The IMACLIM-R Model:

Infrastructures, Technical Inertia and the Costs of Low Carbon Futures under Imperfect Foresight

Supplementary Material

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This Supplementary Material is a complement to the Climatic Change paper "The IMACLIM-R Model: Infrastructures, Technical Inertia and the Costs of Low Carbon Futures under Imperfect Foresight". It provides more detailed information on modeling assumptions in the static equilibrium (section A), on the Nexus describing technical change in the energy sector (section B), on data defining the calibration date and 'natural' growth drivers (Section C), and on the assumptions and calculations supporting the analytical analysis of the drivers of mitigation costs (section D).

A- Equations of the static equilibrium

We distinguish between endogenous variables (marked in bold) and fixed parameters of the static equilibrium at date *t*. For the sake of readability, indexes *i* and *j* are used for sectors, and index *k* is reserved for regions

1. Table of variables

Table SM-1 details the list of variables calculated by the static equilibrium.

Table SM-1: Variables of the static equilibria.

$\mathbf{Income_k}$	Households total revenues in region k
$\mathbf{transfers_k}$	Transfers from States to households in region k
$\mathbf{p_{k,i}}$	Production price of good i in region k
$\mathbf{pC_{k,i}}$	Final consumption price for households for good i in region k
$\mathbf{pG_{k,i}}$	Final consumption price for States for good i in region k
$\mathbf{pI_{k,i}}$	Price for investments for good i in region k
$\mathbf{pIC_{j,i,k}}$	Intermediate consumption price for sector i for good j in region k
$\mathbf{pind_k}$	Households final consumption price index in region k
$\mathbf{wp_i}$	International price of good i
$p_{k,i}^{imp}$	Import price of good i in region k
$\mathbf{w_{k,i}}$	Unitary salary in sector i in region k
$\mathbf{\Omega_{k,i}}$	Increasing cost factor in sector i in region k
$\mathbf{Q_{k,i}}$	Volume of production of good i in region k

Table SM-1 (continued): Variables of the static equilibria.

$\mathbf{C_{k,i}}$	Households final consumption volume of good i in region k
$\mathbf{S}_{k,mobility}$	Households' demand for mobility services
$\mathbf{pkm_{k,mode}}$	Passengers.kilometers travelled per mode (air transport, public transport, private vehicle, non motorized mode) in region k
$\mathbf{I_{k,i}}$	Volume of good i purchased for Gross Fixed Capital Formation (Investment) in region k
$\mathbf{z_k}$	Unemployment level in region k
$\mathbf{M_{k,i}}$	Volume of imports of good i in region k
$\mathbf{X_{k,i}}$	Volume of exports of good i from region k
$\mathbf{X_i}$	Volume of the international market of good i
$MS_{k,i}^{X}$	Market share of exports from region k in the international market of good i
$shareC_{k,i}^{imp/dom}$	Imports (/Domestic production) share in households final consumption of good i in region k
$shareG_{k,i}^{imp/dom}$	Imports (/Domestic production) share in States final consumption of good i in region k
$shareI_{k,i}^{imp/dom}$	Imports (/Domestic production) share in investments of good i in region k
$shareIC_{k,i}^{imp/dom}$	Imports (/Domestic production) share in sector i intermediate consumption of good j in region k
$\mathbf{NRB_k}$	Net regional savings of region k
$\mathbf{GRB_k}$	Gross regional savings of region k
$\mathbf{InvFin_{k,i}}$	Investment allocated to sector i in region k
$\mathbf{pCap_{k,i}}$	Price of one unit of productive capital in sector i and region k
$\mathbf{\Delta Cap_{k,i}}$	New productive capital in sector i and region k

2. Table of parameters

Table SM-2 details the parameters, which are fixed in each static equilibrium and are modified in the recursive framework by dynamic modules

Table SM-2: Parameters of the static equilibria.

$G_{k,i}$	States final consumption of good i in region k
$IC_{j,i,k}$	Sector i intermediate consumption of good i in region k
L_k	Total active population in region k
$l_{k,i}$	Quantity of labour per unit of output in sector i in region k
$aw_{k,i}$	Wage curve parameter for sector i in region k
$\pi_{k,i}$	Markup rate in sector i in region k
ptc_k	Households propensity to spend (one minus saving rate) in region k
$div_{k,i}$	Share of profits in sector i in region k given as revenues to households
$bn_{k,i}$	Basic need of consumption of good i in region k
$\alpha_{k,Ei}^{cars}$	Mean consumption of energy Ei per passenger.kilometer by car in region k
$\alpha_{k,Ei}^{m2}$	Mean consumption of energy Ei per square meter of residential buildings in region k
$Tdisp_k$	Total households travel time in region k
$Cap_{k,i}$	Productive capacity of sector i in region k
$Captransport_{k,j}$	Total capacity of transport mode j in region k
$tax_{k,i}^{w}$	Labour tax rate in sector i in region k
$tax_{k,i}^{M}$	Tax rate on imports of good i in region k
$tax_{k,i}^{X}$	Tax rate on exports of good i from region k
$tax_{k,i}^{domC}$	Tax rate on households final consumption of domestic production of good i in region k
$tax_{k,i}^{impC}$	Tax rate on households final consumption of imports of good i in region k
$shareExpK_k$	Share of gross regional savings of region k exported to the international 'pool' of capital
$shareImpK_k$	Share of the international 'pool' of capital imported in region k
$shareInvFin_{k,i}$	Share of net regional savings of region k allocated to sector i

Table SM-2 (continued): Parameters of the static equilibria.

