To pdf - IMACLIM

From IAMC-Documentation

Reference card - IMACLIM

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 IMACLIM- R I.0

Institution and users Centre international de recherche sur l'environnement et le développement (CIRED), France, http://www.centre-cired.fr.
Societe de Mathematiques Appliquees et de Sciences Humaines (SMASH), France, http://www.smash.fr.

Documentation IMACLIM documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - IMACLIM

Objective Imaclim-R is intended to study the interactions between energy systems and the economy, to assess the feasibility of low carbon development strategies and the transition pathway towards low carbon future.

Concept Hybrid: general equilibrium with technology explicit modules. Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between two years parameters to the equilibrium evolve according to specified functions.

Solution method Imaclim-R is implemented in Scilab, and uses the fonction fsolve from a shared C++ library to solve the static equilibrium system of non-linear equations.

Anticipation Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between two years parameters to the equilibrium evolve according to specified functions.

Temporal dimension Base year:2001, time steps:Annual, horizon: 2050 or 2100

Spatial dimension Number of regions:12

1. USA
2. Canada
3. Europe
4. China
5. India
6. Brazil
7. Middle East
8. Africa
9. Commonwealth of Independant States
10. OECD Pacific
11. Rest of Asia
12. Rest of Latin Amercia

Policy implementation Baseline do not include explicit climate policies. Climate/energy policies can be implemented in a number of ways, depending on the policy. A number of general or specific policy choices can be modelled including: Emissions or energy taxes, permit trading, specific technology subsidies, regulations, technology and/or resource constraints

Socio economic drivers

Model documentation: Socio-economic drivers - IMACLIM

Exogenous drivers

- ☐ Exogenous GDP
- ☐ Total Factor Productivity
- ☑ **Labour Productivity**
- ☐ Capital Technical progress
- ☑ **Energy Technical progress**
- ☐ Materials Technical progress
- ☐ GDP per capita
- ☑ **Population**
- ☑ **Active Population**

Note: Our model growth engine is composed of exogenous trends of active population growth and exogenous trends of labour productivity growth. The two sets of assumptions on demography and labour productivity, although exogenous, only prescribe natural growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labor and capital).

Development

- ☑ **GDP per capita**
- ☐ Income distribution in a region
- ☐ Urbanisation rate
- ☐ Education level
- ☐ Labour participation rate

Macro economy

Model documentation: Macro-economy - IMACLIM

Economic sectors

- ☑ **Agriculture**
- ☑ **Industry**
- ☑ **Energy**
- ☑ **Transport**
- ☑ **Services**
- ☑ **Construction**

Note: The energy sector is divided into five sub-sectors: oil extraction, gas extraction, coal extraction, refinery, power generation. The transport sector is divided into three sub-sectors: terrestrial transport, air transport, water transport. The industry sector has one sub-sector: Energy intensive industry.

Cost measures

- ☑ **GDP loss**
- ☑ **Welfare loss**
- ☑ **Consumption loss**
- ☐ Area under MAC

	☑ **Energy system costs**	
Trade	☑ **Coal** ☑ **Oil** ☑ **Gas** ☐ Uranium ☑ **Electricity** ☑ **Bioenergy crops**	☐ Food crops ☑ **Capital** ☑ **Emissions permits** ☑ **Non-energy goods** ☑ **Refined Liquid Fuels**

Energy

Model documentation: Energy - IMACLIM

Behaviour	Price response (via elasticities), and non-price drivers (infrastructure and urban forms conditioning location choices, different asymptotes on industrial goods consumption saturation levels with income rise, speed of personal vehicle ownership rate increase, speed of residential area increase).	
Resource use	☑ **Coal** ☑ **Oil** ☑ **Gas**	☐ Uranium ☑ **Biomass**
Electricity technologies	☑ **Coal** ☑ **Gas** ☑ **Oil** ☑ **Nuclear**	☑ **Biomass** ☑ **Wind** ☑ **Solar PV** ☑ **CCS**
Conversion technologies	☐ CHP ☐ Heat pumps ☐ Hydrogen	☐ Fuel to gas ☑ **Fuel to liquid**
Grid and infrastructure	☑ **Electricity** ☐ Gas ☐ Heat	☐ CO2 ☐ H2
Energy technology substitution	☑ **Discrete technology choices** ☑ **Expansion and decline constraints**	☑ **System integration constraints**
Energy service sectors	☑ **Transportation** ☑ **Industry**	☑ **Residential and commercial** ☑ **Agriculture**

Land-use

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

Land-use	☑ **Cropland** ☑ **Forest** ☑ **Extensive Pastures** ☑ **Intensive Pastures**	☑ **Inacessible Pastures** ☑ **Urban Areas** ☑ **Unproductive Land**	*Note: Bioenergy production is determined by the fuel and electricity modules of Imaclim-R using supply curves from Hoogwijk et al. (2009) (bioelectricity) and IEA (biofuel). Bioenergy production is then exogenously incorporated into the land-use module. The demand for biofuel is aggregated to the demand for food crops, while the production of biomass for electricity is located on marginal lands (i.e., less fertile or accessible lands). By increasing the demand for land, and spurring agricultural intensification, Bioenergy propels land and food prices.*

Other resources

Model documentation: Non-climate sustainability dimension - IMACLIM

Other resources	☐ Water ☐ Metals	☐ Cement

Emissions and climate

Model documentation: Emissions - IMACLIM; Climate - IMACLIM

Green house gasses	☑ **CO2** ☐ CH4 ☐ N2O	☐ HFCs ☐ CFCs ☐ SF6	*Note: The non-CO2 forcing agents that are not explicitly tracked are represented in the climate module by an exogenously given additional forcing factor.*
Pollutants	☐ NOx ☐ SOx ☐ BC	☐ OC ☐ Ozone	
Climate indicators	☐ CO2e concentration (ppm) ☐ Radiative Forcing (W/m^2)	☐ Temperature change (°C) ☐ Climate damages $ or equivalent	

Model Documentation - IMACLIM

The IMACLIM-R model is a hybrid dynamic general equilibrium model of the world economy that covers the period 2001–2100 in yearly steps through the recursive iteration of annual static equilibria and dynamic modules. The annual static equilibrium determines the relative prices, wages, labour, value, physical flows, capacity utilization, profit rates, and savings at a year t as a result of short-term equilibrium conditions between demand and supply of goods, capital, and labour markets. The dynamic modules are sector-specific reduced forms of technology-rich models, which take the static equilibria at a year *t* as an input, assess the reaction of technical systems to the economic signals, and send new input–output coefficients back to the static model to allow computation of the equilibrium for year *t + 1*. IMACLIM-R is part of the IMACLIM suite of models, further information on which is available on the IMACLIM (http://www.imaclim.centre-cired.fr/Imaclim) homepage.

1) Model scope and methods - IMACLIM

The Imaclim-R model (Sassi et al., 2010 [1]; Waisman et al., 2012[2]), is a multi-region and multi-sector model of the world economy. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. Furthermore, it describes growth patterns in second best worlds with market imperfections, partial uses of production factors and imperfect expectations.

Table 1 shows a list of references involving IMACLIM-R categorized as follows:

1. References describing the structure and results obtained with the Imaclim-R Global model
2. References to models comparison exercises in which Imaclim-R Global model has participated

The references in Table 1 are further divided by technology, behaviour etc. focus.

Table 1: Articles describing IMACLIM and MIP's in which it has been involved

	Description of Imaclim-R structure and results	Models comparison (including Imaclim-R)
Technologies	Bibas and Méjean (2014)[1] (bioenergy)	Kim et al. (2014)[2] (nuclear) Koelbl et al. (2014)[3] (CCS) Krey et al. (2014)[4] Kriegler et al. (2014)[5] Luderer et al. (2014)[6] (renewables) Rose et al. (2014)[7] (bioenergy) Tavoni et al. (2012)[8]
Energy efficiency	Bibas et al. (2015)[9]	Sugiyama et al. (2014)[10]
Fossil fuels	Rozenberg et al. (2010)[11] Waisman et al. (2012)[12] Waisman et al. (2013a)[13]	Bauer et al. (2015)[14] MCCollum et al. (2014)[15]
Transport	Waisman et al. (2013b)[16]	
Macroeconomy	Crassous et al. (2006)[17] (endogenous structural change) Guivarch et al. (2011)[18] (labor markets)	
Evaluation of model	Guivarch et al. (2009)[19] (backcasting)	Kriegler et al. (2015b)[20] (diagnostics)
Scenarios	Guivarch and Mathy (2012)[21] Hamdi-Cherif et al. (2011)[22] Mathy and Guivarch (2010)[23] Rozenberg et al. (2014)[24] Waisman et al. (2014)[25]	Blanford et al. (2014)[26] Kriegler et al. (2015)[27] Luderer et al. (2012a)[28] Luderer et al. (2012b)[29] Riahi et al. (2015)[30]

1.1) Model concept, solver and details - IMACLIM

A hybrid modelling structure to study the interactions between the evolutions of energy systems and economic growth

Assessing the intertwined evolution of technical systems, energy demand behaviors and economic growth, as well as the costs and benefits of transitions to low carbon economies is a major challenge for economic modeling. Ideally, models should (i) be framed in a consistent macroeconomic framework, (ii) include the relevant technical constraints in each sector, such as views about the direction of technical change, (iii) capture the key relationships between economic activity and the environment, e.g., energy and natural resources consumption or greenhouse gases emissions, (iv) have a horizon long enough to assess 'sustainability- a long-term horizon which also implies, incidentally, that the model must be able to represent structural and technical change, yet (v) recognize short-term economic processes critical for assessing transition pathways, such as market imbalance and rigidities.

No model in existence today meets all of these specifications. In fact, current models can be classified along two major fault lines: bottom-up vs. top-down, and long-term vs. short-term.

By design, computable general equilibrium (CGE) models which are classed as top-down, provide a comprehensive macroeconomic framework (i); but they typically adopt oversimplified representations of technical constraints and then fail to explicitly include their interactions with growth trajectories. Conversely, bottom-up engineering models provide a detailed account of technical potentials and limitations (ii), but their macro-engine, if existing at all, is most often rudimentary. Emerging 'hybrid' models developed in the context of climate policy assessment are steps towards addressing these drawbacks. A similar dichotomy occurs with regard to the time horizon. Growth models in the *Solow* tradition are designed to capture key features of long-term development paths (iv), but they do not include short- or medium-term economic processes such as market rigidities (v). On the other hand, short-term models (econometric or structural) will meet requirement (v) but are not designed to project far into the future. Emerging models thus include short/medium-term processes into their analysis of growth in the long-run, although this remains an open research field.

The IMACLIM modelling platform, developed at CIRED, is a step towards the five-point specification outlined above. It comprises a hybrid structure that combines a multi-sectorial top-down macroeconomic framework with bottom-up modules for each sector. A key feature of IMACLIM is its dual representation of economic flows in monetary flows (e.g., euros or dollars) and in physical quantities (e.g., MToe for energy, passenger.km for mobility). This dual representation allows for explicit representation of the material and technological content of economic activity and endogenization of the interactions between these technical dimensions and growth trajectories: the projected economy is supported by a realistic technical background (in the engineering sense) and, conversely, that projected technical systems are bounded by realistic economic flows and consistent sets of prices. This modeling principle facilitates interaction between technical and economic considerations and allows in particular a detailed representation of sectorial characteristics.

A recursive and modular simulation architecture capturing inertias and imperfect foresight

IMACLIM-R models the evolution of the economy over the period 2001-2100, in one year time steps.

Technically, the model can be labelled as a recursive dynamic simulation framework, since it generates an energy-economy trajectory by solving a sequence of yearly static equilibria of the economy, interlinked by dynamic modules. The recursive structure organizes a systematic exchange of information between a top-down annual static equilibrium providing a snapshot of the economy, and bottom-up dynamic modules providing information on the evolution of technical parameters between each annual equilibria as depicted in Figure 1.

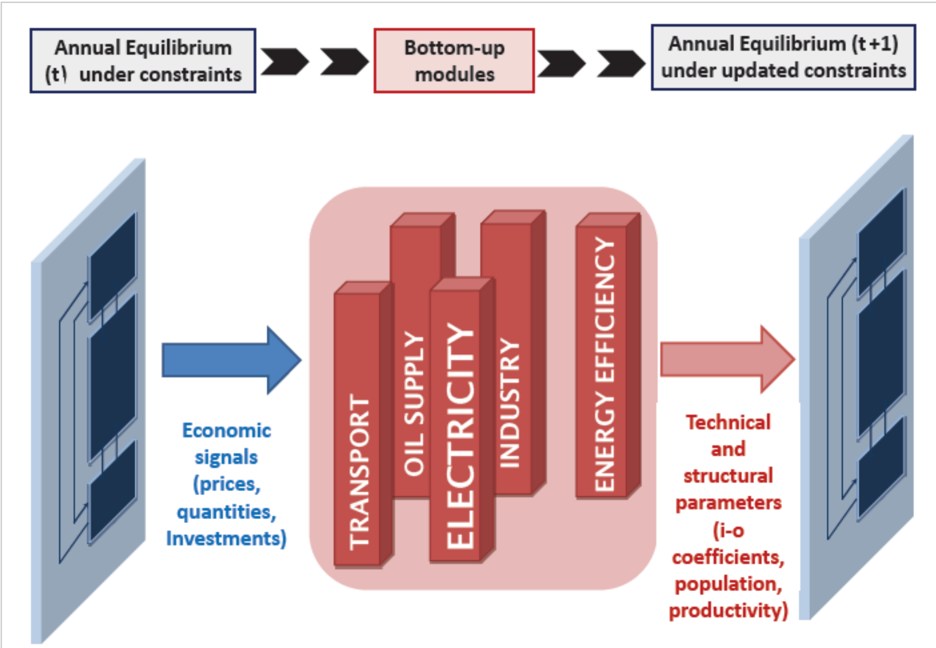

Figure 1: The recursive and modular architecture of the Imaclim-R hybrid model

For each annual static equilibrium, domestic and international markets (besides markets for *factors* such as capital and labour) are fully cleared by a unique set of relative prices that depend on the behaviours of representative agents (producers, households, states) on the demand and supply sides. The calculation of this annual equilibrium determines the following variables: relative prices, wages, labour, quantities of goods and services including energy, value flows, physical flows and capacity utilization.

Households choose their consumption of goods and services to maximize their current utility under both income and time constraints; the former is the sum of wages, capital returns and transfers whereas the latter controls the total time spent in transportation.

The behaviour of producers is not represented by a flexible production function allowing for substitution between factors, as is common practice. Instead, these substitutions occur between two equilibria in sector-specific dynamic modules. Producers are therefore assumed to operate under short-run constraints of (i) a fixed maximal production capacity $Cap_{k,i}$, defined as the maximum level of physical output achievable with the equipment installed, and (ii) fixed input-output coefficients representing that with the current set of installed technologies, producing one unit of a good i in region k requires fixed physical amounts $IC_{j,i,k}$ of intermediate goods j and of labour $l_{k,i}$. In this context, the only room for manouvre producers have is to adjust the utilisation rate $Q_{k,i}/Cap_{k,i}$ according to the relative market prices of inputs and output, taking into account decreasing static returns when capacity utilization approaches saturation. Following (Corrado and Mattey, 1997[3]), decreasing returns reflect the higher labor costs associated to overtime extra-hour, costly night work and increasing maintenance works when capacity utilization approaches saturation. Producers determine their prices using a marginal rate over and above production costs (mark-up) to capture the effect of imperfect competition. The mark-ups are exogenous except in the energy sector where they are endogenous to reflect (a) the market power of fossil fuel producers, (b) specific pricing principles in the power sector (e.g., mean cost pricing), and (c) the different margins over the three inputs for liquid fuels production (oil, biomass, coal). This represents a different paradigm from usual production specifications e,g, with constant elasticity of substitution KLEM production functions, since the 'capital' factor is not always fully utilized.

Total demand for each good (the sum of households' consumption, public and private investments and intermediate uses) is satisfied by a mix of domestic production and imports. For non-energy goods, we adopt Armington specifications (Armington, 1969[4]) to capture the partial substitutability between domestic and foreign goods, while for energy goods (in MToe) physical accounting makes them fully substitutable. All intermediate and final goods are internationally tradable. Domestic as well as international markets for all goods are cleared (i.e. no stock is allowed) by a unique set of relative prices and this determines the utilization rate of production capacities. The partial utilization rate of production capacities allows the represention of operational flexibility through early retirement of those capacities which, although installed, are not used for actual production because they are not competitive in current economic conditions.

Between annual equilibria, dedicated modules describe the investments choices and the evolution of preferences, techniques and land uses; thereby updating the next equilibrium parameters at t+1 (installed production capacities, households equipment, the installed technologies represented by the input-output coefficients).

The equilibrium values of all variables from previous equilibria serve as signals for agents' decisions represented in the dynamic modules. Therefore decisions are taken with no perfect foresight of future values.

Within the dynamic modules, technical choices are available, however only marginal changes in the input-output coefficients embodied in existing equipment vintages (arising from past technical choices) are possible/allowed.

The dynamic modules represent the evolution of technical coefficients resulting from agents' microeconomic decisions on technological choices, under the limits imposed by the *innovation possibility frontier,* IPF, (Ahmad, 1966[5]). They embed a) sectoral level information on economies of scale, learning-by-doing mechanisms and saturation in efficiency progress, and b) expert views about the asymptotes of ultimate technical potentials, the impact of incentive systems, and the role of market or institutional imperfections. The new investment choices and technical coefficients are then sent back to the static module in the form of updated production capacities and input-output coefficients to calculate the t+1 equilibrium.

This general putty-clay representation with fixed technical content of installed capital, is critical to the representation of inertia in technical systems. It allows for distinction between short-term rigidities and long-term flexibilities (Johansen, 1959[6]).

Summary

The IMACLIM-R model endogenizes the rate and direction of technical change by representing the bottom-up impact of investment decisions on the deployment of technical systems. The consistency of the top-down/bottom-up communication is guaranteed by a hybrid structure representing the economy in money values and physical quantities (Hourcade et al, 2006[7]). This dual accounting, following the Arrow-Debreu framework (Arrow and Debreu, 1954[8]), ensures that the projected economy is supported by a realistic technical background and, conversely, that projected technical systems correspond to realistic economic flows and consistent sets of relative prices.

Practical implementation

Imaclim-R is implemented in Scilab, and uses a C solver to solve the static equilibrium system of non-linear equations.

1.3) Temporal dimension - IMACLIM

Imaclim-R model is calibrated in 2001. Its study horizon is 2050 or 2100, and it has a yearly time step.

1.4) Spatial dimension - IMACLIM

Imaclim-R is a global model of the world economy, divided into the following 12 regions and shown in Figure 2:

- USA
- Canada
- Europe
- OECD Pacific
- Former Soviet Union
- China
- India
- Brazil
- Middle East
- Africa
- Rest of Asia
- Rest of Latin America

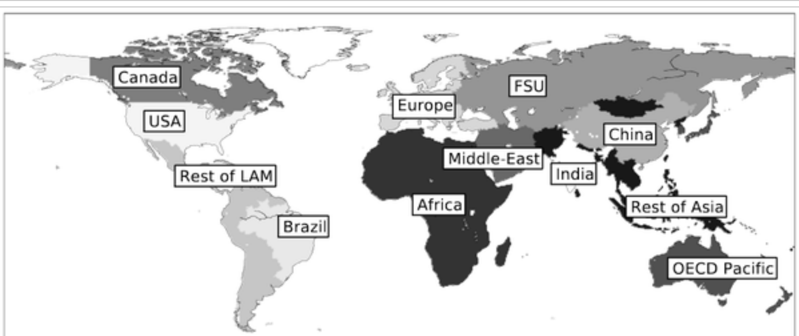

Figure 2: Regional disaggregation of Imaclim-R model. OECD Pacific includes Australia, New Zealand, Japan and South Korea. FSU = Former Soviet Union, Rest of LAM = Rest of Latin America

1.5) Policy - IMACLIM

Baselines do not include explicit climate policies.

A number of general or specific climate/energy policies can be modelled, including:

- Taxes on emissions or energy, either global or differentiated by (group(s) of) regions. Alternative uses of tax revenues (e.g. redistributed in a lump-sum manner to households, used to reduce other pre-existing taxes, etc.) can be studied.
- Emissions permit trading via global or regional schemes. Alternatives on the allocation of permits (i.e. free allocation vs. auctioning, alternative allocation schemes across regions, such as grandfathering, per capita allocation, contraction and convergence, etc.) can also be studied.
- Specific technology subsidies or regulations.
- Technology and/or resource constraints.

2) Socio-economic drivers - IMACLIM

This section describes how change in population (exogenous) and GDP (endogenous) are modelled in IMACLIM-R.

2.1) Population - IMACLIM

In IMACLIM-R model population growth is taken from exogenous demographic trends (by default, UN World Population Prospects, medium scenario, United Nations, 2005)[9].

