To pdf - WITCH

From IAMC-Documentation

Reference card - WITCH

Contents

The reference card is a clearly defined description of model features. The numerous options have been organized into a limited amount of default and model specific (non default) options. In addition some features are described by a short clarifying text.

Legend:

☐ not implemented
☑ **implemented**
☑ **implemented (not default option)**

About

Name and version	WITCH
Institution and users	Fondazione Eni Enrico Mattei (FEEM), Italy, http://www.feem.it. Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy, http://www.cmcc.it.
Documentation	WITCH documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - WITCH

Objective	WITCH evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.
Concept	Hybrid: Economic optimal growth model, including a bottom-up energy sector and a simple climate model, embedded in a `game theory` framework.
Solution method	Regional growth models solved by non-linear optimization and game theoretic setup solved by tatonnement algorithm (cooperative solution: Negishi welfare aggregation, non-cooperative solution: Nash equilibrium)
Anticipation	Perfect foresight
Temporal dimension	Base year:2005, time steps:5, horizon: 2150
Spatial dimension	Number of regions:14

1. cajaz: Canada, Japan, New Zeland
2. china: China, including Taiwan
3. easia: South East Asia
4. india: India
5. kosau: South Korea, South Africa, Australia
6. laca: Latin America, Mexico and Caribbean
7. indo: Indonesia
8. mena: Middle East and North Africa
9. neweuro: EU new countries + Switzerland + Norway
10. oldeuro: EU old countries (EU-15)
11. sasia: South Asia
12. ssa: Sub Saharan Africa
13. te: Non-EU Eastern European countries, including Russia
14. usa: United States of America

Note: The number of regions is not fixed, as they can be aggregated or downscaled until country level.

Policy implementation	Quantitative climate targets (temperature, radiative forcing, concentration), carbon budgets, emissions profiles as optimization constraints. Carbon taxes. Allocation and trading of emission permits, banking and borrowing. Subsidies, taxes and penalty on energies sources.

Socio economic drivers

Model documentation: Socio-economic drivers - WITCH

Exogenous drivers	☐ Exogenous GDP	☑ **Labour Productivity**
	☑ **Total Factor Productivity**	☑ **Capital Technical progress**

☐ Energy Technical progress	☐ GDP per capita
☐ Materials Technical progress	
Development ☐ GDP per capita	☐ Education level
☐ Income distribution in a region	☐ Labour participation rate
☐ Urbanisation rate	

Macro economy

Model documentation: Macro-economy - WITCH

Economic sectors	☐ Agriculture	☐ Transport
	☐ Industry	☐ Services
	☑ **Energy**	☑ **other**

Note: A single economy sector is represented. Production inputs are capital, labor and energy services, accounting for the Energy sector split into 8 energy technologies sectors (coal, oil, gas, wind&solar, nuclear, electricity and biofuels).

Cost measures	☑ **GDP loss**	☐ Area under MAC
	☑ **Welfare loss**	☑ **Energy system costs**
	☑ **Consumption loss**	
Trade	☑ **Coal**	☐ Bioenergy crops
	☑ **Oil**	☐ Food crops
	☑ **Gas**	☐ Capital
	☐ Uranium	☑ **Emissions permits**
	☐ Electricity	☐ Non-energy goods

Energy

Model documentation: Energy - WITCH

Resource use	☑ **Coal**	☑ **Uranium**
	☑ **Oil**	☑ **Biomass**
	☑ **Gas**	
Electricity technologies	☑ **Coal**	☑ **Biomass**
	☑ **Gas**	☑ **Wind**
	☑ **Oil**	☑ **Solar PV**
	☑ **Nuclear**	☑ **CCS**
Conversion technologies	☐ CHP	☐ Hydrogen
	☐ Heat pumps	☐ Fuel to gas

	☐ Fuel to liquid	
Grid and infrastructure	☑ **Electricity**	☑ **CO2**
	☐ Gas	☐ H2
	☐ Heat	
Energy technology substitution	☐ Discrete technology choices	☑ **System integration constraints**
	☑ **Expansion and decline constraints**	
Energy service sectors	☑ **Transportation**	☐ Residential and commercial
	☐ Industry	

Land-use

Model documentation: Land-use - WITCH; Non-climate sustainability dimension - WITCH

Land-use	☑ **Cropland**	☑ **Forest**
	Note: Bioenergy related cost and emissions are obtained by an soft linking with the GLOBIOM model.	

