DOCUMENTS DE TRAVAIL / WORKING PAPERS

C.I.R.E.D.

No 57-2014

The IMACLIM-P Model
Version 3.4

Frédéric Ghersi

July 2014

CIRED Working Papers Series

CIRED

Centre International de Recherches sur l'Environnement et le Développement

ENPC & CNRS (UMR 8568) / EHESS / AGROPARISTECH / CIRAD / MÉTÉO FRANCE

45 bis, avenue de la Belle Gabrielle

F-94736 Nogent sur Marne CEDEX

Tel : (33) 1 43 94 73 73 / Fax : (33) 1 43 94 73 70

www.centre-cired.fr

The IMACLIM models have been developed at CIRED since the 1990's under Jean-Charles Hourcade's scientific supervision. They currently exist in 3 versions:

- *A static version, IMACLIM-S, is mostly applied at a national level to produce counterfactual analyses of environmental fiscal reforms at some historical or projected temporal horizon.*
- *A dynamic, recursive version, IMACLIM-R, articulates growth trajectories for 12 world regions, based on a back-and-forth dialogue between a succession of static macroeconomic equilibria akin to those of IMACLIM-S, and a set of sectoral modules framing the evolution of explicit energy supply and demand technologies.*
- *A prospective version, IMACLIM-P, quite similar to IMACLIM-S, computes the equilibrium consequences of targeted parameters changes between one historical year and a mid- to long-term future (rather than between two counterfactual equilibria at a single year, as IMACLIM-S).*

This descriptive of IMACLIM-P 3.4 massively draws on that of IMACLIM-S 2.3, from which the model directly derives. It thus benefits from contributions by Camille Thubin and Emmanuel Combet (cf. Ghersi et al., 2011).

Table of Contents

Introduction

IMACLIM-P is a direct declination of IMACLIM-S, a computable general equilibrium model (CGEM) designed to assess the medium- to long-term macroeconomic impacts of aggregate price- or quantity-based carbon policies, in an accounting framework where economic *and* physical flows (with a special focus on energy balances) are equilibrated. IMACLIM-S and IMACLIM-P depart from the standard neoclassical model in the main feature that their description of the consumers' and producers' trade-offs, and the underlying technical systems, are specifically designed to facilitate calibration on bottom-up expertise in the energy field, with a view to guaranteeing technical realism to their simulations of even large mutations of the energy systems.

IMACLIM-P computations resort to the well-known method of "comparative statics" (Samuelson, 1947): they explore the consequences of a change of one or a set of parameters on a set of variables, in a system of balanced equations. But they come with a twist: rather than computing *counterfactual* equilibria at some unique time horizon (as IMACLIM-S does), they compute *future* equilibria by considering changes of the main energy/economy growth determinants: demographics, labour productivity and international energy prices. The insights provided are valid under the assumption that the transition from the historical (statistical) equilibrium to its projected counterpart is completed after a series of technical and behavioural adjustments, whose scope are embedded in the production and consumption elasticities retained. The transition process in itself is however not described, but implicitly supposed to be smooth enough to prevent multiple equilibria, hysteresis effects, *etc*.

This working paper describes the 3.4 version of IMACLIM-P, derived from the 2.3 version of IMACLIM-S implemented to sustain an expertise about a French carbon tax (Hourcade *et al.*, 2009). It is applied to 2006 France, whose economy is aggregated in 9 productions and 5 household classes. Section I synthesises the data sources and calibration procedure. Section II gives a comprehensive formulary, in a generalised *n*-good and *m*-household-class format—with a few exceptions warranted by the specific treatment of energy sectors. Section III clarifies the driving forces of the model's projections. Annexes group a comprehensive listing of notations and the particular values of key parameters of the model mobilised in Ghersi and Ricci (2014).

I. Calibration data

I.1. Accounting framework: *TES* and *TEE*

National accounting statistics provide a comprehensive numerical framework for computable general equilibrium models. In its 3.4 version, devised to project 2006 France to mid- to long-term horizons, IMACLIM-P is mainly calibrated on aggregated data from two synthesis tables produced by the French National Institute of Statistics and Economic Studies (INSEE):

- The TES (Tableau Entrées-Sorties, input-output table) balances the uses and resources of products—up to 116 of them in its most disaggregated version.
- The TEE (*Tableau Économique d'Ensemble*) details the primary and secondary distribution of income between 6 'institutional sectors', *i.e.* aggregate economic agents: financial firms, non-financial firms, households, non-profit organisations, public administrations, 'rest of the world'.

Raw TES data are processed to obtain a description of production and consumption in a 'product × product' (rather than product × branch) system, with no accumulation of stocks. Supplementary INSEE tables provide extra detail on the components of the value-added—more specifically a disaggregation of payroll taxes from labour costs, and of fixed capital consumption from the gross operative surplus.

The TEE is aggregated into 4 institutional sectors (households, firms, public administrations and 'rest of the world'), and its many entries are simplified into a set of transfers at a level of aggregation comparable to that of the TES. Its use allows extending the traditional framework of general equilibrium modelling to the distribution of national income between economic agents, the resulting changes in the financial positions of those agents, and the corresponding debt payments.

I.2. Data Hybridising

Considering its focus on energy/economy interactions, IMACLIM-P requires a high degree of realism in the description of the energy inputs to production and the energy consumptions of households. Explicit physical energy quantities are poorly represented by the quasi-quantities commonly obtained from economic data through the normalisation of output prices, and the "single-price" assumption.[1] Therefore, a rigorous calibration of the model requires some accurate accounting of the physical quantities of energy consumed, expressed in a relevant unit (*e.g.* million-tons-of-oil-equivalent, MTOE).

Such an accounting is found in the energy balances of the International Energy Agency (IEA). It is also possible to gather from various sources (IEA, French *Comité Professionnel du Pétrole*—CPDP, PEGASE database from the French Ministry of Industry, *etc.*) prices for each type of energy, or aggregate thereof, which are indeed agent-specific. The term-by-term product of energy balances and agent-specific prices defines a matrix of energy consumptions in monetary terms, which does not match that embedded in the TES for energy products, for a variety of reasons (the inclusion of services beyond the sheer energy consumptions, the heterogeneity of products, biases from the statistical balancing methods, *etc.*). Hybridisation of the TES then consists in imputing the differences between the values found in the TES, and those computed from energy statistics, to some non-energy good—in the model with 9 products, to the aggregate composite good. For lack of a better hypothesis the value-added of the energy products are corrected *pro-rata* this imputation. In this way, the product

[1] Standard CGE models assume that all agents face identical net-of-tax prices for all goods. This is an obvious shortcoming when it comes to energy markets, where firms and households face quite different conditions.

disaggregation is amended, while the total uses and resources across the 9 production sectors are kept consistent with the original statistics.

The calibration of the model on this hybrid TES eventually leads it to depict (*i*) volumes of the non-energy goods that are standardly derived from the single-(normalised)-price assumption, and (*ii*) volumes and prices of the energy goods that are strictly aligned on the available statistics. The differences in price of the same energy good from one agent to the other (*e.g.* the difference in price of a kWh of electricity for a firm *vs.* a household) are accounted for by calibrating 'specific margins' to the different uses.

I.3. Disaggregation of the 'representative household'

The disaggregation of the 'representative household' in 5 living-standard[2] classes is based on an extrapolation of the 2006 *Budget de Famille* Households Expenditure survey by INSEE, which extensively covers the resources and uses of 10,240 French households. Combet (2007) largely documents calibration on an earlier version of the *Budget de Famille* survey—its descriptive is still to be updated.

II. Formulary

IMACLIM-P, a comparative statics model from a mathematical point-of-view, boils down to a set of simultaneous equations:

$$\begin{cases} f_1\,(x_1,\ldots,\,x_n,\,z_1,\ldots,\,z_m) = 0 \\ f_2\,(x_1,\ldots,\,x_n,\,z_1,\ldots,\,z_m) = 0 \\ \ldots \\ f_n\,(x_1,\ldots,\,x_n,\,z_1,\ldots,\,z_m) = 0 \end{cases}$$

with:

- x_i, $i \in [1, v]$, a set of variables (as many as equations),
- z_i, $i \in [1, p]$, a set of parameters,
- f_i, $i \in [1, v]$, a set of functions, some of which are non-linear in x_i.

The f_i constraints are of two quite different natures: one subset of equations describes accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced; the other subset translates various behavioural constraints, written either in a simple linear manner (*e.g.* households consume a fixed proportion of their income) or in a more complex non-linear way

[2] Surveyed households are ranked according to their disposable income *per* consumption unit (1 for the first adult + 0.5 *per* other adult + 0.3 *per* child below 14 following the OECD equivalence scale), then separated in quintiles.

(*e.g.* the trade-offs of firms and households). It is these behavioural constraints that ultimately reflect, in the flexible architecture of IMACLIM-P, a certain economic 'worldview'.

The presentation of the equations successively details the accounting construction of the set of relative prices (section II.1), the accounting and behavioural equations that govern the four institutional sectors represented (households, firms, public administrations and the 'rest of the world', sections 0 to II.5) and the market clearing conditions (section II.6). For reference purposes, variables and parameters are listed and described in a first appendix. A second appendix details the values of central parameters used in Ghersi and Ricci (2014). Any variable name indexed with a '0' designates the specific value taken by the variable in the 2006 equilibrium (*i.e.* the value calibrated on either the 2006 hybrid TES or the 2006 TEE); it thus indicates a parameter of the equation system. Although most equations are written in a generalised *n*-goods *m*-household classes format, when necessary good-specific variables are indexed by the following subscripts:

COMP	For the composite good (an aggregate of all goods not specifically described).
TRANS	For a transportation good, in the market sense *i.e.* excluding transportation by personal means (cars, two-wheelers or soft modes).
LOG	For a housing good calibrated on expenses encompassing real and imputed rents, with quintile-specific prices that allow matching actual housing surface statistics.
BAT	For a construction good, which encompasses housing maintenance and renovation.
EPRIM	For a fossil energy good aggregating crude oil and a small amount of coal.
CARB	For vehicle fuels (including liquefied gases used as such).
RAFF	For other refined petroleum products (including liquefied gases not used as vehicle fuels).
ELEC	For electricity.
GAZ+	For natural gas and heat.