2.2) Economic activity - IMACLIM

Modelling economic growth

An exogenous growth engine composed of demography and labour productivity growth

The IMACLIM-R model growth engine is composed of exogenous demographic trends (See section on Population) and exogenous trends in labor productivity, as proposed in Solow's neoclassical model of economic growth (Solow 1956)[10]. To build these labor productivity trends we draw on stylized facts from the literature, in particular the convergence assumption (Barro and Sala-i-Martin 1992)[11] and two empirical analyses on economic convergence, one investigating past trends by Maddison (1995)[12], and another by Martins and al. (2005)[13] looking at future trends. In the default parameterization of the model, we retain a 'leader', the US, whose labor productivity growth trend lies between 2% in the short run and 1.65% in the long run. The trends in labor productivity of the other regions catch up with that of the leader over time, i.e. their growth in labor productivity is higher the further their level of absolute labor productivity is from the leader's. All sectors within one region exhibit the same growth in labor productivity, while the respective initial levels are sector and region specific

The two sets of assumptions on demography and labor productivity growth describe natural growth (Phelps, 1961)[14], i.e. the growth rate that an aggregated one-sector economy would follow under full employment of factors of production.

Realized GDP growth is endogenous

In this multi-sectoral framework of Imaclim-R, with partial use of factors of production, the effective economic growth rate may depart from the exogenous natural growth rate trend. The structure and rate of realized growth are endogenously determined by: (i) the allocation of labor force across sectors, which is itself governed by the final demand of these sectors, and (ii) the evolution in unemployment rates, which also result from the final demand of these sectors and the constraints of installed productive capacities and their technical characteristics.

First, the twelve production sectors have different productivities, captured by unitary labor requirements for a unit of production. Therefore the effective labor productivity of the economy depends on the allocation of the labor force among production sectors. For instance, the overall productivity of labor increases through structural changes that favour the reallocation of labor towards highly productive sectors. In that case, realized economic growth can be higher than the natural growth rate. Second, exogenous labor productivity gains may not be transformed into actual growth if unemployment increases due to demand shortage or constraints on installed productive capacities.

3) Macro-economy - IMACLIM

A general equilibrium with rigidities

The representation of the economy in Imaclim-R is a multi-sector (12 sectors), multi-region (12 regions) general equilibrium framework. In each region, there are 14 economic agents: one representative household, one representative firm per sector (hence 12 representative firms) and the public administration. Households receive revenues from labor and capital and from transfers from public administrations and save part of their revenues. They chose their consumptions of goods and services depending on relative prices and they pay taxes to the public administrations. Productive sectors chose their production levels to meet demand, earn profits, pay wages and dividends to households and pay taxes to public administrations. Public administrations collect taxes, make public expenditures and invest in public infrastructures, and organize transfers. Regions are linked through international markets for goods and services, and capital. Figure 5 outlines these interrelationships.

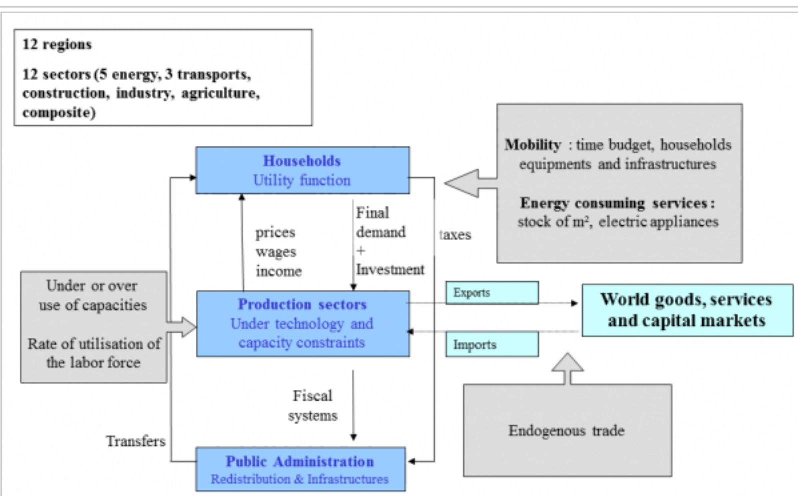

Figure 3: Sectoral interaction in the Imaclim-R hybrid model

Households

Each year, households maximize their current utility under constraints of both revenue received and of their time spent in transport. They save an exogenous share of their revenues. For detailed descriptions of demand formation mechanisms refer to the section on demand representation.

Public administrations

Public administrations collect taxes, make public expenditures including investment in public infrastructures and organize transfers.

Tax rates (and/or subsidies) are calibrated to their values for the model calibration year (2001). Taxes (and/or subsidies) impact upon energy, labor, revenues, added value, production, imports and exports. In the default setting of the model, tax rates are kept constant throughout the modelling period (except for in scenarios that model the introduction of a carbon tax) although alternative assumption on tax rates can also be tested. In a scenario where a carbon tax is introduced, alternative assumptions on the use of the corresponding revenues can be modelled i.e. they are given to households via transfers, used to reduce other pre-existing tax rates or used to finance a subsidy.

In the default setting public expenditures in each region are assumed to follow GDP growth rates, Alternative assumptions on the evolution of public expenditures can also be tested.

Transfers are determined such that the public administration budget is at equilibrium each year. Public debt is not accounted for.

Markets

Markets of goods and services

In the Imaclim-R model, all intermediate and final goods are internationally tradable and total demand for each good (the sum of households' consumption, public and private investments and intermediate uses) is satisfied by a mix of domestic production and imports (see Section on International Trade). Domestic as well as international markets for all goods are cleared (i.e. no stock is allowed) by a unique set of relative prices calculated in the static equilibrium such that demand and supply are equal.

Price

In each region k and sector i, the price equation is:

$$\mathbf{p_{k,i}} = \sum_{sectors\ j} \mathbf{pIC_{j,i,k}} \cdot IC_{j,i,k} + \left(\mathbf{\Omega_{k,i}} \cdot \mathbf{w_{k,i}}\right) \cdot l_{k,i} \cdot \left(1 + tax^{w}_{k,i}\right) + \pi_{k,i} \cdot \mathbf{p_{k,i}} \quad \mathbf{(5)}$$

where $\pi_{k,i}$ is a markup, $IC_{j,i,k}$ are intermediate consumption of good j in sector i in region k, and $\Omega_{k,i}$ is an increasing cost (or decreasing returns) function of the productive capacities utilization rate. This function is applied to labor costs (which include wages $w_{k,i}$ and labor taxes $tax_{k,i}$).

The functional form for Ω is:

$$\mathbf{\Omega_{k,i}} = a_{\Omega} - b_{\Omega} \cdot \tanh\left(c_{\Omega} \cdot \left(1 - \frac{Q}{Cap}\right)\right) \quad \mathbf{(6)}$$

Regional prices thus correspond to the addition of average regional production costs and a margin. This markup, which is fixed in the static equilibrium, encapsulates Ricardian and scarcity rents at the same time and increases with the utilization rate of production capacities in the oil sector.

A further parameter for the oil sector is that Middle-Eastern producers are considered 'swing producers' who are free to strategically set their investment decisions and, until they reach their depletion constraints, to control oil prices through the utilization rate of their production capacities (Kaufmann et al, 2004)[15]. This possibility is justified by the temporary reinforcement of their market power due to the stagnation and decline of conventional oil in the rest of the world. They can in particular decide to slow the development of production capacities below its maximum rate in order to adjust the oil price according to their rent-seeking objectives. They anticipate the level of capacities that will make it possible for them to reach their goals, on the basis of projections of total oil demand and production in other regions.

3.1) Production system and representation of economic sectors - IMACLIM

Productive sectors

A start point for IMACLIM is the recognition that it is almost impossible to find mathematical functions that can handle large departures from a reference equilibrium over a time period of one century and are flexible enough to encompass different scenarios of structural change resulting from the interplay between consumption styles, technologies and localization patterns (Hourcade, 1993)[16].

Beyond the classical production function, or reconciling bottom-up and top-down approaches

In IMACLIM-R, there is no production function, such as a constant elasticity of substitution function, to represent evolutions in production techniques (substitutions between production factors). Instead, evolutions in production techniques are represented in a recursive structure by an exchange of information between static and dynamic modules described as follows:

- An annual static equilibrium module, in which the production function mimics the Leontief specification, with fixed equipment stocks and fixed intensity of labor, energy and other intermediary inputs, but with a flexible utilization rate. Solving this equilibrium at time, *t*, provides a snapshot of the economy at this date showing a set of information about relative prices, levels of output, physical flows and profitability rates for each sector and allocation of investments among sectors.
- Dynamic modules, including demography, capital dynamics and sector-specific reduced forms of technology-rich models, which take into account the economic values of the previous static equilibrium, assess the reaction of technical systems and send back this information to the static module in the form of new input-output coefficients for calculating the equilibrium at time, 't' + 1. Each year, technical choices are flexible but they modify only at the margin the input-output coefficients and labor productivity embodied in the existing equipment that result from past technical choices. This general putty-clay assumption is critical to represent the inertia in technical systems and the role of volatility in economic signals.

This modelling approach allows for abandoning standard aggregate production functions, which have intrinsic limitations in cases of large departures from the reference equilibrium (Frondel et al., 2002)[17] and sea changes of production frontiers over several decades.

As we move away from using a traditional production function, it becomes possible to highlight the influence of factors other than price on decisions affecting the allocation of resources. The use of this modeling approach requires however a comprehensive description of the temporally evolving technical characteristics of each sector.

At each point in time, producers are assumed to operate under constraint of a fixed production capacity $Cap_{k,i}$, defined as the maximum level of physical output achievable with their installed equipment.

However, the model allows short-run adjustments to market conditions through the modification of the utilization rate $Q_{k,i}/Cap_{k,i}$. This represents a different approach from standard production specifications, since in Imaclim the 'capital' factor is not always fully utilized. Supply cost curves in Imaclim-R thus show static decreasing returns: production costs increase when the utilization rate of equipment approaches 1 (100 %) (See Figure 6). In principle, these decreasing returns affect all intermediary inputs and labor. However, for the sake of simplicity and because of the order of magnitude of the correlation between utilization rates and prices (Corrado and Mattey, 1997)[3], we assume that the primary cause of higher production costs is higher labor costs due to overtime operations with lower productivity, costly night work and increased maintenance works. We thus set (i) fixed input-output coefficients representing that, with the current set of embodied techniques, producing one unit of good i in region k requires the fixed physical amount $IC_{j,i,k}$ of intermediate goods j and $l_{k,i}$ of labor; (ii) a decreasing return parameter $\Omega_{k,i} = \Omega(Q_{k,i}/Cap_{k,i})$ on wages only, at the sector level. The treatment of the cost of crude oil production is an exception. The increasing factor weighs on the mark-up rate, to convey the fact that oligopolistic producers can take advantage of capacity shortages by increasing their differential rent.

This solution actually comes back to earlier works on the existence of short-run flexibility of production systems at the sectoral level with putty-clay technologies (Marshall, 1890)[18], (Johansen, 1959)[6] demonstrating that this flexibility comes less from input substitution than from variations in differentiated capacity utilization rates.

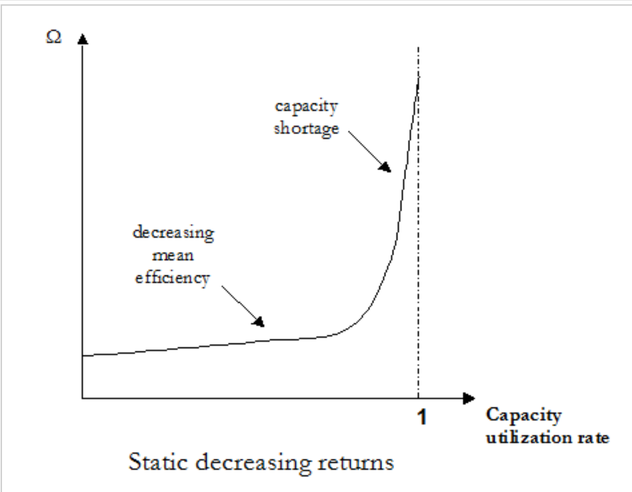

Figure 4: Sectoral interaction in the Imaclim-R hybrid model

Equations

We derive an expression of mean production costs $Cm_{k,i}$, that depends on the prices of intermediate goods $pIC_{j,i,k}$, input-ouput coefficients $IC_{j,i,k}$ and $l_{k,i}$, wages $w_{k,i}$, and production levels through the decreasing return factor $\Omega_{k,i}$ applied to labor costs (including payroll taxes).

$$Cm_{k,i} = \sum_j pIC_{j,i,k} \cdot IC_{j,i,k} + \left(\Omega_{k,i} \cdot w_{k,i}\right) \cdot l_{k,i} \cdot (1 + tax^w_{k,i}) \qquad (1)$$

Market prices and associated profits depend on assumptions regarding the degree of market competition in each sector (e.g. perfect competition or monopoly). Unless otherwise stated, perfect competition is assumed in every production sector, with the market price equal to the marginal production cost.

Producer prices are equal to the sum of mean production costs and mean profits. In the current version of the model, all sectors apply a constant sector-specific mark-up rate $p_{k,i}$ so that the producer price is given by equation (2). This constant mark-up corresponds to a standard profit-maximization for producers whose mean production costs follow equation (1) and who are price-takers, provided that the decreasing return factor can be approximated by an exponential function of utilization rate.

$$\mathrm{p}_{k,i} = \sum_j \mathrm{pIC}_{j,i,k} \cdot IC_{j,i,k} + \left(\Omega_{k,i} \cdot \mathrm{w}_{k,i}\right) \cdot l_{k,i} \cdot (1 + tax^w_{k,i}) + \pi_{k,i} \cdot p_{k,i} \qquad (2)$$

This equation is an inverse supply curve: it shows how a representative producer decides their level of output $Q_{k,i}$ (which is included in the $\Omega_{k,i}$ factor) as a function of all prices and real wages.

From equation (2) we derive wages and profits in each sector:

$$wages_{k,i} = \left(\Omega_{k,i} \cdot w_{k,i}\right) \cdot l_{k,i} \cdot Q_{k,i} \quad (3)$$

$$profits_{k,i} = \pi_{k,i} \cdot p_{k,i} \cdot Q_{k,i} \quad (4)$$

The cost function shows fixed technical coefficients and therefore does not allow for substitution between production factors when relative prices change within the new static equilibrium. Only the level of output $Q_{k,i}$ can be adjusted according to these price changes.

3.2) Capital and labour markets - IMACLIM

Capital markets

A share (*shareExpK*) of gross domestic savings (GRB) is internationally tradable, and distributed via an international capital pool. Each regions receives a share of the international pool (*shareImpK)*. In the default model setting, both shares (*shareExpK and shareImpK*) are exogenous: *shareExpK* is exponentially reduced such that international financial imbalances disappear by 2050 and *shareImpK* remains constant throughout the simulation period.

The remaining share of domestic savings and imported capital (NRB) are then invested in each region respectively.

$$\mathbf{NRB_k} = \mathbf{GRB_k} \cdot (1 - shareExpK_k) + \left(\sum_{countries\ k'} \mathbf{GRB_{k'}} \cdot shareExpK_{k'}\right) \cdot shareImpK_k$$

$$\mathbf{GRB_k} = \mathbf{Income_k} \cdot (1 - ptc_k) + \sum_{sectors\ j} \pi_{k,j} \cdot \mathbf{p_{k,j}} \cdot \mathbf{Q_{k,j}} \cdot \left(1 - div_{k,j}\right) \quad \textbf{(7,8,9)}$$

$$\mathbf{InvFin_{k,i}} = \mathbf{NRB_k} \cdot shareInvFin_{k,i}$$

The total amount of money $InvFin_{k,i}$ available for investment in sector *i* in the region *k* allows new capacities $DCap_{k,i}$ to be constructed at a cost $pCap_{k,i}$ (equation 9-3-5). The cost $pCap_{k,i}$ depends on the quantities $\beta_{j,i,k}$ and the prices $pI_{k,j}$ of goods *j* required by the construction of a new unit of capacity in sector *i* and in region *k*. Coefficient $\beta_{j,i,k}$ is the amount of good *j* necessary to constuct the equipment corresponding to one new unit of production capacity in sector i of the region k. Finally, in each region, the total demand for goods for building new capacities is given by the last equation below.

$$\mathbf{pCap_{k,i}} = \sum_{sectors\ j} \left(\beta_{j,i,k} \cdot \mathbf{pI_{j,i,k}}\right)$$

$$\mathbf{\Delta Cap_{k,i}} = \frac{\mathbf{InvFin_{k,i}}}{\mathbf{pCap_{k,i}}} \quad \textbf{(10,11,12)}$$

$$\mathbf{I_{k,j}} = \sum_{sectors\ i} \beta_{j,i,k} \cdot \mathbf{\Delta Cap_{k,i}}$$

Each sector anticipates future production levels through an anticipation of future prices and demand and formulates the corresponding investment demand. Total available investment $I_{k,j}$ is then distributed among sectors according to their demand.

Labour markets

At each time step, producers operate in static equilibria with a fixed input of labor per unit of output. This labor input, corresponding to labor productivity, evolves between two yearly equilibria following exogenous trends in labor productivity.

Three of the model features explain the possibility of under-utilization of labor as a factor of production, and thus unemployment. First, rigidity of real wages, represented by a wage curve can prevent wages falling to their market-clearing level. Put another way, instantaneous adjustment of wages to the economic context in the static equilibrium does not occur in an optimal manner. Second, in the static equilibrium, the fixed technologies (Leontief coefficients even for labor input) prevent substitution among production factors in the short run. And third, the installed productive capital is not mobile across sectors, which creates rigidities in the reallocations of production between sectors when relative prices change.

In each region *k*, each sector employs the labor force $l_{k,i} \cdot Q_{k,i}$, where $l_{k,i}$ is the unitary labor input (in hours worked) and $Q_{k,i}$ the production. The underutilization of the labor force, equivalently referred to as the 'unemployment rate' in the following, $\_z_k$ is therefore equal to one minus the ratio of the employed labor force across all sectors over L_k, the total labor force:

$$z_k = 1 - \frac{\sum_i l_{k,i} \cdot Q_{k,i}}{L_k}. \qquad \textbf{(13)}$$

Obviously, this definition of the unemployment rate is a limitation of the current calibration of the model. Future developments will look into the possibility to differentiate labor markets per regions. However, one important difficulty lies in the lack of reliable data on the underutilization of the labor forces in all regions, in particular due to informal economy, very diverse accounting rules for unemployment rates and variations in hours worked per person across countries. No endogenous mobility of workers between regions is accounted for in the model. Thus twelve separate labor markets are represented.

We chose to model labor market imperfections through an aggregate regional *wage curve* that links real wage levels to the unemployment rate. This representation is based on labor theories developed in the 1980s and early 1990s in which an aggregate wage curve, or *wage setting curve*, is the primary distinguishing feature (an overview can be found in Layard et al., 2005[19]; Lindbeck, 1993[20]; or Phelps, 1992[21]). The novel approach of these models, when introduced, was to replace the conventional labor supply curve with a negatively-sloped curve linking the level of wages to the level of unemployment. The interpretation of this wage curve is given either by the bargaining approach (Layard and Nickell, 1986)[22] or the wage-efficiency approach (Shapiro and Stiglitz, 1984)[23]. Both interpretations rely on the fact that unemployment represents an outside threat that leads workers to accept lower wages the greater the threat. The bargaining approach emphasizes the role of workers' (or union) power in the wage setting negotiations, power that is weakened when unemployment is high. The wage-efficiency approach takes the firms' point of view and assumes that firms set wage levels so as to discourage shirking; this level is lower when the threat of not finding a job after being caught shirking gets higher. The wage curve specification allows the theories to be consistent with both involuntary unemployment and the fact that real wages fluctuate less than the theory of the conventional flexible labor supply curve predicts. Microeconometric evidence for such formulations was given in a seminal contribution by (Blanchflower and Oswald 1995)[24].

In practice, the wage curve for each region k in our model is implemented through the relation:

$$\frac{w_k}{pind_k} = aw \cdot \frac{wref_k}{pindref_k} \cdot f\left(\frac{z_k}{zref_k}\right), \qquad \textbf{(14)}$$

where *w* is the hourly nominal wage level, *pind* the consumption price index, *z* the unemployment rate, *ref* indexes represent the values of the variables at the calibration date, *pindref* is derived from the final consumption prices and volumes at the calibration date, *wref* is calibrated from the total salaries per sector in the GTAP 6 database (Reference?) and the shares of labor force per sector are taken from International Labor Organisation statistics. By default, *aw* is calibrated to 1 and evolves in parallel to labor productivity so that unitary real wages are indexed on labor productivity. *zref* represents the underutilization of the labor force at the calibration date. *f* is a function equal to one when the unemployment rate is equal to its calibration level, and is negatively sloped, representing a negative elasticity of wages level to unemployment [3]. Choosing a functional form and calibrating the function is particularly tricky, notably due to the lack of reliable data to fully inform the functioning of the labor markets worldwide. We chose a function of the form a.(1-tanh(c.z)), and calibrate the parameters a and c so as to have the desired value and elasticity at the calibration point.

By default, we assume all regions' labor markets to be identical and set the underutilization of the labor force at 10% (Contrary to the definition by the U.S. Bureau of Labor Statistics, the level of unemployment is expressed here in terms of worked hours and not in terms of persons)[4] and the wage curve elasticity at -0.1 for all regions (This is a value emerging from many econometric studies, e.g. (Blanchflower and Oswald 1995)[24], (Blanchflower and Oswald 2005). Guivarch et al. (2011) (http://halshs.archives-ouvertes.fr/docs/00/72/44/87/PDF/Guivarch_et_al_2011_Costs_climate_policies_second_best_world_labour_market_imperfections.pdf)[25] analyzes the critical role of labour markets imperfections, and in particular of the value of the wage curve elasticity, on the formation of climate stabilization costs.