Other resources

Model documentation: Non-climate sustainability dimension - WITCH

Other resources	☑ **Water**	☐ Cement
	☐ Metals	

Emissions and climate

Model documentation: Emissions - WITCH; Climate - WITCH

Green house gasses	☑ **CO2**	☑ **HFCs**
	☑ **CH4**	☑ **CFCs**
	☑ **N2O**	☑ **SF6**
Pollutants	☑ **NOx**	☑ **OC**
	☑ **SOx**	☐ Ozone
	☑ **BC**	
Climate indicators	☑ **CO2e concentration (ppm)**	☑ **Temperature change (°C)**
	☑ **Radiative Forcing (W/m^2)**	☑ **Climate damages $ or equivalent**

Model Documentation - WITCH

WITCH (World Induced Technical Change Hybrid) is an optimal growth model of the world economy that integrates into a unified framework the sources and the consequences of climate change. A climate module links GHG emissions produced by economic activities to their accumulation in the atmosphere and the oceans. The effect of these GHG concentrations on the global mean temperature is derived. A damage function explicitly accounts for the consequences of temperature increases on the economic system.

Regions interact with each other because of the presence of economic (technology, exhaustible natural resources) and global environmental externalities. For each region, a forward-looking agent maximises its inter-temporal social welfare function, strategically and simultaneously to other regions. The inter-temporal equilibrium is calculated as an open-loop Nash equilibrium, or, a cooperative solution can also be solved by aggregating the welfare of each region. More precisely, the Nash equilibrium is the outcome of a non-cooperative, simultaneous, open membership game with full information. Through the optimisation process, regions choose the optimal dynamic path of a set of control variables, namely investments in the main economic variables.

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

The official model documentation is available at [1] (http://doc.witchmodel.org)

1) Model scope and methods - WITCH

1.1) Model concept, solver and details - WITCH

General Framework

WITCH (World Induced Technical Change Hybrid) is an optimal growth model of the world economy that integrates in a unified framework the sources and the consequences of climate change. A climate module links GHG emissions produced by economic activities to their accumulation in the atmosphere and the oceans. The effect of these GHG concentrations on the global mean temperature is derived. A damage function explicitly accounts for the effects of temperature increases on the economic system.

Regions interact with each other because of the presence of economic (technology, exhaustible natural resources) and environmental global externalities. For each region a forward-looking agent maximizes its own inter-temporal social welfare function, strategically and simultaneously to other regions. The inter-temporal equilibrium is calculated as an open-loop Nash equilibrium, or, a cooperative solution can also be solved by aggregating the welfare of each regions. More precisely, the Nash equilibrium is the outcome of a non-cooperative, simultaneous, open membership game with full information. Through the optimization process regions choose the optimal dynamic path of a set of control variables, namely investments in key economic variables.

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

Non-cooperative solution

The game theoretic setup makes it possible to capture the non-cooperative nature of international relationships. Free-riding behaviors and strategic inaction induced by the presence of a global externality are explicitly accounted for in the model. Climate change is the major global externality, as GHG emissions produced by each region indirectly impact on all other regions through the effect on global concentrations and thus global average temperature.

The model features other economic externalities that provide additional channels of interaction. Energy prices depend on the extraction of fossil fuels, which in turn is affected by consumption patterns of all regions in the world. International knowledge and experience spillovers are two additional sources of externalities. By investing in energy R&D, each region accumulates a stock of knowledge that augments energy efficiency and reduces the cost of specific energy technologies.