II.1. Producer and Consumer Prices

p_{Yi} the producer price of good *i* is built following the cost structure of the production of good *i* , that is as the sum of intermediate consumptions, labour costs, capital costs, a tax on production, and a constant mark-up rate (corresponding to the net operating surplus):

$$p_{Yi} = \sum_{j=1}^{n} p_{CIji}\, \alpha_{ji} + p_{Li}\, l_i + p_K\, k_i + \overline{\tau_{Yi}}\, p_{Yi} + \overline{\pi_i}\, p_{Yi} \,. \quad (1)$$

p_{Mi} the price of imported good *i* is good-specific. First, the international composite good is the *numéraire* of the model; its price is consequently assumed constant:

$$p_{MCOMP} = p_{MCOMP0} \,. \quad (2)$$

Secondly, the price of imported crude oil & coal and natural relative to that of the international composite good[3] evolves according to an exogenous hypothesis δ_{pMi} :

[3] Because of the choice of the international composite good as *numéraire*, any price of the model is implicitly expressed relatively to it. This requires a careful treatment when importing price variations from exogenous sources, *e.g.* energy prices from the International Energy Agency scenarios.

$$\forall\ i \in \text{[EPRIM, GAZ+]} \qquad p_{Mi} = \left(1 + \overline{\delta_{pMi}}\right) p_{Mi0}\,. \tag{3}$$

Thirdly, the import price of all other goods is assumed to evolve as the domestic price of these goods, for lack of a better hypothesis:

$$\forall\ i \notin \text{[COMP, EPRIM, GAZ+]} \qquad p_{Mi} = \frac{p_{Yi}}{p_{Yi0}}\, p_{Mi0}\,. \tag{4}$$

The impact of such a crude assumption on growth is small, as the competitiveness of the French production is massively determined by its terms-of-trade on the composite market, which remain endogenous to the model—while the imports of the LOG and BAT goods are anyway nil by definition. It is however of some significance on the refined petroleum products markets, where any competitiveness impact is ruled out. The calibration of the terms-of-trade of final energy products on bottom-up expertise could circumvent this shortcoming by substituting a set of equations of the (3) form to the (4) equations.

p_i the average price of the resource of good *i* is the weighted average of the domestic and import prices:

$$p_i = \frac{p_{Yi}\, Y_i + p_{Mi}\, M_i}{Y_i + M_i}\,. \tag{5}$$

The domestic and foreign varieties of the energy goods are indeed assumed homogeneous. The alternative assumption of product differentiation, adopted by many CGEM through their use of an Armington specification for international trade (Armington, 1969), has the disadvantage of creating 'hybrid' good varieties, whose volume unit is independent from that of the foreign and national varieties they hybridise; this complicates maintaining an explicit accounting of the physical energy flows and thus an energy balance. For the sake of simplicity the non-energy goods are treated similarly to the energy ones.

p_{CIij} the price of good *i* consumed in the production of good *j* is equal to the resource price of good *i* plus trade and transport margins, agent-specific margins (*cf*. Section I.2), a domestic excise on oil products (the *Taxe Intérieure sur les Produits Pétroliers*, TIPP),[4] an aggregate of other excise taxes and a carbon tax.[5]

$$p_{CIij} = p_i\left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSCIij}}\,\right) + t_{TIPPCIi} + t_{AIPi} + \overline{t_{CI}}\,\gamma_{CIij}\,. \tag{6}$$

The consumer price of good *i* for household *h* (p_{Chi}),[6] public administrations (p_{Gi}) and investment (p_{Ii}), and the export price of good *i* (p_{Xi}), are constructed similarly and only differ on whether they are subject to the VAT (the same rate is applied to all consumptions of one good) and the carbon tax or

[4] The TIPP levied on the intermediate and the final fuel consumptions is differentiated to take account of the underlying fuel mixes.

[5] The model is presented in a pricing approach to climate policy where the projected equilibrium can entail a carbon tax. A quantity approach to climate policy is easily derived by setting aggregate, sector- or agent-specific emission quotas, and endogenising the carbon tax rates.

[6] Compared to IMACLIM-S 2.3, the disaggregation of a housing good LOG prompted to differentiate the specific margins on goods by household class, to allow calibrating on observed, class-specific square metre prices.

not. The latter tax applies to household prices only, as national accounting makes households the only final consumer of energy goods.[7]

$$p_{Chi} = \left\lfloor p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSChi}}\right) + t_{TIPPCFi} + t_{AIPi} + \overline{t_{CF}}\, \gamma_{CFi} \right\rfloor \left(1 + \overline{\tau_{TVAi}}\right). \quad (7)$$

$$p_{Gi} = \left\lfloor p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSGi}}\right) + t_{TIPPCFi} + t_{AIPi} \right\rfloor \left(1 + \overline{\tau_{TVAi}}\right). \quad (8)$$

$$p_{Ii} = \left\lfloor p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSIi}}\right) + t_{TIPPCFi} + t_{AIPi} \right\rfloor \left(1 + \overline{\tau_{TVAi}}\right). \quad (9)$$

$$p_{Xi} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSXi}}\right) + t_{TIPPCFi} + t_{AIPi}\, . \quad (10)$$

Trade margins τ_{MCi} and transport margins τ_{MTi} , identical for all intermediate and final consumptions of good *i*, are calibrated on the present (2006) equilibrium and kept constant, with the exception of those on the productions aggregating transport and trade activities—the TRANS and COMP goods, which are simply adjusted, in the projected equilibrium, to have the two types of margins sum up to zero:

$$\sum_{j=1}^{n} \tau_{MCCOMP}\, p_{COMP}\, \alpha_{COMPj}\, Y_j + \tau_{MCCOMP}\, p_{COMP} \left(C_{COMP} + G_{COMP} + I_{COMP} + X_{COMP}\right) + \sum_{i \neq COMP} \sum_j \overline{\tau_{MCi}}\, p_i\, \alpha_{ij}\, Y_j + \sum_{i \neq COMP} \overline{\tau_{MCi}}\, p_i \left(C_i + G_i + I_i + X_i\right) = 0 \quad (11)$$

and similarly:

$$\sum_{j=1}^{n} \tau_{MTTRANS}\, p_{TRANS}\, \alpha_{TRANSj}\, Y_j + \tau_{MTTRANS}\, p_{TRANS} \left(C_{TRANS} + G_{TRANS} + I_{TRANS} + X_{TRANS}\right) + \sum_{i \neq TRANS} \sum_j \overline{\tau_{MTi}}\, p_i\, \alpha_{ij}\, Y_j + \sum_{i \neq TRANS} \overline{\tau_{MTi}}\, p_i \left(C_i + G_i + I_i + X_i\right) = 0\, . \quad (12)$$

Labour costs are equal to the net wage w_i plus payroll taxes (both employers and employees' social contributions in the case of France) that are levied following a unique rate τ_{CS} (common to all productions for want of detailed calibration data) calibrated on present (2006) statistics:

$$p_{Li} = \left(1 + \tau_{CS}\right) w_i\, . \quad (13)$$

The average wage in production *i*, w_i , varies as the average wage across all sectors *w*:

$$w_i = \frac{w}{w_0} w_{i0}\, , \quad (14)$$

which is subject to variations that are dictated by an assumption on the overall rate of unemployment (*cf.* the description of the labour market clearing Section II.6).

The cost of capital is understood as the cost of the 'machine' capital (*cf.* the description of the production trade-offs Section II.3). It is obtained as the average price of investment goods:[8]

[7] Public administrations consume a 'public service', whose energy content appears in the energy consumption of the production in which it is aggregated—and is taxed for its carbon content at this level.

[8] When product aggregation is such that a unique composite good encompasses all non-energy goods this composite good is the only one immobilised, and p_K matches its investment price p_I .

$$p_K = \frac{\sum_{i=1}^{n} p_{Ii}\, I_i}{\sum_{i=1}^{n} I_i} \,. \tag{15}$$

IPC the consumer price index is computed following Fisher, *i.e.* as the geometric mean of a Laspeyres index (variation of the cost of the present basket of goods from the present to the future set of relative prices) and a Paasche index (variation of the cost of the future basket of goods from the present to the future set of relative prices):[9]

$$IPC = \sqrt{\frac{\sum_{i=1}^{n} p_{Ci}\, C_{i0}}{\sum_{i=1}^{n} p_{Ci0}\, C_{i0}} \frac{\sum_{i=1}^{n} p_{Ci}\, C_i}{\sum_{i=1}^{n} p_{Ci0}\, C_i}} \,. \tag{16}$$

II.2. Households

The disaggregation of households into *m* classes (index *h*, $h \in [1, m]$) aims at taking account of income structures and behaviours and adaptation capacities that vary significantly from one household class to the next. Up to Ghersi and Ricci (2014) it is based on simple living standards, although more subtle categories could better represent the heterogeneity of the 'energy vulnerability' of households in future applications of the model.

Income formation, savings and investment decision

$RDBAI_h$ the gross primary income of class *h* is defined as the addition and the subtraction of the following terms:

- A share ω_{Lh} of the sum of aggregate endogenous net wage income $w_i\, l_i\, Y_i$, which varies with the number of active people employed in each class (Equation 83).
- A share ω_{Kh} of the fraction of 'capital income' (the gross operating surplus of national accounting) that goes to households, EBE_H, which corresponds to the real and imputed rents that accrue to households—an assumed constant share of total real and imputed rent payments (Equation 21). The ω_{Kh} (the distribution of EBE_H across household classes) are exogenous and their calibration is based on the *Budget de Famille* survey and the TEE.
- Social transfers, in three aggregate payments (pensions $\rho_{Ph}\, N_{Ph}$, unemployment benefits $\rho_{Uh}\, N_{Uh}$, other social transfers $\rho_{Ah}\, N_{Ah}$), the calculation of which is similarly based on the product of a *per capita* income ρ and a target population *N*. The retired and total populations of class *h*, N_{Ph} and N_h, grow from their reference value by exogenous δ_{NP} *and* δ_N percentages (common to all classes);

[9] Class-specific indexes can similarly be constructed using class-specific prices (differentiated thanks to specific margins) and consumptions and applied to *e.g.* the computation of class-specific real gross disposable income variations.

the number of unemployed N_{Uh} endogenously derives from the conditions on the labour market (Equation 82).

- An exogenous share ω_{ATh} of (small) residual transfers A_{TH} , which correspond to the sum of "other current transfers" and "capital transfers", accounts D7 and D9 of the TEE.
- A 'debt service' $i_H D_h$, which is indeed negative and corresponds to property income (account D4 of the TEE: interests, dividends, real estate revenues, *etc.*) for most if not all income classes (depending on the extent of class disaggregation). This service is the product of the households' net debt D_h , the evolution of which is explained below (Equation 26), and an endogenous effective interest rate i_H (*cf.* Equation 76).

