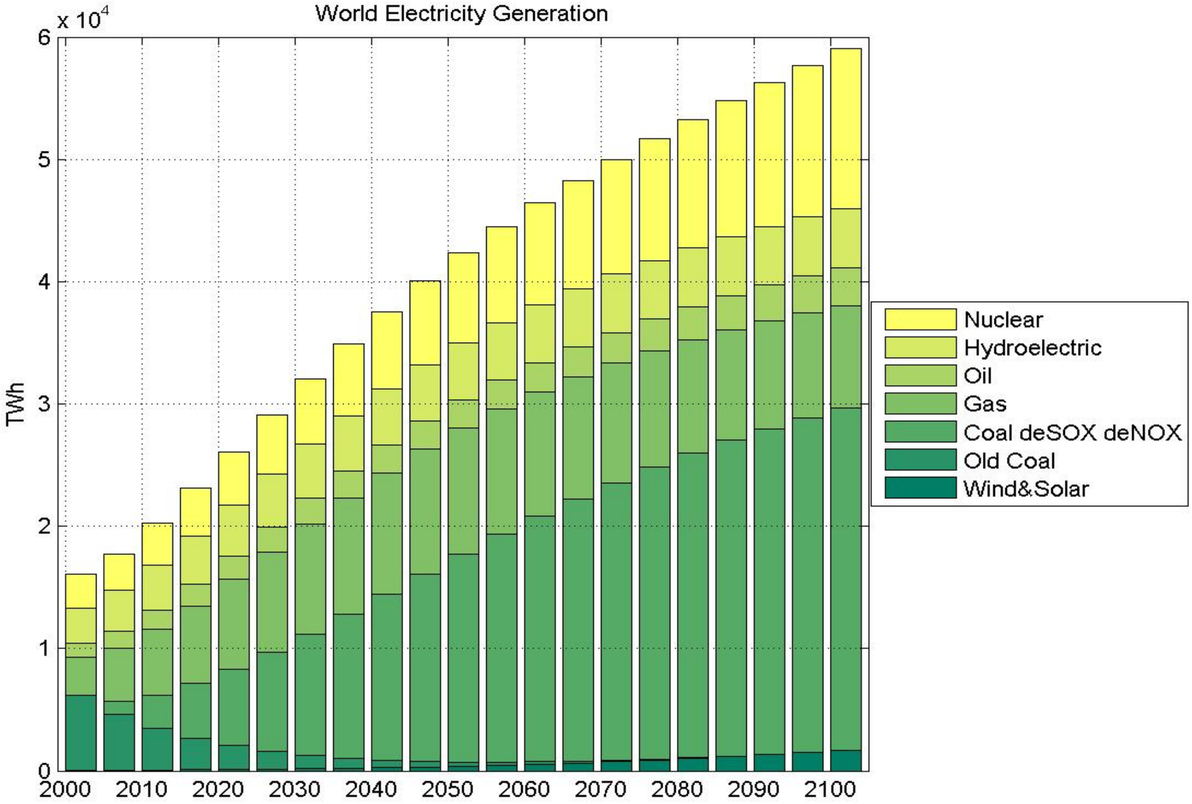


Figure 9: Two Distinct Channels of Endogenous Technical Change: LbD and Energy Saving R&D