$\beta_{j,i,k}$	Quantity of good j necessary to build one unit of productive capacity of sector i in region k
$nit_{k,i}^{it}$	Transport need in mode it for imports of good i in region k
$\xi_{k,i}^{C}$, $\xi_{k,i}^{S}$	Parameters of the utility function
$b_{k,mode}$	Calibration parameters for the constant elasticity of substitution function giving the transport service in function of passengers.kilometers per mode in region k
η_k	$\eta = \frac{s-1}{s}$, with s the elasticity of substitution of the function giving the transport service in function of passengers.kilometers per mode in region k
$wref_{k,i}$	Salaries at calibration date in sector i in region k
$pindref_k$	Households final consumption price index in region k at calibration date
$zref_k$	Underutilization of the labour force at the calibration date for region k
$\rho_{k,i}$	$\rho = \frac{1-\sigma}{\sigma}$
$\sigma_{k,i}$	Armington elasticity for good i in region k
b^{dom}, b^{imp}	Calibration parameters for Armington expression for good i in region k
θ_i	$\theta = \frac{1-\lambda}{\lambda}$
λ_i	Armington elasticity in the international market for good i
$\psi_{k,i}$	Calibration parameter for Armington expression for exports of good i from region k in the international market ‘pool’
$\eta_{k,i}^{imp}$	Parameter for the expression of the imports (/Domestic production) share in households final consumption of good i in region k
$\eta_{k,i}^{X}$	Parameter for the expression of the market share of exports from region k in the international market of good i

3. Core equations of the static equilibrium

Income formation

$$\mathbf{Income_k} = \sum_{sectors\ i} \mathbf{\Omega_{k,i}} \cdot \mathbf{w_{k,i}} \cdot l_{k,i} \cdot \mathbf{Q_{k,i}} + \sum_{sectors\ i} div_{k,i} \cdot \pi_{k,i} \cdot \mathbf{p_{k,i}} \cdot \mathbf{Q_{k,i}} + \mathbf{transfers_k} \quad \text{(SM-1)}$$

Governments' budget

$$\sum \mathbf{taxes} = \sum_{sectors\ i} G_{k,i} \cdot \mathbf{pG_{k,i}} + \mathbf{transfers_k} + InvInfra_k$$

The sum of taxes corresponds to the total of tax revenues, i.e. the tax rates (parameters) applied to the taxable amounts (often endogenous in the equilibrium).

Utility maximisation

$$\mathbf{U_k}\left(\vec{\mathbf{C}}_\mathbf{k}, \vec{\mathbf{S}}_\mathbf{k}\right) = \left[\prod_{\text{goods } i} \left(\mathbf{C_{k,i}} - bn_{k,i}\right)^{\xi^C_{k,i}}\right]\left(\mathbf{S_{k,mobility}} - bn_{k,mobility}\right)^{\xi^S_{k,j}} \quad \text{(SM-2)}$$

$$\mathbf{S_{k,mobility}} = \left(\left(\frac{\mathbf{pkm_{k,air}}}{b_{k,air}}\right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,public}}}{b_{k,public}}\right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,cars}}}{b_{k,cars}}\right)^{\eta_k} + \left(\frac{\mathbf{pkm_{k,nonmotorized}}}{b_{k,nonmotorized}}\right)^{\eta_k}\right)^{\frac{1}{\eta_k}} \quad \text{(SM-3)}$$

Income constraint

$$ptc_k \cdot \mathbf{Income}_k = \sum_{sectors\ i} \mathbf{pC_{k,i}} \cdot \mathbf{C_{k,i}} + \sum_{Energies\ Ei} \mathbf{pC_{k,Ei}} \cdot \left(\mathbf{pkm_k^{cars}} \cdot \alpha^{cars}_{k,Ei} + S_k^{m^2} \cdot \alpha^{m^2}_{k,Ei}\right) \quad \text{(SM-4)}$$

Travel time budget constraint

$$Tdisp_k = \sum_{\text{means of transport j}} \int_0^{\mathbf{pkm_{k,j}}} \tau_{k,j}\left(\frac{u}{Captransport_{k,j}}\right) du\ , \quad \text{(SM-5)}$$

where τ_j represents the marginal efficiency in transport time (the time necessary to travel an additional passenger.kilometer with mode j) :

$$\tau_{k,j}(x) = a_{k,j} \cdot x^{ktrans_{k,j}} + b_{k,j}\ . \quad \text{(SM-6)}$$

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

Sector budget (supply curve)

$$\mathbf{p_{k,i}} = \sum_{sectors\ j} \mathbf{pIC_{j,i,k}} \cdot IC_{j,i,k} + \left(\mathbf{\Omega_{k,i}} \cdot \mathbf{w_{k,i}}\right) \cdot l_{k,i} \cdot (1 + tax^{w}_{k,i}) + \pi_{k,i} \cdot \mathbf{p_{k,i}} \qquad \text{(SM-7)}$$

$\mathbf{\Omega_{k,i}} = \Omega\left(\dfrac{\mathbf{Q_{k,i}}}{Cap_{k,i}}\right)$ represents an increasing cost (or decreasing returns) function of the productive capacities utilisation rate. The functional form for Ω is:

$$\mathbf{\Omega_{k,i}} = a_{\Omega} - b_{\Omega} \cdot \tanh\left(c_{\Omega} \cdot \left(1 - \frac{Q}{Cap}\right)\right) \qquad \text{(SM-8)}$$

Labor market (wage curve)

$$\mathbf{z_k} = 1 - \frac{\sum_{sectors\ i} l_{k,i} \cdot \mathbf{Q_{k,i}}}{L_k} \qquad \text{(SM-9)}$$

$$\frac{\boldsymbol{w_{k,i}}}{\boldsymbol{pind_k}} = aw_{k,i} \cdot \frac{wref_{k,i}}{pindref_k} \cdot f\left(\frac{\boldsymbol{z_k}}{zref_k}\right) \qquad \text{(SM-10)}$$