The effect of knowledge is not confined to the inventor region but it can spread to other regions. Finally, the diffusion of knowledge embodied in wind&solar experience is represented by learning curves linking investment costs with world, and not regional, cumulative capacity. Increasing capacity thus reduces investment costs for all regions. These externalities provide incentives to adopt strategic behaviours, both with respect to the environment (e.g. GHG emissions) and with respect to investments in knowledge and carbon-free but costly technologies.

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

1.3) Temporal dimension - WITCH

The base year is 2005. The time horizon is 150 years, with 30 period of 5 year time step.

Longer time horizon can also be run until 2300 to avoid any end-of-horizon effect, but 2150 is generally sufficient.

Results are usually reported for the period 2005-2100.

1.4) Spatial dimension - WITCH

Countries included within the model are grouped into 17 regions clustered by geography, income and the structure of energy demand.

The regional disaggregation is now flexible and the model can be run on different model configurations, typically from 5 to 17 regions, or more.

Figure 1.1: Regions of the WITCH model

The 17 regions are:

Region	Countries
brazil	Brazil
canada	Canada
china	China, including Taiwan
europe	Europe
seasia	South East Asia
india	India
indonesia	Indonesia
jpnkor	Japan and South Korea
laca	Latin America and the Caribbean
mena	Middle East and North Africa
mexico	Mexico
oceania	Australia and New Zealand
sasia	South Asia
ssa	Sub Saharan Africa
southafrica	South Africa
te	Non-EU Eastern European countries, including Russia
usa	United States of America

WITCH features any regional aggregations in the so-called coalitions. Some common coalitions are:

- regional coalitions : each region is mapped to a coalition containing only this region.
- world coalition : a coalition containing all the world regions.

Coalitions and regions interact with each others because of the presence of economic (technology, exhaustible natural resources) and environmental global externalities.

1.5) Policy - WITCH

When no policy is applied, the model is running a business-as-usual (BAU) case, which serves as a reference case with which the results with policy are compared.

WITCH can handle several types of policies:

- Quantitative climate targets on global temperature, on radiative forcing, on atmospheric carbon concentration, on greenhouse gas emissions or on carbon budget. In these case additional constraints are imposed in the model. The resulting carbon mitigation cost can be obtained in terms of loss of consumption or GDP.
- Carbon taxes can be imposed directly in the model, by adding a cost on carbon emissions.
- A carbon market can be activated, with the possibility to allow an to trade of emission permits. The temporal dimension is also taken in to account with the possibility of "banking and borrowing" over time.
- Additional subsidies, taxes and penalty on energies sources can be introduced.

The model is calibrated for some predefined policies: "BAU", "stabilisation at 450ppm", "stabilisation at 535ppm", "radiative forcing target at 3.2 W/m2" and "radiative forcing target at 2.8 W/m2".

2) Socio-economic drivers - WITCH

2.1) Population - WITCH

Population

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

Economic growth

The GDP data for the new base year are from the World Bank Development Indicators 2007, and are reported in 2005 US\$. We maintain the use of market exchange rates (MER). World GDP in 2005 equals to 44.2 Trillions US\$. Although part of the GDP dynamics is endogenously determined in the WITCH model, it is possible to calibrate growth of different countries by adjusting the growth rate of total factor productivity, the main engine of macroeconomic growth.
Economic growth rates and the level of convergence are strong determinants of energy demand and, therefore, GHG emissions. In the model, we depart from existing IPCC scenarios, and base our projections for regional GDP growths on assumptions regarding labour productivity convergence.
OECD countries are assumed to reach a rather constant growth rate while the catch-up of non-OECD is driven by labour productivity which should bring most developing countries closer to the level of OECD countries by the end of the century. The convergence is nonetheless slow in per capita terms given the higher population growth of developing countries. Sub-Saharan Africa, in particular, experiences delays in catch-up. Eastern Europe shows the highest convergence rate. The model is therefore dynamically calibrated to match a growth path consistent with these underlying assumptions on convergence and growth.