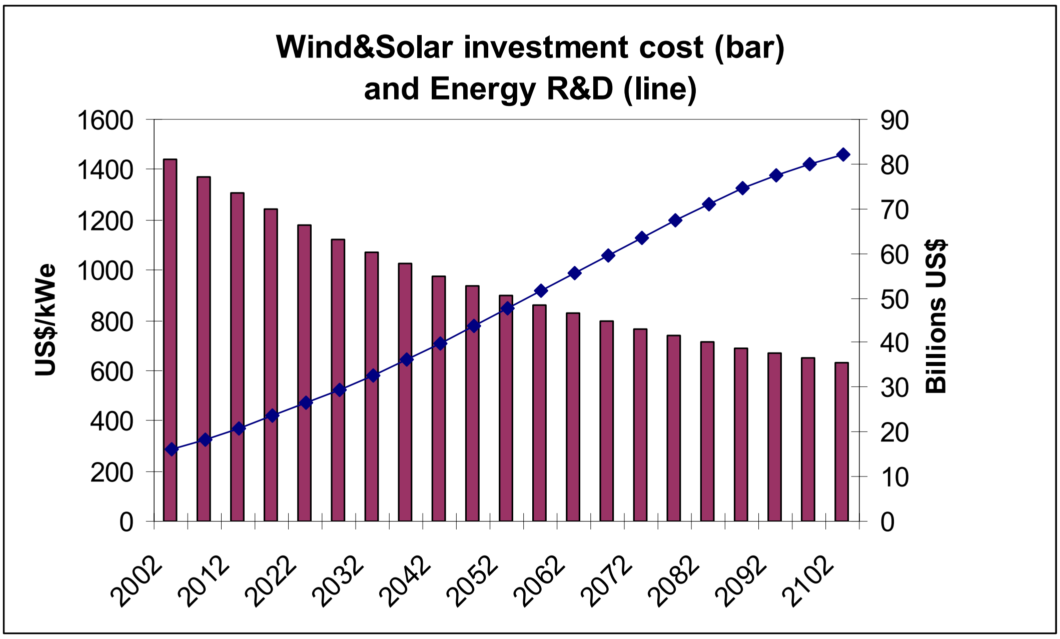


Figure 10: Emissions with Different Model Specification

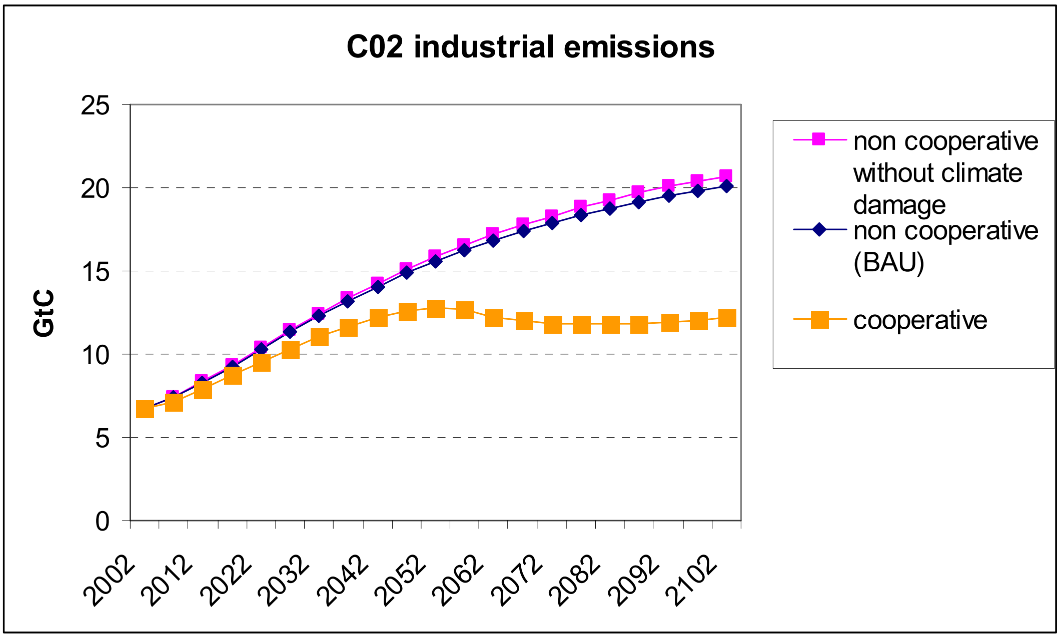


Figure 11: Power Generation Mix in the Cooperative Solution

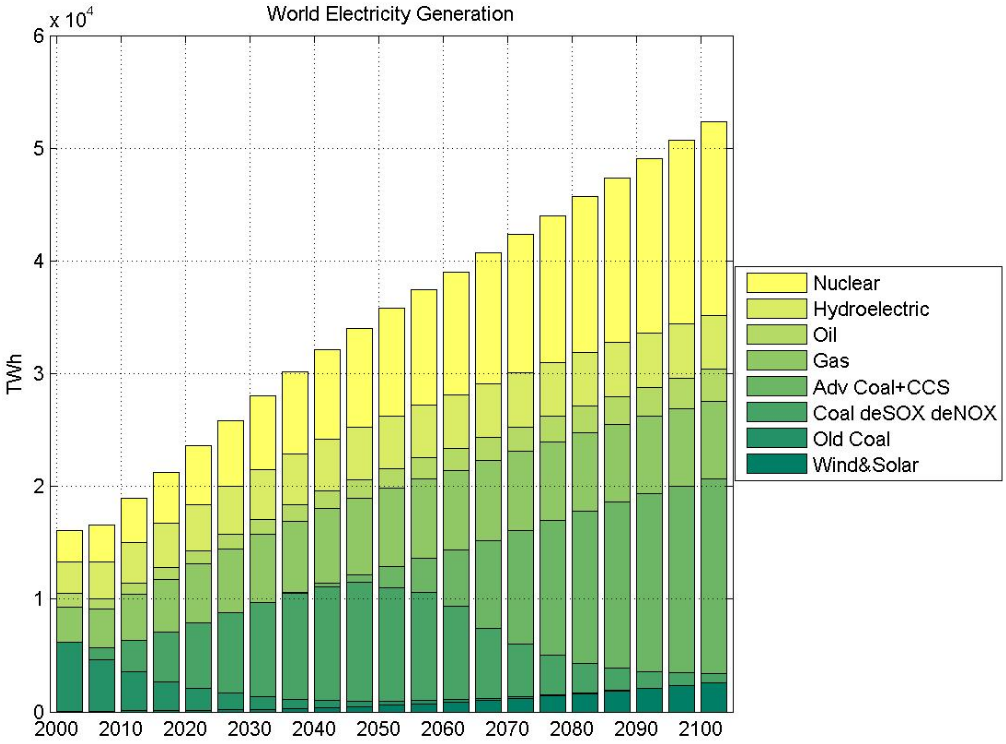


Table 1: Power Plant Costs (1995 USD) and Technical Specification for Each Country

Investment Cost for Power Generation Capacity - US$/kWe

	Coal	IGCC+CCS	Oil	Gas	Nuclear	Hydro	W&S
USA	1418	2000	679	523	2000	1400	1500
OLDEURO	1446	2000	768	591	2000	1400	1500
NEWEURO	1288	2000	770	592	2000	1400	1500
KOSAU	1276	2000	645	496	2000	1400	1500
CAJANZ	1900	2000	1076	700	2000	1400	1500
TE	1412	2000	748	576	2000	1400	1500
MENA	1350	2000	1076	601	2000	1400	1500
SSA	1350	2000	1076	601	2000	1400	1500
SASIA	983	2000	758	583	2000	1400	1500
CHINA	948	2000	758	583	2000	1400	1500
EASIA	1350	2000	758	583	2000	1400	1500
LACA	1481	2000	1008	601	2000	1400	1500

Source: our calculation based on NEA/IEA (1998, 2005)

Cost for Operation and Maintenance - US$/kWe per year

	Coal	IGCC+CCS	Oil	Gas	Nuclear	Hydro	W&S
USA	44	51	27	23	136	51	24
OLDEURO	52	60	32	27	143	57	24
NEWEURO	35	40	32	27	147	41	24
KOSAU	26	30	30	25	131	55	24