Equilibrium constraints on physical flows

$$\mathbf{M_{k,i}} = \mathbf{shareC^{imp}_{k,i}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG^{imp}_{k,i}} \cdot G_{k,i} + \mathbf{shareI^{imp}_{k,i}} \cdot \mathbf{I_{k,i}} + [\sum_{sectors\ j} \mathbf{Q_{k,j}} \cdot IC^{imp}_{i,j,k} \cdot \mathbf{shareIC^{imp}_{i,j,k}}] \qquad \text{(SM-11)}$$

$$\mathbf{Q_{k,i}} = \mathbf{shareC^{dom}_{k,i}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG^{dom}_{k,i}} \cdot G_{k,i} + \mathbf{shareI^{dom}_{k,i}} \cdot \mathbf{I_{k,i}} + [\sum_{sectors\ j} \mathbf{Q_{k,j}} \cdot IC_{i,j,k} \cdot \mathbf{shareIC^{dom}_{i,j,k}}] + \mathbf{X_{k,i}} \qquad \text{(SM-12)}$$

Investment formation

$$\mathbf{NRB_k} = \mathbf{GRB_k} \cdot (1 - shareExpK_k) + \left(\sum_{countries\ k'} \mathbf{GRB_{k'}} \cdot shareExpK_{k'} \right) \cdot shareImpK_k \quad \text{(SM-13)}$$

$$\mathbf{GRB_k} = \mathbf{Income_k} \cdot \left(1 - ptc_k\right) + \sum_{sectors\ j} \pi_{k,j} \cdot \mathbf{p_{k,j}} \cdot \mathbf{Q_{k,j}} \cdot \left(1 - div_{k,j}\right) \quad \text{(SM-14)}$$

$$\mathbf{InvFin_{k,i}} = \mathbf{NRB_k} \cdot shareInvFin_{k,i} \quad \text{(SM-15)}$$

$$\mathbf{pCap_{k,i}} = \sum_{sectors\ j} \left(\beta_{j,i,k} \cdot \mathbf{pI_{j,i,k}} \right) \quad \text{(SM-16)}$$

$$\mathbf{\Delta Cap_{k,i}} = \frac{\mathbf{InvFin_{k,i}}}{\mathbf{pCap_{k,i}}} \quad \text{(SM-17)}$$

$$\mathbf{I_{k,j}} = \sum_{\text{sectors } i} \beta_{j,i,k} \cdot \mathbf{\Delta Cap_{k,i}} \quad \text{(SM-18)}$$

4. Intermediate variables for international trade

Armington goods

$$\mathbf{C_{k,i}} = \left(b_{k,i}^{dom} \cdot \left(\mathbf{C_{k,i}^{dom}}\right)^{-\rho_{k,i}} + b_{k,i}^{imp} \cdot \left(\mathbf{C_{k,i}^{imp}}\right)^{-\rho_{k,i}} \right)^{-\frac{1}{\rho_{k,i}}} \quad \text{(SM-19)}$$

$$\mathbf{pC_{k,i}} = \left(\left(b_{k,i}^{dom}\right)^{\sigma_{k,i}} \left(\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{domC})\right)^{1-\sigma_{k,i}} + \left(1-b_{k,i}^{dom}\right)^{\sigma_{k,i}} \left(\mathbf{p_{k,i}^{imp}} \cdot (1+tax_{k,i}^{impC})\right)^{1-\sigma_{k,i}} \right)^{\frac{1}{1-\sigma_{k,i}}} \quad \text{(SM-20)}$$

$$\mathbf{shareC_{k,i}^{dom}} = \left(b_{k,i}^{dom} \cdot \frac{\mathbf{pC_{k,i}}}{\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{domC})} \right)^{\sigma_{k,i}} \quad \text{(SM-21)}$$

$$\mathbf{shareC_{k,i}^{imp}} = \left(\left(1-b_{k,i}^{dom}\right) \cdot \frac{\mathbf{pC_{k,i}}}{\mathbf{p_{k,i}^{imp}} \cdot (1+tax_{k,i}^{impC})} \right)^{\sigma_{k,i}} \quad \text{(SM-22)}$$

Similar equations to (SM-19)–(SM-22) are valid for public consumptions, investments and intermediate consumptions.

$$\mathbf{p_{k,i}^{imp}} = \mathbf{wp_i} \cdot \left(1+taxe_{k,i}^{M}\right) + \sum_{means\ of\ tranport\ it} \mathbf{wp_{it}} \cdot nit_{k,i}^{it} \quad \text{(SM-23)}$$

$$\sum_{countries\ k} \left(\mathbf{shareC_{k,i}^{imp}} \cdot \mathbf{C_{k,i}} + \mathbf{shareG_{k,i}^{imp}} \cdot G_{k,i} + \mathbf{shareI_{k,i}^{imp}} \cdot \mathbf{I_{k,i}} + \sum_{sectors\ j} \mathbf{shareIC_{i,j,k}^{imp}} \cdot IC_{i,j,k} \cdot \mathbf{Q_{k,j}} \right) = \mathbf{X_i} = \left[\sum_{countries\ k} \psi_{k,i} \cdot \mathbf{X_{k,i}^{-\theta_i}} \right]^{-\frac{1}{\theta_i}} \quad \text{(SM-24)}$$

$$\mathbf{X_{k,i}} = \left[\psi_{k,i} \cdot \frac{\mathbf{wp_i}}{\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{X})} \right]^{\lambda_i} \cdot \mathbf{X_i} \quad \text{(SM-25)}$$

$$\mathbf{wp_i} = \left(\sum_{countries\ k} \left(\psi_{k,i}\right)^{\lambda_i} \left(\mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{X})\right)^{1-\lambda_i} \right)^{\frac{1}{1-\lambda_i}} \quad \text{(SM-26)}$$