3) Macro-economy - WITCH

Production function

The production side of the economy is very aggregated. Each region produces one single commodity that can be used for consumption or investments. The final good is produced using
capital, labour and energy services. In the first place capital and labor are aggregated using a Cobb-Douglas production function. This nest is then aggregated with energy services with a Constant Elasticity of Substitution production function (CES), see Figure 2.3.1 .

The optimal path of consumption is determined by optimising the intertemporal social welfare function, which is defined as the an isoelastic utility function of per capita consumption, weighted by regional population. The pure rate of time is set at 1% per year.

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

Energy used in final production is a combination of electric and non electric energy. Electric energy can be generated using a set of different technology options and non electric energy also entails different fuels. Each region will choose the optimal intertemporal mix of technologies and R&D investments in a strategic way

Figure 2.3.1 The nested production function

4) Energy - WITCH
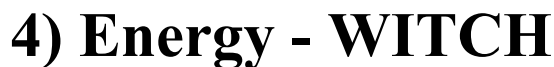
4.1) Energy resource endowments - WITCH

The price of fossil fuels and exhaustible resources (oil, gas, coal and uranium) is also endogenously determined by the marginal cost of extraction, which in turn depends on current and cumulative extraction, plus a regional mark-up to mimic different regional costs. The prices of fossil fuels and exhaustible resources have been revised upwards,

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

- 55 US$/bbl for oil, or roughly 8US$/GJ

- 7.14 US$/GJ for natural gas

- 60 US$/ton for coal, equivalent to 2 US$/GJ. In order to match the large difference in price increases shown in the Enerdata database, we adjust the mark-up prices

- Uranium ore price tripled from 2002 to 2005, and we thus update to this new level. The cost of conversion was increased from 5 US$/kg to 11 US$/kg, while enrichment costs stayed roughly constant. We thus slightly increased the cost of conversion and enrichment from 221 to 230 1995 US$/kg.

Country specific mark-ups are set to reproduce regional figures from IEA (2007). Concerning bioenergies, biofuels supply curves are exogenously set. They have been computed from the outcomes of the GLOBIOM model.

4.2) Energy conversion - WITCH

4.2.1) Electricity - WITCH

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

All the main technology features are represented: yearly utilisation factors, fuel efficiencies, investment, and operation and maintenance costs. For CCS, supply costs of injection and sequestration reflect sites? availability at the regional level, as well as energy penalty, capture and leakage rates. IGCC-CCS competes with traditional coal which is replaced for a sufficiently high carbon price signal. For nuclear power, waste management costs are also modeled, but no exogenous constraint is assumed. Hydroelectric power is assumed to evolve exogenously to reflect limited site availability. Breakthrough in power generation technologies is modelled by introducing a backstop technology, that can be better thought of as a compact representation of a portfolio of advanced technologies that can substitute nuclear power.

The cost of electricity generation is endogenous and it combines capital costs, O&M expenditure and the expenditure for fuels.

Despite the detailed description of the power generation sub-sector, not all types of power plants are modeled explicitly in WITCH (for instance, the model does not distinguish gas with no combined cycle). We therefore assume the standard use of factors for new power plants. This assumption helps us to avoid accounting difficulties for multi-fuel and marginal power plants. Efficiency of fuel consumption in power generation plants are close to the implied values in the new Enerdata database. Following recent debates over the technical feasibility, the investment costs for Integrated Gasification Combined Cycle (IGCC) technologies is 3170 US$ 2005/kW.

We assume the average efficiency of gas and coal power plants improves autonomously to 60% and 45%, respectively, over the next decades. Similarly, the utilisation factor of Wind&Solar is assumed to increase from 2500 to 3500 hours per year within a 30-year time frame.

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

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

4.2.2) Heat - WITCH

Heat production (centralized or decentralized) is not explicitly modelled.

4.2.6) Grid, pipelines and other infrastructure - WITCH

Grid and infrastructure are not explicitly modelled in the model WITCH. However, the installation of renewable power plants are subject to system integration constraints to address the reliability of the electric grid.

4.3) Energy end-use - WITCH

4.3.1) Transport - WITCH

The transport sector is part of the non-electric sector.