CAJANZ	46	53	29	24	161	67	24
TE	31	36	27	23	113	53	24
MENA	52	60	32	27	161	67	24
SSA	52	60	32	27	161	67	24
SASIA	27	31	28	23	128	54	24
CHINA	34	39	28	23	126	48	24
EASIA	30	35	28	23	127	51	24
LACA	17	20	12	10	133	54	24

Source: our calculation based on NEA/IEA (1998, 2005)

Technical parameters for electricity generation

	Coal	IGCC+CCS	Oil	Gas	Nuclear	Hydro	W&S
load factor	0.85	0.85	0.85	0.85	0.85	0.5	0.3
efficiency	0.33/0.38	0.40	0.39	0.50	0.35	1.00	1.00
lifetime (years)	40	40	25	25	40	45	30
depreciation rate	5.6%	5.6%	8.8%	8.8%	5.6%	5.0%	7.4%

Source: our calculation based on NEA/IEA (1998, 2005)

Table 2: Population

(a) Population (millions)

	2002	2030		2100	
	Population	Population	2030/2002	Population	2100/2002
USA	287	331	*1.15*	351	*1.22*
OLDEURO	389	378	*0.97*	299	*0.77*
NEWEURO	74	71	*0.95*	53	*0.71*
KOSAU	114	156	*1.37*	202	*1.78*
CAJANZ	161	161	*1.00*	122	*0.75*
TE	405	406	*1.00*	297	*0.73*
MENA	323	485	*1.50*	757	*2.34*
SSA	652	1088	*1.67*	1890	*2.90*
SASIA	1407	1866	*1.33*	2321	*1.65*
CHINA	1336	1525	*1.14*	1455	*1.09*
EASIA	565	737	*1.30*	836	*1.48*
LACA	532	703	*1.32*	885	*1.66*
WORLD	6,244.77	7,906.13	*1.27*	9,466.95	*1.52*