Energy goods

$$\mathbf{C_{k,i}} = \mathbf{C_{k,i}^{dom}} + \mathbf{C_{k,i}^{imp}} \quad \text{(SM-27)}$$

$$\mathbf{pC_{k,i}} = \mathbf{shareC_{k,i}^{dom}} \cdot \mathbf{p_{k,i}} \cdot (1+tax_{k,i}^{domC}) + \mathbf{shareC_{k,i}^{imp}} \cdot \mathbf{p_{k,i}^{imp}} \cdot (1+tax_{k,i}^{impC}) \quad \text{(SM-28)}$$

$$\mathbf{shareC^{imp}_{k,i}}(\mathbf{t}) = \frac{shareC^{imp}_{k,i}(t-1)\cdot\left(\frac{\mathbf{p^{imp}_{k,i}}(t)\cdot(1+tax^{impC}_{k,i}(t))}{p^{imp}_{k,i}(t-1)\cdot(1+tax^{impC}_{k,i}(t-1))}\right)^{\eta^{imp}_{k,i}}}{shareC^{imp}_{k,i}(t-1)\cdot\left(\frac{\mathbf{p^{imp}_{k,i}}(t)\cdot(1+tax^{impC}_{k,i}(t))}{p^{imp}_{k,i}(t-1)\cdot(1+tax^{impC}_{k,i}(t-1))}\right)^{\eta^{imp}_{k,i}} + \left(1-shareC^{imp}_{k,i}(t-1)\right)\cdot\left(\frac{\mathbf{p_{k,i}}(t)\cdot(1+tax^{domC}_{k,i}(t))}{p_{k,i}(t-1)\cdot(1+tax^{domC}_{k,i}(t-1))}\right)^{\eta^{imp}_{k,i}}}$$

(SM-29)

$$\mathbf{shareC^{dom}_{k,i}}(\mathbf{t}) = 1 - \mathbf{shareC^{imp}_{k,i}}(\mathbf{t}) \qquad \text{(SM-30)}$$

Similar equations to (SM-27)–(SM-30) are valid for public consumptions, investments and intermediate consumptions.

$$\mathbf{p^{imp}_{k,i}} = \mathbf{wp_i}\cdot\left(1+taxe^M_{k,i}\right) + \sum_{means\ of\ tranport\ it} \mathbf{wp_{it}}\cdot nit^{it}_{k,i} \qquad \text{(SM-31)}$$

$$\sum_{countries\ k}\left(\mathbf{shareC^{imp}_{k,i}}\cdot\mathbf{C_{k,i}} + \mathbf{shareG^{imp}_{k,i}}\cdot G_{k,i} + \mathbf{shareI^{imp}_{k,i}}\cdot\mathbf{I_{k,i}} + \sum_{sectors\ j}\mathbf{shareIC^{imp}_{i,j,k}}\cdot IC_{i,j,k}\cdot\mathbf{Q_{k,j}}\right) = \mathbf{X_i}$$

(SM-32)

$$\mathbf{MS^X_{k,i}}(\mathbf{t}) = \frac{MS^X_{k,i}(t-1)\cdot\left(\frac{\mathbf{p_{k,i}}(t)\cdot\left(1+tax^X_{k,i}(t)\right)}{p_{k,i}(t-1)\cdot\left(1+tax^X_{k,i}(t-1)\right)}\right)^{\eta^X_{k,i}}}{\sum_{countries\ k'} MS^X_{k',i}(t-1)\cdot\left(\frac{\mathbf{p_{k',i}}(t)\cdot\left(1+tax^X_{k',i}(t)\right)}{p_{k',i}(t-1)\cdot\left(1+tax^X_{k',i}(t-1)\right)}\right)^{\eta^X_{k',i}}} \qquad \text{(SM-33)}$$

$$\mathbf{X_{k,i}} = \mathbf{MS^X_{k,i}}(t)\cdot\mathbf{X_i} \qquad \text{(SM-34)}$$

$$\mathbf{wp_i} = \frac{\sum_{countries\ k}\mathbf{p_{k,i}}\cdot\left(1+tax^X_{k,i}\right)\cdot\mathbf{X_{k,i}}}{\sum_{countries\ k}\mathbf{X_{k,i}}} \qquad \text{(SM-35)}$$

B- The dynamic modules of IMACLIM-R

The purpose of this section is to describe the Nexus of IMACLIM-R, which determine technical change through the evolution of production costs and end-use equipments. We start by describing the evolution of the constraints on fossil fuel production (oil, coal, gas) before turning to energy transformation (liquid fuels and electricity). Finally, we turn our attention to the technical coefficients driving final energy consumption in both stationary uses (industry and residential uses) and non-stationary uses (freight and passenger transportation).

1 Modelling primary supply of fossil fuels

1.1 Oil supply

The ‘oil supply’ Nexus embarks three crucial specificities of oil supply:
(a) a small group of suppliers benefits from a market power.
(b) the geological nature of oil reserves imposes a limited adaptability of oil supply.
(c) uncertainties on the technical, geopolitical and economical determinants of oil markets alter agents' expectations. The assumption of perfectly optimizing atomistic agents, which remains a useful analytical benchmark, fails to provide a good proxy for the oil economy.

We distinguish seven categories of conventional and five categories of non-conventional oil resources in each region. Each category *i* is characterized by the amount of ultimate resources[1] $Q_{\infty,i}$ and by a threshold selling price above which producers initiate production, $p^{(0)}(i)$. This price is a proxy for production costs and accessibility.