Hence

$$N_{Ph} = \left(1+\delta_{NP}\right) N_{Ph0} \, , \tag{17}$$

$$N_h = \left(1+\delta_N\right) N_{h0} \, , \tag{18}$$

$$RDBAI_h = \omega_{Lh} \sum_{i=1}^{n} w_i \, l_i \, Y_i + \overline{\omega_{Kh}} \, EBE_H + \rho_{Ph} \, N_{Ph} + \rho_{Uh} \, N_{Uh} + \rho_{Ah} \, N_h + \overline{\omega_{ATh}} \, A_{TH} - i_h \, D_h \, , \tag{19}$$

with A_{TH} a constant share ω_{ATH} of A_T (*cf.* Equation 74) and EBE_H, which is massively composed of imputed rents, a constant share ω_{KH} of p_{LOG} *LOG*:

$$A_{TH} = \overline{\omega_{ATH}} \, A_T \tag{20}$$

$$EBE_H = \overline{\omega_{KH}} \, p_{LOG} \, LOG \tag{21}$$

The gross disposable income RDB_h of class *h* is obtained by subtracting from $RDBAI_h$ the income tax T_{IRh} levied at a constant average rate (Equation 56), and other direct taxes T_h that are indexed on *IPC* (Equation 57). R_h , the consumption budget of class *h*, is inferred from disposable income by subtracting savings. The savings rate τ_{Sh} is exogenous (calibrated to accommodate the values of RDB_h and R_h in the present equilibrium).

$$RDB_h = RDBAI_h - T_{IRh} - T_h \tag{22}$$

$$R_h = \left(1-\overline{\tau_{Sh}}\right) RDB_h \tag{23}$$

A further exploration of the data available in the TEE gives households' investment $FBCF_h$ (*Formation Brute de Capital Fixe*, *i.e.* Gross Fixed Capital Formation) as distinct from their savings; $FBCF_h$ is assumed to follow the simple rule of a fixed ratio to gross disposable income (Equation 24). The difference between savings and investment gives the self-financing capacity (SFC) of class *h*, CAF_h.

$$\frac{FBCF_h}{RDB_h} = \frac{FBCF_{h0}}{RDB_{h0}} \tag{24}$$

$$CAF_h = \overline{\tau_{Sh}} \, RDB_h - FBCF_h \tag{25}$$

The evolution of CAF_h between the present and future equilibrium can then be used to estimate the evolution of net debt D_h . The computation is based on the simple assumption that the average SFC over the years of projection t_{PROJ} is a mean of the present and future SFC.

$$D_h = D_{h0} - t_{PROJ} \frac{CAF_{h0} + CAF_h}{2} \tag{26}$$

Consumption

Representing households trade-offs requires both supplementary good disaggregations and good aggregations in intermediate consumption bundles. The following consumptions are thus added to the 9 productions distinguished by the model:

ELEC1	The specific (non-substitutable) share of electricity consumptions—calibrated on quintile-specific data from a 2006 Housing Survey by INSEE (the *Enquête Logement*).
ELEC2	Any ELEC not resorting to ELEC1, *i.e.* the non-specific, substitutable electricity consumptions covering space heating, water heating and cooking.
TRANS1	The share of the consumption of public transports constrained by the housing location choice (public transports share of daily transportation needs including, but not limited to, commuting)—calibrated on quintile-specific data from a 2006 Transport survey by INSEE (the *Enquête Transports*).
TRANS2	Any TRANS not resorting to TRANS1, *i.e.* leisure-motivated public transports (including aviation).
CARB1	The share of the consumption of automotive fuels constrained by the housing location choice (automotive share of daily transportation needs including, but not limited to, commuting)—calibrated on quintile-specific data from a 2006 Transport survey by INSEE (the *Enquête Transports*).
CARB2	Any CARB not resorting to CARB1, *i.e.* leisure-motivated automotive fuel consumption (including aviation).
TCONT	A bundle of TRANS1 and CARB1, aggregated through a CES specification above a floor consumption (*cf. infra*). Arbitrary 2006 value (without impact on modelling results).
TLOIS	A bundle of TRANS2 and CARB2, aggregated through a CES specification above a floor consumption (*cf. infra*). Arbitrary 2006 value (without impact on modelling results).
CONS	A bundle of TLOIS and COMP, aggregated through a CES specification above a floor consumption (*cf. infra*). Arbitrary 2006 value (without impact on modelling results).
EDNS	A bundle of ELEC2, RAFF and GAZ+, aggregated through a CES specification above a floor consumption, and modified by exogenous trends (*cf. infra*).
SEDNS	A CES bundle of EDNS and BAT.

At the core of their consumption trade-offs, households devote a constant share of their consumption budget *R* (we drop the class index *h* for the sake of readability) to housing expenses p_{LOG} *LOG*:

$$\frac{p_{LOG}\,LOG}{R} = \frac{p_{LOG0}\,LOG_0}{R}\,, \tag{27}$$

which amounts to considering, following the conclusions of urban economics synthesised by Fujita (1989), that a Cobb-Douglas utility function governs consumer choices between square metres of housing and other expenses. The evolution of the demand for housing square metres mechanically induces that of the constrained share of households transport demand, *TCONT*, based on some assumption on the minimum housing surface $\beta_{LOG}\,LOG_0$:

$$\frac{p_{TCONT}\,TCONT}{R} = 1 - \left(\frac{LOG}{\beta_{LOG}\,LOG_0}\right)^{b_{TCONT}} \tag{28}$$

with β_{LOG} the proportion of the present housing surface LOG_0 that corresponds to the minimum housing surface and b_{TCONT} a coefficient calibrated on present (2006) data.

Similarly to the way it implies *TCONT*, *LOG* mechanically induces a consumption of substitutable energy services *SEDNS*. The relationship is assumed isoelastic, following an exogenous elasticity b_{SEDNS} of *SEDNS* demand to *LOG*:

$$SEDNS = a_{SEDNS}\,LOG^{b_{SEDNS}} \tag{29}$$

with a_{SEDNS} calibrated on present data (*SEDNS* can be normalised without impact on modelling results).

By contrast, specific electricity consumptions ELEC1, calibrated on data from a 2006 Housing Survey by INSEE (the *Enquête Logement*), are supposed isoelastic to total population with elasticity b_{ELEC1} (*cf.* Annex 2):

$$ELEC1 = a_{ELEC1}\,N^{b_{ELEC1}}\,, \tag{30}$$

with a_{ELEC1} calibrated on present (2006) data, *ELEC1* being expressed as million tons-of-oil-equivalent (as all other energy consumptions following data hybridising, *cf.* Section I.2).

All other trade-offs are settled by CES (Constant Elasticity of Substitution) specifications, but only beyond floor consumptions that are meant to represent 'basic needs', thereby enhancing the ability of the consumption model to calibrate on *bottom-up* expertise (following Ghersi and Hourcade, 2006).[10] This concerns the trade-off between *TRANS1* and *CARB1* in *TCONT*; that between *TLOIS* and *COMP* in *CONS*; that between *ELEC2*, *RAFF* and *GAZ+* in *EDNS*; that between *EDNS* and *BAT* (in a quite specific version, *cf. infra*) in *SEDNS*. For these trade-offs, if the goods (or bundles) *A*, *B* and *C* are substitutable within some aggregate *X*, then the optimal consumption of good *A* (that minimising the budget necessary to form *X*) is:

[10] It is thus only the flexible shares of consumptions that substitute following a constant elasticity. The substitution elasticities of total consumption volumes are decreasing with total consumption volumes.

$$C_A = \beta_A C_{A0} + R_X \left(\frac{\lambda_A}{p_{CA}}\right)^{-\sigma_X} \sum_{j\in\{A,B,C\}} \lambda_j^{\sigma_X} p_{Cj}^{1-\sigma_X} \qquad (31)$$

with β_A C_{A0} the basic need of good A; p_{Ci} the consumer price of good i; σ_X the substitution elasticity of the consumptions of A, B and C for the shares superseding their basic needs; λ_j a set of coefficients calibrated on the present budget structures; R_X the consumption budget of good X. As an exception, C_{EDNS} the consumption of substitutable residential energy is modified by a supplementary exogenous trend that combines assumptions on the efficiency of the post-2006 building stock and on specific electricity consumption: the (1-a_{HEAT}) share of projected EDNS consumption devoted to cooking and water heating is supposed to progress as population N; assuming a δ_{LOG} depreciation rate, the a_{HEAT} share of projected EDNS is unmodified for a share $(1-\delta_{LOG})^{t_{PROJ}}$ representing the pre-2006 stock remaining in 2035 but it is cut down by a ω_{HEAT} efficiency factor symbolising strengthened building regulations for the post-2006 construction (in this equation we reintroduce the class index h to make clear that a_{HEAT}, δ_{LOG} and ω_{HEAT} are not class-specific):

$$C_{EDNSh} = \left(a_{HEAT} \left((1-\delta_{LOG})^{t_{PROJ}} + \omega_{HEAT} \frac{LOG_h - (1-\delta_{LOG})^{t_{PROJ}} LOG_{h0}}{LOG_h} \right) + (1-a_{HEAT}) \frac{N_h}{N_{h0}} \right)$$
$$\left(\beta_{EDNS} C_{EDNS0} + R_{SEDNS} \left(\frac{\lambda_{EDNS}}{p_{CEDNS}}\right)^{-\sigma_{SEDNS}} \sum_{j\in\{EDNS,BAT\}} \lambda_j^{\sigma_{SEDNS}} p_{Cj}^{1-\sigma_{SEDNS}} \right) \qquad (32)$$

R_X is straightforwardly defined as:

$$R_X = p_{CX} C_X \qquad (33)$$

with the exception of R_{CONS}, which is defined to acknowledge the aggregate budget constraint, as R the total consumption budget minus all expenses but these on COMP and TLOIS (TRANS2 and CARB2):

$$R_{CONS} = R - \sum_{X\neq COMP,TRANS2,CARB2} p_{CX} C_X \qquad (34)$$

At last, the CES price of aggregate X follows the textbook formula

$$p_{CX} = \left(\sum_{j\in\{A,B,C\}} \lambda_j^{\sigma_X} p_{Cj}^{1-\sigma_X} \right)^{\frac{\rho_X - 1}{\rho_X}} \qquad (35)$$

where for the sake of convenience

$$\rho_X = \frac{\sigma_X - 1}{\sigma_X} \qquad (36)$$

Note at last that EPRIM the consumption of primary fossil fuels boils down to a residual consumption of coal in 2006, which disappears from statistics in 2007. For this reason projected EPRIM consumptions are arbitrarily fixed to 0 across all household classes.