Light Duty Vehicles

WITCH model has been designed to incorporate a range of competing vehicle types to assist in the determination of the dominant modes of light duty vehicles LDV transport that will tend to be selected to adequately satisfy demand for mobility.

Transport has been included in the model through the incorporation of the impact of investments in LDVs and fuel expenditures on the level of consumption. This means that increased LDV travel (in terms of kilometres travelled per vehicle) as well as the costs of the vehicle and fuel expenditure directly impact utility through the corresponding effect of decreasing consumption on other goods and services.

Demand for vehicles is set exogenously based on the assumption that constant travel patterns correspond to given levels and growth rates of GDP and population. This assumption is important as the demand for private transport will likely continue to be high and have a strong correlation with national income, unless a significant change in the way public transport is provided occurs.

The possibility of introducing a "Travel Elasticity Switch" and a ?"Vehicle - ownership Elasticity Switch" provides feedback effects which test the sensitivity of these constraints (these elasticity impacts will be reviewed in future and are not imposed within this analysis). Figure 3.3.1 shows the transportation module within the WITCH model structure. As noted, the model separates consumption in transport from the rest of consumption, which allows for the direct modelling of the costs involved in switching between vehicles and fuels for a given demand of mobility. Investments in vehicle capital and supplementary costs decrease the level of consumption. A Leontief production function (LDV Trans in Figure 3.3.1) represents the fixed proportions of operation & maintenance (O&M) costs, fuel and investment cost required for each technological type. Fuel demand and fuel category depend upon the vehicle chosen.

Figure 3.3.1 The transport module
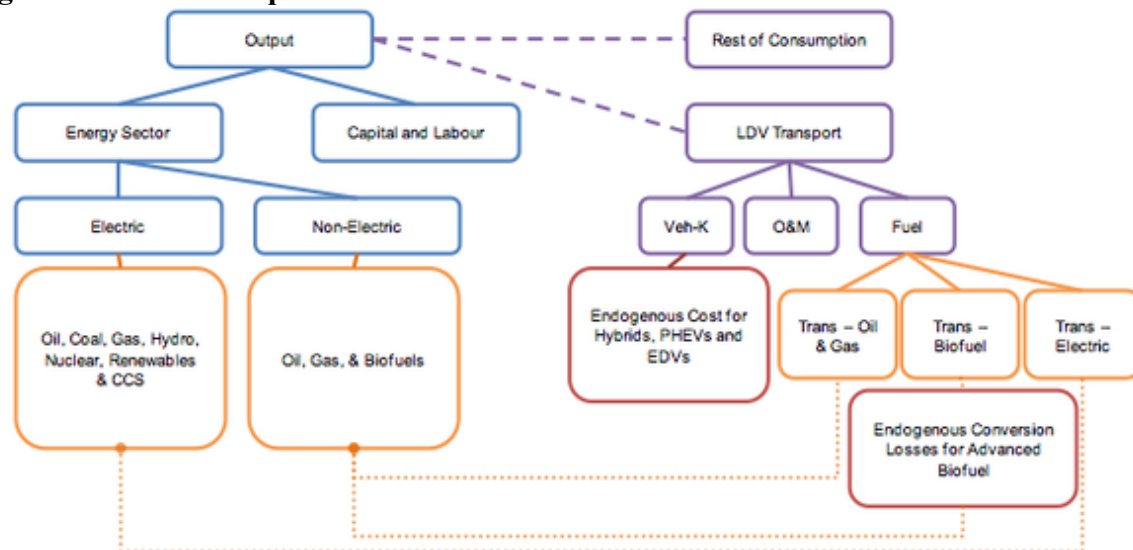
4.3.2) Residential and commercial sectors - WITCH

The residential and commercial sector is not detailed in WITCH. It is part of the Non-electric sector

4.3.3) Industrial sector - WITCH

The industrial sector is not detailed in WITCH. It is part of the non-electric sector, see the Non-electric sector section .

4.3.4) Other end-use - WITCH

Non-electric sector

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

Biofuels consumption is currently low in all regions of the world and the overall penetration remains modest over time given the conservative assumptions on their large scale deployment.