Each oil category is submitted 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), who combine analyzes of discovery processes (Uhler, 1976) and of the “mineral economy” (Reynolds, 1999), we impose, at each date *t*, an upper bound $\Delta Cap_{\max}(t,i)$ on the increase of production capacity for an oil category *i:*

[1] Ultimate resource of a given category is the sum of resources extracted before 2001 and recoverable resources.

$$\frac{\Delta Cap_{\max}(t,i)}{Cap(t,i)} = \frac{b_i \cdot \left(e^{-b_i(t-t_{0,i})} - 1\right)}{\left(1 + e^{-b_i(t-t_{0,i})}\right)} \qquad \text{(SM-36)}$$

The parameter b_i (in t^{-1}) controls the intensity of constraints on production growth: a small (high) b_i means a flat (sloping) production profile to represent slow (fast) deployment of production capacities. 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 soil given past exploitation decisions.

The production decisions of non-Middle-East producers are those of 'fatal producers' who do not act strategically on oil markets and invest in new production capacity if an oil category becomes profitable given the selling oil price p_{oil}. They develop production capacities at their maximum rate of increase in eq (1) for least-cost categories ($p_{oil} > p^{(0)}(i)$) but stop 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, whereas their deployment profile passes through a plateau if prices decrease below the profitability threshold.

Middle-East producers are 'swing producers' who fill the gap between fatal producers' supply and global oil demand. The stagnation and decline of conventional oil in the rest of the world temporarily reinforces their market power and they can control the time profile of oil prices through the utilization rate of production capacities (Kaufmann et al, 2004). They can decide to slow the development of production capacities down (below the maximum increase given by eq (1)) in order to adjust the oil price according to their rent-seeking objective.

Total oil production capacity at date t is given by the sum over oil categories with different production costs (captured by different $p^{(0)}(i)$ threshold). This means that projects of various merit orders coexist at a given point in time, consistently with the observed evidence[2] and theoretical justifications[3].

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[2]for example, low-cost fields in Saudi Arabia and high-cost non-conventional production in Canada are simultaneously active on oil markets

[3](Kemp and Van Long, 1980) have indeed demonstrated that, in a general equilibrium context, the lowest-cost deposits are not necessarily exploited first. (Holland, 2003) even demonstrates that least-cost-first extraction rule does not hold in partial equilibrium under capacity constraints, like those envisaged for geological reasons here.

1.2 Gas supply

The evolution of worldwide natural gas production capacities meets demand increase until available reserves enter a depletion process. Distribution of regional production capacities in the 'gas supply' Nexus is made using an exogenous distribution key calibrated on the output of the POLES energy model (LEPII-EPE, 2006), which captures reserve availability and regional production facilities. Gas markets follow oil markets with a 0.68 elasticity of gas to oil price. This behavior is calibrated on the World Energy Model (IEA, 2007) 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 margin for the possessors of the remaining reserves.

1.3 Coal markets

Unlike oil and gas markets, cumulated coal production has a weak influence on coal prices because of large world resources. Coal prices then depend on current production through 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 (latter) corresponding to a price reaction to a production increase (decrease). Tight coal markets exhibit a high value of η^{+}_{coal} (i.e the coal price strongly increases if production rises) and low value of η^{-}_{coal} (the price decreases only slightly if production drops).

2. Energy transformation

2.1 Liquid fuels

The 'substitutes to oil' Nexus considers two large-scale substitutes to oil for liquid fuel production.

The first large-scale substitute to oil for liquid fuels production consist in first and second generation biofuels from renewable land resources. Their diffusion is controlled by supply curves: at each date, biofuels' market share is an increasing function of oil price, carbon tax included, $S_{bio}(t,p_{oil})$.[4] This captures, although in a simplistic manner, the competition between biofuels and oil-based liquid fuels: everything else being equal, the former are more competitive and their penetration into the market is more prominent when higher oil price make the latter more expensive. The supply curves include asymptote representing explicit limits on production due to constraints on land availability and competition with other biomass uses. They are modified from one date to the other to account for learning-by-doing improvements. The diffusion of biofuels is in addition submitted to the constraint of a time delay, Δt_{bio}, which captures inertia on the deployment of raw products (biomass) and of refining capacity.

The second alternative to oil is Coal-To-Liquid (CTL). We consider it as an inexhaustible[5] backstop technology but submitted to capacity constraints. In line with Amigues et al (2001), production of the inexhaustible substitute starts before all the least-cost deposits of the exhaustible resource are exploited. To capture competition with oil-based fuels, Coal-To-Liquid becomes competitive (and then enters the market) as soon as oil prices (carbon tax included) exceed a threshold value p_{CTL}. To determine their market potential at a given date, CTL producers form (imperfect) anticipations about future agents' endogenous decisions in terms of liquid fuel demand $D(t)$ and supply by other sources (refined oil and biofuels) $S(t)$. CTL producers are then willing to fill the expected gap by targeting a production level $[D(t)-S(t)]$. But, CTL production may be limited by constraints on delivery capacity due to past investment decisions if, due to imperfect foresight, profitability prospects for CTL were underestimated. These prospects are an increasing function of oil prices at each point in time[6] and cumulative investment on CTL over time is then a function of the sum of past oil prices: $p_{cum}(t) = \sum_{i=2010}^{t-\Delta t_{CTL}} p_{oil}(i)$, where the time delay Δt_{CTL} represents investment inertia. The dynamics of investment affects the availability of production capacity and imposes limits on the share s of the targeted CTL production that can be realized at a given date. We adopt a linear dependence between s and cumulative investments measured by $p_{cum}(t)$. As soon as the oil price exceeds p_{CTL}, the contribution of CTL to the supply on liquid fuel markets is given by:

$$CTL(t) = s\left(p_{cum}(t)\right)\left[D(t) - S(t)\right]. \tag{SM-37}$$

[4]This captures in a simplistic manner the competition between biofuels and oil-based liquid fuels: everything else being equal, the former are more competitive and their penetration into the market is more prominent when higher oil price make the latter more expensive.