II.3. Production (institutional sector of firms)

Gross disposable income and investment decision

Similar to that of households, the firms' disposable income RDB_S is defined as the addition and subtraction of:

- An exogenous share ω_{KS} of capital income *i.e. EBE* (*cf.* Equation 47),
- A 'debt service' (interests, dividends) $i_S\, D_S$, which is strongly positive in the present equilibrium (firms are net debtors in 2006), and served at an interest rate i_S that varies in the same way as i_H (Equation 76),
- Corporate tax payments T_{IS} ,
- And an exogenous share ω_{ATS} of other transfers A_T, which are assumed a constant share of GDP (Equation 74).

$$RDB_S = \overline{\omega_{KS}}\, EBE - i_S\, D_S - T_{IS} + \overline{\omega_{ATS}}\, A_T \,. \tag{37}$$

The ratio of the gross fix capital formation of firms $FBCF_S$ to their disposable income RDB_S is assumed constant; similar to households and in accordance with national accounting their self-financing capacity CAF_S then arises from the difference between RDB_S and $FBCF_S$. The net debt of firms D_S is then calculated from their CAF_S following the same specification as that applied to households.

$$\frac{FBCF_S}{RDB_S} = \frac{FBCF_{S0}}{RDB_{S0}} \,. \tag{38}$$

$$CAF_S = RDB_S - FBCF_S \,. \tag{39}$$

$$D_S = D_{S0} - t_{PROJ}\, \frac{CAF_{S0} + CAF_S}{2} \,. \tag{40}$$

Production trade-offs

For reasons similar to those presented for the demand of households, the production trade-offs, which are the subject of a specific publication (Ghersi and Hourcade, 2006), are limited by technical asymptotes that constrain the unit consumptions of factors above some floor values. Compared to Ghersi and Hourcade (2006) the restrictive assumption is made that the *variable* shares of the unit consumptions of the 11 factors (9 secondary inputs, labour and capital) are substitutable according to a CES specification—similar to household consumption, the existence of a fix share of each of these consumptions implies that the elasticities of substitution of *total* unit consumptions (sum of the fix and variable shares) are not fixed, but decrease as the consumptions approach their asymptotes.

Under these assumptions and constraints, the minimisation of unit costs of production leads to a formulation of the unitary consumptions of secondary factors α_{ji} , of labour l_i and of capital k_i which can be written as the sum of the floor value and a consumption above this value. The latter corresponds to the familiar expression of conditional factor demands of a CES production function with an elasticity of σ_i (the coefficients of which, λ_{CIij}, λ_{Li0} and λ_{Ki0} , are calibrated in the present equilibrium).

$$\alpha_{ji} = \Theta_i \left[\beta_{ji}\, \alpha_{ji0} + \left(\frac{\lambda_{ji}}{p_{CIji}} \right)^{\sigma_i} \left(\sum_{j=1}^{n} \lambda_{ji}^{\sigma_i}\, p_{CIji}^{\;1-\sigma_i} + \lambda_{Li}^{\sigma_i} \left(\frac{p_{Li}}{\phi_i} \right)^{1-\sigma_i} + \lambda_{Ki}^{\sigma_i}\, p_K^{\;1-\sigma_i} \right)^{-\frac{1}{\rho_i}} \right] \tag{41}$$

$$l_i = \frac{\Theta_i}{\phi_i} \left[\beta_{Li}\, l_{i0} + \left(\frac{\lambda_{Li}\, \phi_i}{p_{Li}} \right)^{\sigma_i} \left(\sum_{j=1}^{n} \lambda_{ji}^{\sigma_i}\, p_{CIji}^{\;1-\sigma_i} + \lambda_{Li}^{\sigma_i} \left(\frac{p_{Li}}{\phi_i} \right)^{1-\sigma_i} + \lambda_{Ki}^{\sigma_i}\, p_K^{\;1-\sigma_i} \right)^{-\frac{1}{\rho_i}} \right] \tag{42}$$

$$k_i = \Theta_i \left[\beta_{Ki}\, k_{i0} + \left(\frac{\lambda_{Ki}}{p_{Ki}} \right)^{\sigma_i} \left(\sum_{j=1}^{n} \lambda_{ji}^{\sigma_i}\, p_{CIji}^{\;1-\sigma_i} + \lambda_{Li}^{\sigma_i} \left(\frac{p_{Li}}{\phi_i} \right)^{1-\sigma_i} + \lambda_{Ki}^{\sigma_i}\, p_K^{\;1-\sigma_i} \right)^{-\frac{1}{\rho_i}} \right], \tag{43}$$

where for convenience

$$\rho_i = \frac{\sigma_i - 1}{\sigma_i}. \tag{44}$$

This sum is however modified to take into account the combination of an exogenous labour productivity improvement factor ϕ_i ,[11] and of endogenous decreasing returns Θ_i . The latter impact all factor consumptions by assuming them elastic to the volume produced, by a fixed elasticity $\sigma_{\Theta Yi}$, which is calibrated under the assumption of marginal cost pricing.

$$\Theta_i = \left(\frac{Y_i}{Y_{i0}} \right)^{\sigma_{\Theta Yi}} \tag{45}$$

$$\sigma_{\Theta Yi} = \frac{\overline{\pi_i}}{1 - \overline{\pi_i}}. \tag{46}$$

Let us emphasise again that the 'cost of capital' p_K entering the trade-offs is *stricto sensu* the price of 'machine capital', *i.e.* equal to a simple weighted sum of the investment prices of immobilised goods (Equation 15), and unrelated to the interest rates charged on financial markets: on the one hand production trade-offs are based upon the strict cost of inputs, including that of physical capital k_i (calibrated on the consumption of fixed capital of the TES); on the other hand, notwithstanding this arbitrage, the firms' activity and a rule of self-investment ($FBCF_S$, Equation 38) lead to a change in their financial position D_S , whose service is not assumed to specifically weigh on physical capital as an input.

[11] In IMACLIM-S the Φ_i designate an endogenous growth coefficient that links factor consumptions (not only labour but all of them, following a Hicks-neutral hypothesis) to production levels. This specification is irrelevant to the exogenous growth framework of IMACLIM-P.

Gross operating surplus

Capital consumptions, constant rates of operating margin π_i and specific margins *MS* determine the gross operating surplus (*Excédent Brut d'Exploitation*, EBE):

$$EBE = \sum_{i=1}^{n} \left(p_{Ki}\, k_i\, Y_i + \overline{\pi_i}\, p_{Yi}\, Y_i \right) + M_S \tag{47}$$

This *EBE*, which corresponds to capital income, is split between agents following constant shares (calibrated on the present equilibrium). By construction, the specific margins on the different sales M_S sum to zero in the present equilibrium (this is a constraint of the hybridising process), however they do not in the future equilibrium, their constant rates being applied to varying prices. Their expression is then:

$$M_S = \sum_i \left(\sum_j \overline{\tau_{MSCI_{ij}}}\, p_i\, \alpha_{ij}\, Y_j + \sum_h \overline{\tau_{MSCh_i}}\, p_i\, C_{hi} + \overline{\tau_{MSG_i}}\, p_i\, G_i + \overline{\tau_{MSX_i}}\, p_i\, X_i \right) \tag{48}$$

II.4. Public administrations

Tax, social security contributions and fiscal policy

Tax and social security contributions form the larger share of government resources. In this 3.4 version of IMACLIM-P, all tax rates other than the carbon tax are supposed constant, while excise taxes are scaled up by the consumer price index *IPC*:

$$\forall\, X \in [\text{CI, CF}] \qquad t_{TIPPXi} = IPC\, t_{TIPPXi0}\,, \tag{49}$$

$$t_{AIPi} = IPC\, t_{AIPi0}\,. \tag{50}$$

The various tax revenues are defined by applying these rates to their respective bases:

$$T_Y = \sum_{i=1}^{n} \overline{\tau_{Y_i}}\, p_{Yi}\, Y_i\,, \tag{51}$$

$$T_{TIPP} = \sum_{i=1}^{n}\sum_{j=1}^{n} \overline{t_{TIPPCI_{ji}}}\, \alpha_{ji}\, Y_i + \sum_{i=1}^{n} \overline{t_{TIPPCF_i}} \left(C_i + G_i + I_i \right), \tag{52}$$

$$T_{AIP} = \sum_{i=1}^{n}\sum_{j=1}^{n} \overline{t_{AIP_j}}\, \alpha_{ji}\, Y_i + \sum_{i=1}^{n} \overline{t_{AIP_i}} \left(C_i + G_i + I_i \right), \tag{53}$$

$$T_{TVA} = \sum_{i=1}^{n} \frac{\overline{\tau_{TVA_i}}}{1 + \tau_{TVA_i}} \left(p_{Ci}\, C_i + p_{Gi}\, G_i + p_{Ii}\, I_i \right), \tag{54}$$

$$T_{IS} = \overline{\tau_{IS}}\, EBE_S\,, \tag{55}$$

$$T_{IRh} = \overline{\tau_{IRh}}\, R_{DBAIh}\,. \tag{56}$$

Similar to excise taxes and for lack of more detail on its composition the sum of households' direct taxes other than the income tax T_{IR} is assumed to grow as the general price level:

$$T_h = IPC\, T_{h0} \,. \tag{57}$$

The sum of social contributions T_{CS} follows the same logic as other tax revenues again:

$$T_{CS} = \tau_{CS} \sum_{i=1}^{n} w_i\, l_i\, Y_i \,. \tag{58}$$

So does the carbon on intermediate consumptions (t_{CI}) and on final consumptions (t_{CF}) except that it is exogenous:

$$T_{CARB} = \sum_{i=1}^{n} \sum_{j=1}^{n} \overline{t_{CI}}\, \gamma_{CIji}\, \alpha_{ji}\, Y_i + \sum_{i=1}^{n} \overline{t_{CF}}\, \gamma_{CFi}\, C_i \,. \tag{59}$$

In the dynamic framework of IMACLIM-P the 'budget neutrality' condition of counterfactual analyses is reinterpreted as a constraint on public debt accumulation, enforced as a constant ratio of public debt to GDP (Equation 43b). The variables that adjust to meet this constraint are the *per capita* social transfers ρ_U, ρ_P and ρ_A, which are scaled up or down by a common factor. In the case when a carbon tax provides supplementary tax income, the pressure on these transfers is lessened.

$$\frac{D_G}{PIB} = \frac{D_{G0}}{PIB_0} \tag{60}$$

At last, T is the sum of taxes and social contributions:

$$T = T_{CS} + T_Y + T_{TIPP} + T_{AIP} + T_{TVA} + T_{IS} + \sum_{h=1}^{m} T_{IRh} + \sum_{h=1}^{m} T_h + T_{CARB} \tag{61}$$

Gross disposable income, public spending, investment and transfers

Similar to households and firms (following the logic prevailing in the TEE), the gross disposable income of public administrations RDB_G is the sum of taxes and social contributions, of exogenous shares ω_{KG} of *EBE* and ω_{ATG} of 'other transfers' A_T , from which are subtracted public expenditures $p_G\, G$, a set of social transfers R_P , R_U and R_A , and a debt service $i_G\, D_G$:

$$RDB_G = T + \overline{\omega_{KG}}\, EBE + \overline{\omega_{ATG}}\, A_T - \sum_{i=1}^{n} p_{Gi}\, G_i - R_P - R_U - R_A - i_G\, D_G \tag{62}$$

Public expenditures $p_G\, G$ are assumed to keep pace with national income and are therefore constrained as a constant share of GDP:

$$\frac{\sum_{i=1}^{n} p_{Gi}\, G_i}{PIB} = \frac{\sum_{i=1}^{n} p_{Gi0}\, G_{i0}}{PIB_0} \,, \tag{63}$$

Social transfers R_P , R_U and R_A are the sum across household classes of the transfers defined as components of their before-tax disposable income (Equation 19):

$$R_P = \sum_{h=1}^{m} \rho_{Ph} \, N_{Ph} \tag{64}$$

$$R_U = \sum_{h=1}^{m} \rho_{Uh} \, N_{Uh} \tag{65}$$

$$R_A = \sum_{h=1}^{m} \rho_{Ah} \, N_h \;, \tag{66}$$

with *per capita* transfers ρ_P , ρ_U and ρ_A variables of the model aimed at the constraint on public debt (Equation 43).