3.3) Monetary instruments - IMACLIM

Monetary instruments are not included in IMACLIM.

3.4) Trade - IMACLIM

International Trade

For each good, exports from all world regions are blended into an international variety, which is then imported by each region based on its specific terms-of-trade measured between the price of the aggregate international variety, and the production price of the domestic good.

International trade is treated 'upstream': the competition of the domestic and imported varieties of each good is settled in an aggregate manner, not at the level of each domestic agent.

A well-known modelling issue is then to avoid 'knife-edge' solutions, *i.e.* to prevent cheaper goods systematically winning market shares over more expensive ones. We follow the most common approach to addressing this issue, the Armington (1969)[1] specification, which assumes that the domestic and imported varieties of the same good aggregate in a common quantity index, although in an imperfectly substitutable way which is typically derived from assuming that the two varieties combine through a constant elasticity of substitution (CES) function. This allows representing markets in which both domestic production and imports have a share, despite the fact that they are priced differently.

Despite its straightforward treatment of imperfect product competition, the Armington specification has the major drawback of introducing aggregate volumes that do not sum up the volumes of imported and domestic varieties. While this shortcoming can be ignored for non-descript 'composite' goods, where quantity units are indexes of no direct significance to the economy-energy-environment interactions, it is not compatible with the obvious need to track energy balances expressed in real physical units. Competition between energy goods is thus settled through simplified specifications. In the case of national models, the hypothesis of a constant elasticity of substitution is retained, but the construction of a composite index is dropped. Imports and domestic production are simply summed up to form the resource that is available to the importing economy. For the multi-regional version of Imaclim, a market-sharing formula is implemented. The international market buys energy exports at different prices and sells them at a single average world price to importers; shares of exporters on the international market and regional shares of domestic *vs.* imported energy goods dependent on relative prices, export and import taxes, and market fragmentation parameters that are calibrated to reproduce the existing markets structure.

For all goods, export prices include the producer prices, export taxes or subsidies, and average transportation costs. This allows the model to take into account that increasing energy prices would impact on transportation costs and eventually on commercial flows and industrial location patterns.

Consumption of good i in region k is:

$$\mathbf{C_{k,i}} = \left(b_{k,i}^{dom} \cdot \left(\mathbf{C_{k,i}^{dom}}\right)^{-\rho_{k,i}} + b_{k,i}^{imp} \cdot \left(\mathbf{C_{k,i}^{imp}}\right)^{-\rho_{k,i}} \right)^{-\frac{1}{\rho_{k,i}}}$$

Its price is:

Armington goods

$$\mathbf{pC_{k,i}} = \left(\left(b_{k,i}^{dom}\right)^{\sigma_{k,i}} \left(\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{domC})\right)^{1-\sigma_{k,i}} + \left(1-b_{k,i}^{dom}\right)^{\sigma_{k,i}} \left(\mathbf{p_{k,i}^{imp}} \cdot (1+tax_{k,i}^{impC})\right)^{1-\sigma_{k,i}} \right)^{\frac{1}{1-\sigma_{k,i}}} \quad \textbf{(15,16,17)}$$

The shares of domestic and imported goods i in region k are:

$$\mathbf{shareC_{k,i}^{dom}} = \left(b_{k,i}^{dom} \cdot \frac{\mathbf{pC_{k,i}}}{\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{domC})} \right)^{\sigma_{k,i}}$$

$$\mathbf{shareC_{k,i}^{imp}} = \left(\left(1-b_{k,i}^{dom}\right) \cdot \frac{\mathbf{pC_{k,i}}}{\mathbf{p_{k,i}^{imp}} \cdot (1+tax_{k,i}^{impC})} \right)^{\sigma_{k,i}}$$

Similar equations to (8-1)–(8-4) are valid for public consumptions, investments and intermediate consumptions.

The price of the imported good is:

$$\mathbf{p_{k,i}^{imp}} = \mathbf{wp_i} \cdot \left(1+taxe_{k,i}^{M}\right) + \sum_{means\ of\ tranport\ it} \mathbf{wp_{it}} \cdot nit_{k,i}^{it} \quad \textbf{(18,19,20)}$$

Market clearing equation:

$$\sum_{countries\ k} \left(\mathbf{shareC_{k,i}^{imp}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG_{k,i}^{imp}} \cdot G_{k,i} + \mathbf{shareI_{k,i}^{imp}} \cdot \mathbf{I_{k,i}} + \sum_{sectors\ j} \mathbf{shareIC_{i,j,k}^{imp}} \cdot IC_{i,j,k} \cdot \mathbf{Q_{k,j}} \right) = \mathbf{X_i} = \left[\sum_{countries\ k} \psi_{k,i} \cdot \mathbf{X_{k,i}^{-\theta_i}} \right]^{-\frac{1}{\theta_i}}$$

With $X_{k,i}$ the exports of goods i from region k, and wp_i the world price:

$$\mathbf{X_{k,i}} = \left[\psi_{k,i} \cdot \frac{\mathbf{wp_i}}{\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{X})} \right]^{\lambda_i} \cdot \mathbf{X_i} \quad \textbf{(21,22)}$$

$$\mathbf{wp_i} = \left(\sum_{countries\ k} \left(\psi_{k,i}\right)^{\lambda_i} \left(\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{X})\right)^{1-\lambda_i} \right)^{\frac{1}{1-\lambda_i}}$$

Energy goods

Consumption of good i in region k is:

$$\mathbf{C_{k,i}} = \mathbf{C_{k,i}^{dom}} + \mathbf{C_{k,i}^{imp}}$$

Its price is:

$$\mathbf{pC_{k,i}} = \mathbf{shareC_{k,i}^{dom}} \cdot \mathbf{p_{k,i}} \cdot (1 + tax_{k,i}^{domC}) + \mathbf{shareC_{k,i}^{imp}} \cdot \mathbf{p_{k,i}^{imp}} \cdot (1 + tax_{k,i}^{impC})$$

(23,24,25)

The shares of domestic and imported goods i in region k are:

$$\mathbf{shareC_{k,i}^{imp}}(\mathbf{t}) = \frac{shareC_{k,i}^{imp}(t-1) \cdot \left(\frac{\mathbf{p_{k,i}^{imp}}(t) \cdot (1 + tax_{k,i}^{impC}(t))}{p_{k,i}^{imp}(t-1) \cdot (1 + tax_{k,i}^{impC}(t-1))} \right)^{\eta_{k,i}^{imp}}}{shareC_{k,i}^{imp}(t-1) \cdot \left(\frac{\mathbf{p_{k,i}^{imp}}(t) \cdot (1 + tax_{k,i}^{impC}(t))}{p_{k,i}^{imp}(t-1) \cdot (1 + tax_{k,i}^{impC}(t-1))} \right)^{\eta_{k,i}^{imp}} + (1 - shareC_{k,i}^{imp}(t-1)) \cdot \left(\frac{\mathbf{p_{k,i}}(t) \cdot (1 + tax_{k,i}^{domC}(t))}{p_{k,i}(t-1) \cdot (1 + tax_{k,i}^{domC}(t-1))} \right)^{\eta_{k,i}^{imp}}}$$

$$\mathbf{shareC_{k,i}^{dom}}(\mathbf{t}) = 1 - \mathbf{shareC_{k,i}^{imp}}(\mathbf{t})$$

Similar equations to (8-9)–(8-12) are valid for public consumptions, investments and intermediate consumptions.

The price of the imported good is:

(26,27,28)

$$\mathbf{p_{k,i}^{imp}} = \mathbf{wp_i} \cdot \left(1 + taxe_{k,i}^{M}\right) + \sum_{means\ of\ tranport\ it} \mathbf{wp_{it}} \cdot nit_{k,i}^{it}$$

Market clearing equation:

$$\sum_{countries\ k} \left(\mathbf{shareC_{k,i}^{imp}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG_{k,i}^{imp}} \cdot G_{k,i} + \mathbf{shareI_{k,i}^{imp}} \cdot \mathbf{I_{k,i}} + \sum_{sectors\ j} \mathbf{shareIC_{i,j,k}^{imp}} \cdot IC_{i,j,k} \cdot \mathbf{Q_{k,j}} \right) = \mathbf{X_i}$$

With $MSH_{k,i}$ the market share of region k, $X_{k,i}$ the exports of goods i from region k, and wp_i the world price:

$$\mathbf{MS_{k,i}^{X}}(\mathbf{t}) = \frac{MS_{k,i}^{X}(t-1) \cdot \left(\frac{\mathbf{p_{k,i}}(t) \cdot \left(1 + tax_{k,i}^{X}(t)\right)}{p_{k,i}(t-1) \cdot \left(1 + tax_{k,i}^{X}(t-1)\right)} \right)^{\eta_{k,i}^{X}}}{\sum_{countries\ k'} MS_{k',i}^{X}(t-1) \cdot \left(\frac{\mathbf{p_{k',i}}(t) \cdot \left(1 + tax_{k',i}^{X}(t)\right)}{p_{k',i}(t-1) \cdot \left(1 + tax_{k',i}^{X}(t-1)\right)} \right)^{\eta_{k',i}^{X}}}$$

(29,30,31)

$$\mathbf{X_{k,i}} = \mathbf{MS_{k,i}^{X}}(t) \cdot \mathbf{X_i}$$

$$\mathbf{wp_i} = \frac{\sum_{countries\ k} \mathbf{p_{k,i}} \cdot \left(1 + tax_{k,i}^{X}\right) \cdot \mathbf{X_{k,i}}}{\sum_{countries\ k} \mathbf{X_{k,i}}}$$

3.5) Technological change - IMACLIM

Technological change is represented in a variety of ways in Imaclim-R:

- There is cost-reducing learning-by-doing factor for technologies that are explicitly represented, i.e. power generation technologies. See Section on electricity and private vehicles (see Section on transport.
- For sectors where explicit portfolios of technologies are not represented, the model nonetheless covers (price induced) endogenous energy efficiency improvements and substitutions with other sectors. See Section on productive sectors.

- Moreover, the model includes inertias and path-dependencies, via capacity stocks (capital generations), as well as constraints on the maximal speed of technology deployment.
- The current version of the model uses exogenous trends in labor productivity to model exogenous technical change of labor. See Section on economic growth.

4) Energy - IMACLIM

This section describes how the various components of the Energy System are modelled in IMACLIM-R.

4.1) Energy resource endowments - IMACLIM

Fossil fuels are the only energy resource endowments considered in IMACLIM-R.

4.1.1) Fossil energy resources - IMACLIM

Modelling the long-term dynamics of oil markets

The IMACLIM-R framework includes the following four properties of oil markets in dedicated bottom-up modules describing the dynamics of oil supply and demand:

(a) A small group of suppliers benefit from market power; Middle-Eastern countries (ME) at the core of the Organization of the Petroleum Exporting Countries (OPEC)) can dictate (*Granger cause*) world oil prices (Gulen, 1996)[26] until such time as they approach their depletion constraint.
(b) The geological nature of World oil reserves dictates that oil supply has a limited adaptability to demand. Total production is constrained by the amount of economically exploitable reserves and by technical constraints that lead to inertias in the deployment of production capacities. The former depends on producers' response to price-signals whereas the latter affects the conversion of economically exploitable reserves into actual production.
(c) Oil demand depends on agents' microeconomic trade-offs. This concerns both agents' decisions affecting their oil consumption, as well as incentives aimed at increasing the production of alternatives to oil based fuels (biofuels, Coal-To-Liquid). Those price-driven decisions will determine the short term oil demand, as well as the long-run oil-dependency of the economy.
(d) Uncertainties on the technical, geopolitical and economical determinants of oil markets alter agents' expectations. Four such forces are presented: increasing demand over time; exogenous decrease of production costs due to technological change; incentives for further exploration given by the inverse relationship between marginal extraction costs and reserves; and increases in aggregate production capacity due to production at newly developed sites. The assumption of perfectly optimizing isolated agents, which remains a useful analytical benchmark, fails to provide a good proxy for the oil economy.

Oil supply

Imaclim-R includes seven categories of conventional and five categories of non-conventional oil resources in each region. Each category (i) is characterized by an amount of recoverable resources (Total resource of a given category is the sum of resources extracted before 2001 and recoverable resources); and by a threshold selling price above which producers initiate production. This price is a proxy for production costs and accessibility. **???** gives the inhouse numerical assumptions made on the amount of ultimate resources in the main groups of regions. The figures are consistent with conservative estimates (shale oil excluded) made elsewhere (USGS, 2000[27]; Greene et al., 2006[28]; Rogner, 1997[29]). Due to the specificities related to the exploitation of shale oil and the associated high production costs, we consider shale oil as an alternative to oil instead of a new category of oil.

<figtable id="tab:resources">

Assumptions about oil resources in the central case (Trillion bbl)

Resources extracted before 2001	**Recoverable resources beyond 2001§**				
	Conventional oil		Non-conventional oil (Heavy oil and Tar sands)		
	Middle East	RoW	Canada	Latin America	Row
0.895	0.78	1.17	0.220	0.38	0.4

§*"recoverable resources" are 2P reserves (Proven+Probable) remaining in the soil, which has been identified as the relevant indicator to investigate global oil peak (Bentley et al, 2007)*[30]

Each oil category is subject to geological constraints (inertias in the exploration process and depletion effects), which limit the pace of expansion of their production capacity. In line with (Rehrl and Friedrich, 2006)[31], who combine analyzes of discovery processes (Uhler, 1976)[32] and of the 'mineral economy' (Reynolds, 1999)[33], the maximum rate of increase of production capacity for an oil category i at date t, $\Delta Cap_{max}(t,i)$, is given by:

$$\frac{\Delta Cap_{\max}(t,i)}{Cap(t,i)} = \frac{b_i \cdot \left(e^{-b_i(t-t_{0,i})} - 1\right)}{\left(1 + e^{-b_i(t-t_{0,i})}\right)}$$

The parameter b_i (in t^{-1}) controls the intensity of the constraints on production growth: a lowb_i means a flat production profile that represents slow deployment of production capacities whereas a high b_i means a sloping production profile which represents the opposite effect. We retain b_i=0.061/year for conventional oil as estimated by Rehrl and Friedrich (2006)[31] and, for the sake of simplicity, the same value for non-conventional oil in the median case. The parameter $t_{0,i}$ represents the date at which production capacities of the concerned oil category are expected to start their decline due to depletion effects. It is endogenous and varies in time since it depends on the amount of oil remaining in the field given past exploitation decisions.

Non-Middle-Eastern producers are seen as 'fatalistic producers' who do not act strategically on oil markets. Given the selling oil price p_{oil}, they invest in new production capacity if an oil category becomes profitable: they develop production capacities at their maximum rate of increase $\Delta Cap_{max}(t,i)$ for least-cost categories of oil ($p_{oil}>p^{(0)}(i)$) but do not undertake investments in high-cost categories ($p_{oil}<p^{(0)}(i)$). If prices continuously increase, production capacities of a given oil category follow a bell-shape trend i.e. the reach a point of capactity saturation, whereas their deployment profile passes through a plateau if prices decrease below the profitability threshold.

Middle-Eastern producers are 'swing producers' who are free to strategically determine their investment decisions and, until such time as they reach their depletion constraints, to control oil prices through the utilization rate of their production capacities (Kaufmann et al, 2004)[15]. This possibility is justified by the recent temporary reinforcement of their market power due to the stagnation and decline of conventional oil sources in the rest of the world. They can in particular decide to slow the development of production capacities to below their maximum rate of construction in order to adjust the oil price according to their rent-seeking objectives.

Total production capacity at date *t* is given by the sum over all oil categories with different production costs (captured by different threshold). This means that projects of various merit orders coexist at a given point in time, consistent with the observed evidence and theoretical justifications. For example, low-cost fields in Saudi Arabia and high-cost non-conventional production in Canada are simultaneously active on oil markets. In addition Kemp and Van Long, (1980)[34] have demonstrated that, in a general equilibrium context, the lowest-cost deposits are not necessarily exploited first. Holland, (2003)[35] even demonstrates that least-cost-first extraction rule does not hold in a partial equilibrium framework under capacity constraints, like those envisaged for geological reasons here.

Formation of oil prices

The oil price which forms in static equilibrium reflects the level of tension between supply and demand. The price formation equation is:

$$p_{k,oil} = \sum_j pIC_{j,oil,k} \cdot IC_{j,oil,k} + \left(\Omega_{oil,k}\left(\frac{Q_{oil,k}}{Cap_{oil,k}}\right)\right) \cdot l_{oil,k} \cdot (1+tax^{w}_{oil,k}) + \pi_{oil,k} \cdot \frac{Q_{oil,k}}{Cap_{oil,k}} \cdot p_{oil,k}$$

The regional prices thus correspond to the addition of the average regional production costs and a margin that encapsulates Ricardian and scarcity rents at the same time. The swing producer uses this equation to anticipate the level of capacities that will make it possible for them to reach their goal on the basis of projections of total oil demand and production in other regions.

Other fossil fuels

Coal and gas reserves are *a priori* subjected to less important availability constraints on the market than crude oil. In the present version of the model, the treatment of production capacity evolution of these two sectors as well as the mechanisms of their price formation are thus more simply treated.

Natural gas supply

In the model the evolution of worldwide natural gas production capacities meets demand increases until available reserves enter a depletion process. The distribution of regional production capacities in the 'gas supply' dynamic module is made using exogenous weights calibrated on the output of the POLES energy model (LEPII-EPE, 2006)[36], which captures both reserve availability and the capacity of regional production facilities. Gas markets follow oil markets with an elasticity of 0.68 of gas to oil price. This behavior is calibrated on the World Energy Model (IEA, 2007)[37] and is valid as long as oil prices remain below a threshold $p_{oil/gas}$. At high price levels reflecting tensions due to depletion of reserves, gas prices are driven by production costs and the increased profit margin for the possessors of the remaining reserves.

Coal supply

Unlike oil and gas markets, cumulitive coal production has a weak influence on coal prices because of large world resources. Coal prices instead depend on current levels of production through specific elasticity coefficients. To represent the asymmetry in coal price response to production variations, we consider two different values of this elasticity, η_{coal} and η^{-}_{coal}. The former corresponds to a price reaction to a production increase while the latter corresponds to the opposite effects. Tight coal markets exhibit a high value of η_{coal} (i.e the coal price increases strongly if production rises) and low value of η^{-}_{coal} (the price decreases only slightly if production drops).

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[1] Four such forces are presented: increasing demand over time; exogenous decrease of production costs due to technological change; incentives for further exploration given by the inverse relationship between marginal extraction costs and reserves; and increases in aggregate production capacity due to production at newly developed sites.

4.2) Energy conversion - IMACLIM

This section describes how various primary energy carriers are converted to electricity and liquid fuels.

4.2.1) Electricity - IMACLIM

Generating electricity: taking account of load curve constraints

The electricity production sector is particularly influenced by climate policies since it is the sector with the highest greenhouse gas emissions. In 2004 it was responsible for 20% of worldwide emissions of the six gases covered by the Kyoto Protocol. Emissions grew by 53% between 1990 and 2004 to reach 10.7 Gt of CO2 in 2004. These emissions are caused by the combustion of fossil resources, namely coal, oil and gas, in power plants.

The production and technological choices taken in the electricity sector arise from the difficulty associated with storage of the sector main output: electricity. In an electricity distribution network it is necessary to ensure a constant balance between the power available and the power demanded by the sum of final end uses (the load). Production must therefore adapt to major fluctuations in daily and seasonal network demand. Facing the uncertainty of future real demand, possible breakdowns and the intermittence of certain production means (renewables), a centralized producer must choose between a level of risk of electricity supply shortages and the construction of spare or auxilary capacity. When the electricity market is liberalized, this control of the evolution of capacities becomes more difficult unless one of the producers has sufficient scale to assure adjustment of the total capacities according to the needs of the economy (e.g. EDF in France). Correspondingly, the profitability of production technologies - or put another way, the total production cost per kWh - depends on the annual operating time, fixed and variable costs for each respective production technology as well as on operational technical constraints. Therefore, both long term investment choices and choices concerning putting existing capacities into operation depend on the network load curve, a curve which indicates the evolution of power demanded by the network over time.

The detail of a top-down / bottom-up model hybridization are particularly palpable here: without the physical and temporal constraints of the network load curve, the choice of electricity production technologies would be simply oriented towards the cheapest technology available although eventually taking other constraints into account (social acceptability, investment risk, size of production units, market structure, etc.). However, due to the variation in the load curve, the representation of investment choices and the decision to dispatch existing capacities is complex. This complexity can be decomposed as consisting of the following components:

- A detailed representation of the large types of technologies that can be distinguished by their cost characteristics and their own physical or socio-economic constraints (basic or cutting edge technologies, limited potential, social and environmental acceptability, etc.);
- An explicit representation of the load curve and its evolution over time;
- An investment optimization procedure dependant on the projected future load curve and long term price and demand expectations;
- A decision mechanism for choosing when to dispatc hexisting production capacities according to the load curve and current primary energy prices.

We describe each of these elements in detail in the following four sub-sections.