[5]We assume that coal is a sufficiently abundant input factor

[6] Indeed, higher oil prices drive higher prices of liquid fuels, including those produced from coal, and then higher profitability prospects for CTL.

2.2 Electricity generation

The 'power generation' Nexus represents an explicit set of 16 standard technologies, either already active or close to maturity.[7] Each of them is characterized by its technico-economic parameters determining the average production discounted cost per kilowatt hour produced. These parameters are: capital costs (dollars per kilowatt installed), energy efficiency (in percentage, for technologies functioning with fossil fuels), exploitation and maintenance costs, fixed or variable costs (respectively in dollars per kilowatt and in dollars per kilowatt hour). The discount rate incorporates capital opportunity cost and a risk factor, which covers both the risk of defect and the social risk associated to controversial technologies (nuclear, CCS). The technico-economic parameters are calibrated either on sectoral technological models (for example the POLES model) or on information from the literature (Grubler et al, 2002; Rao et al, 2006; Sims et al, 2007). They evolve in time according to technical progress, including learning-by doing processes.

Technological choices are based on a minimization of the average production total cost compatible with future electricity demand across six segments of the load curve, representing the annual fluctuations of electricity demand.[8] This optimal planning procedure for choosing power generation technologies under imperfect anticipations is decomposed into four steps:

- projecting future demand and fuel prices with adaptive anticipations of electricity demand growth over the coming ten years and with future fossil fuels prices.
- choosing renewable production capacities distinguished between hydroelectricity and on-shore and off-shore wind[9], given competition with conventional technologies. The share of each renewable energy in total electricity production is an increasing function of the ratio between its complete production cost per kWh and of the more profitable conventional technology. This share is bounded by the saturation of production potentials and the limits of intermittent production.

[7] five coal-powered units (Coal Conventional Thermal, Lignite Conventional Thermal, Super Critical Pulverised Coal, Integrated Coal Gasif. Comb. Cycle), two gas-powered units (Gas Conventional Thermal, Gas Turbines Combined Cycle), two oil-powered units (Oil Conventional Thermal, Oil Fired Gas Turbines), two nuclear technologies (standard and new design), three renewables (large hydro, onshore wind, offshore wind). In addition, one technology with CCS is available for coal- and gas-powered units, respectively

[8] The six segments are divided according to broad categories of annual load length defined by six threshold values between 0h and full year operation (8760h): 8030h, 6570h, 5110h, 3650h, 2190h,. 730h

[9] wind is the only non-hydraulic renewable energy explicitly represented in the NEXUS. However, solar energy is implicitly represented in "very low energy" .buildings

- projecting the optimal conventional production park under demand constraint at a 10-year horizon by comparison of unitary discounted production costs among technologies.
- allocating investments to reorient the existing production park towards the ideal anticipated production park by the end of the decade, under the constraints of available capital.

New investment choices affect total production capacity only at the margin, given the inertia in the renewal of the park. We represent the park in capital vintages, and a formerly installed production unit remains available for a certain period in function of its life time. However, available capacities are not necessary mobilized for actual production, which is allocated to production units ensuring lower operational costs. This choice is differentiated along the seven segments of the load curve to represent the different mix of technologies for base and peak production. This assumption allows representing operational flexibility through early retirement of those capacities that, although installed, are not profitable in current economic conditions.

3. Final energy demand

Historically, the literature on the decoupling between energy and growth has focused on autonomous energy efficiency improvements (implicitly encompassing end-use energy efficiency and structural changes) and on the energy efficiency gap, i.e. the difference between the most energy efficient technologies available and those actually in use.

However important it may be, energy efficiency is not the only driver of energy demand. Indeed, the rate and direction of technical progress and its energy content depend, not only on the transformation of the set of available techniques, but also on the structure of households' demand. This is why the NEXUS endogenize both energy efficiency *stricto sensu,* and the structural change resulting from the interplay between consumption, technology and localization patterns. This enables us to capture the effect of non-energy determinants of energy demand, such as the prices of land and real estate, and political bargaining (set exogenously) over urban infrastructure to be represented. This endogenization of technical change is made for both stationary uses (industry and services, buildings) and non-stationnary uses (freight and passenger transportation).

3.1 Stationnary uses

3.1.1 Industry and services

The industrial and services sectors are represented in an aggregated manner, each of them covering a large variety of economic sub-sectors and products. Technical change then covers not only changes and technical progress in each sub-sector but also the structural effects across sectors. In addition to autonomous energy efficiency gains, the "Industry' and 'services' Nexus represent the structural drop in energy intensity due to a progressive transition from energy-intensive heavy industries to manufacturing industries, and the choice of new techniques which results in both energy efficiency gains and changes in the energy mix.

On the one hand, the progressive switch from industry to services is controlled by saturation levels of per capita consumption of industrial goods (in physical terms, not necessarily in value terms), via an asymptote at κ_{ind} multiplied by its level in 2001. For developing countries, these saturation levels represent various types of catch-up to the consumption style in developed countries.

On the other hand, changes of techniques are driven by operational costs, including energy costs and the other costs linked to their use (capital, maintenance, variable costs). The share of each energy in the new capacities is decided in a logistic function with arguments the total cost of using each energy source and a market heterogeneity parameter measuring the substitutability potentials. In these sectors, these decisions affect the selection of new production capacities but do not influence existing ones. This putty-clay assumption implies that changes in final energy use are dependent on the turnover rate of production capacities, defined by their lifetime Δt_{ind} .

3.1.2 Buildings

The 'Housing and Buildings' nexus represents the dynamics of energy consumption as a function of the energy service level per square meter (heating, cooling, etc.) and the total housing surface.