At last, the interest rate i_G of public debt evolves as do i_H and i_S (Equation 76).

Public investment $FBCF_G$, same as public expenditures $pG\ G$, is supposed to mobilise a constant share of GDP. Subtracting it from RDB_G produces CAF_G , which determines the variation of the public debt:

$$\frac{FBCF_G}{PIB} = \frac{FBCF_{G0}}{PIB_0} \tag{67}$$

$$CAF_G = RDB_G - FBCF_G \tag{68}$$

$$D_G = D_{G0} - t_{PROJ} \frac{CAF_{G0} + CAF_G}{2} \tag{69}$$

II.5. ‘Rest of the world’

Trade balance

Competition on international markets is settled through relative prices. The ratio of imports to domestic production on the one hand, and the ‘absolute’ exported quantities on the other hand, are elastic to the terms of trade, according to constant, product-specific elasticities:

$$\frac{M_i}{Y_i} = \frac{M_{i0}}{Y_{i0}} \left(\frac{p_{Mi0}}{p_{Yi0}} \frac{p_{Yi}}{p_{Mi}} \right)^{\sigma_{Mpi}} \tag{70}$$

$$\frac{X_i}{X_{i0}} = \left(\frac{p_{Mi0}}{p_{Xi0}} \frac{p_{Xi}}{p_{Mi}} \right)^{\sigma_{Xpi}} \left(1 + \delta_{Xi}\right) \tag{71}$$

The different treatment of imports and exports merely reflects the assumption that, notwithstanding the evolution of the terms of trade, import volumes rise in proportion to domestic economic activity (domestic production), while exports are impacted by global growth. The latter fact is captured by assuming an extra, exogenous δ_{Xi} increase of volumes exported. In total, as far as exports are concerned France is depicted as supplying a terms-of-trade elastic share of a δ_{Xi} expanded international market.

The only exception to this terms-of-trade treatment is the international market for primary fossil energies EPRIM. Considering the paucity of France in such resources domestic EPRIM production is arbitrarily set to 0 in the projected equilibrium, and the imports are assumed to mechanically balance the market on the resources' side.

Capital flows and self-financing capacity

Capital flows from and to the 'Rest of the World' (ROW) are not assigned a specific behaviour, but are simply determined as the balance of capital flows of the three national institutional sectors (households, firms, public administrations) to ensure the balance of trade accounting. This assumption determines the self-financing capacity of the ROW, which in turn determines the evolution of D_{RDM} , its net financial debt:

$$CAF_{RDM} = \sum_{i=1}^{n} p_{Mi} M_i - \sum_{i=1}^{n} p_{Xi} X_i + \sum_{K=H,S,G}^{n} i_K D_K - \sum_{K=H,S,G}^{n} A_{TK} \ , \qquad (72)$$

$$D_{RDM} = D_{RDM0} - t_{PROJ} \frac{CAF_{RDM0} + CAF_{RDM}}{2} \ . \qquad (73)$$

By construction the self-financing capacities (SFC) of the 4 agents clear (sum to zero), and accordingly the net positions, which are systematically built on the SFCs, strictly compensate each other in the projected as in the present equilibrium—indeed a nil condition on the sum of net positions could be substituted to equation 73 without impacting the model. The hypothesis of a systematic 'compensation' by the ROW of the property incomes of national agents without any reference to its debt D_{RDM} may seem crude, but *in fine* only replicates the method of construction of the TEE. Indeed, in the 2006 calibration equilibrium the effective interest rate of the ROW (ratio of net debt to its property income), which ultimately results from a myriad of debit and credit positions and from the corresponding capital flows, is negative—unworkable for modelling purposes.

At last, as previously mentioned other transfers A_T (« other current transfers » and « capital transfers », aggregates D7 and D9 of the TEE) are defined as a fixed share of GDP[12]:

$$\frac{A_T}{PIB} = \frac{A_{T0}}{PIB_0} \qquad (74)$$

[12] The sum across agents of the D7 and D9 accounts being nil by definition (they aggregate transfers between agents), A_T is in fact calibrated on the sum of the net transfers that are strictly positive. As a consequence the shares ω_{ATH}, ω_{ATS}, ω_{ATG} and ω_{ATRDM} , summing to 0 by construction, are ratios properly speaking.

II.6. Market balances

Goods markets

Goods market clearing is a simple accounting balance between resources (production and imports) and uses (intermediate consumption, households and public administrations' consumption, investment, exports). Thanks to the process of hybridisation, this equation is written in MTOE for energy goods and consistent with the 2006 energy balance of the IEA (notwithstanding that the *G* and *I* of energy goods are nil by definition).

$$Y_i + M_i = \sum_{j=1}^{n} \alpha_{ij} Y_j + C_i + G_i + I_i + X_i \quad (75)$$

Of course the aggregate consumption of households C_i sums up the consumptions of all classes C_{ih}.

Investment and capital flows

The effective interest rates i_H , i_S and i_G faced by households, firms and public administrations, settle to balance capital markets: their shift from a common point differential δ_i (Equation 67) impacts the households' and firms' disposable incomes RDB_H and RDB_S , hence their investment decisions $FBCF_H$ and $FBCF_S$, in order to match the supply of capital they correspond to, adding up to the public GFCF $FBCF_G$, to the demand for investment goods $p_{Ii}\, I_i$ (Equation 77). This demand is in turn constrained by the assumption that the ratio of each of its real components I_i to total fixed capital consumption (the sum of $k_i\, Y_i$) is constant. In other words, the capital immobilised in all productions is supposed homogeneous, and all its components vary as the total consumption of fixed capital.

$$\forall\ K \in [H, S, G] \qquad i_K = i_{K0} + \delta_i \quad (76)$$

$$\sum_{K=H,S,G} FBCF_K = \sum_{i=1}^{n} p_{Ii}\, I_i \quad (77)$$

$$\frac{I_i}{\sum_{j=1}^{n} k_j\, Y_j} = \frac{I_{i0}}{\sum_{j=1}^{n} k_{j0}\, Y_{j0}} \quad (78)$$

Therefore the closure of the model is on the investment supply of agents, which mechanically adapts to the investment demand from productions. Through an adjustment of interest rates it leads to fluctuations in financial flows between creditors and debtors, and eventually in some evolution of their net financial positions.

Employment

The labour market results from the interplay of labour demand from the production systems, equal to the sum of their factor demands $l_i\, Y_i$, and of labour supply from households. The labour endowment of households L_0 grows by an exogenous, common rate δ_L, calibrated on the total full-time equivalent of the active population in the present and future equilibrium. However the model allows for a strictly positive unemployment rate u and the market clearing condition writes:

$$(1-u)(1+\delta_L)L_0 = \sum_{i=1}^{n} l_i\, Y_i \,. \qquad (79)$$

Rather than explicitly describing labour supply behaviour, the model treats as exogenous the overall unemployment rate u:

$$u = \bar{u} \,. \qquad (80)$$

Changes in employment corresponding to the evolution of u are then split between the household classes according to their specific unemployment rates u_h:

$$u_h = u_{h0} \frac{u}{u_0} \,, \qquad (81)$$

hence N_{Uh} the number of unemployed in each class follows:

$$N_{Uh} = u_h \left(1+\delta_L\right) L_{h0} \,. \qquad (82)$$

N_{Lh} the number of employed in class h (defined as $(1+\delta_L)\, L_{h0} - N_{Uh}$) allows moreover to determine the share ω_{Lh} of total labour income that accrues to class h:

$$\omega_{Lh} = \frac{\dfrac{N_{Lh}}{N_{Lh0}} \omega_{Lh0}}{\sum_{h=1}^{m} \dfrac{N_{Lh}}{N_{Lh0}} \omega_{Lh0}} \,. \qquad (83)$$

III. Main driving forces of the modelling results

The future economic conditions projected by IMACLIM-P result from the combination of a series of assumptions. Some are straightforwardly embodied in some of the parameters of the model. Others are more intricately implied by some of the model's equations. This last section discusses the most significant of them.

III.1. Demographic and productivity drivers

At the core of the model, two demographic and productivity assumptions, together with the unemployment rate u, can be seen as shaping the potential growth of the projected economy:

δ_L the growth of labour supply. It is based on that of the labour force but can embark any contrasted assumption on the evolution of working hours.

ϕ_i the 1×9 vector of labour productivity growths. Each production can benefit from specific productivity improvements, although the forecasts available in the literature are generally not differentiated.

u the unemployment rate, is inseparable from the two former assumptions, for the obvious reason that it fixes the share of the labour supply that is actively employed.

Two other demographic drivers impact on potential growth by their distributive consequences, as they define the candidate populations to generic social transfers, and pensions.

δ_N the growth of total population,

δ_{NP} the growth of the pensioned population.

III.2. Consumption and input trade-offs

Floor consumptions to the production inputs

In intermediate consumption there are floor volumes of the 11 inputs (2 primary facors, 9 secondary factors) *per unit of production*. They can be interpreted as technical frontiers that are assumed insuperable at the t_{PROJ} horizon at which the economy is projected. For instance, for *i* = CARB and *j* = TRANS, β_{ij} is the percentage of the 2006 fuel input into one unit of transport service that is supposed to endure whatever the change in relative prices observed after t_{PROJ} years. It is to be shaped by combining assumptions on the maximum expected progress in ICE efficiency (including the possible development of hybrid motorisation) and road-to-rail substitution, but might also consider some minimum expected development of air transportation, for which no substitutes to conventional fuels are currently anticipated. Incidentally, the floor input intensities are a useful way to circumvent the 'flat' (rather than nested) nature of the production process of IMACLIM-P, as they allow fixing input-specific substitution elasticities: with σ_{TRANS} the elasticity prevailing in the production of TRANS, the specific substitution elasticity of CARB in TRANS is $(1-\beta_{CARB/TRANS})\ \sigma_{TRANS}$.