Explicit production technologies described in terms of capital generation

The description of the power generation mix is based on a discrete set of 13 technologies. Each of the 13 technologies is characterized by a set of techno-economic parameters that make it possible to calculate their average discounted production cost per kilowatt hour produced. These parameters include: capital costs ($/kW installed), energy efficiency (in %, for the technologies that use fossil fuels), operation and maintenance costs, fixed or variable costs (in $/kW and in $/kWh respectively) and a discount rate incorporating both the opportunity cost of capital and a unique risk factor for each technology. This risk factor can cover both an objective assessment of the risk of outage as well as an assessment of social risk, for example for the cases of nuclear power or CCS (Carbon Capture and Sequestration). The techno-economic parameters associated with each technology are calibrated either from sectoral technological models (for example the POLES model) or using information from literature (Grubler et al, 2002[38]; Rao et al, 2006[39]; Sims et al, 2007[40]).

??? gives the calibration values for the United States of the techco-economic parameters characterizing the 13 technologies described in this version of the model. The last four rows of the table contain the calculation results for each technology at the year of calibration and the different components of the discounted average production cost: investment cost, operation and maintenance cost, fuel cost, for an annual usage duration of 8760 hours (One year).

<figtable id="tab:discount_cost">

Techno-economic parameters for electricity production technologies for the United States in 2001. The discounted average costs are calculated for a usage duratio technologies are available with or without carbon capture and sequestration (CCS).The characteristics of the technologies that are not yet mature can evolve signi learning processes which are represented in the model either by autonomous evolution or by an endogenous mechanism. For example, the efficiency of the produ coal can be improved substantially with the deployment of advanced technologies such as supercritical cycle gasification power plants.

				Natural gas	Natural gas	Natural gas	Coal	Coal	Coal	Coal	Coal		Renewables
Parameter	**Notation in equations**	**Unit**	**Oil**	**Simple Cycle**	**Combined Cycle**	**Combined Cycle with CCS**	**Thermal**	**Super critical**	**Super critical with CCS**	**Gasification and combined cycle**	**Gasification and combined cycle with CCS**	**Nuclear**	**Hydro**
Operational at the calibration year			yes	yes	yes	no	yes	no	no	no	no	yes	yes
Investment Cost	*CINV_KW*	$2001/kw	1000	400	500	1120	1050	1600	2700	1500	2400	2600	2000
Fixed OPEX(Operation expenditure)	*OM_Cost_fixed*	$2001/kw	15	26	10	50	53	35	60	37	70	58	20
Life Time	*life_time*	Years	30	30	30	30	30	30	30	30	30	30	45
Discount rate	*disc*	%	10	10	10	10	10	10	10	10	10	10	10
Variable OPEX	*OM_Cost_var*	$2001/kWh	0.0017	0.0014	0.0014	0.0022	0.0024	0.0028	0.0034	0.0024	0.0029	0.0012	
Cost of fuel		$2001/Toe	237	160	160	160	71	71	71	71	71		
Energy Efficiency	*rho_elec*	%	36	35	53	47	35	45	35	42	36		
Availability rate		%	100	100	100	100	100	100	100	100	100	100	100
Average discounted investment cost		$2001/MWh	12.1	4.8	6.1	13.6	12.7	19.4	32.7	18.2	29.1	31.5	23.1
Average discounted fuel cost		$2001/MWh	56.6	39.3	26.0	29.3	17.4	13.6	17.4	14.5	17.0	5.0	0.0
Average discounted operation and maintenance cost		$2001/MWh	5.3	3.0	1.5	6.1	6.1	4.0	14.1	4.2	17.0	7.8	2.3
Average discounted production cost		$2001/MWH	**74.0**	**47.1**	**33.5**	**48.9**	**36.2**	**36.9**	**64.2**	**36.9**	**63.0**	**44.3**	**25.4**

For the technologies listed in **???** which are classed as being mature (See Row 3: Operational at the calibration year) the data given corresponds to the model reference year (2001). Data in the table for technologies that are not considered to be mature yet, corresponds to various years which are dependant on the scenario under consideredation. The data are not, however, averages for each region in the calibration/reference year, since the installed capacity of production plants also include less efficient older production units. Likewise, at future dates in the scenarios modeled, the average characteristics of the installed production capacity will be the weighted average of the technical characteristics of the different generations of power plants still in operation. The inertia of equipment and the embodied character of technologies are represented through a follow up of capital through the generations along with that of their technological characteristics. Hence, each unit of a given technology's production capacity constructed at time t is active until $t+life\_time_{k,TECH}$, where $life\_time_{k,TECH}$ is the expected technology lifetime in region *k* for each technology, *TECH*. The overall installed production capacity park at time *t* is decomposed according to the duration of the year in which the various production units are dispatched. For each technoloy *TECH* and each region *k*, the electricity production capacity (measured in MW) is obtained by summing up the generations of capital in activity:

$$Cap\_elec\_MW_{k,TECH}(t) = \sum_{i=1}^{life\_time_{k,TECH}} Cap\_MW_{k,TECH}^{vintage}(t+i)$$

Every year *(t+1)*, the production capacities that reach the end of their lifetimes are eliminated (lifetime varies according to the type of technology installed). One thus obtains a depreciated installed production capacity, $Cap\_MW\_depreciated_{k,TECH}$. At each time period this is combined with the new investments to obtain the total installed production capactity:

$$Cap\_MW\_depreciated_{k,TECH}(t) = \sum_{i=2}^{life\_time_{k,TECH}} Cap\_MW_{k,TECH}^{vintage}(t+i)$$

The capacity of the new generation of capital $Cap\_MW_{k,TECH}^{vintage}(t+life\_time_{k,TECH})$ and its technological characteristics is determined by electricity producers investment choices, represented as described in the following sections.

Physical and temporal constraint of the load curve

The production load curve represents the time dependence of the power generated by a system. It meets the demand fluctuation at the scale of a day or a season.

In order to model investments, it is common to aggregate the daily load curves over the 365 days of the year into a single curve called a monotonous load curve divided into 8760 hourly segments. This monotonous load curve decreases depending on the load duration averaged over the year (i.e. not in the chronological order of power dispatch). The maximum load over the transmission network (peakload) is given by the maximum of the curve at its intersection with the Y-axis. The minimal level of power that is supplied throughout the year is the value of this monotonous load curve over the 8760 hours (baseload).

The shape of the monotonic power is unique to each region because it is directly linked to the temporal variability of the electricity demand. This variability depends on the seasonal climate variations of the region as well as on the nature of the electricity demand e.g. over time household demand is much more variable than that of the industrial sector. For numeric simplicity, the monotonous regional load curves have been schematized as segmented linear functions (See figure below) according to the following specifications:

- The possible annual loads (measured in hours) are divided into seven intervals with the following boundaries: (0, 730, 2190, 3650, 5110, 6570, 8030, 8760);
- The maximum load lasts for a duration of 730 hours (peakload);
- The minimum load lasts for a duration of 8760 hours (baseload);
- The load level for the other periods of time is calculated by dividing the interval between baseload and peakload into six equal segments i.e. 760 hours of baseload, 760 hours of peak load and five segments in between of 1460 hours each.

Using this simplified scheme, the monotonous load curve of each region can be thus completely characterized by two parameters: peakload and baseload.

The monotonous load curve also links the production capacities (expressed in megawatts) and the quantity of energy produced annually (measured in megawatt hours or other energy units) by dispatching existing capacities in a flexible manner according to demand on the network. The annual electricity produced is obtained simply by calculating the total of the monotonous load curve for the interval [0 to 8760] and is equivalent to the surface beneath the curve presented in the figure below.

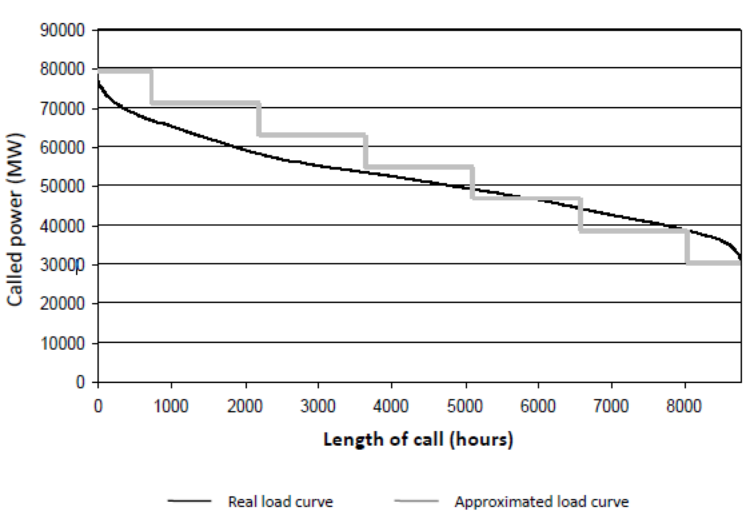


FIGURE CAPTION: Example of monotonous load curve approximation method.

The calculation of produced energy based on the installed capacity is carried out at every step of the simulation to recalibrate the technical coefficients of the electricity sector. These depend on the dispatch choices of the installed capacity according to the variable costs of each type. The reverse calculation of installed capacities from energy produced, is necessary during investment programming because it is important to know how the monotonous load curve corresponds to the anticipated annual energy demand.

To calibrate and reconfigure the monotonous load curve at each time period, we assume that the ratio of peakload to baseload, (written bp_ratio_k) remains constant and equal to a value supplied by the POLES model.In principle, this ratio could vary in an exogenous or endogenous manner to integrate, for example, its modification under the effect of policies of demand management. However, in the current version of the model it is kept constant. Using our method of approximating the monotonous load curve into linear segments, the calculation of the monotonous load curve associated to a quantity Q_elec_k of electricity produced in region k, is obtained by solving the equation system, formed by the ratio constancy equation and the constraint equation on the quantity of energy produced:

$$\frac{base\_MW_k}{peak\_MW_k} = bp\_ratio_k$$

$$base\_MW_k \times 8760 + \frac{peak\_MW_k - base\_MW_k}{6} \times (8030 + 6570 + 5110 + 3650 + 2190) + peak\_MW_k \cdot 730$$
$$= Q\_elec_k$$

where $base\_MW_k$ and $peak\_MW_k$ are the power levels required during the base or peak periods respectively.

Optimal planning of investments in imperfect foresight

With the compact representation of electricity production technologies and the load curve that has been presented above, we posess the necessary technical details to model investment choices in the electricity sector for each date t, choices which will progressively modify the size and technical composition of the installed capacity. It is more explicitly a question of representing an optimal planning procedure given imperfect foresight, a procedure which determines the make-up of the installed capacity in the current time period and and the investment necessary to meet projected future electricity demand while minimizing the average total cost of production.

The decision-making procedure is decomposed into five successive steps:

- Projecting future demand and future fuel prices;
- Choosing wind turbine electricity production capacities;
- Choosing hydroelectric production capacities;
- Projecting the optimal conventional (non-renewable) production capacity (the optimal installed capacity) to meet residential demand;
- Deciding on the annual investment increase necessary to move the existing production capacity towards the optimal capacity that has just been calculated (see previous bullet point).

Separating the treatment of wind and hydroelectric energy is justified by the specificities of these energy carriers. A more detailed explanation of these specificities is given below.

Projecting demand and anticipating fuel prices

The optimal installed capacity and level of annual investments are determined using adaptive anticipation of electricity demand growth and future fossil fuels prices over the coming ten years.

The regional projections of electricity production for the period $t+10$, written $Q\_elec\_anticip_k$ are calculated on the basis of the current growth rate of electricity production, $tendency\_Q\_elec_k$ which is taken to be stable for the next ten years, and the current electricity production, $Q_{k,elec}$ (in megawatt hours).

$$Q\_elec\_anticip_k = Q_{k,elec} \cdot (1 + tendency\_Q\_elec_k)^{10}$$

Anticipated electricity production from conventional (non-renewable) energy carriers is associated with an anticipated monotonous load curve which is determined using the results from the resolution of the equation system given above. The installed production capacity in the $t+10$ period should also supply a baseload $base\_MW\_anticip_k$, and a peakload $peak\_MW\_anticip_k$. Production capacities $Cap\_MW\_anticip\_duree\_i_k$ are defined by the equation below and issued for the different segments of the load curve (8030, 6570, 5110, 3650, 2190, 730):

$$Cap\_MW\_anticip\_duree\_i_k = \frac{peak\_MW\_anticip_k - base\_MW\_anticip_k}{6}$$
$$\text{for } i \in \{8030, 6570, 5110, 3650, 2190, 730\}$$

As far as fuel prices are concerned, we confine ourselves to a "myopic" anticipation hypothesis: current prices are taken as anticipated future prices. We thus suppose that facing the uncertainty of short-term fluctuations in fossil resources prices, electricity producers take current prices as the best available information. In addition the agents are taken to be myopic about the carbon tax profile fixed by the regulator in the stabilization scenarios. The anticipated values of taxed prices for the three fossil fuels, coal, oil and gas, are written respectively $p\_coal\_anticip\_taxed_k$, $p\_oil\_anticip\_taxed_k$ and $p\_gas\_anticip\_taxed_k$. For electricity production technologies which use CCS, a specific attenuation coefficient is applied to the tax so that only the diminished CO_2 emissions are taken into account. In future versions of the model, we plan to introduce more sophisticated modes of anticipation, notably the possibility of representing a range of price anticipations and an optimization approach under uncertainty.

Determining upstream investments in non-hydroelectric renewable production capacities

Non-hydroelectric renewable energies are treated separately because of (i) the intermittent character of their electricity production, (ii) the possibilities of decentralised production of renewable electricity, for example in buildings, which by satisfying part of the demand reduce the total demand on the network. In the current version of the model, these two characteristics are taken into account in an aggregated manner in the form of three hypotheses:

- The only renewable energy explicitly represented in the investment choices of the supply mix is wind turbine energy, either on- or off-shore. It is assumed that solar energy is used only when integrated in buildings, making it possible for them to satisfy part of the residential needs through this decentralized production and also to reduce demand to below the 50 $kWh/m^2/yr$ threshold we categorise as a VLE building.
- In fact, the dimensioning of wind farms is made through the allocation of production from wind in the total energy production, $share\_ENR\_elec_k$. This share is assumed to depend on the ratio between the total production cost of wind energy (per kWh) and the total minimal anticipated baseload electricity production with conventional technologies. The value of this share varies according to the region under consideration taking into account (i) the physical limits of the penetration of of intermittent renewable electricity on the distribution network (although in certain cases, the distribution of wind turbines/farms across the region can guarantee a given power almost all year long) and (ii) constraints linked to saturation of the regional renewable production potentials. In the default setting of the model, it is assumed that ithis value cannot exceed 40 % in any region. The quantity of wind turbine energy in the optimal production capacity at t+10 is therefore given by the equation:

$$Q\_elec\_ENR\_anticip_k = Q\_elec\_anticip_k \cdot share\_ENR\_elec_k$$

- Progressive planning of investments to assure the necessary production capacities to furnish this wind turbine energy - written $Cap\_elec\_MW\_anticip_{k,TECH\_ENR}$- again requires a split between onshore and offshore wind turbines, a split which depends on the relative profitability of the two categories of technology. In addition, in order to determine the production capacity that must be installed to meet a certain energy production in each of these two categories, the average availability factor of each technology is be taken into account.

Investment in hydroelectricity

The quantity of power remaining to be supplied, in addition to that provided by wind turbines (described in previous section), is written $Q_elec_CONV_anticip_k$and is obtained by subtracting the energy that will be supplied by the wind turbines under construction from the total anticipated demand. The available hydroelectric capacities - rather than other conventional forms of energy - are dispatched first from the conventional production capacity that will be needed to supply $Q\_elec\_CONV\_anticip_k$.

Hydroelectricity is treated in a specific manner because investments in this technology are both dependent on its relative profitability and on the available geographical sites. In this module we make no distinction between run-of-the-river and conventional (dammed) hydro power plants and hydroelectric production capacities are dispatched with reference to all other conventional technologies to meet the baseload or higher levels.

In each region covered by the model, information calibrated on the MARKAL model (Labriet et al., 2004)[41] supplies the potential volume of hydroelectric production that are technically exploitable (expressed in gigawatts). In the same manner as for wind energy, the electricity sector anticipates the share of hydroelectricity that will be needed during the period *t+10* by comparing the complete production cost per kWh of new hydro capacity with the total minimum anticipated electricity production cost in the set of other conventional technologies during the baseload period. By applying this share to the regional potential of hydroelectric production, the model assumes a prioritisation of the dispatch of hydroelectric production capacity, $Cap\_elec\_MW\_anticip_{k,Hydro}$, for the long production periods (baseload and the dispatch segment just above it).

In order to determine the remaining conventional production capacities to satisfy the anticipated monotonous power load curve constraint, the optimization calculation of the conventional installed capacity without hydroelectricity will be made on the monotonous load curve truncated at the bottom at a power equaling the anticipated hydroelectric production capacities.

Conventional installed production capacity

The 'Residual' monotonous power load curve is that remaining once the wind and hydroelectric capacities have been deducted. It determines for all 7 segments of the annual utilization period, a portion of the conventional production capacity that should be available at date, *t+10*. In the projected least cost installed production capacity certain capacities will be constructed to be used in the base load period (that is to say, 8760 hours per year) while others will be constructed to be used 8030 or less hours per year up to the peak capacities which will be used only 730 hours per year.

Planning the conventional installed production capacity at minimal cost for the period, *t+10*, means determining, for each discrete segment of annual utilization, the cheapest production technology. Assessing the competitiveness of a technology to satisfy a fixed annual utilization period is done by calculating the discounted total production cost of a kilowatt hour for this availability factor. This total cost corresponds to the total discounted cost over the equipment lifetime of a kilowatt of installed capacity that includes:

- The capital cost or construction cost
- The fixed total discounted operation and maintenance costs per kWh installed
- The variable total discounted operation and maintenance costs per kWh produced
- The total discounted fuel costs, calculated using the final price scenarios of the anticipated fossil energies.

The total discounted cost for the technology lifetime in each segment of the utilization period serves as the basis for calculating the fixed annuity equivalent to paying this discounted total cost. The total discounted production cost of a kilowatt-hour for this utilization period is then obtained by dividing this annuity by the kilowatt-hour produced.

Calculating the total discounted production cost of a kWh for each conventional technology makes it possible to determine the technologies that are most profitable for each possible annual availability factor. The penetration of these technologies will thus be favoured in the new capacity installed however without allowing them to capture the entire market. Market heterogeneities and uncertainties linked to the discounted production costs mean that for the purpose of modelling diversifying the portfolio of technologies and their coexistence within the same installed capacity of competitive technologies, is justified (Clarke and Edmonds, 1993)[42].

Specifically, the partitioning of the different technologies among the anticipated production capacities dedicated to an annual use of fixed length is carried out according to a logit function. For each utilization period, this logit function is calibrated to the reference year to reproduce the observed market shares of the period according to the anticipated production costs calculated in the model. These anticipated costs incorporate an additional cost called the intangible cost, of which the value makes it possible to calibrate the market shares of the different technologies in the reference year to the observed values of the electricity sector in the regions of the model at the same date.

The capacities of the optimal conventional installed capacity at *t+10*, (*Cap_elec_MW_anticipk*,*TECH*) are obtained by summing up the desired production capacities of the 7 segments of the load period.

Calculating the current investment: minimizing the distance between the optimal production capacity and the installed capacity

The procedure described in the preceding sub-section allows us to define at each date, *t*, the optimal anticipated production capacity for the period *t+10*. Investment decisions at date t then aim at reorienting the existing production capacity towards the optimal anticipated production capacity by the end of the decade, under the constraints of available capital.

To achieve the anticipated optimal capacity at *t+10*, one needs only to make capacities evolve in 10 equal time steps. For example, between *t* and *t+1*, the evolution in capacities will be given by the equation below. However, this evolution can face financial constraints on the one hand and the need to depreciate certain capacities before the end of their life time on the other.

$$\Delta Cap\_MW\_G_{k,TECH} = \frac{Cap\_MW\_exp_{k,TECH} - Cap\_MW\_depreciated_{k,TECH}}{10}$$

In the present version of the model, it is not possible to either remove certain production capacities before the end of their life-time or modify the technologies embodied in the installed capacities, i.e. there is no early decommissioning or retrofitting. We thus treat the inertia of the equipment and technologies as if they are utilized for their full life-time. This hypothesis makes it necessary to rewrite the above equation under the double constraint of:

- Disposing of no disinvestments for certain technologies;
- Not obtaining a total size of new investments (in megawatts) that would lead to an over-dimensioned installed electricity capacity for the period *t+1* with reference to anticipated electricity production.

The composition of the actual investment made, written *Inv_MWk,TECH*, is obtained by solving a program for minimizing the difference between the investment made and the net desired investment under the constraint of the quantity of capital actually allocated to the electricity sector, *Inv_elec_valk*.

This investment generates a new generation of capital that marginally modifies the composition of the installed electricity production capacity for the next static equilibrium:

$$Cap\_MW_{k,TECH}^{Vintage} = Inv\_MW_k, TECH$$

On the basis of this new installed generation capacity, the new technical parameters characterizing thetechnologies embodied in the electricity sector capacities remain to be calculated so as to solve the next static equilibrium.