The former is represented by coefficients encompassing the technical characteristics of the existing stock of end-use equipment and buildings and the increase in demand for energy services: heating, cooking, hot water, lighting, air conditioning, refrigeration and freezing and electrical appliances. The evolution of resulting energy-needs per square meter is captured by coefficients for coal $\alpha_{res}^{coal}(t)$, gas $\alpha_{res}^{gas}(t)$, liquid fuels $\alpha_{res}^{fuel}(t)$ and electricity $\alpha_{res}^{elec}(t)$. These parameters evolve according to the exogenous trajectories calibrated on the outputs of the POLES energy model, which encompass changes in residential energy consumption due to (i) cost variations of the services either due to efficiency gains or energy price variations, (ii) increase in household's income driving access to certain energy services beyond basic needs and (iii) the physical characteristics of buildings (surfaces, insulation, architectural conception).

We also account for the diffusion of "Very Low Energy" buildings at very high energy price, carbon price included. They are represented by a unique alternative housing with annual energy consumption at 50kWh/m2 (80% electricity and 20% gas). The diffusion of this technology in rupture with current trends represents implicitly a multiplicity of advancements, including the autonomous production of energy, the efficient insulation of buildings but also large plans of thermal renovation and regulations reforms in developing countries.

Housing surface per capita has an income elasticity of η_H, and region-specific asymptotes for the floor area per capita, h_{max}. This limit reflects spatial constraints, cultural habits as well as assumptions about future development styles (including the lifestyles in emerging countries vis-à-vis the US, European or Japanese way of life). In the constitution of scenarios, the hypotheses about these asymptotes are made coherent with those concerning the infrastructures of transport, keeping in mind that all are linked to territorial and urban zoning policies.

3.2 Non-Stationnary uses

3.2.1 Freight transport

In the "Transportation NEXUS", the dynamics of the energy intensity of freight transport is driven by an exogenous trend $\mu_f(t)$ and a short-term fuel price elasticity ε_f. They capture autonomous and endogenous energy efficiency gains as well as short-term modal shifts, with the long-term price response resulting from the sequence of those short-term adjustments.

Total energy demand is then driven by freight mobility needs, in turn depending on the level of economic activities and their freight content. Even though the share of transportation in total costs is currently low, decoupling freight mobility demand and economic growth is an important determinant of long-term mitigation costs. In the absence of such a decoupling (constant input-output coefficient), and once efficiency potentials in freight transportation have been exhausted, constraining sectoral carbon emissions from freight transportation would amount to constraining economic activity.

3.2.2 Passenger transport

Passenger mobility needs and their modal breakdown across four travel modes (ground-based public transport, air transport, private vehicles and non-motorized modes) result from the maximization of households' utility under the assumption of constant travel time (Zahavi and Talvitie, 1980) and budget constraints. This helps to represent two crucial determinants of the demand for passenger transportation, namely the induction of mobility demand by infrastructure and the conventional rebound effect consecutive to energy efficiency gains on vehicles (Greening et al, 2000).

The former effect operates through the travel time budget constraint. Indeed, the attractiveness of each transportation mode is determined by vehicle performance and the degree of infrastructure saturation. When mobility demand exceeds the normal load conditions of a given type of infrastructure (e.g., road, airport), speed decreases. In the absence of further investment, households will reallocate their travel time budget to other, more efficient, modes in order to restore efficiency. We can represent the effects of the deployment of alternative infrastructure: a policy in which the building of transportation infrastructure follows the evolution of modal mobility favoring roads for private car mobility *vs.* public policies that redirect part of the investment to railways and other public transport infrastructure.

A drop in mobility costs (mainly the user's car costs), along with progress in the energy efficiency of vehicles, endogenously generates a rebound effect on mobility demand as a result of utility-maximization under income budget constraint. Energy efficiency in private vehicles results from households' decisions on the purchase of new vehicles, based on a mean cost minimization criterion between different types of available technologies (including standard, hybrid and electric vehicles). These vehicles types are differentiated by their capital costs and unitary fuel consumption, the former decreasing in function of the learning-by-doing process at the rate γ for each doubling of cumulated investment in the technology.

In addition to the availability of transportation infrastructure and energy efficiency, mobility needs are dependent upon agents' localization choices (Grazi et al., 2008). This is captured by differences in regional households' motorization rates, everything else being equal (income, energy prices), with dispersed spatial organizations implying a higher dependence on private transport. In each region, the motorization rates increase with disposable per capita income through variable income-elasticity η_{mot}: *(a)* low for very poor people whose access to motorized mobility relies on non-motorized and public modes; *(b)* high for households with a medium per capita income with access to private motorized mobility *(c)* low again, because of saturation effects, for per capita income level comparable to that of the OECD. In addition, the impact of local location choices is represented through basic needs of mobility, which represent the travels imposed by daily journeys (especially, for commuting to work and access to services).

C- Data

1. Calibration

Calibration of the IMACLIM-R model is based on the GTAP database, which provides a set of balanced input-output tables of the world economy. Given the launch date of the RECIPE project, we did not calibrate IMACLIM-R with the more recent GTAP-7 database, but used instead GTAP-6 database (Dimaranan, 2006) which details the world economy in 87 regions and 57 sectors for the year 2001. From this basic material, calibration is done by aggregating the GTAP database according to the IMACLIM-R mapping in 12 regions and 12 sectors and by embarking information from external datasets giving physical quantities for energy and passenger transportation sectors. This hybrid matrix ensuring consistency between money flows and physical quantities is built by modifying input-output tables from the GTAP-6 dataset to make them fully compatible with 2001 energy balances from IEA (in Mtoe) and passenger mobility (in passenger-km) from (Schafer and Victor, 2000). This is done by assuming uniform production prices across uses in each region and for each energy and transport sectors, and substituting money flows reported for those activities in the GTAP-6 database by the expenditures for physical quantities valued at their end-use price, including consumption taxes. This forcing ensures that energy and mobility quantities are preserved, but brings about some adjustments in the input-output tables to restore sectoral supply-use equilibrium conditions in monetary values. This last step is done by reporting the gap in equilibrium conditions in the composite sector.