(b) Population Growth Rate (average per year)

	2002-2030	2030-2100	2002-2100
USA	-1.3%	0.1%	-0.3%
OLDEURO	-3.5%	-0.3%	-1.3%
NEWEURO	-10.3%	-0.4%	-3.5%
KOSAU	-7.3%	0.4%	-2.0%
CAJANZ	-4.9%	-0.4%	-1.8%
TE	-1.8%	-0.4%	-0.9%
MENA	1.4%	0.6%	0.9%
SSA	1.7%	0.8%	1.1%
SASIA	0.9%	0.3%	0.5%
CHINA	0.4%	-0.1%	0.1%
EASIA	0.9%	0.2%	0.4%
LACA	0.9%	0.3%	0.5%
WORLD	0.8%	0.3%	0.4%

Table 3: GDP, Growth and Distribution

(a) GDP (trillions 1995 USD)

	2002	**2030**		**2100**	
	GDP	GDP	2030/2002	GDP	2100/2002
USA	8.85	15.43	*1.74*	29.08	*3.29*
OLDEURO	10.35	16.97	*1.64*	28.83	*2.78*
NEWEURO	0.33	1.04	*3.20*	4.49	*13.79*
KOSAU	1.31	3.12	*2.37*	11.58	*8.81*
CAJANZ	6.42	10.85	*1.69*	18.79	*2.93*
TE	0.84	2.92	*3.48*	9.73	*11.61*
MENA	0.82	2.80	*3.41*	21.61	*26.28*
SSA	0.21	0.79	*3.81*	8.37	*40.09*
SASIA	0.64	4.14	*6.46*	26.40	*41.19*
CHINA	1.34	6.17	*4.59*	24.65	*18.34*
EASIA	0.80	4.78	*5.95*	23.87	*29.70*
LACA	1.97	5.72	*2.90*	26.75	*13.56*
WORLD	33.89	74.73	*2.21*	234.15	*6.91*

(b) GDP per Capita (thousands 1995 USD)

	2002	**2030**		**2100**	
	Y / L	Y / L	2030/2002	Y / L	2100/2002
USA	30.83	46.65	*1.51*	82.81	*2.69*
OLDEURO	26.63	44.90	*1.69*	96.34	*3.62*
NEWEURO	4.39	14.77	*3.37*	85.17	*19.41*
KOSAU	11.56	19.96	*1.73*	57.20	*4.95*
CAJANZ	39.75	67.36	*1.69*	154.46	*3.89*
TE	2.07	7.19	*3.47*	32.81	*15.84*
MENA	2.54	5.77	*2.27*	28.56	*11.23*
SSA	0.32	0.73	*2.28*	4.43	*13.82*
SASIA	0.46	2.22	*4.87*	11.38	*24.97*
CHINA	1.01	4.05	*4.02*	16.94	*16.83*
EASIA	1.42	6.49	*4.56*	28.54	*20.08*
LACA	3.71	8.15	*2.20*	30.23	*8.16*
WORLD	5.43	9.45	*1.74*	24.73	*4.56*

(c) Cross-Regional Comparison of GDP and GDP per Capita (Y / L)

	2002		**2030**		**2100**	
	GDP	Y / L	GDP	Y / L	GDP	Y / L
USA	1	1	1	1	1	1
OLDEURO	1.17	0.86	1.10	0.96	0.99	1.18
NEWEURO	0.04	0.14	0.07	0.32	0.15	1.07
KOSAU	0.15	0.37	0.20	0.43	0.40	0.69
CAJANZ	0.73	1.29	0.70	1.44	0.65	1.93
TE	0.09	0.07	0.19	0.15	0.33	0.43
MENA	0.09	0.08	0.18	0.12	0.74	0.33
SSA	0.02	0.01	0.05	0.02	0.29	0.05
SASIA	0.07	0.01	0.27	0.05	0.91	0.14
CHINA	0.15	0.03	0.40	0.09	0.85	0.21
EASIA	0.09	0.05	0.31	0.14	0.82	0.35
LACA	0.22	0.12	0.37	0.17	0.92	0.36