The floors are grouped into 3 matrices:

β_{CI} is the 9×9 matrix of intermediate consumption floors (shares of the 2006 consumptions per unit that remain after t_{PROJ} years notwithstanding relative price changes).

β_L is the 1×9 vector of floors to the labour intensity of productions (shares of the 2006 labour time per unit that remain after t_{PROJ} years notwithstanding relative price changes).

β_K is the 1×9 vector of floors to the capital intensity of productions (shares of the 2006 fixed capital consumption per unit that remain after t_{PROJ} years notwithstanding relative price changes).

Basic needs of the household classes

In final consumption, the floor consumptions are class-specific minima to the aggregate consumption of each class, for each good. They can also be set for aggregates, when the competition between the goods constituting the aggregate is not to be constrained by floors at their level. The situation of each aggregate and product is specific enough to warrant clarifications.

COMP: the composite good, although it aggregates with many other goods such essential consumptions as water, food and clothing, is not assigned any basic need ($\beta_{COMP} = 0$). Considering its magnitude in current budget structures it is treated as an adjustment variable. It is left to the modeller to judge if the projected variations in *COMP* threaten the sustainability of the modelled scenario.

TRANS1: A β_{TRANS1} vector of class-specific basic needs (expressed as shares of $TRANS1_0$) can be defined to link a minimal, necessary consumption of public transports with the urban organisation embodied in the combination of β_{LOG} and β_{TCONT}, the basic housing space and transportation needs of household classes. The *TCONT* volume induced by β_{TRANS1} should be smaller than β_{CONT}, by definition of the latter (*cf. infra*).

TRANS2: *cf. TRANS1* immediately above, a β_{TRANS2} vector of class-specific basic needs can be specified, although by definition 'leisure' transportation *TLOIS* is more open to trade-off than constrained transportation *TCONT*.

LOG: A β_{LOG} vector of class-specific basic square-metre needs (expressed as shares of LOG_0) is central to the demand system of the projection. It is to be set in consistency with the β_{TCONT}, β_{ELEC1}, β_{EDNS} and β_{BAT} vectors, to combine into a *minimum minimorum* to the housing conditions of class *h*, and its transportation consequences. Thanks to the hybridising process C_{LOGh0} / N_{h0} is the housing square metre per person of class *h* in 2006, and can be used to define the class's basic need, considering the growth of its population.

BAT: *cf. LOG* immediately above. Contrary to *LOG*, *BAT* does not have an interpretable physical unit. Defining basic needs to *BAT* boils down to making some assumption about the share of observed *BAT* consumptions that are unavoidable in the maintenance of $\beta_{LOG}\ LOG_0$.

EPRIM: considering the assumption of an *EPRIM* consumption systematically brought down to 0 there is no need to define any basic need to *EPRIM*.

CARB1: *cf. TRANS1* above, a β_{CARB1} vector of class-specific basic needs can be defined to link a minimal, necessary consumption of vehicle fuels with the urban organisation embodied in the combination of β_{LOG} and β_{TCONT}, the basic housing space and transportation needs of household classes. The *TCONT* volume induced by β_{CARB1} should be smaller than $\beta_{TCONT}\ TCONT_0$, by definition of the latter (*cf. infra*).

CARB2: *cf. TRANS2* above, a β_{CARB2} vector of class-specific basic needs can be specified, although by definition 'leisure' transportation is more open to trade-off than constrained transportation *TCONT*.

RAFF: over a temporal horizon compatible with the inertia of heating systems there is no obvious restriction to the substitutability of gas and electricity to light fuel oil for the heating and cooking purposes backing the *RAFF* consumptions of households. Still, A β_{RAFF} vector is available to project over shorter terms, or test more restrictive assumptions.

ELEC1: *cf. LOG* above. As *LOG*, *ELEC1* is expressed in an interpretable physical unit, namely MTOE. Its basic needs are best set by assuming some minimal kWh per square-metre consumption of specific electricity, then converting and scaling up to the aggregate basic need of square metres $\beta_{LOG}\ LOG_0$.

ELEC2: *cf. RAFF* above. β_{ELEC2} is available to set a minimum bound to electric heating and cooking.

GAZ+: *cf. RAFF* above. β_{GAZ+} is available to set a minimum bound to gas heating and cooking, and possibly a network heat component.

CONS: there does not seem to be any reason to define a basic need to *CONS* other than the volume produced by the basic need of *TLOIS* ($\beta_{CONS} = 0$).

TCONT: *cf. LOG* above. *TCONT* does not have an interpretable physical unit, but is composed of goods that do, *TRANS1* in pkm and *CARB1* in MTOE. Basic needs to *TCONT* are best obtained from computing what volume of *TCONT* is produced by 'polar' scenarios where the minimum transportation effort compatible with $\beta_{LOG}\ LOG_0$ is realised by exclusive consumptions of *TRANS1* or *CARB1*.

EDNS: *cf. LOG* above. *EDNS* does not have an interpretable physical unit, but is composed of goods that do, *ELEC2*, *RAFF* and *GAZ+* in MTOE. Basic needs to *EDNS* can be obtained from computing the volume of *EDNS* produced by basic needs of *ELEC2*, *RAFF* or *GAZ+*, compatible with $\beta_{LOG}\ LOG_0$.

SEDNS: there does not seem to be any reason to define a basic need to *SEDNS* other than the volume produced by the basic need of *EDNS* or *BAT* ($\beta_{SEDNS} = 0$).

TLOIS: *cf. TCONT* above, *TLOIS* does not have an interpretable physical unit, but is composed of goods that do, *TRANS2* in pkm and *CARB2* in MTOE. Basic needs to *TLOIS* are best obtained from computing what volume of *TLOIS* is produced by alternative basic needs of *TRANS2* or *CARB2*. The case for a basic need to a leisure consumption is of course slimmer than in the case of *TCONT*.

Production elasticities

At this stage the production function assumed for all productions is a 'flat' (rather than nested) construction that allows differentiating the treatment of the various inputs through specific floor-consumptions only (*cf. supra*). For each of the 9 productions, one elasticity parameter drives the way in which the 'flexible' shares of factor consumptions (those above the floor consumptions) substitute in the course of t_{PROJ} years, considering the shifts in relative prices induced by the projection:[13]

σ_j is the 1×9 vector of substitution elasticities between the variable (above floor consumptions) shares of all 11 inputs in each of the 9 productions.

[13] These shifts are primarily caused by the assumptions on international energy prices, and the equilibrium wage deriving from the tensions on the labour market induced by the labour productivity and unemployment assumptions.

Elasticities and functional relationships in the demand system

The case of household demand is quite different from that of production: the specifications covering household behaviour are specifically meant to ease calibration on bottom-up expertise of household energy systems. For each CES relationship a specific elasticity is fixed:

σ_{TCONT} is the 1 × 5 vector of substitution elasticities between the TRANS1 and CARB1 aggregates. The substitution between public transportation and private car use is generally thought low, but this is partly a misconception due to confusion with the price elasticity of fuel consumption (based on observations of the fuel demand and the price of fuel relative to the consumer price index rather than that of public transportation).

σ_{SEDNS} is the 1 × 5 vector of substitution elasticities between the EDNS and BAT aggregates. This is an important parameter of energy demand management, as it shapes the substitution possibilities between investment in insulation, heating equipment or distributed energy systems, and network energy requirements.

σ_{EDNS} is the 1 × 5 vector of substitution elasticities between the ELEC2, RAFF and GAZ+ consumptions, that is the energy carriers providing heating and cooking services.

σ_{CONS} is the 1 × 5 vector of substitution elasticities between the TLOIS and COMP consumptions. Considering the 'remainder' nature of composite consumption in IMACLIM-P, σ_{CONS} is a close proxy of the price elasticity of the flexible share of leisure transportation TLOIS.

σ_{TLOIS} is the 1 × 5 vector of substitution elasticities between the TRANS2 and CARB2 aggregates. It should not depart too much from σ_{TCONT}, to account for the statistical fact that people who are constrained to have a car for daily life transportation tend to use it for leisure also—especially in the perspective of an equilibrium where short-term fluctuations are not accounted for.

III.3. Other central assumptions

International trade

Three exogenous parameters combine to shape the impact of international markets on the projected economy:

δ_X is the 1 × 9 vector of the exogenous expansion of the French export markets, that is the development of French exports that is projected before terms-of-trade shifts corrections are accounted for. In other terms, if the ratio of domestic to international production prices for good *i* is unchanged, the volume of good *i* exports progresses by δ_{Xi}. This is meant to capture the impact of expected global sectoral growths on French exports, competitiveness issues set aside.

δ_{EPRIM} is the growth in international oil & coal prices (relative to the international composite good). It must combine hypotheses on the prices and mix shares of the two fossil energies.

σ_{Xp} is the 1×9 vector of elasticities of French exports to the terms-of-trade (the ratio of domestic to international prices). It is applied to the volume of 2006 exports exogenously augmented by δ_X rather than to the raw data (*cf. supra*). The current elasticities are retained for their aggregate compatibility with the conclusions of a 2008 INSEE study (Cachia, 2008).

σ_{Mp} is the 1×9 vector of elasticities of French 'import intensity' (the share of imports in total resources) to the terms-of-trade (the ratio of domestic to international prices). The current elasticities are retained for their aggregate compatibility with the conclusions of a 2008 INSEE study (Cachia, 2008).

Note that with the active labour force and labour productivity exogenous, these parameters have distributive consequences much greater than any impact they have on real GDP.

Public administrations

The behaviour of public administrations unfolds in 3 different dimensions, which are implicit in some of the model's equations rather than embodied in identifiable parameters. First, direct public expenses and public investment amount to a constant share of GDP (Equations 63 and 67). Secondly, all tax rates are constant (excise taxes are deflated by the CPI to be maintained in real terms). Thirdly, a stabilised ratio of public debt to GDP is enforced by a simultaneous, homothetic adjustment of *per capita* social transfers. This again has strong repercussions on the distribution of growth, considering that social transfers are massively cut down to accommodate the social budget strain of a rapidly increasing retired population. All sorts of alternate rules are of course thinkable.

Other significant behavioural assumptions

The savings and investment rates of all household classes are assumed constant (Equations 23 and 24). Aging of the population might induce increased savings behaviour though, which could be investigated.

References

Armington P., 1969, “A Theory of Demand for Products Distinguished by Place of Production”, *IMF Staff papers* 16 (1), 159-78.

Boonekamp, P.G.M., 2007, “Price elasticities, policy measures and actual developments in household energy consumption – A bottom up analysis for the Netherlands”, *Energy Economics* 29 (2), 133-157.

Cachia, F., 2008, *Les Effets de l’Appréciation de l’Euro sur l’Économie Française*, Division Synthèse Conjoncturelle, INSEE, 47 p.