2. 'Natural Growth' drivers

The natural growth rate of the economy defines the growth rate that the economy would follow if it produced a composite good at full employment, like in standard neoclassical models developed after Solow (1956). It is given by exogenous assumptions on active population and labor productivity growth. Demographic data for active population are derived from medium UN scenario (UN, 2007) and are summarized in Table SM-3.

Table SM-3: Active population in the IMACLIM-R model (Millions)

	2001	2010	2030	2050	2100
USA	178	195	203	207	205
Canada	20	22	22	23	20
Europe	374	384	359	330	320
OECD Pacific	132	131	116	100	46
Former Soviet Union	169	178	168	155	126
China	824	930	958	895	827
India	572	702	925	1034	1128
Brazil	104	124	154	167	173
Middle-East	93	122	173	203	250
Africa	397	534	894	1224	1668
Rest of Asia	496	582	706	756	713
Rest of Latin America	193	230	286	309	321

Labor productivity growth is built upon a convergence hypothesis (Barro and Sala-i-Martin, 1992), the parameters being calibrated on historic trajectories (Maddison, 1995) and 'educated guess' assumptions of long-term trends (Oliveira-Martins et al., 2005). Basically, we assume that USA remains the world leader in productivity per worker with a steady growth of 1.7% per year, whereas the dynamics of productivity in other countries is driven by a partial catch-up. This means that regions with lower absolute productivity per worker in a country experience the faster labor productivity growth (see Table SM-4).

Table SM-4: Average labor productivity growth in the IMACLIM-R model (%)

	2010-2030	2030-2050	2050-2100
USA	1.9	1.7	1.7
Canada	1.8	1.9	1.7
Europe	2.4	1.9	1.7
OECD Pacific	2.0	1.8	1.7
Former Soviet Union	3.9	2.3	1.7
China	5.8	3.4	1.8
India	5.2	4.2	2.0
Brazil	3.3	2.4	1.7
Middle-East	2.0	2.0	2.0
Africa	2.0	2.0	2.0
Rest of Asia	3.9	3.6	1.8
Rest of Latin America	3.1	2.6	1.8

D- An analytical analysis of the drivers of mitigation costs in second-best economies

We detail here the simplified model used in Section 3.2 to identify the major determinants of mitigation costs in the IMACLIM-R model. To this aim, we incorporate the core specificities of second-best macroeconomic interactions in the static equilibrium of the IMACLIM-R model: imperfect competition and imperfect labour markets. To ensure analytical solvability, we consider an economy producing a composite good with energy and labour as input factors.

Imperfect competition is represented through a mark-up pricing rule for the composite good resulting in a margin rate π over production costs:

$$p = p_E e(1+\tau_E) + wl + \pi p \quad \text{(SM-38)}$$

where e and l are the unitary energy and labour requirements for production, p_E the price of energy, τ_E a tax on energy (taken as a proxy for a carbon tax in case of climate policy) and w the wage rate.[10]

Imperfect labour markets are described by a wage curve introducing an inverse relationship between the real wage rate and unemployment (or under-utilization of the labour force).[11] With Q the total production and L the total labour force, the unemployment rate z is:

$$z = 1 - \frac{lQ}{L} \quad \text{(SM-39)}$$

The wage curve is then given by:

$$\frac{w}{p} = az^{-\alpha} \quad \text{(SM-40)}$$

where, a is a constant and $\alpha > 0$ is the elasticity of the wage curve: the higher α, the more flexible the labour markets.

We introduce Q_0, w_0 and z_0 as the production level, the real wage rate and the unemployment rate in absence of carbon tax. They are implicitly defined by:

$$p_E e(1+\tau_E) + wl = p_E e + w_0 l \quad \text{(SM-41)}$$

$$\frac{p_E e \tau_E}{w_0 l} + \left(\frac{z}{z_0}\right)^{-\alpha} = 1 \quad \text{(SM-42)}$$

[10] Equation (SM-38) is a simplified version of the price equation in IMACLIM-R, which incorporates a term of decreasing static returns when production capacity approaches saturation (see Section A above).

[11] Microeconometric evidence for such formulation was given in a seminal contribution by (Blanchflower and Oswald 1995) and extensive theories have been developed to support such representation of the labour market (see (Layard et al., 2005), (Lindbeck, 1993) and (Phelps, 1992) for an overview). The basic idea is that high unemployment represents an outside threat that leads workers to accept lower wages as from either the bargaining approach (Layard and Nickell, 1986) or the wage-efficiency approach (Shapiro and Stiglitz, 1984). The former emphasizes the weakening of the power of workers' unions in wage setting negotiations at high unemployment. The latter adopts firms' point of view, who set wages so as to discourage shirking; this level is lower when the threat of not finding a job after being caught shirking gets higher.

$$\frac{L}{l} = \frac{Q_0}{1 - z_0} \tag{SM-43}$$

Combining equations (SM-38)-(SM-43), the production level Q can then be derived as:

$$Q = \frac{Q_0}{1 - z_0} \cdot \left[1 - z_0 \left(1 - \frac{p_E . e . \tau_E}{w_0 l} \right)^{-\frac{1}{\alpha}} \right] \tag{SM-44}$$

The variation of activity $\Delta Q = Q - Q_0$ is then given by:

$$\frac{\Delta Q}{Q_0} = \frac{z_0}{1 - z_0} \cdot \left[1 - \left(1 - \frac{p_E . e}{w_0 l} \tau_E \right)^{-\frac{1}{\alpha}} \right] \tag{SM-45}$$

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