Calculating average production cost from the installed generation capacity

Once investments have been made according to imperfect foresight of future prices and demand, the actual division of production across the existing production capacities depends on the real load curve. For the model to be completely coherent, the day-to-day operating choices for the different capacities must be integrated into a static equilibrium since they are no longer a question of long term investment choice but rather of short term considerations which depend on instantaneous energy market conditions. Nevertheless, it was judged that integrating these choices into the static equilibrium was too complex, and so they were left in the preceding dynamic module. In this approach, an approximation is made by calculating the technical coefficients of the electricity sector on the basis of projected fossil fuel prices at *t+1* instead of calculating them on the basis of actual variables.

In every region of the model, electricity producers make an estimate of the electricity production that needs to be constructed for the following period. The average installed capacity of wind energy estimated in its planning meets some of this production. This wind energy produced is then deducted from the total anticipated demand.

The electricity sector then anticipates that the residual demand is split up according to an anticipated monotonous load curve calculated by following the same procedure as before but at *t+1* instead of *t+10*. The electricity sector next tries to minimize production cost variables so as to meet the demand not satisfied by the electricity from wind power by taking account of the anticipated monotonous load curve. The control variable is the anticipated availability factor for each installed unit of production capacity. Depending on the current prices of fossil energies calculated in the preceding static equilibrium, the technologies of conventional production are classified according to increasing variable production cost. The projected monotonous load curve determines the seven load segments associated to the seven discrete utilization periods. The available production capacities are used by increasing variable costs to supply the power demanded per segment of decreasing utilization periods. In practice this approach shows that the technology with the lowest variable production cost will be used for the longest utilization periods (e.g baseload) until:

- Either the power called for exceeds the available production capacity for this technology and the next cheapest installed production capacity is exploited to obtain the additional power,
- Or the available production capacities of this technology exceed the power demanded for this load duration and the remaining available production capacities will be used to answer demand associated with the load duration that is immediately inferior.

The figure below gives a stacked example of the technologies by order of merit according to their lengths of use.

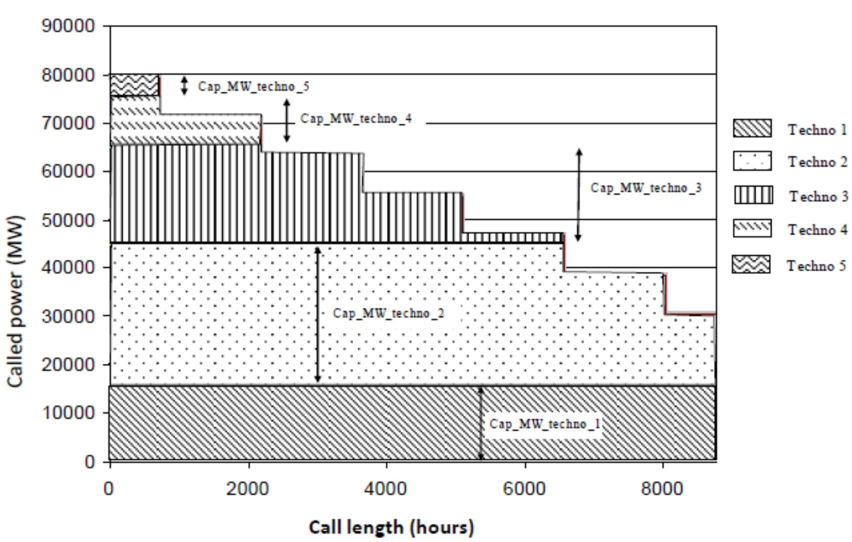


FIGURE CAPTION: Example of the calculation of the annual utilization periods for the five different technologies classified according to increasing variable production cost (technology n°1 has the lowest variable production cost and n°5 the highest) and of which the available production capacities, written *Cap_MW_techno_i* for *i* belonging to the discrete set (1; 2; 3; 4; 5).

This production cost minimization program makes it possible to associate an average annual utilization period (in hours) in each region *k* to each stock of installed production capacity using technology, *TECH*. The product of these two terms makes it possible to determine the quantity of electricity actually produced by the technology under consideration.

For conventional technologies using fossil fuels, the fuel consumption associated to the electricity produced is calculated directly from the average energy efficiency of electricity generation of the installed capacity of the technology.

The technical unitary coefficients of production which characterize the electricity sector (quantities of different fuels required to produce a unit of electricity) are determined for coal, gas and liquid fuels by the three equations below:

$$IC_{coal,elec,k} = \frac{\sum_{tech\_coal} \frac{prod\_elec\_techno_{k,tech\_coal}}{rhoelec_{k,tech\_coal}}}{Q\_elec\_anticip\_t + l_k}$$

$$IC_{gas,elec,k} = \frac{\sum_{tech\_gas} \frac{prod\_elec\_techno_{k,tech\_gas}}{rhoelec_{k,tech\_gas}}}{Q\_elec\_anticip\_t + l_k}$$

$$IC_{Et,elec,k} = \frac{\sum_{tech\_Et} \frac{prod\_elec\_techno_{k,tech\_Et}}{rhoelec_{k,tech\_Et}}}{Q\_elec\_anticip\_t + l_k}$$

4.2.4) Liquid fuels - IMACLIM

Alternative liquid fuels

The description of alternative liquid fuel production in the model is crucial for the assessment of future energy supplies, in particular if global climate change mitigation policies are implemented or if oil markets become more volatile due to for example increasing depletion of oil supplies. The supply of liquid fuel is important for road and air transport, which are today mainly powered by internal combustion engines using oil-based liquid fuels. There are two major possibilities for technical change in this sector: the use of liquid fuels from sources other than oil - which is the subject of this section - and the use of other types of engines and transportation modes.

In the current version of Imaclim-R, biofuels (ethanol and biodiesel) and synthetic fuels produced from the liquefaction of coal (hereafter referred to as CTL for Coal to Liquids) are the main alternatives available to refined oil over the course of the 21st century. In the dynamic module of the model which governs alternative fuel supply on liquid fuel markets, these fuels are considered to be perfect substitutes for refined oil. In the reference year, production consists solely of refined crude oil, and over the course of modeled scenarios alternative fuels are produced as soon as they become profitable.

The dynamic module of the model which is dedicated to alternative fuels (the ?alternatives to refined oil? sector) covers: (i) the evolution of their market shares, (ii) the evolution of the sectorial cost structure, which is a weighted average of the cost structure of the production of each fuel (See Equation below), and (iii) the evolution of sectorial GHG emission coefficients, which depend on the fuel mix structure of the sector.

$$\begin{aligned} Cost_{k,Et} &= Cost_{k,refined\_oil} \cdot share_{k,refined_{oil}} + .. \\ &+ Cost_{k,ethanol} \cdot share_{k,ethanol} + Cost_{k,biodiesel} \cdot share_{k,biodiesel} + .. \\ &+ Cost_{k,CTL} \cdot share_{k,CTL} \end{aligned}$$

The technical coefficients of the production structure of the Alternatives to Oil sector ($Cost_{k,Et}$) - namely the intermediary unitary consumptions $IC_{i,Et,k}$, the unitary labor need $l_{k,Et}$, the unitary profit rate $?_{k,Et}$, and the emission coefficients per unit of liquid fuel produced - are obtained by weighting the technical coefficients of the different supply options. These technical coefficients (indexed as refined_oil, ethanol, biodiesel and CTL) are calibrated on engineering information taken from sectorial technological models or technical reports.

The market shares of alternative fuels (ethanol, biodiesel and CTL) in the regional basket of refined products depend on their relative costs and on the constraints imposed on their production. The market share of refined crude oil is driven by the evolution of oil production capacities.

Biofuels

First and second generation biofuels are the first large-scale substitutes to oil for liquid fuel production that are discussed here. The IEA (2014) describes/defines biofuels as ?transportation fuels derived from biological sources". They can come in liquid (ethanol or biodiesel) or gaseous (biogas or hydrogen) form. Biofuels can be produced from crop sources (either food crops or non-food crops, e.g. switchgrass) and non-crop sources (e.g. forestry residues, industrial waste) (IEA, 2004). The current version of IMACLIM-R models the supply of ethanol and biodiesel.

There are currently three main feedstock types for ethanol production: (i) sugar cane or sugar beet, (ii) grains such as wheat or corn, and (iii) lignocellulosic materials such as wood and straw from agriculture and forest residues. Ethanol is typically used as a substitute for petrol. Biodiesel, for instance produced from oilseed crops can be used as a substitute for petroleum diesel and has similar physical properties to conventional diesel (Bozbas, 2005). In IMACLIM-R, ethanol and biodiesel are assumed to be directly usable in internal combustion engines (i.e. no engine modification is necessary), by mixing with oil-based fuels (petrol and diesel, respectively) according to set proportions.

Supply constraints and market share

The penetration of biofuels in liquid fuel markets depends on their availability and their competitiveness with oil-based fuels and other alternatives. Most importantly, the supply of biofuels is subject to global upstream constraints related to the availability of land. The IMACLIM-R framework aims at eventually being coupled with a land-use module (see wiki page on Land-Use) that will specify the evolution of land rents from; competition for land uses and; the production choices made by farmers. In the current version of the model this is replaced by supply curves for ethanol and biodiesel. Using these supply curves the constraint on the availability of agricultural land is thus captured by a threshold value on biofuels production. These supply curves are calibrated on the results of sectorial modelling to 2100 (IEA, 2006a), which were interpolated to obtain an annual continuum of worldwide supply curves between 2001 and 2100. The supply curves define the maximum amount of biofuels that can penetrate the liquid fuel market at a given date and for a given price (including taxes) of oil refined products. This captures in a simplistic manner the competition between biofuels and oil-based liquid fuels: all else being equal, high oil prices allow biofuels to compete with oil-based fuels. The price of refined crude oil can include a tax on the CO_2 emissions from oil in the case that climate change mitigation policies are put into place. Biofuel supply curves include explicit limits on its production related to land availability and competition with other uses of biomass.

The supply curves evolve over time to account for technical improvements in production processes: the production potential of various biofuels increases and their production costs decrease through technical change. Two alternatives can be considered for the calibration of the supply curve. A conservative alternative assumes that in 2030 maximum global biofuel production is at 14 EJ/year, increasing to 42 EJ/year in 2050 from technical progress. These assumptions are quite conservative with respect to recent estimates about biofuels potential (Chum et al., 2011) and a more optimistic alternative is also introduced, assuming 20 EJ/year in 2030 and 60 EJ/year in 2050. The increase in the production potential is mainly due to the medium term maturing of second-generation technologies , i.e. the use of cellulosic lignite to produce ethanol and biomass liquefaction for biodiesel production. Second generation technologies may modify the location of biofuel production considerably if large scale production potential at reasonable cost becomes available in temperate climates. Up until now large-scale production of ethanol has been traditionally found in tropical regions with high crop yields. The case of Brazilian sugar cane is a prime example.

An exogenous constraint that covers other kinds of inertias that could affect the deployment of these technologies is imposed on the annual growth in biofuel production. In modelling terms, this constraint is represented by a time delay, $?t_{bio}$, which captures the inertia of the production of raw biomass and the deployment of refining capacity. These constraints and their feedback on the cost of biofuels are one major reason why synthetic fuels like Coal-to-Liquids may become another competitive alternative to oil.

Price formation and cost structure

Global production of biofuels is distributed across the regions of the model according to two specific distribution keys: the price formation and cost structure. The evolution of the share of biofuels in the liquid fuel market shapes the global cost structure of the ?alternatives to oil? sector via a new weighting of the cost structures of all alternative fuels. The cost structures of the two main types of biofuels, ethanol and biodiesel, are built on the basis of their selling price, which is set equal to the price of refined oil. For this it is assumed that the income from biofuel sales is allocated to the consumption of intermediary goods from the agricultural sector. This means that the cost structure of biofuel refining is neglected but this will be better represented in a future version of the model. Nevertheless, the model accounts for the income transfers to the agricultural sector from the production of biofuels, the use of agricultural production capacities to produce biofuels and the use of energy to produce crops for biofuel production *via* the consumption of agricultural goods.

When biofuels enter the liquid fuel mix, the regional unit emission coefficients associated with burning liquid fuels decrease accordingly. This is because the specific emission coefficient of the ?alternatives to oil? sector only accounts for the emissions associated with the conversion of energy crop into biofuels, not the emissions associated with burning biofuels. The emissions associated with growing crops for biofuel production are accounted for via the energy use of the agricultural sector.

The land-use dynamic module will be crucial to deliver insights about the competition between food and biofuels.

Synthetic fuels

The second alternative to oil-based fuels is Coal-To-Liquid (CTL). Coal is mainly used for electricity generation but can also be converted into liquid fuels. Carbon-to-liquid technologies include the gasification of coal combined with Fischer-Tropsch synthesis (this process is also called indirect coal liquefaction), and the direct liquefaction of coal which involve dissolution of the coal in a solvent at elevated temperature and pressure and catalysed hydrocracking, (IEA, 2006b). According to the IEA, converting coal to liquid fuels emits seven to ten times more CO_2 than crude oil refining. However, with carbon capture and storage, emissions from coal liquefaction would be similar to those from crude refining, (IEA, 2006b). The low price and wide availability of coal (although it is a finite resource too) are the main drivers for the development of coal-to-liquids technology, (IEA, 2006b).

Supply constraints and market share

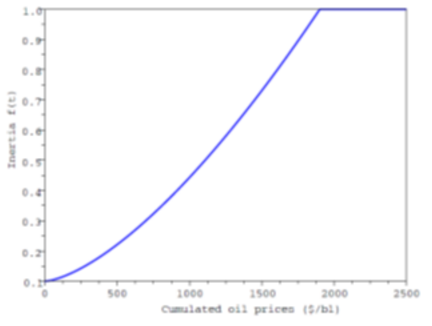
We assume CTL is an inexhaustible ?backstop? technology subject to capacity deployment constraints. In line with Amigues et al. (1998), the production of inexhaustible substitutes starts before all least-cost deposits of the exhaustible resource are exploited. The development of coal liquefaction depends on its profitability compared to traditional oil-based fuels. CTL enters the market as soon as the liquid fuel selling price exceeds the total cost of CTL, p_{CTL}, including production processes and risk premium. This threshold value p_{CTL} is set at 100 US$/barrel. Once this threshold is reached, CTL producers are willing to take the risk of launching large-scale production and fill the gap between total liquid fuel demand, D(t), and total supply from other sources (refined oil and biofuels), S(t). CTL producers are willing to fill a growing fraction of the gap between total fuel demand and the supply of refined oil and biofuels.

$$D^{CTL}(t) = s(p_{cum}(t)) \cdot max[D(t) - S(t), 0]$$

However, CTL production may be limited by constraints on production capacity caused by past investment decisions. The level of CTL production depends on investors? beliefs in the profitability of investments in CTL production capacity. For instance, production constraints may arise due to the underestimation of the profitability of CTL because of imperfect foresight. This effect is captured through $s(p_{cum}(t))$, an increasing function of cumulative oil prices from 2001.

$$p_{cum}(t) = \sum_{i=2001}^{t} min[p(i), p_{max}] \qquad with \quad p_{max} = 110\ US\$/barrel$$

High cumulative oil prices give confidence in CTL profitability and increase the level of desired CTL production (see f(t) in figure below). The share s(t) of the potential market for CTL (D(t) - S(t)) that is actually available to be filled by CTL production is thus an increasing function of cumulative prices. Cumulative investment on CTL over time is also a function of past oil prices.



Investors' beliefs in profitability of investments in CTL production capacity

Finally, constraints on the delays of maturation of investments in production capacity and on the time necessary to adapt distribution networks are captured by a constraint on CTL production growth:

$$Q^{CTL} = max[Q^{CTL}(t-1) + \Delta Q^{CTL}_{IEA}, D^{CTL}(t)]$$

Where is the largest possible increase in CTL production. This is calculated as a linear interpolation between values for 2030, 2035 and 2050 from IEA scenarios (2008).

Given the uncertainty of prospects for large-scale CTL production, several scenario variants may be used, depending on whether CTL is considered as a mature technology expanding smoothly (low threshold price and no inertia on deployment) or if is considered to be less mature and subject to deployment constraints (high threshold price and deployment time-lag).

Price formation and cost structure

The technological features of coal liquefaction are drawn from the Energy Technology Perspectives study (IEA, 2006c). The cost structure for CTL production includes a technical coefficient for the unitary consumption of coal corresponding to a 50% energy efficiency of the liquefaction process and a profit rate which is set to obtain a total production cost of CTL equal to 100 US$/barrel (i.e. the threshold price). This level of profit reflects the highly capitalistic character of coal liquefaction technologies.

Emissions related to the production of Coal-To-Liquid account for the lower efficiency of this production process. Two thirds of the carbon originally contained in coal is emitted during the liquefaction process (IEA, 2006c), while the rest is emitted during fuel combustion in its final usage. The CO_2 emissions occurring during the liquefaction process can be sequestered.

In the current version of IMACLIM, the production of synthetic fuels from hydrocarbons is limited to the liquefaction of coal, mainly because of the abundance of coal resources. The liquefaction of gas and the extraction of shale gas are not modelled. These technology options all have low production rates and high CO_2 process emissions. However, natural gas resources are assumed to be only used in the most efficient direct combustion processes and the extraction of shale gas is not envisaged due to its impact on the environment and its very low efficiency.

4.3) Energy end-use - IMACLIM

This section describes the technical representation of end-use sectors and how the evolution of technical parameters such as efficiency change unit consumption.

4.3.1) Transport - IMACLIM

Modeling the dynamics of the transportation sector

In static equilibrium, the transport of passengers and merchandise are characterized by the following parameters:

- The number and charachteristics of households personal vehicles,
- The efficiency of the fleet of personal vehicles,
- The physical capacities of the different modes of transport,
- The coefficients of intermediary energy use in the transport sectors,
- The coefficients of intermediary consumption of transport in all sectors.

In the recursive dynamic structure of Imaclim-R the "transport" dynamic module represents the evolutions of these parameters.

Waisman et al. (2013)[2] give a detailed description of the representation of the transportation sector in Imaclim-R, and analyze the sector's role in the development of low-carbon pathways. The section below gives a description of the representation of the dynamics of the sector in Imaclim-R.

Personal vehicles: stock and energy intensity

The evolution in the rate of motorization in each region has been found to be strongly linked to the evolution of average income per inhabitant and to the distribution of income in the population. It is however only slightly sensitive to variations in fuel prices (Storchmann, 2005)[43]. The representation of these links in IMACLIM-R are based upon the *SMP* model, a sectorial model of energy use in the transport sector developed in a collaboration between the International Energy Agency and the World Energy Council (Fulton and Eads, 2004)[44]. The key feature of the *SMP* model is that it uses an income elasticity that varies depending on the rate of motorization. In practice this means an elasticity that varies with income. Regional variation resulting from historical and geographical factors, mean that the correlation between an absolute level of wealth and the possession of a vehicle is not transposable from one region to another. The saturation effect on the possession of personal vehicles thus appears at a level of average income that depends on the region.

The income elasticity, α_k, is linked to the rate of motorization according to a formula adapted from the *SMP* model and schematized in Figure 5. In the regions where the annual average income (measured in purchasing power parity) does not exceed \$5000 per capita, this elasticity is maintained equal to 0.3 regardless of the rate of motorization, in order to represent the threshold effects linked to accessing auto-mobility in today's least developed economies. By multiplying *Cars_pc* by the total population one obtains the total size of the car fleet, denoted *CARS*. The size of the personal vehicle fleet, *CARS,* then determines the capacity of transport associated with the automobile mode, a parameter which is taken into account in the budget-time constraint of households in static equilibrium.

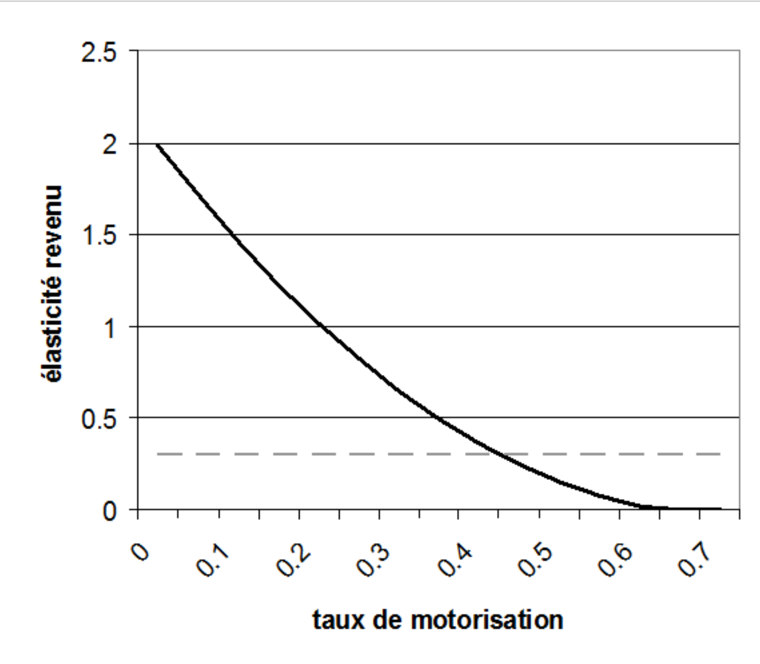


Figure 5: Evolution of the α_k elasticity income according to the rate of motorization.