Combet, E., 2007, “Evaluation des effets distributifs de politiques publiques dans un cadre d'équilibre général calculable - Application au cas de réformes fiscales environnementales : le double-dividende revisité”, mémoire de Master EDDEE, CIRED.

Combet, E., Ghersi, F., Hourcade, J.-C., Thubin, C., 2009, “Economie d’une fiscalité carbone en France”, CIRED report to the CFDT, 141 p. http://www.centre-cired.fr/IMG/pdf/Fiscalite_cired_ires_03nov09.pdf

Ghersi, F., Hourcade, J.-C., 2006, “Macroeconomic consistency issues in E3 modeling: the continued fable of the elephant and the rabbit”, *The Energy Journal*, Special Issue n°2, 27-49.

Ghersi, F., Thubin, C., Combet, E., 2011, “The IMACLIM-S Model. Version 2.3”, CIRED Working Paper, 32 p. http://www.imaclim.centre-cired.fr/IMG/pdf/IMACLIM-S_27jan11Eng.pdf

Ghersi, F., Ricci, O., 2014, “A macro-micro outlook on fuel poverty in 2035 France”, CIRED Working Paper, 31 p.

Samuelson, P., 1947, *The Foundations of Economic Analysis*, Harvard University Press, Cambridge MA, Unite-States.

Annex 1
Notations of the model

Calibration consists in providing a set of values to all variables and then determining the values that should be given to the parameters so that the set of equations defining the model holds. The exercise is therefore to determine what values the parameters must take in order for the values drawn from national accounts to be linked by the set of equations.

However, all parameters do not receive their values from the calibration: the carbon tax, for instance, is a purely exogenous parameter; other parameters have their values set according to some econometric estimation on data beyond the national accounts as described by the TES and the TEE. As a result of these distinctions, the notations below are presented in three categories, (*i*) the variables of the model properly speaking, (*ii*) the parameters of the model that are calibrated on statistical data, and (*iii*) the exogenous parameters. Within each of these categories the notation are listed in alphabetical order (the Greek letters are classified according to their English name rather than according to their equivalent in the Latin alphabet).

Variables

α_{ij}	Technical coefficient, quantity of good *i* entering the production of one good *j*
A_T	Other transfers (equivalent of accounts D7 and D9 of the TEE)
A_{TH}	Other transfers to the households
A_{TS}	Other transfers to firms
A_{TG}	Other transfers to the public administrations
CAF_h	Self-financing capacity of household class *h*
CAF_S	Self-financing capacity of firms
CAF_G	Self-financing capacity of the public administrations
CAF_{RDM}	Self-financing capacity of the rest of the world
C_{ih}	Final consumption of good *i* by household class *h*
D_h	Net debt of class *h* Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*
D_S	Net debt of firms Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE

Comptes de patrimoine

D_G Net public debt
Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*

D_{RDM} Net debt of the rest of the world
Calibrated on the net financial assets (*patrimoine financier net*) of the INSEE *Comptes de patrimoine*

δ_i Projection-induced interest rate differential

EBE_H Gross operating surplus accruing to households

EBE_S Gross operating surplus accruing to firms

EBE_G Gross operating surplus accruing to public administrations

$FBCF_h$ Gross fixed capital formation of household class *h*

$FBCF_S$ Gross fixed capital formation of firms

$FBCF_G$ Gross fixed capital formation of public administrations

G_i Final public consumption of good *i*

i_H Effective interest rate on the net debt of households

i_S Effective interest rate on the net debt of firms

i_G Effective interest rate on the net debt of public administrations

I_i Final consumption of good *i* for the investment

IPC Consumer price index

k_i Capital intensity of good *i*

L Total active population in full-time equivalents

L_h Active population of household class *h* in full-time equivalents

l_i Labour intensity of good *i*

ω_{Lh} Share of labour income accruing to household class *h*

M_i Imports of good *i*

M_S Sum across goods and uses of the specific margins

N Total population

N_h Total population of household class *h*

N_{Ph} Retired population of household class *h*

N_{Lh} Employed population of household class *h* (full time equivalent)

ω_{KH} Share of capital income accruing to households (all classes).

p_{Mi} Import price of good *i*

p_i Average price of the resource in good *i* (domestically produced and imported)

p_{CIij} Price of good *i* for the production of good *j*

p_{Cih} Price of good *i* for household class *h* (*i* extends to aggregates specific to household consumption

p_{Gi} Public price of good *i*

p_{Ii} Investment price of good *i*

p_K Cost of capital input (weighted sum of investment prices)

p_{Li} Cost of labour input in the production of good *i*

p_{Xi} Export price of good *i*

p_{Yi} Production price of good *i*

$RDBAI_h$ Before-tax gross disposable income of household class *h*

RDB_H Gross disposable income of household class *h*

RDB_S Gross disposable income of firms

RDB_G Gross disposable income of public administrations

R_h Consumed income of household class *h*

R_A Social transfers to households not elsewhere included

R_U Sum of unemployment benefits

R_S Sum of retirement pensions

ρ_{Ah} Average *per capita* not-elsewhere-included transfers benefitting to household class *h*

ρ_{Ph} Average *per capita* pensions benefitting to the retired of household class *h*

ρ_{Uh} Average *per capita* unemployment benefits accruing to the unemployed of household class *h*

$\sigma_{\Theta i}$ Elasticity of the decreasing returns coefficient of production *i* to its output

γ_{CIij}

T Total taxes and social contributions

T_{CS} Sum of social contributions of the employer and the employee

T_{TIPP} Fiscal revenues from the 'internal tax on petroleum products' (*Taxe Intérieure sur les Produits Pétroliers*)

T_{AIP} Fiscal revenues of excise taxes other than the TIPP

T_{TVA} VAT revenues

T_{IS} Corporate tax revenues

T_{IRh} Household class *h* income tax payments

T_h Other direct taxes paid by household class *h*

T_{CARB} Carbon tax revenues

Θ_i Decreasing returns coefficient for the production of good *i*

τ_{CS} Social contribution rate applicable to net wages

τ_{MCCOM} Commercial mark-up on the commercial good or on the aggregate encompassing it

$\tau_{MCTRANS}$ Transport mark-up on the transport good or on the aggregate encompassing it

u_h Unemployment rate of household class *h*

w_i Average net wage in the production of good *i*

w Average net wage across productions

X_i Good *i* exports

Y_i Good *i* production

Parameters calibrated on statistical data

δ_L Growth of total active population in full-time equivalents (INSEE demographic projections)

δ_N Growth of total population (INSEE demographic projections)

δ_{NP} Growth of retired population (INSEE demographic projections, alternatively *Conseil d'Orientation sur les Retraites*)

γ_{CIij} CO_2 emissions per unit of good *i* consumed in the production of good *j* (calibrated to match UNFCC sectoral emission data)

γ_{CFi} — CO_2 emissions per unit of good *i* consumed by households (calibrated to match UNFCC sectoral emission data).

λ_{ij}, λ_{Li}, λ_{Ki} — Coefficients of the CES production function governing the variables shares of conditional factor demands. Calibrated on the first order conditions of cost minimisation applied to the present equilibrium (functions of prices p_{CIij0} , p_{Li0} and p_{Ki0} , of quantities α_{ij0} , l_{i0} et k_{i0} , and of basic need shares β_{ij} , β_{Ki} et β_{Li}).

λ_{Ah} — Coefficients of the CES functions aggregating good A (A = CONS, TRANS1, CARB1, EDNS, BAT, TLOIS, COMP, TRANS2, CARB2, ELEC2, RAFF, GAZ+) for the consumption of class *h*. Calibrated on the first order conditions of volume maximisation under budget constraint applied to the present equilibrium (functions of prices p_{Ch0} , of quantities and basic needs C_{Ah0} and β_{Ah0} C_{Ah0}).

$\overline{\omega_{ATh}}$ — Share of the other transfers accruing to households received by household class *h*. Calibrated as the share accruing to household class *h* of revenues other than those of labour, in the *m*-class aggregation of the 10,240 households of the *Budget de Famille* 2006 survey by INSEE.

$\overline{\omega_{ATS}}$ — Share of other transfers accruing to firms. Calibrated on the TEE (aggregate of financial and non-financial firms, and of non-profit organisations).

$\overline{\omega_{ATG}}$ — Share of other transfers accruing to public administrations. Calibrated on the TEE.

$\overline{\omega_{Kh}}$ — Share of the capital income of households accruing to household class *h*. Calibrated as the share accruing to household class *h* of revenues other than those of labour, in the *m*-class aggregation of the 10305 households of the *Budget de Famille* 2001 survey by INSEE.

$\overline{\omega_{KS}}$ — Share of capital income accruing to firms. Calibrated on the TEE (aggregate of financial and non-financial firms, and of non-profit organisations).

$\overline{\omega_{KG}}$ — Share of capital income accruing to public administrations. Calibrated on the TEE

$\overline{\pi_i}$ — Mark-up rate (rate of net operating surplus) in the production of good *i*. Calibrated as the ratio of net operating surplus to distributed output (TES and other INSEE data).

$\overline{t_{AIPi}}$ — Excise taxes other than the TIPP *per* unit of consumption of good *i*. Calibrated as the ratio of the corresponding fiscal revenue of each good *i* (TES data after subtraction of the TIPP) to total domestic consumption in the reference equilibrium $Y_{i0} + M_{i0} – X_{i0}$ (exports are assumed to be exempted).

$\overline{t_{TIPPCFi}}$ — TIPP per TOE of automotive fuel of household consumption. The TIPP is isolated from other excise taxes and split between goods GG15 and GG2B of the TES: refined petroleum products and natural gas. The split between TIPP on intermediate *vs.* final sales is calibrated on data from the *Comité Professionnel Du Pétrole* (CPDP).

$\overline{t_{TIPPCIi}}$ TIPP per TOE of automotive fuel of intermediate consumption. The TIPP is isolated from other excise taxes and split between goods GG15 and GG2B of the TES: refined petroleum products and natural gas. The split between TIPP on intermediate *vs.* final sales is calibrated on data from the *Comité Professionnel Du Pétrole* (CPDP).

$\overline{\tau_{IRh}}$ Effective income tax rate of household class *h*. Calibrated as the ratio of income tax payments to the before-tax gross disposable income. Both aggregates are distributed among household classes based on the shares observed in the *m*-class aggregation of the 10,240 households of the *Budget de Famille* 2006 survey by INSEE.

$\overline{\tau_{IS}}$ Effective corporate tax rate. Calibrated as the ratio of the corporate tax fiscal revenue to the share of the gross operating surplus accruing to firms.

$\overline{\tau_{MSCIij}}$ Specific mark-up rate on intermediate consumptions. Defined during the hybridisation process (*cf.* Section I.2).