Table 4: Primary Supply of Fossil Fuels and Relative Shares

Total Primary Supply of Fossil Fuels (MToe)

	electric			non-electric			
	Coal	**Oil**	**Gas**	**Coal**	**Oil**	**Gas**	**Total**
2002	1,626	276	594	811	3,262	1,470	**8,039**
	20%	*3%*	*7%*	*10%*	*41%*	*18%*	
2030	2,595	496	1,625	811	5,550	2,844	**13,919**
	19%	*4%*	*12%*	*6%*	*40%*	*20%*	
2100	7,661	741	1,776	811	7,861	4,216	**23,066**
	33%	*3%*	*8%*	*4%*	*34%*	*18%*	

Table 5: Power Generation Mix

Power Generation Mix (TWh)

	Coal	**IGCC**	**Oil**	**Gas**	**Nuclear**	**Hydro**	**W&S**	**Total**
2002	6,127	-	1,173	3,129	2,713	2,859	53	**16,053**
	38%	*0%*	*7%*	*19%*	*17%*	*18%*	*0.3%*	
2030	9,535	-	2,054	8,224	4,880	4,283	139	**29,116**
	33%	*0%*	*7%*	*28%*	*17%*	*15%*	*0.5%*	
2100	27,389	-	3,016	8,578	12,398	4,815	1,481	**57,676**
	47%	*0%*	*5%*	*15%*	*21%*	*8%*	*2.6%*	

Table 6: Power Generation Costs in 2002, 2030 and 2100 (1995 cUSD)

Electricity Generation Cost - cUSD/kWh - 2002

	Coal	IGCC	Oil	Gas	Nuclear	Hydro	W&S
USA	3.5		5.8	3.6	5.3	4.3	8.0
OLDEURO	4.0		6.1	3.5	5.4	4.5	8.0
NEWEURO	3.0		6.9	3.5	5.5	4.1	8.0
KOSAU	2.4		6.3	3.6	5.3	4.5	8.1
CAJANZ	4.6		6.1	3.7	5.7	4.7	8.0
TE	3.3		5.8	3.0	5.6	5.1	9.3
MENA	4.3		4.5	2.8	6.4	5.6	9.5
SSA	4.1		8.8	3.4	6.2	5.4	9.2
SASIA	2.6		7.0	4.1	5.8	5.0	9.1
CHINA	2.7		6.9	3.9	5.9	5.1	9.4
EASIA	3.4		5.7	3.3	5.8	5.0	9.2
LACA	4.1		6.2	3.1	5.9	5.1	9.3

Electricity Generation Cost - cUSD/kWh - 2030

	Coal	IGCC	Oil	Gas	Nuclear	Hydro	W&S
USA	4.1		7.0	3.4	4.9	3.7	6.0
OLDEURO	4.7		7.3	3.4	5.2	4.0	6.3
NEWEURO	4.4		8.7	3.7	6.2	4.7	8.0
KOSAU	3.1		7.7	3.5	5.1	4.0	6.4
CAJANZ	5.2		7.1	3.6	5.4	4.2	6.4
TE	4.3		7.8	2.9	5.6	4.9	7.8
MENA	4.8		5.4	2.6	5.8	4.7	7.0
SSA	4.9		11.0	3.2	5.9	4.8	7.0
SASIA	3.8		8.8	4.2	6.3	5.5	8.6
CHINA	3.7		8.4	3.9	6.0	5.0	8.1
EASIA	4.6		7.5	3.3	6.1	5.3	8.4
LACA	4.6		7.5	2.9	5.4	4.3	6.9

Electricity Generation Cost - cUSD/kWh - 2100

	Coal	IGCC	Oil	Gas	Nuclear	Hydro	W&S
USA	4.8		15.5	7.4	5.0	3.2	3.3
OLDEURO	5.2		15.8	7.3	5.1	3.3	3.4
NEWEURO	4.7		18.6	7.4	5.4	3.3	3.6
KOSAU	3.9		17.2	7.5	5.1	3.5	3.5
CAJANZ	5.6		14.5	7.1	5.4	3.6	3.4
TE	4.7		20.3	7.7	4.8	3.4	3.5
MENA	5.3		13.7	7.5	5.7	4.1	3.7
SSA	6.3		26.3	8.2	5.9	4.2	3.9
SASIA	4.2		18.5	8.8	5.0	3.4	3.4
CHINA	4.1		17.8	7.9	4.9	3.2	3.4
EASIA	4.6		17.2	7.9	4.9	3.3	3.4
LACA	5.1		17.2	7.8	5.2	3.5	3.6