The efficiency of the automobile fleet depends both upon technical progress and upon technological choices households make upon acquisition of their vehicles. In the model the automobile fleet is charachterised by different generations of vehicles categorised according to the year in which they were put into service and further grouped into four types of vehicles: conventional or hybrid with, in both cases, standard or improved technology. This schematic representation, includes contrasting characteristics for the four types of vehicles : purchase price, energy efficiency and fixed and variable maintenance costs. All costs are calibrated with data from the International Energy Agency (IEA, 2006)[45] and evolve over time in resopnce to technical progress. Hybrid vehicle technology is assumed to improve so as to make possible consumption levels in the order of 1.5 litres per 100 kilometres. This figure can also be understood as being an average of electrical vehicles and rechargeable hybrid vehicles.

At every time step, 'the technological composition of the new generation of vehicles' results from the households' choosing from among the four specific technologies. This choice is carried out by comparing, for each of the four available vehicle technologies, the levelised average cost associated with the production of a vehicle-kilometre. This average cost is calculated using technological characteristics of the different types of vehicles in a manner similar to that used in calculating the complete cost of the technologies used to produce electricity. In doing so it is assumed that households formulate a myopic view of the trajectory of future energy prices, that is to say, they consider that future prices will be equal to those of the preceding static equilibrium. In the case where an explicit carbon policy in introduced, it is assumed that households anticipate perfectly future values of the tax and add it to their myopic scenario of energy prices. The levelized average production cost of a vehicle-kilometer for a specific technology, denoted *TECH* in the following, is obtained using Equation 1 by summing up the fixed and variable costs linked to the possession and usage of the vehicle respectively. The fixed costs are made up of the levelized purchase cost (denoted $CINV\_cars_{k,TECH}$) and the annual fixed running costs associated with the possession of a vehicle (e.g. insurance).Both fixed and running costs are normalised to a kilometre covered on the basis of a hypothesis on the annual average distance covered by vehicles (denoted $average\_km\_per\_year_k$) applied to each region on. Variable costs group the fuel costs which depend both on the anticipated final price scenarios (denoted *_p_fuel_anticip_taxed_cars_*) and the fuel consumption of the vehicle type per vehicle.kilometre (denoted sym). In all of these calculations, the discount rate adopted by the households, denoted $disc_{k,CAR}$, is fixed as a scenario hypothesis between 0.12 and 0.18, according to the region.

$$LC_{k,TECH} = \frac{CRF\_cars_{k,TECH} \cdot CINV\_cars_{k,TECH} + OM\_fixed\_cars_{k,TECH}}{average\_km\_per\_year_k} + CRF\_cars_{k,TECH} \cdot \sum_{i=1}^{life\_time_{k,CAR}} \left(\frac{p\_fuel\_anticip\_taxed\_cars_k(t+i) \cdot \alpha_{k,ENER}^{CARS,TECH}}{\left(1+disc\_cars_{k,TECH}\right)^i} \right) + OM\_var\_cars_{k,TECH} \quad \textbf{(1)}$$

with:

$$CRF\_cars_{k,TECH} = \frac{disc\_cars_{k,TECH}}{\left(1-\left(1+disc\_cars_{k,TECH}\right)^{-life\_time_{k,CAR}}\right)} \quad \textbf{(2)}$$

The market shares of each new vehicle technology is obtained by a logit function which makes it possible to take into account heterogeneities in household choices and the coexistence on the market of several different vehicle types (Clarke and Edmonds, 1993)[42]:

$$MS\_cars_{kTECH} = \frac{LC_{kTECH}^{-\gamma_{kCARS}}}{\sum_{TECH\_j}\left(LC_{kTECH\_j}^{-\gamma_{kCARS}}\right)} \quad \textbf{(3)}$$

These shares are then allocated to the new generation of vehicles, denoted *CAR_new*, obtained by the difference between the new total size of the *CARS* fleet and the old depreciated fleet.

Finally, the **new average energy intensity of automobile transport** (expressed in Mtoe per passenger.kilometre) is obtained by taking into account the composition of the fleet and the levels of use of the different generations and types of vehicles:

$$\alpha_{k,ENER}^{CARS}(t+1) = \frac{\sum_{TECH}\left(\sum_{j=1}^{life\_time_{k,CARS}} CARS_{TECH,k}^{vintage}(t+j)\cdot\frac{\alpha_{k,ENER}^{vintage,CARS}(t+j)\cdot on\_road\_gap\_factor_k}{occupancy_k}\right)}{\sum_{TECH}\left(\sum_{j=1}^{life\_time_{k,CARS}} CARS_{TECH,k}^{vintage}(t+j)\right)} \quad \textbf{(4)}$$

This equation includes two behavioural parameters drawn from the *SMP* model which are necessary togo from the theoretical energy use levels for the four types of vehicles to the average energy intensity of the whole fleet per passenger.kilometer: (1) the average occupation rate of the vehicles, denoted $occupancy_k$, and (2) the relationship between the theoretical energy use level of the vehicles and actual observed energy use level, denoted $on\_road\_gap\_factor_k$.

Other means of transport: capacities and energy use

The evolution of passenger transport capacity is directly linked to the evolution in transport infrastructures that follows from public and private sector decisions. By default, these public and private sector decisions finance capacity evolution in responce to demand increases either explicitly through state spending on road infrastructures or *via* the investment decisions of the respective transport sectors. The evolution in the levels of capacity then modifies the 'time-efficiency' of the different transport modes used in the calculation of the time-budget constraint in the households' utility maximization program in the static equilibrium (Figure 6).

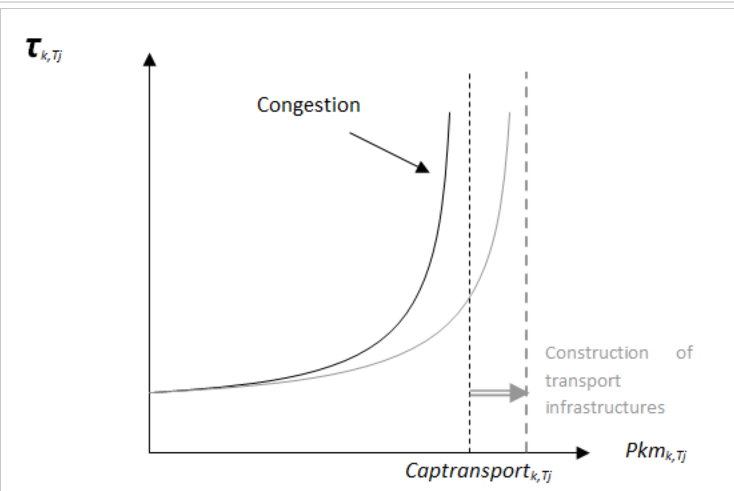


Figure 6: The effect of the extension of capacities on the marginal efficiency of transport time.

The non-automobile **transport intermediary energy use** respond to reduced, simple forms of efficiency improvement:

- In the air sector, fuel use declines by 0.7% per year due to autonomus technical progress that includes both advances in airplane design and the improved use of flight and destination organizational measures aimed at filling plane seats.
- In the maritime sector, intermediary energy use per unit of transport remains unchanged.
- In the which includes sector of freight and passenger transport by land, the average use of liquid fuels evolves in response to a price elasticity of fuels, denoted $elast\_Et\_OT_k$, which is fixed at -0.3 but does not go below an asymptote fixed at 25% of its initial level (See Equation 5). This aggregated representation is a preliminary step towards a more detailed representation of this sector divided into sub-sectors. In fact, in the present version of the model, the sector 'public land transport' groups road and rail freight and road (bus) and rail passenger transport. This level of aggregation follows directly from the GTAP data format upon which the model is calibrated. This format does not distuinguish different sub-sectors of transport. The dynamic evolution of the energy use of this sector is thus a function of vehicle technological progress, modal shifts (particularly shifts in freight between road and rail) and modifications in the structural composition of the sector arising from changes in the relative weights of the comprising sub-sectors.

$$IC\_new_{Et,Other\,Trans,k} = max\left(IC_{Et,Other\,Trans,k}(1)\cdot\left(\frac{pIC_{Et,Other\,Trans,k}(t)}{pIC_{Et,Other\,Trans,k}(1)}\right)^{elast\_Et\_OT_k}, IC_{Et,Other\,Trans,k}(1)\cdot Asympt\_Et\_OT_k\right) \quad \textbf{(5)}$$

Evolution in the transport demand of other sectors

Production technologies used in each sector are described using Leontief functions. The functions have fixed levels of labor, energy and other intermediary inputs. This means that at a given point in time, that the transport demand of production sectors in each of the three freight transportation modes (air, water and land) is measured by input-output coefficients, F_{jIC}, which describe a linear dependence in a given mode of freight transport, j, to production volumes.

The input-output coefficients, F_{jIC}, capture implicitly (a) the spatial organization of the production processes in terms of specialization/concentration of production units and (b) the constraints imposed on distribution in terms of distance to markets and just-in-time processes, and these two factors drive the modal breakdown and the intensity of demand for freight mobility. The input-output coefficients can evolve exogenously over time to capture assumptions on changes in the energy efficiency of freight vehicles, in the logistic organization of the production/distribution process and in the modal breakdown.

For enterprises making organizational and production decisions an uncertainty exists regarding their reaction to variations in the price of transport however small. Therefore it has been decided to fix the evolution of these parameters exogenously. In the default model setting, these coefficients of intermediate consumption of transport by sectors are maintained constant. This is in line with observed historical tendencies.

4.3.2) Residential and commercial sectors - IMACLIM

Residential sector

In the structure of the IMACLIM-R model, the use of energy in the residential sector is determined in each static equilibrium via the α^{m2} parameters. The parameters acts as a physical constraint on household budgets because they are directly linked to the physical stock of buildings available during the current period, and to the coefficients of unit consumption of energy (kWh/m^2) rather than to the maximization of utility. Determining residential sector energy use in the static equilibrium thus means assuming that its energy demand for various end-uses is inelastic to price and income variations over the short term. Hence, households' energy demand depends mainly on the equipment choices they have made over the preceeding years.

In the dynamic modules, the amount of living space per capita changes according to the income per capita which isdetermined endogenously in the preceding static equilibrium. It is assumed that there is an asymptote of floor area per capita specific to each region, and that the asymptote incorporates spatial constraints, choices in the styles of building development and density and cultural habits. In the construction of scenarios, the assumptions made about these asymptotes are kept consistent with those concerning the development of transport infrastructure, bearing in mind that all such dynamics are linked to territorial and urban zoning policies.

The equation below relates the evolution of floor area per capita for the residential sector to the evolution of income per capita, $Income\_pc_k$, over the two preceding static equilibrium periods and an elasticity,$\alpha_k(m^2\_pc(t))$, which decreases as floor area per capita increases:

$$m^2\_pc(t+1) = m^2\_pc(t) \cdot \left(1 + \alpha_k(m^2\_pc(t)) \cdot \frac{Income\_pc_k(t)}{Income\_pc_k(t-1)}\right)$$

The total residential floor area, $S_{k;housing}$, is the product of this surface per capita and of the total population. The newly constructed residential surface is equal to the difference between this total surface and the old residential surface depreciated by the surfaces at end of life (lifetime, $Life\_time_{k;housing}$):

$$S\_new_{k,housing}(t) = S_{k,housing}(t+1) - S\_new_{k,housing}(t) \cdot \left(1 - \frac{1}{Life\_time_{k,housing}}\right)$$

Energy use per m^2 depends on the average composition of equipment installed in the housing stock, and of the thermal charachteristics of building construction. Their evolution depends on the choices agents' technological make in responce to different economic signals and the available technologies.

In the reference scenario, energy use per m^2,$\alpha^{m2}{}_{k;ener}\ (t+1)$, evolves according to an exogenous trajectory calibrated to outputs from the POLES energy model, that have themselves been calculated to be coherent with macroeconomic trajectories from IMACLIM-R during coupling exercises between the two models. This trajectory encompasses the evolution dynamics of household equipment, the conversion efficiency betweenbetween final energy and energy services and the buildings physical characteristics (insulation, use of renewable energies).

In the emission reduction scenarios the carbon price signal induces efficiency gains in building phyisical charachteristics and equipment. These technological options are represented with a unique type of alternative housing called a Very Low Energy building (VLE) whoose annual energy consumption is 50kWh/m^2 (80% electricity and 20% gas). Technologies which can bring about this level of unit energy consumption are already commercialised e.g. on-site energy production of energy and efficient insulation of buildings, and are represented in the model in an aggregated manner. To increse the deployment of VLE?s we assume the introduction of what we call *technological rupture policies*, expected to launch large scale thermal renovation plans and the tightening of building regulations in the developing countries. Following this scheme, two types of housing can coexist in the same stock: (i) standard homes (BAU) which have the same energy characteristics as those of the reference scenario and incorporate progressive gains in energy efficiency and (ii) newly built Very Low Energy (VLE) homes. The penetration speed of VLE's into the building stock is determined by two reduced functional forms that link the level of a carbon tax to (i) the percentage of new built dwellings that are VLE's and (ii), the annual rate of renovation in the existing building stock that converts a BAU into a VLE (with a maximum annual rate fixed at 2,5%). This maximum level is reached at a carbon price of $100 per ton of CO_2 while VLE buildings begin to penetrate the market from $10 per ton of CO_2.

Unit consumption of the existing dwelling stock is then obtained by averaging the energy characteristics of the BAU and VLE housing stocks, weighted by their shares in the total dwelling stock.

Commercial sector

The evolution of this composite sectors (aggregating light industries and services) intermediate consumption of energy follows the same structure of representation as that of the industrial sector (see following section).

4.3.3) Industrial sector - IMACLIM

Energy use by productive sectors

Induced technical change in productive sectors of the economy is modelled in Imaclim-R according to two assumptions. First, energy efficiency improvements are induced by devolopments in energy prices. Second, energy substitution occurs driven by learning-by-doing processes. At the aggregate level, energy efficiency improvements and energy substitution may result from structural changes in economic activity.

Energy efficiency improvements in productive sectors

For each productive sector (industry, construction, services, agriculture), the region with the lowest final energy use per unit of production at base year is identified as the most energy efficient region, thus dividing the world into one leader region and eleven followers for each sector. The energy efficiency of the leader evolves as a function of an energy price index, and an exogenous trend in energy efficiency improvements at constant energy prices. The energy price index is determined endogenously, and the energy efficiency growth rate of the leader will increase (resp. decrease) in response to increases (resp. decreases) in energy prices. For each sector, the energy intensity of the followers is assumed to converge towards the performance of the leader. The speed of convergence also depends on the level of energy prices. Some emerging economies appear to be more energy efficient in some sectors at the year of calibration. From combining IEA energy matrices and GTAP input-output tables, agriculture in Africa appears to be 12% more efficient than the leader (Japan). This can be due to missing data, or difference in the structures of the sectors, and thus suggests precaution with the use of the data. Conforti and Giampietro (1997) [46] also reports that some African countries display a very high energy output to input ratio (Uganda is 380 times more 'efficient' than Japan). In more efficient regions, the energy intensity of the relevant sectors is allowed to start with lower levels of energy intensity then the leader, before converging towards the leader. Energy efficiency improvements are assumed to be in part free, and in part linked to higher cost of capital. Energy efficiency improvements in productive sectors are not biased towards low carbon energy sources meaning that the use of fossil and non-fossil energy decreases uniformly. A shift from carbon intensive to low carbon energy use in these sectors may be induced by an increase in fossil fuel energy prices brought about by the introduction of a carbon price. In general, substitutions between energy carriers (coal, oil, gas, electricity, refined fuel) and transportation modes (road, rail, air, water) are driven by relative prices given explicit constraints on energy production and end-use equipment.

Energy efficiency improvements induce lower energy consumption per unit of output (ICu_{ener}) in each productive sector. This may result in higher or lower aggregated energy consumption (IC_{ener}), depending on the relative effects of lower unit consumption and higher sectoral production (Q) induced by lower prices. Lower overall energy consumption affects energy prices in two ways: a decrease in wholesale energy prices because of lower energy use (IC_{ener}) and lower emissions lead to a relaxation of the carbon tax required to reach a set climate objective. Overall, lower energy consumption thus results in lower tax-inclusive energy prices. As energy efficiency improvements are driven by the energy price index, lower energy prices may in turn counterbalance energy efficiency improvements. On the production side, lower unitary energy requirements (ICu_{ener}) decrease production costs and prices (p), driving up demand and production (Q).

Substitution and structural change

Substitution between energy carriers (i.e. coal, oil, natural gas, electricity, refined liquid fuels) and substitution between transportation modes (i.e. by road, rail, air or water) are driven by relative prices, given explicit constraints on energy production and end-use infrastructure e.g. energy production and conversion capacities and available end-use equipment. These substitutions occur at the end-use sector level.

At the micro level, learning-by-doing may induce substitution between technologies, which may in turn induce energy carrier substitution e.g. from coal to gas for electricity production. Technology substitution is also explicitly modelled at the end-use level for transport, e.g. between conventional and electric cars. Energy efficiency improvements are not biased towards low or high carbon energy carriers, as the consumption of all types of energy decreases uniformly. However, for the sectors using fossil fuels, carbon pricing will increase the energy price index. The substitution between energy carriers however depends on relative prices and relies on a logit decision function for new vintages of productive capacities and equipment (the sectoral energy mix being the sum of energy demands of all vintages). Technical change may occur at the level of specific technologies through learning-by-doing processes. The cost of technologies is assumed to decrease with cumulative investment and production through learning-by-doing, using learning curves for all explicit technologies. The pace of cost reductions down the learning curve depends on the initial installed capacity, the learning rate and the cost floor. This approach has been used to characterise energy technologies, see for instance (McDonald and Schrattenholzer, 2001 [47]; Neij, 2008 [48]). It is used in Imaclim-R to model electricity and oil production technologies, or for demand technologies (such as cars). In energy production sectors, learning-by-doing for low-carbon electricity production technologies (triggered by carbon prices) may improve the carbon efficiency of energy transformation through the substitution from fossil energy towards low carbon-alternatives. At the macro level, carbon pricing policies may induce a change in the structure of demand both at the household and firm levels by altering energy prices. This may in turn change the nature of the goods produced, and hence the structure of each sector and in the relative weight of each sector in total economic output.

4.3.4) Other end-use - IMACLIM

Agriculture, industry, construction and services

By default, supply-side energy consumption in these four sectors changes according to global energy efficiency improvements and shifts in the energy carrier mix for new vintages of capital. Both are driven by the relative prices of energy. On the demand side, income elasticities of consumption of industrial and agricultural goods are assumed to decline to represent saturation, when per-capita income increases. This leads to an endogenous dematerialisation.

4.4) Energy demand - IMACLIM

Households final demand

Households' final demand for goods and services, including energy services, results from solving the current utility maximization program of a representative consumer for each region.

Income and savings

Household income in each region k is equal to the sum of *(i)* wages received from all sectors j of this region (we assume a non-mobile labor supply), *(ii)* dividends of the productive sectors that are equal to a fixed share of sectoral profits within each region (we don't take into account the holding of foreign capital and their returns), and *(iii)* public transfers.

Households' savings are a proportion of their income. Saving rates are taken as exogenous trends. By default, this trend is calibrated on results from the INGENUE model (Hairault and Kempf, 2002) that links savings behaviors to the dynamics of regional population pyramids.

Utility function

The arguments of the utility function U are the goods $C_{k,i}$ produced by the agriculture, industry and services sectors, with basic needs $bn_{k,i}$, and the services of mobility $S_{k,mobility}$ (in passenger.kilometers) and housing $S_{k,housing}$ (in square metres). Households thus make a trade-off between the consumption of different goods and services, including the purchase of new end-use equipment stocks.

$$U = \prod_{goods\ i} (C_i - bn_i)^{\xi_i} \cdot (S_{housing} - bn_{housing})^{\xi_{housing}} \cdot (S_{mobility} - bn_{mobility})^{\xi_{mobility}}$$

Energy commodities are considered as production factors of mobility and housing services: they are not directly included in the utility function, but the associated energy burden weighs on the income constraint. Energy consumption for housing results from efficiency coefficients characterizing the existing stock of end-use equipment per square meter. The link between mobility services and energy demand is more complex. It encompasses not only the energy efficiency of the vehicles but also the availability and efficiency of four transport modes: terrestrial public transport, air transport, private vehicles and non-motorized transport. Owing to differences in services delivered by each mode and to regional particularities, the transport modes are imperfect substitutes for one another. They are, therefore, nested in a constant elasticity of substitution function.

$$S_{mobility} = CES\,(pkm_{air}, pkm_{public}, pkm_{cars}, pkm_{non\ motorized})$$

Final energy consumptions, directly borne by households, are derived from the level of housing and private vehicle services *via* the equation:

$$C_{k,E_i} = pkm_{cars} \cdot \alpha^{cars}_{k,E_i} + S_{k,housing} \cdot \alpha^{m^2}_{k,E_i}$$

where α^{cars} represents the mean amount of each energy needed to travel one passenger-km with the current stock of private cars, and α^{m2} the consumption of each energy product per square meter of housing. These parameters are maintained constant during the static equilibrium resolution; their evolution between two static equilibria is done in the dynamic modules.