4.4) Energy demand - WITCH

The energy service demand is part of the Constant Elasticity of Substitution production function. Energy services have endogenous improvements in energy efficiency. Energy efficiency increases with investments in dedicated energy R&D, which build up the stock of knowledge. The stock of knowledge can then replace (or substitute) physical energy in the production of energy services.

The energy demand is mainly determined by the economic growth, which is calibrated from the growth rate of total factor productivity.

4.5) Technological change in energy - WITCH

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

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

International spillovers of knowledge and experience

Learning processes via knowledge investments and experience are not likely to remain within the boundaries of single countries, but to spill to other regions too. The effect of international spillovers is deemed to be important, and its inclusion in integrated assessment models desirable, since it allows for a better representation of the innovation market failures and for specific policy exercises.

The WITCH model is particularly suited to perform this type of analysis, since its game theoretic structure allows distinguishing first- and second-best strategies, and thus to quantify optimal portfolios of policies to resolve all the externalities arising in global problems such as climate change.

WITCH features spillovers of experience for Wind&Solar in that the Learning-by-Doing effect depended on world cumulative installed capacity, so that single regions could benefit from investments in virtuous countries, thus leading to strategic incentives. An enhanced version was developed to include spillovers in knowledge for energy efficiency improvements.

Energy knowledge depends not only on regional investments in energy R&D, but also on the knowledge stock that has been accumulated in other regions. Similarly to the Learning-By-Doing for Wind&Solar, WITCH assumes experience accrues with the diffusion of technologies at the global level. We also assume knowledge spills internationally. The amount of spillovers entering each world region depends on a pool of freely available knowledge and on the ability of each country to benefit from it, i.e. on its absorption capacity. Knowledge acquired from abroad combines with domestic knowledge stock and investments and thus contributes to the production of new technologies at home.

5) Land-use - WITCH

Land-use in WITCH is taken into account through soft-linking the model to the GLOBIOM (http://www.globiom.org/) model. Given the importance of land use emissions, of the link between agriculture, biomass energy and forest management, modelling land-use is of key importance in integrated assessment models. Rather than being modelled in its full detail, land-use in WITCH is represented by the mean response functions produced by the Global Biosphere Management Model (GLOBIOM) land-use model (Havlik et al. 2014). GLOBIOM is a partial equilibrium model that covers agriculture and forestry, including bioenergy. It is used for analysing land-use scenarios over many years. In GLOBIOM, the world is divided into 30 economic regions, in which consumer behaviour is modelled through isoelastic demand functions. Commodity uses "Simulation Units", which are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class in the same country. For crops, grass, and forest products, Leontief production functions covering alternative production systems are calibrated from biophysical models including EPIC (Izaurralde et al. 2006). Economic optimization is based on a spatial equilibrium approach and regional price-quantity equilibria are computed.

5.2) Forestry - WITCH

Forestry is an important contributor of CO2 emissions and, similarly to non-CO 2 gases, it might provide relatively convenient abatement opportunities. Forestry sector models differ substantially from energy-economy ones, so that normally the interaction is solved via soft link (e.g. iterative) coupling. WITCH is enhanced with baseline emissions and supply mitigation curves for reduced deforestation. The focus is on REDD given its predominant role in CO2 emissions and the policy importance of this option as stressed in the 2007 Bali Action Plan.

Baseline emissions are provided by the Brent Sohngen GTM model. REDD supply mitigation cost curves have been built and made suitable to be incorporated in the WITCH model.
Two versions of abatement cost curves have been incorporated in the model representing two extreme cases. The first version includes abatement curves for the whole century for the Brazilian tropical forest only and have been developed using Brazil?s data from the Woods Hole Research Center. A second version includes abatement curves for all world tropical forests, based on the Global Timber Model of Brent Sohngen, Ohio State University, used within the Energy Modeling Forum 21 and data from the IIASA cluster model.