Table 7: Decomposition of Power Generation Costs in 2002, 2030 and 2100 (1995USD)

Decomposition of electricity generation costs - USD/kWh - 2002

	Coal			Oil			Gas		
	Plant	O&M	Fuel	Plant	O&M	Fuel	Plant	O&M	Fuel
USA	2.0	0.6	0.9	1.3	0.4	4.2	1.0	0.3	2.3
	58%	17%	25%	22%	6%	72%	27%	9%	64%
OLDEURO	2.0	0.7	1.2	1.4	0.4	4.2	1.1	0.4	2.1
	51%	18%	31%	23%	7%	70%	31%	10%	59%
NEWEURO	1.8	0.5	0.7	1.4	0.4	5.0	1.1	0.4	2.1
	61%	16%	23%	21%	6%	73%	31%	10%	59%
KOSAU	1.8	0.3	0.2	1.2	0.4	4.7	0.9	0.3	2.3
	77%	15%	8%	19%	6%	74%	26%	9%	65%
CAJANZ	2.7	0.6	1.3	2.0	0.4	3.7	1.3	0.3	2.1
	58%	13%	28%	33%	6%	61%	34%	9%	57%
TE	2.4	0.4	0.5	1.6	0.4	3.8	1.2	0.3	1.4
	72%	12%	16%	28%	6%	66%	41%	10%	48%
MENA	2.4	0.7	1.2	2.4	0.4	1.7	1.3	0.4	1.1
	56%	16%	28%	53%	10%	37%	47%	13%	41%
SSA	2.3	0.7	1.2	2.3	0.4	6.1	1.3	0.4	1.7
	55%	17%	28%	26%	5%	69%	38%	11%	51%
SASIA	1.6	0.4	0.6	1.6	0.4	5.0	1.2	0.3	2.6
	63%	14%	23%	23%	5%	72%	30%	7%	63%
CHINA	1.7	0.5	0.6	1.7	0.4	4.8	1.3	0.3	2.3
	62%	17%	21%	24%	5%	70%	33%	8%	59%
EASIA	2.3	0.4	0.7	1.6	0.4	3.8	1.2	0.3	1.7
	67%	12%	21%	28%	7%	66%	38%	9%	53%
LACA	2.5	0.2	1.3	2.2	0.2	3.9	1.3	0.1	1.7
	62%	6%	32%	35%	3%	63%	41%	4%	55%

Decomposition of electricity generation costs - USD/kWh - 2002

	Nuclear				Hydroelectric		Wind&Solar	
	Plant	O&M	Uranium	Enrich.	Plant	O&M	Plant	O&M
USA	2.8	1.9	0.05	0.5	3.2	1.2	7.0	0.9
	53%	36%	1%	10%	73%	27%	89%	11%
OLDEURO	2.8	2.0	0.05	0.5	3.2	1.3	7.0	0.9
	52%	37%	1%	10%	71%	29%	88%	12%
NEWEURO	2.8	2.1	0.05	0.5	3.2	0.9	7.1	0.9
	52%	38%	1%	10%	77%	23%	89%	11%
KOSAU	2.9	1.9	0.05	0.5	3.2	1.3	7.1	0.9
	54%	35%	1%	10%	72%	28%	89%	11%
CAJANZ	2.8	2.3	0.05	0.5	3.2	1.5	7.0	0.9
	50%	40%	1%	10%	68%	32%	89%	11%
TE	3.4	1.6	0.05	0.5	3.9	1.2	8.3	0.9
	61%	29%	1%	10%	76%	24%	90%	10%
MENA	3.5	2.3	0.05	0.5	4.0	1.5	8.6	0.9
	55%	35%	1%	8%	72%	28%	90%	10%
SSA	3.4	2.3	0.05	0.5	3.8	1.5	8.2	0.9
	54%	36%	1%	9%	72%	28%	90%	10%
SASIA	3.4	1.8	0.05	0.5	3.8	1.2	8.2	0.9
	58%	32%	1%	9%	76%	24%	90%	10%
CHINA	3.5	1.8	0.05	0.5	4.0	1.1	8.5	0.9
	60%	30%	1%	9%	78%	22%	90%	10%
EASIA	3.4	1.8	0.05	0.5	3.8	1.2	8.2	0.9
	59%	31%	1%	9%	77%	23%	90%	10%
LACA	3.4	1.9	0.05	0.5	3.9	1.2	8.3	0.9
	58%	32%	1%	0.09	0.76	0.24	90%	10%