Maximization Program

The representative consumer of each region maximizes its utility under two budget constraints:

- A **disposable income constraint** which lays down the equality between *(i)* the sum of purchases of non-energy goods, services and energy expenditures (induced by housing end-use equipment and private cars) and *(ii)* the disposable income for consuming, given a consumer price vector:

$$Income_k - savings_k = \sum_{goods\ i} pC_{k,i} \cdot C_{k,i} + \sum_{Energies\ \ E_i} pC_{k,E_i} \cdot (pkm_{k,cars} \cdot \alpha^{cars}_{k,E_i} + S_{k,housing} \cdot \alpha^{m^2}_{k,E_i})$$

- A **travel-time budget constraint** imposing a ceiling to the average daily travel time of households. This constraint is justified by empirical an finding, known as the **Zahavi law** (Zahavi and Talvitie, 1980), which shows that the average daily travel time remains constant over decades and across a large panel of cities.

The choice between different transportation modes depends not only on their relative prices but also on the marginal efficiency of travelling-time: $\tau_{k,Tj}$, i.e. the inverse of the marginal time used to travel one more kilometer. Each transportation mode (T_j) is thus characterized by its travel time efficiency. This parameter depends on both the average speed allowed by the available infrastructures, the speed of vehicles and the gap between modal mobility demand and the capacity of the network. When mobility demand overshoots the normal load condition of the infrastructure *(*$CapTransport_{k,Tj}$, expressed in road-, rail- or seat-kilometers), the travel time efficiency of this transportation mode decreases. This phenomenon is due to either congestion or infrastructures' unavailability for the considered mode. Investments in transportation can thus lower the congestion of transportation networks and restore their efficiency where the amount of these investments that are allocated for each type of infrastructure is decided in the dynamic modules. In this modeling structure, mobility demand is induced by infrastructure in the long-term: the deployment of new infrastructures and the availability of more efficient vehicles push households to travel more within their income and time budget. There is thus a positive feedback loop between technical choices in the transportation sector, households' modal choices and the overall demand for mobility.

The 'travel-time budget' constraint is formalized as follows:

$$Tdisp_k = \sum_{mean\ \ of\ \ transport\ \ T_j} \int_0^{pkm_{k,\tau_j}} \tau_{k,T_j}\left(\frac{u}{Captransport_{k,T_j}}\right) du$$

Assuming a travel time of 1.1 hours per day (in the default parameterization of the model), the total yearly time used to travel is equal to $Tdisp_k$=1.1·365·L_k, where L_k corresponds to the total population of region k.

Behavioural change

Households consumption choices are determined by current utility maximization under constraints of both revenues and time spent in transport. The utility function depends on the consumption of goods and services, from which basic needs are subtracted, and on mobility (from which basic needs are subtracted as well). See above for a detailed description. With such a representation, relative price changes induce changes in consumption choices between different types of goods.

In addition, a number of non-price mechanisms are included in the modelling framework, which can represent evolutions in lifestyles or households preferences:

- There is a saturation of the consumption volume of agricultural and industrial goods when revenues increase. A function represents the decrease of households' budget shares devoted to agricultural and industrial goods when their revenue increases. Alternative parameterizations of this function allows for the exploration of the role of different evolutions of lifestyles.
- The evolution of basic needs of mobility (exogenous trends) is used to represent the influence of urban forms and infrastructure on constrained mobility.
- A function represents the rate of private car ownership increase with increasing revenues (see Section on Transport). Alternative parameterizations of this function allows for exploration of the role of different evolutions of lifestyles and preferences concerning private mobility.
- Another function represents the rate of increase of residential floor area per capita with increasing revenues (see Section on Residential Sector). Alternative parameterizations of this function allows for the exploration of the role of different evolutions of lifestyles and preferences concerning housing.

4.5) Technological change in energy - IMACLIM

Technological change is represented in a variety of ways in Imaclim-R:

- For technologies that are explicitly represented, i.e. power generation technologies there are cost-reducing learning-by-doing factors. See Section on electricity and private vehicles (see Section on transport.
- For sectors where explicit portfolios of technologies are not represented, the model nonetheless covers (price induced) endogenous energy efficiency improvements and substitutions with other sectors. See Section on productive sectors.
- For general technical change see Section on Technical Change.

5) Land-use - IMACLIM

This section presents the land-use module of IMACLIM-R. This model is currently run independently of IMACLIM-R. The linkage to IMACLIM-R is in progress. The version 1.0 of the land-use model is extensively described in Souty et al. (2012)[49](open access).

Modelling strategy

The Nexus Land-Use model (NLU) is designed to represent the processes of global agricultural intensification, which are viewed as being a key factor in the resolution of the conflicts on land-use. NLU provides a bioeconomic modelling framework that ensures consistency between economic behaviors and spatial biophysical constraints at the global level. Global land area is divided into 12 regions (see section Spatial process), and 6 land-use types: forests, 2 croplands types and 3 pasture types.

The representation of the production system is chosen to account for various biophysical features as well as agronomic practices. This representation relies on three main components: (i) a detailed representation of the livestock production system, based on the Bouwman et al. (2005)[50] model; (ii) potential crop yields, from the Lund-Postdam-Jena dynamic global vegetation model for managed Land (LPJmL, Bondeau et al.,2007)[51]; and, (iii) a non-linear biomass production function, mimicking the crop yield response function to inputs (such as nitrogen fertilizers).

Such a modelling strategy implies that among the four main factors of production of the agricultural sector: (i) land, (ii) chemical inputs and their associated embodied energy, (iii) labor and (iv) capital; that the former two are modelled in detail while the latter two are not. As a consequence, NLU is better suited to dealing with land-use and energy-related issues, including the effects of carbon pricing than it is for, for example, for sketching the consequences of agricultural intensification on labor markets. Land-fertilizer substitution is a core mechanism of the model, as this process is seen to be a major driver of future agricultural changes. This is because of the trends in rising fertilizer prices spurred by tensions on the fossil energy and phosphorus markets. Irrigation is incorporated into the model by differentiation of the potential yields of rainfed and irrigated lands.

The economic principles governing farmer decisions used in the NLU follow from Ricardian rent theory (Ricardo, 1817)[52]. In line with this theory, we consider that the poorer lands are the last to be cultivated. In the NLU modelling framework, the *Ricardian frontier* represents a dividing line between an intensive agricultural system, composed of a mosaic of crops and pastures, and an extensive agricultural system, exclusively composed of pastures. In the model the line moves as the former progressively expands into the latter as the demand for land rises. Hence, unlike the original Ricardian vision in which the agricultural system reacts to a growing demand for land by expanding the size of arable lands into natural ecosystems, adjustments occur from reallocations inside the boundaries of the already exploited land between intensive and extensive agriculture. This vision is consistent with the report made by Bouwman et al. (2005)[50] that "most of the increase in meat and milk production during the past three decades has been achieved by increasing production in mixed and industrial production systems and much less so in pastoral systems. Despite the fast increase of ruminant production by 40% in the 1970--1995 period, the global area of grassland has increased by only 4 %".

Model functioning

For the base year (2001), a representative potential yield is computed at the scale of a 0.5°×0.5° grid from the potential yields given for 11 crop functional types (CFT) by the vegetation model LPJmL. Grid points with the same potential yield are grouped together in land classes. The actual yield of each land class is a function of the chemical inputs used, such as fertilizers and pesticides. This yield-fertilizer function is characterized by decreasing returns, with the potential yield as asymptote. In each land class, the consumption of chemical inputs and the associated yield are determined by cost minimization. The yield/fertilizer relationship is calibrated using fertilizer consumption values (Nitrogen, Phosphorus, Potassium) calculated from FAOSTAT data (FAO, 2013)[38]. It can also be calibrated on GTAP 6 values as done in Souty et al. (2012)[49]. Two of the parameters of the yield-fertilizer relationship -minimum yield and slope at the origin- are calibrated so as to minimize the error between modeled and observed crop yields over the 1961- 2006 period. Nitrogen application via manure and leguminous crop residues are implicitly considered in the calibration of the yield-fertiliser function.

Following Bouwman et al. (2005)[53], the livestock production system is divided into an extensive and an intensive production system. The extensive production system produces only grass-fed ruminants. The intensive production system includes both ruminants and monogastrics (non-grazing animals). In the intensive production system, ruminants are fed with a mix of grass, food crops, residues, fodder and other roughages. In both systems, grass is assumed to come from permanent pastures that can be grazed or cut for hay where permanent pastures are defined according to the Food and Agriculture Organization nomenclature. Two types of permanent pastures, intensive and extensive, are distinguished according to the system to which they provide grass. Monogastric animals are fed with food crops, residues and fodder and animal products. Fodder for monogastric and intensive ruminants is grown on cropland. Croplands are assumed to be located exclusively on the most productive lands including pastures feeding the intensive production system. Conversely, the extensive pastures are located on the least productive lands. This split of agricultural land we carry out does not completely fit with the data since a sizeable share of today?s extensive pastures belong to land classes with high-yields. Therefore, we consider an additional category of extensive pastures, which we call residual pastures.

Each type of land-use; forest, cropland, intensive, extensive and residual pastures, is distributed among the land classes, giving for each land class of potential yield the area fractions of forest, cropland, intensive, extensive and residual pastures. At each time step, NLU calculates a global supply/demand balance from exogenous data on total calorific consumption of food crops for agrofuels, plant foods (food crops for humans), ruminants and monogastric products. The total land supply for agriculture, excluding croplands not represented in LPJmL, is deduced from the exogenously set annual evolution i.e. increase or decrease, of the forest area.

In NLU the agricultural sector, with one representative farmer per land class, minimizes hs production costs under two constraints, (i) land availability and (ii) a global resource-use balance of plant food and ruminant calories. To do this minimization, the representative farmer can substitute both cropland for fertilizer input and extensive livestock production for intensive. There is a link between both these two types of substitution, as the intensification in crop production (i.e. substituting cropland for fertilizer) (i) makes the production of feed for animals more profitable, but on the other hand (ii) mitigates the pressure on land and thus reduces the scarcity rent. The former effect benefits the intensive system and the latter benefits the extensive one. The combination of these two effects determines the exact repartition and position of the *Ricardian frontier* between the intensive and extensive production systems.

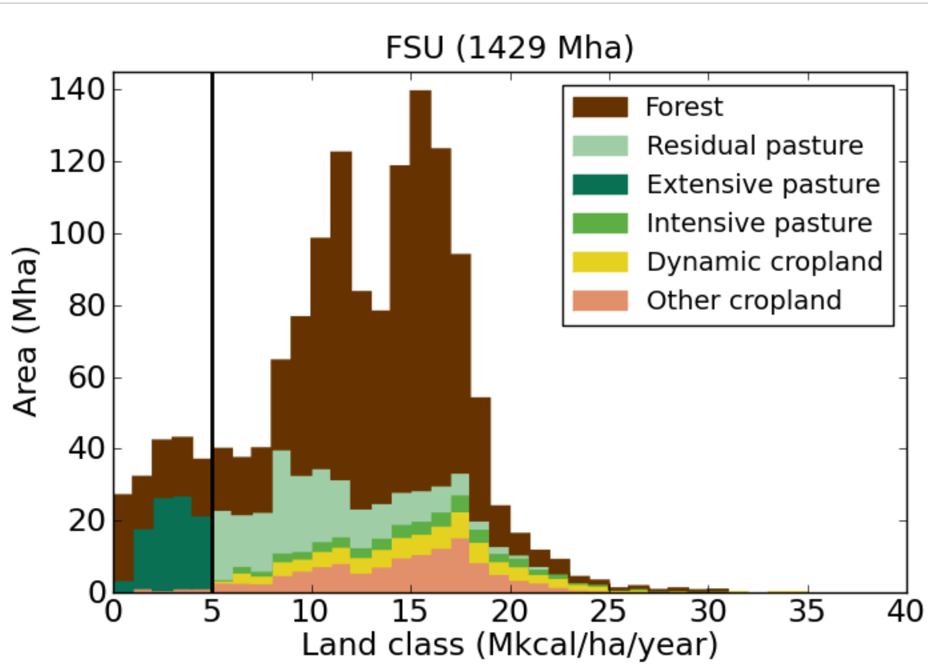


Figure 7: Illustration of the land distribution of potential yields for Former Soviet Union. The black line represents the Ricardian production frontier

When the level of profit of the intensive system increases relative to the extensive one, the Ricardian production frontier moves to land classes with lower fertility (the black vertical bar moves to the left in Figure 7) and the corresponding extensive pastures becomes part of the intensive system. In the opposite case, the frontier moves to more fertile land classes and the extensive system increases at the expense of the intensive one. The cropland-fertilizer substitution elasticity is not parameterized, but is derived from a cost-minimization program. Its value decreases as the Ricardian production frontier moves towards less productive lands, where it becomes less profitable to substitute land for fertiliser.

The shadow price of land (= land rent) is endogenously computed in the NLU model, as the lagrangian multiplier associated with the land constraint in the cost-minimization program. Fertilizer prices are driven by an econometric equation in which the explanatory variables are the exogenous variations of oil, gas and industry prices provided by the energy modules of IMACLIM-R (currently not linked to the NLU module).

The hypothesis of a single representative agent means neglecting the differences between different farms and different situations and assuming they are all characterized by the same potential yield in a given region. The difference between farm types, especially farms of different sizes, however, is not very problematic, as (Chavas, 2008)[54] has shown that long run economies of scale in terms of land-use are small.

NLU balances edible biomass resources and their use, in physical terms. Data is obtained from the FAO and is expressed in kilocalories (kcal), which is the common unit used to represent nutrition (1 kcal=4.1868 kJ). For the model base year (2001), the resource-use balance is established using data from the global agriculture database, Agribiom (Dorin, 2011)[55]. Using calories makes it possible to deal with different types of biomass for human consumption. In NLU, plant food, ruminant and monogastric calories are thus separated, and each type of calories is associated with a specific production process.

International trade is modelled by using a pooled representation of product flows without any consideration of the geographic origin of products. The value of imports and exports are determined by relative regional calorie prices, taking into account a simple representation of imperfect competition and food sovereignty considerations. Regions can trade food crops with each other as well as ruminant products (the trade of monogastric products is held constant).

Due to data availability constraints, two categories of crops are distinguished in NLU: (i) "dynamic" crops, modeled in LPJmL which correspond to most cereals, oilseeds, sugar beet and cassava, and a small share of fodder crops and (ii) "other" crops, not modeled in LPJmL, which correspond to sugar cane, palm oil, fruits and vegetables , some fodder crops and remaining crops. "Dynamic" crop yield is determined endogenously, by taking into account the amount of fertiliser used and biophysical constraints .

The share of "other" crops in total crop production is assumed to be constant over the projection period 2005-2050. The "other" crop yield is an exogenous parameter calculated based on projections from Alexandratos and Bruinsma (2012)[56].

In 2001 (model base year), the land area use is based on the land-use map from Ramankutty et al. (2008)[57]. The total cropland area amounts to 1472 Mha, divided between 748 Mha of "dynamic" crops and 724 Mha of "other" crops. Production on "dynamic" cropland represents 75% of the global calorie production reported by the global database Agribiom.

Model equations

All the model equations are discribed in Souty et al. (2012)[49] (open access).

Main input data

Table 1: Main input data for each region of the model for the base year, 2001. Cropland and pasture areas (in Mha) are taken from Ramankutty et al. (2008)[57] and forests areas (in Mha) are from Poulter et al. (2011)[58], while other data are from Agribiom (Dorin, 2011)[55]. Population is in millions. Diet is calorie consumption in kcal per capita and per day with the fraction of animal products in consumption in brackets. Consumption of seed, agricultural waste at the farm level and other food crops used in the production of lubricants and cosmetics in kcal/capita/day. Net imports of food crops and animal products in kcal/capita/day. Food crops used as feed in kcal kcal/capita/day (Sect. 5.4). 1 kcal=4.1868 kJ.

Regions	Population	Diet	Seed, waste	Net imports of food		Food crops	Area		
			Other	Crops	Animal	for animals	Cropland	Pasture	Forest
USA	311	4105 (30 %)	861	−3344	−135	6939	180	224	334
Canada	31	4167 (30 %)	1424	−7408	−435	9174	42	19	458
Europe	585	3875 (30 %)	1053	930	−52	4248	154	77	220
OECD Pacific	197	2988 (20 %)	364	1919	−165	2208	34	277	276
FSU	280	3101 (20 %)	1010	138	62	2515	205	332	894
China	1284	3005 (17 %)	598	254	19	1314	141	272	209
India	1060	2310 (8 %)	284	34	−2	212	169	11	65
Brazil	177	3168 (22 %)	1146	−2161	−72	2674	50	176	526
Middle East	146	3076 (12 %)	488	2550	74	1626	29	88	36
Africa	826	2510 (6 %)	438	636	26	458	213	764	788
Rest of Asia	884	2430 (8 %)	502	−379	17	500	154	130	359
Rest of LAM	324	3067 (19 %)	782	−721	94	1623	108	325	553
World	6106	2893 (16 %)	603	–	–	1644	1477	2694	4721

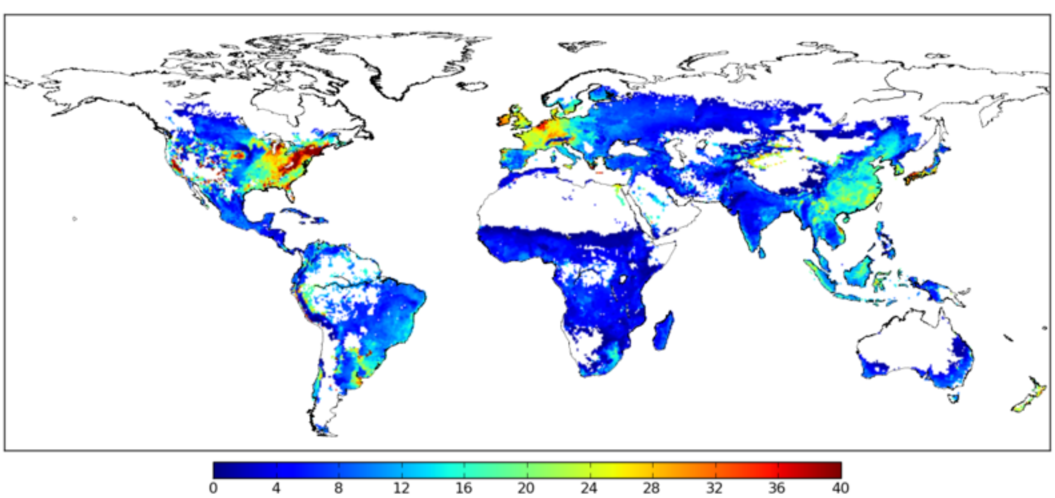


Figure 8: Representative actual yield of crops modelled in the LPJmL model (dynamic crops), average over the 1999--2003 period

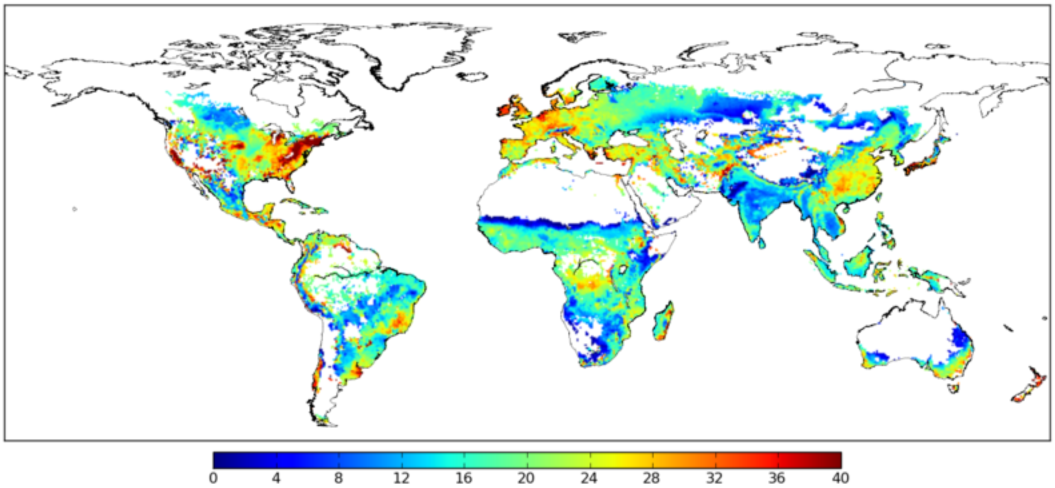


Figure 9: Representative potential yield of crops modelled in the LPJmL model (dynamic crops), average over the 1999--2003 period

Other input data (land distribution of potential yields, crop aggregates, feed conversion factors of monogastrics and ruminants, consumed grass yield...) can be found in Souty et al. (2012)[49].

