The IMACLIM-R model

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy that is split into 12 regions and 12 sectors (Sassi et al. 2007). The base year of the model is 2001 and it is solved in a yearly time step. IMACLIM-R is built on the GTAP-6 database that provides, for the year 2001, a balanced Social Accounting Matrix (SAM) of the world economy, detailed in 87 regions and 57 sectors. The original GTAP-6 dataset has been modified (i) to aggregate regions and sectors according to the IMACLIM-R mapping (see Appendix for detail) (ii) to make it fully compatible with the 2001 IEA energy balances.

Like any conventional general equilibrium model, IMACLIM-R provides a consistent macroeconomic framework to assess the energy-economy relationship. It represents the interactions between sectors and countries over time through the clearing of commodities markets. It brings specific insights into economic impacts of changes occurring within the energy sector at a macro-level (e.g. welfare changes, competitiveness losses or gains) or at the micro-level (e.g. energy burden in sectoral production costs, household energy spending).

Specific efforts have been made to build a modelling architecture allowing easy incorporation of technological information coming from bottom-up models and experts' judgement within the simulated economic trajectories. IMACLIM-R is thus based on an explicit description of the economy both in money metric values and in physical quantities linked by a price vector. This dual vision of the economy is a precondition to guarantee that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and consistent sets of relative prices. The existence of explicit physical variables allows a rigorous incorporation of sector-based information about how final demand and technical systems are transformed by economic incentives, especially for very large departures from the reference scenario.

The full potential of the dual representation of the economy in both financial and physical terms that characterises IMACLIM-R could not be exploited without abandoning the conventional KLE or KLEM production functions which, after Berndt and Wood (1975) and Jorgenson (1981), were admitted to mimic the set of available techniques and the technical constraints impinging on an economy. Regardless of questions about their empirical robustness[1], it remains the case that, whatever their mathematical form, they are calibrated on cost-shares data through the Shepard's lemma. The domain within which this systematic use of the envelope theorem provides a robust approximation of real technical sets is limited by (i) the assumption that economic data, at each point in time, result from an optimal response to the current price vector and (ii) the lack of technical realism of constant elasticities over the entire space of relative prices, production levels and time horizons under examination in sustainability issues.

IMACLIM-R is thus based on the recognition that it is almost impossible to find functions with mathematical properties suited to cover large departures from the reference equilibrium and flexible enough to encompass different scenarios of structural change resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade, 1993).

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1 Having assessed one thousand econometric works on the capital-energy substitution, Frondel and Schmidt conclude that "*inferences obtained from previous empirical analyses appear to be largely an artefact of cost shares and have little to do with statistical inference about technology relationship*" (Frondel and Schmidt, 2002, p.72).

The absence of a formal production function is compensated by a recursive structure (Figure 5) that allows a systematic exchange of information between:

- An annual static equilibrium module, in which the production function mimics the Leontief specification, with fixed equipment stocks and fixed intensity of labour, energy and other intermediary inputs, but with a flexible utilisation rate. Solving this equilibrium at *t* provides a snapshot of the economy at this date: a set of information about relative prices, levels of output, physical flows and profitability rates for each sector and allocation of investments among sectors;

- Dynamic modules, including demography, capital dynamics and sector-specific reduced forms of technology-rich models which take into account the economic values of the previous static equilibria, assess the reaction of technical systems and send back this information to the static module in the form of new input-output coefficients to calculate the equilibrium at *t+1*.

Each year, technical choices are flexible but they modify only at the margin the input-output coefficients and labour productivity embodied in existing equipment that result from past technical choices. This general clay putty assumption is critical to represent the inertia in technical systems and the role of volatility in economic signals.