Decomposition of electricity generation costs - USD/kWh - 2030

		Coal			**Oil**			**Gas**	
	Plant	O&M	Fuel	Plant	O&M	Fuel	Plant	O&M	Fuel
USA	1.6	1.5	1.0	1.1	0.4	5.6	0.8	0.3	2.3
	39%	37%	24%	15%	5%	80%	24%	9%	67%
OLDEURO	1.8	1.6	1.3	1.3	0.4	5.6	1.0	0.4	2.1
	37%	34%	28%	17%	6%	77%	29%	11%	61%
NEWEURO	2.2	1.4	0.8	1.6	0.4	6.7	1.2	0.4	2.1
	50%	32%	18%	19%	5%	76%	34%	10%	56%
KOSAU	1.6	1.3	0.3	1.1	0.4	6.2	0.8	0.3	2.3
	50%	40%	9%	14%	5%	81%	24%	10%	67%
CAJANZ	2.3	1.5	1.4	1.8	0.4	4.9	1.2	0.3	2.1
	44%	29%	26%	25%	5%	70%	32%	9%	59%
TE	2.3	1.3	0.7	1.6	0.4	5.9	1.2	0.3	1.4
	54%	31%	15%	20%	5%	75%	41%	11%	49%
MENA	1.9	1.6	1.3	2.0	0.4	3.0	1.1	0.4	1.1
	40%	34%	27%	36%	8%	56%	42%	14%	44%
SSA	1.9	1.6	1.3	2.0	0.4	8.5	1.1	0.4	1.7
	40%	33%	27%	18%	4%	78%	35%	11%	54%
SASIA	1.8	1.3	0.7	1.7	0.4	6.7	1.3	0.3	2.6
	48%	33%	19%	20%	4%	76%	32%	7%	61%
CHINA	1.6	1.4	0.7	1.6	0.4	6.4	1.3	0.3	2.3
	44%	37%	18%	19%	4%	76%	33%	8%	59%
EASIA	2.4	1.3	0.8	1.7	0.4	5.4	1.3	0.3	1.7
	53%	29%	18%	23%	5%	72%	39%	9%	52%
LACA	2.0	1.1	1.4	1.8	0.2	5.5	1.1	0.1	1.7
	44%	25%	31%	24%	2%	73%	37%	5%	58%

Decomposition of electricity generation costs - USD/kWh - 2030

		Nuclear			**Hydroelectric**		**Wind&Solar**	
	Plant	O&M	Uranium	Enrich.	Plant	O&M	Plant	O&M
USA	2.3	2.0	0.11	0.5	2.5	1.2	5.1	0.9
	46%	41%	2%	11%	68%	32%	85%	15%
OLDEURO	2.4	2.1	0.11	0.5	2.7	1.3	5.4	0.9
	47%	41%	2%	10%	67%	33%	86%	14%
NEWEURO	3.4	2.2	0.11	0.5	3.8	0.9	7.1	0.9
	55%	35%	2%	9%	80%	20%	89%	11%
KOSAU	2.5	1.9	0.11	0.5	2.8	1.3	5.5	0.9
	49%	38%	2%	11%	69%	31%	86%	14%
CAJANZ	2.4	2.3	0.11	0.5	2.7	1.5	5.4	0.9
	45%	43%	2%	10%	64%	36%	86%	14%
TE	3.3	1.7	0.11	0.5	3.7	1.2	6.9	0.9
	58%	30%	2%	10%	75%	25%	88%	12%
MENA	2.8	2.3	0.11	0.5	3.2	1.5	6.1	0.9
	49%	40%	2%	9%	67%	33%	87%	13%
SSA	2.9	2.3	0.11	0.5	3.2	1.5	6.1	0.9
	49%	40%	2%	9%	68%	32%	87%	13%
SASIA	3.7	1.9	0.11	0.5	4.2	1.2	7.7	0.9
	59%	30%	2%	9%	77%	23%	89%	11%
CHINA	3.4	1.9	0.11	0.5	3.9	1.1	7.2	0.9
	58%	31%	2%	9%	78%	22%	89%	11%
EASIA	3.6	1.9	0.11	0.5	4.1	1.2	7.4	0.9
	59%	31%	2%	9%	78%	22%	89%	11%
LACA	2.8	2.0	0.11	0.5	3.1	1.2	5.9	0.9
	51%	37%	2%	0.10	0.72	0.28	87%	13%