6) Emissions - WITCH

6.1) GHGs - WITCH

CO2 emissions

Energy-related and land-use CO2 emissions have a detailed representation in the WITCH model.

non-CO2 emissions

Non-CO2 GHGs are important contributors to global warming, and might offer economically attractive ways of mitigating it. WITCH models explicitly emissions of CH4, N2O, SLF (short-lived fluorinated gases, i.e. HFCs with lifetimes under 100 years) and LLF (long-lived fluorinated, i.e. HFC with long lifetime, PFCs, and SF6). We also distinguish SO2 aerosols, which have a cooling effect on temperature. Since most of these gases are determined by

agricultural practices, we rely on estimates for reference emissions and a top-down approach for mitigation supply curves. For the baseline projections of non-CO2 GHGs, we use EPA regional estimates (EPA, 2012). The regional estimates and projections are available until 2020 only: beyond that date, we use growth rates for each gas as specified in the IIASA-MESSAGE-B2 scenario, which has underlying assumptions similar to the WITCH ones. SO2 emissions are taken from MERGE v5 and MESSAGE B2: given the very large uncertainty associated with aerosols, they are translated directly into the temperature effect (cooling), so that we only report the radiative forcing deriving from GHGs. In any case, sulphates are expected to be gradually phased out over the next decades, so that eventually the two radiative forcing measures will converge to similar values.

6.2) Pollutants and non-GHG forcing agents - WITCH

The WITCH model represents the black carbon (BC), carbon monoxide (CO), ammoniac (NH3), nitrogen oxides (NOx), organic carbon (OC), sulfur dioxide (SO2), volatile organic compounds (VOCs).

The air quality module relates the pollution economic activities to emission levels of the most important air pollutants. It allows the assessment of air pollution emissions in baseline scenarios or under a climate or pollution regulation scenario. The implementation originates from the LIMITS project and its emission factors have been calculated from the GAINS model in the context of the EMF30 exercise. In the WITCH model we use information on both fuel use and the type of electricity generation technologies employed.

In WITCH we do not model all the activities that generate air pollution, therefore the non-energy-related pollution is accounted for exogenously. For this non-modelled sector the emissions are taken directly from available databases and mapped into the (SNAP sectors), which are generally sector categories for reporting air pollutant levels. The emissions of the exo-sectors (sectors that are related to energy but are not accounted in the model directly, see the table in appendix), from the EMF30 database. The non-energy sectors, such as solvents, waste (landfills, waste water, non-energy incineration), agriculture waste burning on fields, agriculture, Grassland burning and Forest burning and the ammonia emissions follow the RCP8.5 emissions from the RCP database.

6.3) Carbon dioxide removal (CDR) options - WITCH

The CDR options modelled in WITCH are BECCS and Direct Air Capture (DAC).

7) Climate - WITCH

WITCH included an internal climate module, which translates the regional emissions into global temperature through atmospheric concentrations. It has been building upon the DICE climate equations (Nordhaus and Sztorc 2013). Alternatively, and to make the climate outcome comparable with other models, it allows a soft link with the MAGICC6 climate model (Meinshausen, Raper, and Wigley 2011) for reporting a number of climate outcomes based on this widely used model.

7.1) Modelling of climate indicators - WITCH

World GHG emissions

The regional emissions are collected into the world emission and converted into CO2 equivalent using the the global warming potentials over a time horizon of 100 years (AR4 IPCC report,2007).

Carbon-cycle

The carbon-cycle model is a 3-layer linear model calibrated to MAGICC. The carbon dioxide emissions go into the atmosphere box and alter the atmospheric carbon concentration, then the carbon is exchanged through the ocean-biosphere-atmosphere carbon fluxes. The ocean carbon sink is divided in two layers: the upper layer u (shallow oceans) and the lower layer l (deep oceans). In this representation, the upper layer also includes the biosphere. The CO2 atmospheric concentrations are computed by the carbon-cycle equations.

Accumulation of non-CO2 GHG in the atmosphere

The non-CO2 greenhouse gases are accumulated in the atmosphere using a decay function given a yearly retention factor, and a constant one-period retention factor. These function are calibrated on a stock of the greenhouse gas at equilibrium, which is not subject to decay.