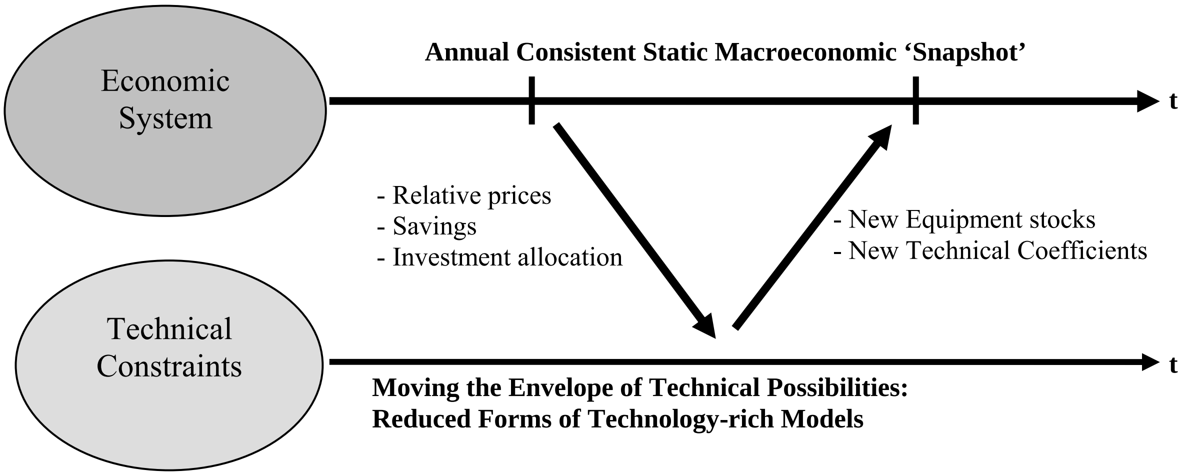

Figure 1 : Iterative Top-down / Bottom-Up dialogue in IMACLIM-R

Technically, the IMACLIM-R model generates an economic trajectory by solving successive yearly static equilibria of the economy interlinked by dynamic modules. Within the static equilibrium, domestic and international markets for all *goods* – not including *factors* such as capital and labour – are cleared by a unique set of relative prices that depend on the behaviours of representative agents on the demand and supply sides. The calculation of this equilibrium determines the following variables: relative prices, wages, labour, quantities of goods and services, value flows.

In each region, the demand for each good comes from household consumption, government consumption, investment and intermediate uses from other production sectors. This demand can be provided either by domestic production or imports and all goods and services are traded on world markets.

For non-energy sectors, domestic and imported products are assumed to be non-perfect substitutes and the model uses the conventional Armington assumption (Armington, 1969) to describe the trade patterns. This specification enables the representation of markets in which domestically produced goods keep a share of domestic markets even though their price is higher than the world price, and in which different exporters co-exist on the world market even with different prices. While ensuring the closure of domestic and international markets in value terms, the Armington specification has the major drawback of not allowing the summing of international trade flows in physical terms. While this modelling choice can be maintained for generic "composite goods", where quantity units are indexes that are not used directly in the analysis of the economy-energy-environment interfaces, it is not compatible with the need to track energy balances expressed in real physical units. Therefore, for energy goods, the model assumes a perfect substitutability that makes it relevant to sum all flows. But, to avoid that the cheapest exporter supplies the entire market, the model instead follows a mere market sharing formula.

Within each static equilibrium, the behaviour of producers is not represented, in the IMACLIM-R model, by a production function allowing for substitution between factors. These substitutions are treated separately in sector-specific dynamic modules. Producers are therefore assumed to operate under short-run constraints of (i) a fixed maximal production capacity $Cap_{k,i}$, defined as the maximum level of physical output achievable with the equipment built and accumulated previously, and (ii) fixed input-output coefficients representing that, with the current set of embodied techniques, producing one unit of a good i in region k requires fixed physical amounts $IC_{j,i,k}$ of intermediate goods j and $l_{k,i}$ of labour. In this context, the only margin of freedom of producers is to adjust the utilisation rate $Q_{k,i}/Cap_{k,i}$ according to the relative market prices of inputs and output. This represents a slightly different paradigm from usual production specifications, since the 'capital' factor is not always fully operated.