Decomposition of electricity generation costs - USD/kWh - 2100

		Coal			Oil			Gas	
	Plant	O&M	Fuel	Plant	O&M	Fuel	Plant	O&M	Fuel
USA	1.3	1.6	1.9	0.9	0.4	14.2	0.7	0.3	6.4
	27%	33%	40%	6%	2%	92%	10%	4%	86%
OLDEURO	1.4	1.7	2.2	1.1	0.4	14.3	0.8	0.4	6.1
	26%	32%	42%	7%	3%	91%	11%	5%	84%
NEWEURO	1.4	1.5	1.8	1.1	0.4	17.0	0.9	0.4	6.1
	29%	32%	39%	6%	2%	92%	12%	5%	83%
KOSAU	1.3	1.3	1.2	0.9	0.4	15.9	0.7	0.3	6.4
	34%	35%	32%	5%	2%	92%	10%	4%	86%
CAJANZ	1.8	1.6	2.2	1.5	0.4	12.6	1.0	0.3	5.8
	33%	29%	39%	10%	3%	87%	14%	5%	82%
TE	1.4	1.4	1.9	1.1	0.4	18.9	0.8	0.3	6.5
	30%	30%	40%	5%	2%	93%	11%	4%	85%
MENA	1.5	1.7	2.1	1.7	0.4	11.6	0.9	0.4	6.2
	29%	32%	39%	12%	3%	84%	13%	5%	83%
SSA	1.6	1.7	3.0	1.8	0.4	24.1	1.0	0.4	6.8
	26%	27%	47%	7%	2%	92%	12%	4%	83%
SASIA	1.0	1.4	1.8	1.1	0.4	17.0	0.8	0.3	7.7
	23%	33%	44%	6%	2%	92%	9%	4%	87%
CHINA	0.9	1.5	1.7	1.1	0.4	16.4	0.8	0.3	6.8
	22%	36%	42%	6%	2%	92%	10%	4%	86%
EASIA	1.3	1.4	1.9	1.1	0.4	15.7	0.8	0.3	6.8
	28%	31%	41%	6%	2%	92%	10%	4%	86%
LACA	1.6	1.2	2.3	1.5	0.2	15.5	0.9	0.1	6.8
	30%	24%	46%	9%	1%	90%	11%	2%	87%

Decomposition of electricity generation costs - USD/kWh - 2100

		Nuclear			Hydroelectric		Wind&Solar	
	Plant	O&M	Uranium	Enrich.	Plant	O&M	Plant	O&M
USA	1.8	2.3	0.29	0.5	2.0	1.2	2.4	0.9
	37%	46%	6%	11%	63%	37%	73%	27%
OLDEURO	1.9	2.4	0.29	0.5	2.0	1.3	2.5	0.9
	37%	47%	6%	11%	61%	39%	73%	27%
NEWEURO	2.1	2.4	0.29	0.5	2.3	0.9	2.7	0.9
	39%	45%	5%	10%	71%	29%	75%	25%
KOSAU	2.1	2.2	0.29	0.5	2.3	1.3	2.6	0.9
	40%	43%	6%	11%	64%	36%	74%	26%
CAJANZ	1.9	2.6	0.29	0.5	2.1	1.5	2.5	0.9
	36%	49%	5%	10%	58%	42%	73%	27%
TE	2.0	2.0	0.29	0.5	2.2	1.2	2.6	0.9
	42%	41%	6%	11%	65%	35%	74%	26%
MENA	2.3	2.6	0.29	0.5	2.5	1.5	2.8	0.9
	40%	46%	5%	9%	62%	38%	76%	24%
SSA	2.4	2.6	0.29	0.5	2.7	1.5	2.9	0.9
	41%	45%	5%	9%	64%	36%	76%	24%
SASIA	2.0	2.2	0.29	0.5	2.2	1.2	2.5	0.9
	40%	44%	6%	11%	64%	36%	73%	27%
CHINA	1.9	2.1	0.29	0.5	2.1	1.1	2.5	0.9
	39%	44%	6%	11%	66%	34%	73%	27%
EASIA	1.9	2.2	0.29	0.5	2.1	1.2	2.5	0.9
	39%	44%	6%	11%	64%	36%	73%	27%
LACA	2.1	2.2	0.29	0.5	2.3	1.2	2.6	0.9
	41%	43%	6%	0.10	0.65	0.35	74%	26%