$\overline{\tau_{MSChi}}$ Specific mark-up rate on household *h*'s consumption of good *i*. Defined during the hybridisation process (*cf.* Section I.2).

$\overline{\tau_{MSGi}}$ Specific mark-up rate on public energy consumptions (if *i* is not an energy good then the rate is nil). Defined during the hybridisation process (*cf.* Section I.2). Under the convention that public energy consumptions are nil (*cf.* footnote 7) this parameter is useless.

$\overline{\tau_{MSXi}}$ Specific mark-up rate on energy exports (if *i* is not an energy good then the rate is nil). Defined during the hybridisation process (*cf.* section I.2).

$\overline{\tau_{Sh}}$ Savings rate of household class *h*. Calibrated as the ratio of the savings of class *h* to its gross disposable income, from data from all the main data sources (TES, TEE, data from the *Budget de Famille* survey aggregated in *m* classes).

$\overline{\tau_{TVAi}}$ VAT rate applying to the final consumption of good *i*. Calibrated on TES data by treating the VAT as a simple sales tax levied indifferently on *C*, *G* and *I*.[14]

Exogenous parameters

β_{Ah}	Share of household class *h* 2006 consumption of good A that is a basic need of good A in the projected economy (A = TCONT, LOG, ELEC1, TRANS1, CARB1, EDNS, BAT, TLOIS, TRANS2, CARB2, ELEC2, RAFF, GAZ+).
β_{ji}	Technical asymptote of the technical coefficient α_{ji}.
β_{Ki}	Technical asymptote of the capital intensity of good *i*.
β_{Li}	Technical asymptote of the labour intensity of good *i*.
σ_i	Substitution elasticity of the variable shares of production factors.
σ_A	Substitution elasticity of the variable shares of products or aggregates forming aggregate A (A = TCONT, SEDNS, EDNS, CONS, TLOIS).
σ_{Mpi}	Elasticity of the ratio of imports to domestic production of good *i*, to the corresponding terms of trade.
σ_{Xpi}	Elasticity of good *i* exports to the corresponding terms of trade.
t_{CI}	Carbon tax on the carbon emissions of intermediate consumptions.
t_{CF}	Carbon tax on the carbon emissions of household consumptions.
t_{PROJ}	Number of years projected.
u	Unemployment rate

[14] In the TES investment is conventionally valued at prices that include the VAT. Treating the VAT as a sales tax cancels some distributive effects between productions, all the more negligible as the good aggregation is high. In most policy runs it is virtually without discernible effect on macroeconomic results or those concerning the distribution of income between households.

Annex 2
Parameterisation of Ghersi and Ricci (2014)

This second annex details the parameters backing the 4 macroeconomic scenarios of Ghersi and Ricci (2014). For the sake of concision it focuses on those parameters shaping the driving forces identified Section III above, thereby not reporting on the many statistical parameters calibrated on static 2006 TES or TEE data.

Households trade-offs

Before detailing the parameterisation of the quintiles' trade-offs, we report the constrained or specific proportions of *TRANS*, public transports, *CARB* automotive fuels consumptions and *ELEC* electricity consumption (Table 1). The former two are derived from a 2006 Transport Survey by INSEE (*Enquête Transport*); the latter from a 2006 Housing Survey by INSEE (*Enquête Logement*).

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Constrained share of TRANS	39%	21%	34%	23%	35%
Constrained share of CARB	44%	44%	43%	43%	40%
Specific share of ELEC	46%	57%	50%	49%	46%

Table 1 Constrained/specific shares of the consumptions of public transports, automotive fuels and electricity in 2006
*Source: INSEE (*Enquête Logement, Enquête Transport*), author's computations.*

Basic need shares of 2006 consumptions, for lack of bottom-up expertise, are mostly set to 0—we only report below strictly positive values. The assumption of a minimum floor space of 9 square metres *per* consumption unit is used to define, on data from the *Budget de Famille* Household Expenditure INSEE survey (which details living areas), the share of total living areas observed in 2006 that would correspond to this constraint. *RAFF* and *ELEC2* are also marginally adjusted (from zero) in the process of calibrating residential energy trade-offs on the modeling of Giraudet (2011). This is regretfully done without quintile differentiation for want of a distributional dimension to Giraudet's work.

The elasticity of non-specific energy services to housing surface (of *SEDNS* to *LOG*), b_{SEDNS}, is set to 1 for all quintiles for lack of a better hypothesis. Total specific electricity consumption grows exogenously by 29% in all scenarios, following RTE (2011); it is distributed among quintiles on a *per capita* basis, thus envisioning a convergence of usages across quintiles, which amounts to a much larger increase of *per capita* consumptions for the lower quintiles.

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
β_{LOG} (housing surface)	20.83%	18.92%	18.38%	16.89%	13.97%
β_{RAFF} (ref. petroleum products)	1.74%	1.74%	1.74%	1.74%	1.74%
β_{ELEC2} (non-specific electricity)	0.18%	0.18%	0.18%	0.18%	0.18%

Table 2 **Non-zero basic needs expressed as shares of 2006 consumptions**
*Source: INSEE (*Budget de Famille *survey), author's computations.*

At last, we report the elasticities of substitution of (*i*) *CARB1* and *TRANS1* in *TCONT*, (*ii*) *CARB2* and *TRANS2* in *TLOIS*, (*iii*) *TLOIS* and *CONS* in *COMP*, (*iv*) *ELEC2*, *RAFF* and *GAS* in *EDNS*, (*v*) *EDNS* and *BAT* in *SEDNS* (Table 3). The elasticity between leisure transport and other consumption is set at 99%, *i.e.* at close to a Cobb-Douglas level; those between public transport and fuels are set conservatively at 10%, considering the weakness of our model on the particular matter of modal shifts.[15] Finally, the two elasticities of residential energy consumptions are differentiated between quintiles on the simple assumption of a bell-shaped distribution (lower flexibility for the lower quintiles because of budget and credit constraints, and for the higher quintiles because of lower average budget shares): the elasticities of quintiles 1 and 5 are assumed 20% lower, those of quintiles 2 and 4 10% lower than that of quintile 3. This constraint is set on the calibration process performed on the modelling results of Giraudet (2011).

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
σ_{CONS2} (TLOIS *vs.* COMP)	99%	99%	99%	99%	99%
σ_{SEDNS} (EDNS *vs.* BAT)	159%	179%	199%	179%	159%
σ_{EDNS} (ELEC2 *vs.* RAFF *vs.* GAZ)	145%	163%	181%	163%	145%
σ_{TCONT} (TRANS1 *vs.* CARB1)	10%	10%	10%	10%	10%
σ_{TLOIS} (TRANS2 *vs.* CARB2)	10%	10%	10%	10%	10%

Table 3 **Substitution elasticities of the consumptions following CES specifications above basic needs**
Source: calibration on modelling results of Giraudet (2011), author's assumptions.

[15] This is the focus of ongoing developments aiming at representing (*i*) the vanishing comparative advantage of public transports as urban forms sprawl; (*ii*) the public investment requirements attached to any public transport development.

Firms' trade-offs

Firms' trade-offs regard the optimal balance of 11 inputs to production, *i.e.* 9 intermediate consumptions (secondary factors), and the 2 primary factors of Labour and Capital. Considering its focus on household behaviour, and the substantial increase of the number of goods disaggregated from overall activity compared to previous versions (from 4 to 9 aggregate goods), the model currently does not calibrate the behaviours of the production systems on dedicated techno-economic expertise (*cf.* Hourcade and Ghersi, 2006).

Trade-offs between inputs in the 9 productions are thus represented in a standard way, through as many CES-type functions, with *a priori* constant substitution elasticities. However, these CES forms only partially apply to the 2006 input volumes: input-specific technical asymptotes are assumed, to schematise the physical constraints weighing upon the evolution of production processes; substitution elasticities are thus not constant, but rather decrease as input intensities approach their asymptotes. This is arguably a necessary feature when considering trade-offs in technical systems, including energy ones, at the middle- to long-term horizon of 29 years (2006 to 2035). Boonekamp (2009) argues in favour of such a limitation to adaptive capacity in the case of households.

The floors to input intensities are generally set at conservative levels, tending to consider substantial rigidities over the projected horizon—at least compared to standard CGEMs where they are implicitly systematically nil.[16] For intermediate consumptions they are deliberately set at higher levels when the underlying consumptions are simultaneously quite explicit and presumably little flexible. One example is the intensity in EPRIM (*i.e.* crude oil) of the production of CARB (automotive fuels): the floor is set at 100%, which amounts to the Leontief assumption of a fixed intermediate consumption coefficient in a context where EPRIM relative prices strongly increase.

The substitution elasticities between the tradable shares of each input are set at 120% for all productions. For each input this value must be corrected by the share of their 2006 consumption deemed adjustable to measure the effective substitution elasticity (measured over the entire consumption and not only on its flexible share) to all other inputs. For example the elasticity of substitution of labour to other inputs to the composite good production is 25% of 120%, that is 30% only. This value furthermore only prevails at the 2006 equilibrium. The point elasticity of substitution is indeed lower in any equilibrium where the labour intensity is lower than its 2006 value—indeed it tends towards 0 as the labour intensity draws closer to its floor value, 25% below its 2006 level as far as composite production is concerned.

[16] The point-of-view of our comment could be turned around and the standard model underlined as envisaging extremely weak rigidities.

	COMP	TRANS	LOG	BAT	EPRIM	CARB	RAFF	ELEC	GAZ+
COMP	75%	95%	95%	95%	95%	95%	95%	95%	95%
TRANS	75%	95%	95%	95%	95%	95%	95%	95%	95%
LOG	50%	50%	50%	50%	50%	50%	50%	50%	50%
BAT	95%	95%	95%	95%	95%	95%	95%	95%	95%
EPRIM	50%	50%	50%	50%	50%	100%	100%	50%	100%
CARB	50%	50%	50%	50%	50%	50%	50%	50%	50%
RAFF	50%	50%	50%	50%	50%	50%	50%	50%	50%
ELEC	50%	50%	50%	50%	50%	50%	50%	50%	50%
GAZ+	50%	50%	50%	50%	50%	50%	50%	50%	50%
K	75%	80%	80%	80%	80%	80%	80%	80%	80%
L	75%	80%	80%	80%	80%	80%	80%	80%	80%

Factors are in line, productions in column: 75% of the intensity in composite good of the composite good is incompressible; 95% of the intensity in composite good of the public transport services production is incompressible; *etc.* The 9x9 matrix concerning intermediate consumptions, the 1x9 matrices regarding K and L are the β_{ji} , β_{Ki} *and* β_{Li} matrices of equations 41 *et seq.* p. 14.

The definitions of the 9 productions are given p. 9. K and L conventionally designate the capital and labour intensities.

Table 4 Incompressible share of 2006 factor intensities for 9 productions