Radiative forcing

The CO2 radiative forcing is calculated according to the TAR expression, proportional to the natural logarithm of the ratio of the current concentration to preindustrial level. While the radiative forcing of the greenhouse gases CH4 and N2O are interdependent and have a complex formulation, WITCH uses an approximation as in the MERGE model v5. The radiative forcing of short-lived and long-lived F-gases are proportional to the concentration levels. Exogenous radiative forcing from aerosols is coming from the RCP3D scenario, and the exogenous radiative forcing from ozone depletion substances (ODS) is also coming from the RCPs scenarios. The radiative forcing of all greenhouse gases are summed up to compute the total radiative forcing.

Global temperature increase from pre-industrial levels

The global temperature increase from pre-industrial level is obtained from an energy balance 2-layer model with two major coefficients: the atmosphere ocean exchange coefficient and the climate sensitivity.

8) Non-climate sustainability dimension - WITCH

8.1) Air pollution and health - WITCH

The WITCH air pollution module relates the pollution economic activities to emission levels of the most significant air pollutants. It allows the assessment of air pollution emissions in baseline scenarios or under a climate or pollution regulation scenario.

Implementation

The implementation originates from the LIMITS project (http://www.feem-project.net/limits) and Its emission factors have been calculated from the GAINS model (http://gains.iiasa.ac.at/models) in the context of the EMF30 (https://emf.stanford.edu/projects/emf-30-short-lived-climate-forcers-air-quality) exercise. In the WITCH model we use information on both fuel use and the type of electricity generation technologies employed to compute the

emissions E of pollutant p at time period t according to where ef is the emission factor related

to activity, A of sector j. We consider the air pollutants p: carbon monoxide CO, methane CH4, black carbon BC, organic carbon OC, sulfur dioxide SO2, nitrogen oxides NOx, ammonia NH3 and volatile organic compounds VOC.

The emission factors *ef* are calculated using the ratio of emissions(E) over activities(A) provided by GAINS, these are at a first stage aggregated over the WITCH sectors (see sector mapping on the Appendix),

where *j* are the WITCH sectors and *p* is the pollutant.

The emission factors are then aggregated into the WITCH regions, using the mean weighted by country's level of CO_2 emissions.

In WITCH we do not model all the activities that generate air pollution, therefore the non-energy related pollution is accounted for exogenously. For this non-modelled sectors the emissions are taken directly from available databases and mapped into the (SNAP sectors (http://www.emep.int/UniDoc/node7.html)), which are sector categories for reporting air pollutant levels. The emissions of the exo-sectors (sectors that are related to energy but are not accounted in the model directly, see the table in Appendix), from the EMF30 database. The non-energy sectors, such as Solvents, Waste (landfills, waste water, non-energy incineration), Agriculture waste burning on fields, Agriculture, Grassland burning and Forest burning and the emissions of ammonia follow the RCP8.5 emissions from the RCP (http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome)) database.

Air Pollution Policies

Air pollution emissions depend on two important factors, the activity level of the pollutant sector, and the emission factor of that given activity. Therefore the implementation of policies can be done via structural measures, such as changes in the model endogenous activities, or via air pollution controls. the latter is undertaken by controlling the emission factor *ef* for activity category *j* and for pollutant *p*.

Accordingly, the *ef* are defined per air pollution scenario/baseline/policy, which corresponds to different levels of control, also called End-of-Pipe (EOP), measures. The air pollution scenarios are CLE (current legislation), SLE (stringent legislation) and MFR (maximum feasible reduction). The CLE scenario corresponds to the implementation until 2030 of all the legislation already (in 2013) foreseen and/or enforced for that period; The SLE scenario foresees the implementation of 75% of the MFR scenario which corresponds to the maximal technological frontier of EOP.

For the exogenous sectors the implementation of policies has to be carried out via emission pathways.

9) Appendices - WITCH

10) References - WITCH

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