The partial use of capacities comes from this short-run rigidity of available techniques on the supply side, the utilisation rate being determined by the equilibrium between supply and demand. Supply curves are shaped by the existence of static decreasing returns: production costs increase when the capacity utilisation rate of equipments approaches one. In this version of the model, the decreasing return parameter (noted $\Omega_{k,i}$) weighs on sectoral wages and all sectors apply a constant mark-up rate $\pi_{k,i}$ to their inputs' costs. The producer price $p_{k,i}$ is then given by the sum of unitary intermediate input purchases $pIC_{j,i,k} . IC_{j,i,k}$, unit real labour cost $\Omega_{k,i} w_{k,i}\, l_{k,i}$ and labour taxes $tax_{k,i}^{w}$, and profit $p_{k,i}\,\pi_{k,i}$, as shown by the following equation:

$$\mathrm{p_{k,i}} = \sum_{j} \mathrm{pIC_{j,i,k}} \cdot IC_{j,i,k} + \left(\Omega_{\mathrm{k,i}} \cdot \mathrm{w_{k,i}}\right) \cdot l_{k,i} \cdot (1 + tax_{k,i}^{w}) + \pi_{k,i} \cdot p_{k,i} \quad (1)$$

where i, j, k stand for sectors, products and regions. This equation represents an inverse supply curve, since it shows how the representative producer decides its level of output $Q_{k,i}$ (which is included in the $\Omega_{k,i}$ factor*)* as a function of all prices and real wages.

Consumers' final demand results from solving the utility maximisation programme of a representative consumer. The distinctive features of this programme consist in the arguments of the utility function and the existence of two budget constraints.

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

$$U = \prod_{\substack{goods\ i \\ (agriculture, \\ industry, \\ services)}} \left(C_i - bn_i\right)^{\xi_i} \cdot \left(S_{\text{housing}} - bn_{\text{housing}}\right)^{\xi_{\text{housing}}} \cdot \left(S_{\text{mobility}} - bn_{mobility}\right)^{\xi_{\text{mobility}}} \qquad (2)$$

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

$$S_{mobility} = CES\left(pkm_{air}, pkm_{public}, pkm_{cars}, pkm_{non\ motorized}\right) \qquad (3)$$

This utility function allows an explicit representation of the end-use potential to decouple energy consumption and growth. It is confronted by two budget constraints:

- The income budget (eq. (4)), i.e. the sum of (i) wages received from all sectors *i* in region *k* (non mobile labour supply), (ii) dividends (a fixed share of profits within a region) and (iii) lump-sum public transfers must equal all expenditures, including induced energy consumption, plus savings (which equal a fixed share of income).
- A 'travel-time budget' justified by empirical findings (Zahavi and Talvitie, 1980) showing the average daily travel time of households in a large panel of cities remains constant over decades.

$$\begin{aligned} Income = S + \sum_{\substack{\text{non-energy} \\ \text{non-transport} \\ \text{goods i}}} \text{p}_\text{i} \cdot \text{C}_\text{i} + \left(\sum_{\text{energies Ei}} p_{Ei} \cdot \alpha_{Ei}^{\text{housing}} \cdot stock^{m^2} \right) \\ + \left(p_{public} \cdot pkm_{public} + p_{air} \cdot pkm_{air} + \sum_{\text{Fuels Fi}} \left(pkm_{cars} \cdot \alpha_{Fi}^{cars} \right) \right) \end{aligned} \qquad (4)$$

where p_i are prices, $stock^{m^2}$ is the total surface of housing and $\alpha^{housing}$ the consumption of each energy product per square meter of housing; α^{cars} are coefficients describing the mean amount of each energy needed to travel one passenger-kilometer with the current stock of private cars. The technical coefficients α^{cars} and $\alpha^{housing}$ linking the households' consumption of energy services to final energy requirements are fixed within each static equilibrium. Their evolution across time is determined by specific dynamics submodules.