Evaluation of the model performances

The performance of the model is investigated by undertaking a backcasting exercise for the period 1961-2006. Estimations of cropland areas in each region are evaluated against historical data in each region from Ramankutty and Foley (1999)[59]. Results are shown in Table 2. At the global scale, the simulated cropland area matches the measured cropland rather well. The root-mean-square errors (RMSE) amounts to 52.3 Mha p.a. in absolute terms and 3.6% p.a. in relative ones. The model performs well for half of the modelled regions (USA, Europe, China, India, Rest of Asia, Rest of Latin America), with a RMSE in absolute terms lower than 10% p.a.. The difference between estimations and measured data is more substantial for Canada, Former Soviet Union (FSU), Brazil and Africa, with RMSEs ranging from 11.9% p.a. to 16.6% p.a. However, the NLU fails to accurately model the evolution of cropland area for OECD Pacific (RMSE = 25.3% p.a.) and for the Middle-East (RMSE = 45.6% p.a.). For some regions the model does not explain or reproduce some structural changes visible from the measured data. For instance, for the FSU, the increase in fertilizer input before the collapse of the USSR was not matched by a corresponding yield increases. In OECD Pacific, yields decreased with fertilizer increase for many years, a phenomena the model cannot reproduce either.

Table 2: Root-mean square errors (RMSE) of simulated cropland area against observations over the period 1961-2006.

Region	Absolue RMSE (in Mha p.y.)	Relative RMSE (in % p.y.)
USA	11.8	6.4%
Canada	5.5	12.5%
Europe	7.6	4.6%
OECD Pacific	7.8	25.3%
FSU	30.7	14.2%
China	13.5	9.1%
India	2.9	1.8%
Brazil	5.5	11.9%
Middle-East	12.5	45.6%
Africa	30.9	16.6%
Rest of Asia	9.2	7.1%
Rest of LAM	9.1	9.5%
World	52.3	3.6%

There is no systematic over- or under- estimation bias for the model, as cropland areas are rather under-estimated in half of the regions (Canada, Europe, India, Rest of LAM, Brazil, China), while they are rather over-estimated in the other half (USA, OECD, Pacific, MiddleEast, Africa, Rest of Asia).

Overall, the modelled evolution of cropland areas appears to be more variable than the measured cropland data. A possible explanation for this could be public intervention and price stabilization. For a number of decades, the use of industrial fertilizers has been largely subsidized, directly or indirectly, in many regions of the world. These subventions, as well as interventions in commodity markets, contributed to the stabilization of farmers revenues. In fertilizer price statistics, subsidies are deducted wherever possible, thus, the fertilizer price provided by the World Bank does probably not correspond to the actual price paid by farmers. This would thus introduce errors in our simulations over historic periods. Fertilizer subsidies have however been progressively suppressed since the 80's/90's. Therefore, we can expect such errors to have less influence in future simulations.

6) Emissions - IMACLIM

6.1) GHGs - IMACLIM

IMACLIM-R computes CO_2 emissions from the combustion of fossil fuels , using consistent energy balances and emission coefficients for each fuel. CO_2 emissions from Land-Use and Land-Use changes are modelled in the Land-Use Nexus.

Non-CO_2 GHG gases are not modeled explicitly. If climate indicators need to be computed, exogenous trends are assumed for non-CO_2 GHG gases.

6.2) Pollutants and non-GHG forcing agents - IMACLIM

Non-CO_2 forcing agents are not explicitly tracked in the model. They are represented in the climate module by an exogenously given 'additional forcing factor'.

7) Climate - IMACLIM

7.1) Modelling of climate indicators - IMACLIM

Modelling of Climate indicators

The impact of emissions scenarios on climate indicators is computed using a simplified 3-box carbon cycle model and a simplified 2-box climate model (Ambrosi, 2003).

Radiative Forcing from Other Gases

The radiative forcing from other gases are taken as exogenous assumptions.

Carbon Cycle Model and Climate Model

The carbon cycle is a three-box model, after Nordhaus and Boyer (2010)[60]. The model is a linear three-reservoir model (atmosphere, biosphere + ocean mixed layer, and deep ocean). Each reservoir is assumed to be homogenous (well-mixed in the short run) and is characterized by a residence time inside the box and corresponding mixing rates with the two other reservoirs (for longer timescales). Carbon flows between reservoirs depend on constant transfer coefficients. GHGs emissions (CO_2 solely) accumulate in the atmosphere and are slowly removed by biospheric and oceanic sinks.

The stocks of carbon (in the form of CO_2) in the atmosphere, in the biomass and upper ocean, and in the deep ocean are, respectively, *A*, *B*, and *O*. The variable *E* is the CO_2 emissions. The evolution of *A*, *B*, and *O* is given by

$$\frac{dA}{dt} = -\phi_C^{A,B} + E,$$

$$\frac{dB}{dt} = \phi_C^{A,B} - \phi_C^{B,O}, \text{ and}$$

$$\frac{dO}{dt} = \phi_C^{B,O};$$

The fluxes are equal to

$$\phi_C^{A,B} = a_{21}A - a_{12}B, \text{ and}$$

$$\phi_C^{B,O} = a_{23}B - a_{32}O;$$

The initial values of *A*, *B*, and *O*, and the parameters *a12*, *a21*, *a23*, and *a32* determine the fluxes between reservoirs. The main criticism which may be addressed to this Carbon-cycle model is that the transfer coefficients are constant. In particular, they do not depend on the carbon content of the reservoir (e.g. deforestation hindering biospheric sinks) nor are they influenced by ongoing climatic change (e.g. positive feedbacks between climate change and the carbon cycle).

Nordhaus' original calibration has been adapted to reproduce both; data until 2010 and; results from the IMAGE model for a given trajectory of CO_2 emissions. This gives the following results (for a yearly time step): *a12*= 0.02793, *a21*=0.03427, *a23*=0.007863, *a32*=0.0003552, with the initial conditions: *A*2010=830 *GtC* (i.e. 391ppm), *B*2010=845 *GtC* and *O*2010=19254 *GtC*. The additional forcing caused by CO_2 and *non-*CO_2 gases is given by

$$F_A = F_{2X}\frac{\log\left(\frac{A}{A_{PI}}\right)}{\log 2} + F_{non-CO_2},$$

where A_{PI} is the pre-industrial CO_2 concentration (280 ppm), F_{2x} is the additional radiative forcing for a doubling of the CO_2 concentration (3.71 W.m^-2^), and $F_{non-CO2}$ is the additional radiative forcing of *non-*CO_2 gases.

The temperature model is a two-box model, after Schneider and Thompson (1981)[61] and Ambrosi et al. (2003)[62], with the atmosphere temperature T_A and the ocean temperature T_O as follows:

$$\frac{dT_A}{dt} = \sigma_1\left(-\frac{F_{2X}}{T_{2X}}T_A - \sigma_2\phi_T + F_A\right),$$

$$\frac{dT_O}{dt} = \sigma_3\phi_T, \text{ and}$$

$$\phi_T = T_A - T_O,$$

where *T2x* is the equilibrium temperature increase at the doubling of the CO_2 concentration, that is, it represents climate sensitivity. All parameters have been calibrated to reproduce results from CMIP5 from CNRM-CERFACS global climate model, CNRM-CM5, over the 21st century for RCP3-PD and RCP4.5 radiative forcing trajectories (using a least squares method). This calibration leads to the following parameter values for heat transfer rates (for a yearly time step): *σ1*= 0.054$C.W^{-1}$-$1.m^2$, *σ2*= 0.664 $C.W^{-1}$-$1.m^2$ and *σ3*= 0.0308, and a climate sensitivity of 2.6°C.

9) Appendices - IMACLIM

9.1) Mathematical model description - IMACLIM

Equations of the static equilibria

The calculation of the equilibria determines the following variables at each date t : relative prices, wages, labour, quantities of goods and services including energy, value flows, physical flows, capacity utilization.

Equations of the static equilibrium
Bold=variable
k index represents regions, i and j indexes represents sectors.

Core equations

Income formation

$$Income_k = \sum_{sectors\ i} \Omega_{k,i} \cdot w_{k,i} \cdot l_{k,i} \cdot Q_{k,i} + \sum_{sectors\ i} div_{k,i} \cdot \pi_{k,i} \cdot p_{k,i} \cdot Q_{k,i} + transfers_k \qquad (2.1)$$

Governments' budget

$$\sum taxes = \sum_{sectors\ i} G_{k,i} \cdot pG_{k,i} + transfers_k + InvInfra_k \qquad (2.2)$$

The sum of taxes corresponds to the total of tax revenues, i.e. the tax rates (parameters) applied to the taxable amounts (often endogenous to the equilibrium): for instance the tax rate on labour $tax^w_{k,i}$ applied to total salaries $\sum \Omega_{k,i} \cdot w_{k,i} \cdot l_{k,i} \cdot tax^w_{k,i} \cdot Q_{k,i}$.

Utility maximisation

t refers to the date of the equilibrium, (t-1) to the previous equilibrium.

$$U_k\left(\vec{C_k}, \vec{S_k}\right) = \prod_{goods\ i,\ services\ j} \left(C_{k,i} - bn_{k,i}\right)^{\xi^C_{k,i}} \cdot \left(S_{k,j} - bn_{k,j}\right)^{\xi^S_{k,j}}, \qquad (2.3)$$

with:

$$S_{k,mobility} = \left(\left(\frac{pkm_{k,air}}{b_{k,air}}\right)^{\eta_k} + \left(\frac{pkm_{k,public}}{b_{k,public}}\right)^{\eta_k} + \left(\frac{pkm_{k,cars}}{b_{k,cars}}\right)^{\eta_k} + \left(\frac{pkm_{k,nonmotorized}}{b_{k,nonmotorized}}\right)^{\eta_k}\right)^{\frac{1}{\eta_k}} \qquad (2.4)$$

Income constraint

$$ptc_k \cdot Income_k = \sum_{sectors\ i} pC_{k,i} \cdot C_{k,i} + \sum_{Energies\ Ei} pC_{k,Ei} \cdot \left(pkm_{k,cars} \cdot \alpha^{cars}_{k,Ei} + S^{m^2}_k \cdot \alpha^{m^2}_{k,Ei}\right) \qquad (2.5)$$

Travel time budget constraint

$$Tdisp_k = \sum_{means\ of\ transport\ j} \int_0^{pkm_{k,j}} \tau_{k,j}\left(\frac{u}{Captransport_{k,j}}\right) du, \qquad (2.6)$$

where $\tau_{k,j}$ represents the marginal efficiency in transport time (the time necessary to travel an additional passenger-kilometer with mode j) and is an increasing function of the form $\tau_{k,j}(x) = atrans_{k,j} \cdot x^{ktrans_{k,j}} + btrans_{k,j}$.

The first order conditions give N+S equations, with N the number of consumption goods and S the number of services, and add two unknowns, the Lagrange multipliers for both constraints.

Sector budget (supply curve)

$$p_{k,i} = \sum_{sectors\ i} pIC_{j,i,k} \cdot IC_{j,i,k} + \left(\Omega_{k,i} \cdot w_{k,i}\right) \cdot l_{k,i} \cdot \left(1 + tax^w_{k,i}\right) + \pi_{k,i} \cdot p_{k,i} \qquad (2.7)$$

$\Omega_{k,i} = \Omega\left(\frac{Q_{k,i}}{Cap_{k,i}}\right)$ represents an increasing cost (or decreasing returns) function of the productive capacities utilisation rate. The functional form for Ω is: $a - b \cdot tanh\left(c \cdot \left(1 - \frac{Q}{Cap}\right)\right)$.

Labor market (wage curve)

$$z_k = 1 - \frac{\sum_{sectors\ i} l_{k,i} \cdot Q_{k,i}}{L_k} \qquad (2.8)$$

$$\frac{w_{k,i}}{pind_k} = aw_{k,i} \cdot \frac{wref_{k,i}}{pindref_k} \cdot f\left(\frac{z_k}{zref_k}\right) \qquad (2.9)$$

Equilibrium constraints on physical flows

$$M_{k,i} = shareC^{imp}_{k,i} \cdot C_{k,i} + shareG^{imp}_{k,i} \cdot G_{k,i} + shareI^{imp}_{k,i} \cdot I_{k,i} + \left[\sum_{sectors\ j} Q_{k,j} \cdot IC^{imp}_{i,j,k} \cdot shareIC^{imp}_{i,j,k}\right] \qquad (2.10)$$

$$Q_{k,i} = shareC^{dom}_{k,i} \cdot C_{k,i} + shareG^{dom}_{k,i} \cdot G_{k,i} + shareI^{dom}_{k,i} \cdot I_{k,i} + \left[\sum_{sectors\ j} Q_{k,j} \cdot IC^{dom}_{i,j,k} \cdot shareIC^{dom}_{i,j,k}\right] + X_{k,i} \qquad (2.11)$$

Investment formation

$$NRB_k = GRB_k \cdot \left(1 - shareExp_k\right) + \left(\sum_{countries\ k'} GRB_{k'} \cdot shareExp_{k'}\right) \cdot shareImp_k \qquad (2.12)$$

$$GRB_k = Income_k \cdot \left(1 - ptc_k\right) + \sum_{sectors\ j} \pi_{k,j} \cdot p_{k,j} \cdot Q_{k,j} \cdot \left(1 - div_{k,j}\right) \qquad (2.13)$$

$$InvFin_{k,i} = NRB_k \cdot shareInvFin_{k,i} \qquad (2.14)$$

$$pCap_{k,i} = \sum_{sectors\ j} \beta_{j,i,k} \cdot pI_{j,i,k} \qquad (2.15)$$

$$\Delta Cap_{k,i} = \frac{InvFin_{k,i}}{pCap_{k,i}} \qquad (2.16)$$

$$I_{k,i} = \sum_{sectors\ i} \beta_{j,i,k} \cdot \Delta Cap_{k,i} \qquad (2.17)$$

Intermediate variables
Armington goods

$$\boldsymbol{C_{k,i}} = \left(b_{k,i}^{dom} \cdot \left(\boldsymbol{C_{k,i}^{dom}}\right)^{-\rho_{k,i}} + b_{k,i}^{imp} \cdot \left(\boldsymbol{C_{k,i}^{imp}}\right)^{-\rho_{k,i}}\right)^{-\frac{1}{\rho_{k,i}}} \tag{2.18}$$

$$\begin{aligned}\boldsymbol{pC_{k,i}} =& \Big[\left(b_{k,i}^{dom}\right)^{\sigma_{k,i}} \cdot \left(\boldsymbol{p_{k,i}} \cdot \left(1+tax_{k,i}^{domC}\right)\right)^{1-\sigma_{k,i}} \\ &+ \left(1-b_{k,i}^{dom}\right)^{\sigma_{k,i}} \cdot \left(\boldsymbol{p_{k,i}^{imp}} \cdot \left(1+tax_{k,i}^{impC}\right)\right)^{1-\sigma_{k,i}}\Big]^{\frac{1}{1-\sigma_{k,i}}}\end{aligned} \tag{2.19}$$

$$\boldsymbol{shareC_{k,i}^{dom}} = \left(b_{k,i}^{dom} \cdot \frac{\boldsymbol{pC_{k,i}}}{\boldsymbol{p_{k,i}} \cdot \left(1+tax_{k,i}^{domC}\right)}\right)^{\sigma_{k,i}} \tag{2.20}$$

$$\boldsymbol{shareC_{k,i}^{imp}} = \left(\left(1-b_{k,i}^{dom}\right) \cdot \frac{\boldsymbol{pC_{k,i}}}{\boldsymbol{p_{k,i}^{imp}} \cdot \left(1+tax_{k,i}^{impC}\right)}\right)^{\sigma_{k,i}} \tag{2.21}$$

Similar equations to the four previous are valid for the States final consumptions, the investments and the intermediate consumptions.

$$\boldsymbol{p_{k,i}^{imp}} = \boldsymbol{wp_i} \cdot \left(1+tax_{k,i}^{M}\right) + \sum_{means\ of\ transport\ tt} \boldsymbol{wp_{it}} \cdot nit_{k,i}^{tt} \tag{2.22}$$

$$\begin{aligned}\sum_{countries\ k} &\Bigg(\boldsymbol{shareC_{k,i}^{imp}} \cdot \boldsymbol{C_{k,i}} + \boldsymbol{shareG_{k,i}^{imp}} \cdot G_{k,i} + \boldsymbol{shareI_{k,i}^{imp}} \cdot \boldsymbol{I_{k,i}} \\ &+ \sum_{sectors\ j} \boldsymbol{Q_{k,j}} \cdot IC_{i,j,k}^{imp} \cdot \boldsymbol{shareIC_{i,j,k}^{imp}}\Bigg) \\ &= \boldsymbol{X_i} = \left[\sum_{countries\ k} \Psi_{k,i} \cdot \boldsymbol{X_{k,i}}^{-\theta_i}\right]^{-\frac{1}{\theta_i}}\end{aligned} \tag{2.23}$$

$$\boldsymbol{X_{k,i}} = \left[\Psi_{k,i} \cdot \frac{\boldsymbol{wp_i}}{\boldsymbol{p_{k,i}} \cdot \left(1+tax_{k,i}^{X}\right)}\right]^{\alpha_i} \cdot \boldsymbol{X_i} \tag{2.24}$$

$$\boldsymbol{wp_i} = \left(\sum_{countries\ k} \left(\Psi_{k,i}\right)^{\alpha_i} \cdot \left(\boldsymbol{p_{k,i}} \cdot \left(1+tax_{k,i}^{X}\right)\right)^{1-\alpha_i}\right)^{\frac{1}{1-\alpha_i}} \tag{2.25}$$

Energy goods

$$\boldsymbol{C_{k,i}} = \boldsymbol{C_{k,i}^{dom}} + \boldsymbol{C_{k,i}^{imp}} \tag{2.26}$$

$$\boldsymbol{pC_{k,i}} = \boldsymbol{shareC_{k,i}^{dom}} \cdot \boldsymbol{p_{k,i}} \cdot \left(1+tax_{k,i}^{domC}\right) + \boldsymbol{shareC_{k,i}^{imp}} \cdot \boldsymbol{p_{k,i}^{imp}} \cdot \left(1+tax_{k,i}^{impC}\right) \tag{2.27}$$

$$\boldsymbol{shareC_{k,i}^{imp}}(t) = \frac{shareC_{k,i}^{imp}(t-1) \cdot \left(\frac{p_{k,i}^{imp}(t) \cdot \left(1+tax_{k,i}^{impC}(t)\right)}{p_{k,i}^{imp}(t-1) \cdot \left(1+tax_{k,i}^{impC}(t-1)\right)}\right)^{\eta_{k,i}^{imp}}}{shareC_{k,i}^{imp}(t-1) \cdot \left(\frac{p_{k,i}^{imp}(t) \cdot \left(1+tax_{k,i}^{impC}(t)\right)}{p_{k,i}^{imp}(t-1) \cdot \left(1+tax_{k,i}^{impC}(t-1)\right)}\right)^{\eta_{k,i}^{imp}} + shareC_{k,i}^{dom}(t-1) \cdot \left(\frac{p_{k,i}(t) \cdot \left(1+tax_{k,i}^{domC}(t)\right)}{p_{k,i}(t-1) \cdot \left(1+tax_{k,i}^{domC}(t-1)\right)}\right)^{\eta_{k,i}^{imp}}} \tag{2.28}$$

$$\boldsymbol{shareC_{k,i}^{dom}}(t) = 1 - \boldsymbol{shareC_{k,i}^{imp}}(t) \tag{2.29}$$

Similar equations to the four previous are valid for the States final consumptions, the investments and the intermediate consumptions.

$$\boldsymbol{p_{k,i}^{imp}} = \boldsymbol{wp_i} \cdot \left(1+tax_{k,i}^{M}\right) + \sum_{means\ of\ transport\ tt} \boldsymbol{wp_{it}} \cdot nit_{k,i}^{tt} \tag{2.30}$$

$$\begin{aligned}\sum_{countries\ k} &\Bigg(\boldsymbol{shareC_{k,i}^{imp}} \cdot \boldsymbol{C_{k,i}} + \boldsymbol{shareG_{k,i}^{imp}} \cdot G_{k,i} + \boldsymbol{shareI_{k,i}^{imp}} \cdot \boldsymbol{I_{k,i}} \\ &+ \sum_{sectors\ j} \boldsymbol{Q_{k,j}} \cdot IC_{i,j,k}^{imp} \cdot \boldsymbol{shareIC_{i,j,k}^{imp}}\Bigg) = \boldsymbol{X_i}\end{aligned} \tag{2.31}$$

$$\boldsymbol{MS_{k,i}^{X}}(t) = \frac{MS_{k,i}^{X}(t-1) \cdot \left(\frac{p_{k,i}(t) \cdot \left(1+tax_{k,i}^{X}(t)\right)}{p_{k,i}(t-1) \cdot \left(1+tax_{k,i}^{X}(t-1)\right)}\right)^{\eta_{k,i}^{X}}}{\sum_{countries\ k'} MS_{k',i}^{X}(t-1) \cdot \left(\frac{p_{k',i}(t) \cdot \left(1+tax_{k',i}^{X}(t)\right)}{p_{k',i}(t-1) \cdot \left(1+tax_{k',i}^{X}(t-1)\right)}\right)^{\eta_{k',i}^{X}}} \tag{2.32}$$

$$\boldsymbol{X_{k,i}} = \boldsymbol{MS_{k,i}^{X}}(t) \cdot \boldsymbol{X_i} \tag{2.33}$$

$$\boldsymbol{wp_i} = \frac{\sum_{countries\ k} \boldsymbol{p_{k,i}} \cdot \left(1+tax_{k,i}^{X}\right) \cdot \boldsymbol{X_{k,i}}}{\sum_{countries\ k} \boldsymbol{X_{k,i}}} \tag{2.34}$$

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