A Hybrid Modelling Framework to Incorporate Expert Judgment in Integrated Economic and Energy Models – The IEA WEM-ECO model

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Abstract

Decision makers' growing call for advice on strategies and actions to mitigate climate change and energy security threats creates a twin new challenge for economy-energy-environment modellers. First, the focus on *short-term* mitigation strategies requires the integration of expert judgment on short term trends within longer-term scenarios; second, the modelling framework should be constructed so as to facilitate *interaction* with both decision makers and a large variety of sectoral and technology experts. WEM-ECO is a hybrid model coupling the bottom-up technology-rich IEA WEM model with the top-down general equilibrium model IMACLIM-R. The iterative coupling procedure can be implemented at different levels depending on the time horizon considered and the uncertainty about technological and economic parameters. The WEM-ECO modular framework serves as a bridge and analytical framework for discussion between different communities of experts, while ensuring the internal consistency of the IEA energy-economy scenarios. The paper describes how the model architecture was specifically designed to facilitate the incorporation of expert judgment and facilitate convergence towards a common set of internally consistent scenarios. The lessons drawn from the interaction process between the various experts and the central role played by the model as an integrator of different visions within a consistent view of the future are discussed.

1 Introduction

The twin challenges of energy security and climate change have driven an intense modelling activity of long term energy-economy-environment (E3) scenarios over the past decade. As a global policy consensus on the reality of climate change and on the urgency to act is emerging, policy makers are increasingly looking for advice on short- to medium-term policies consistent with the longer-term objective of climate change and energy security threats mitigation. In parallel, knowledge about the various technological, economic and social dimensions of climate change is building up, such that the integration of these different dimensions in a consistent modelling framework is more challenging than ever. This joint dynamic is defining a new challenge for the modelling community in the years to come, calling for integrated cross-disciplinary modelling frameworks with a focus on high resolution short- to medium-term realistic trajectories and actions within longer-term consistent scenarios.

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[1] See www.worldenergy outlook.org for more information on the *World Energy Outlook* publications

Models used in the economy-energy-environment research community have traditionally been categorised as either "top-down" (TD) models or "bottom-up" (BU) models. The so-called "bottom-up" models describe in detail current and future energy technologies on the demand and supply side, but lack a realistic portrayal of microeconomic decision-making by businesses and consumers when selecting technologies, and fail to represent potential macroeconomic feedbacks. They also lack an integrated macroeconomic framework to evaluate different energy pathways and policies in terms of changes in welfare, productivity and trade. In contrast, the so-called "top-down" models address these deficiencies by representing macroeconomic feedbacks in a general equilibrium framework but their aggregate representation of the energy sector lacks a realistic description of the corresponding technologies and regulations that drive its evolution. Hourcade et al. (2006) provide a synthesis of the BU/TD division and a graphical representation of the three dimensions differentiating BU and TD models (Figure 1).

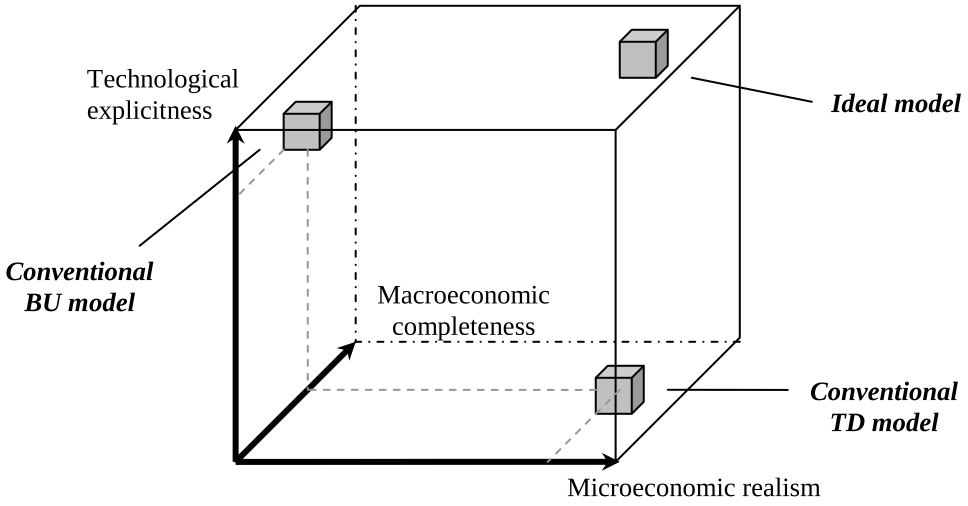

Figure 1 : Representation of BU and TD models' strengths and weaknesses. Source: Hourcade et al. (2006)

This traditional dichotomy has been gradually phased out over the past decade as "hybrid" models combining to various degrees technological explicitness, microeconomic realism and macroeconomic feedback have concentrated much research effort and tended to benefit from the advantages of bottom-up and top-down modelling knowledge (Boringher, 1998; Hourcade et al., 2006). The hybridisation process can take different forms. Some original bottom-up or top-down models can evolve toward a hybridised architecture. This often means that BU models include macro-economic feedbacks (Manne and Wene, 1992) or micro-economic realism (Rivers and Jaccard, 2005) for technology choices in their architecture or TD models incorporate explicit technology description in their general equilibrium framework (McFarland et al., 2004). Even if the MARKAL-MACRO model developed by Manne and Wene (1992) resulted in the coupling of a large BU model with a macro module, the previous examples mainly refer to modifications of existing architecture toward hybridisation.

Another strategy has been explored to build hybrid modelling frameworks. This strategy rests on the coupling of two existing BU and TD models. Despite some computational obstacles and some problems emerging from the ability of existing models to take into account external information, these attempts showed promising results and open the path to a broader interaction between BU and

TD analysis. For example, Drouet et al. (2004) produced a coupled model between a computable general equilibrium model of the Swiss economy and a MARKAL model of the Swiss housing sector. At a wider scale, Schafer and Jacoby (2005) informed the transportation sector of the EPPA world general equilibrium model through a coupling with a MARKAL model and a modal split model.

Over the last years, 15 years, the International Energy Agency has produced an important modelling effort to build the World Energy Model, a technology-rich partial equilibrium model of the energy sector. The WEM is annually used to simulate global energy scenarios until 2030. These scenarios are the base material of the World Energy Outlook publication. Considering new political needs and growing knowledge coming from the hybrid modelling community, the IEA jointly developed with CIRED[2] the WEM-ECO model that has been specially designed (i) to take into account macroeconomic feedbacks in the WEM energy scenario and (ii) to answer the need for more interaction with policy and decision makers, and the need to take expert judgment into account to produce realistic and high resolution short- to medium-run pathways within longer-term scenarios. These specifications require a modelling framework that insures a strong macroeconomic consistency of scenarios and facilitates the debate on key drivers and parameters. There is also a willingness to break the so-called “black box” syndrome that undermines interaction with the non-scientific community and does not provide an appropriate framework to incorporate information and feedback from sectoral and technological experts.

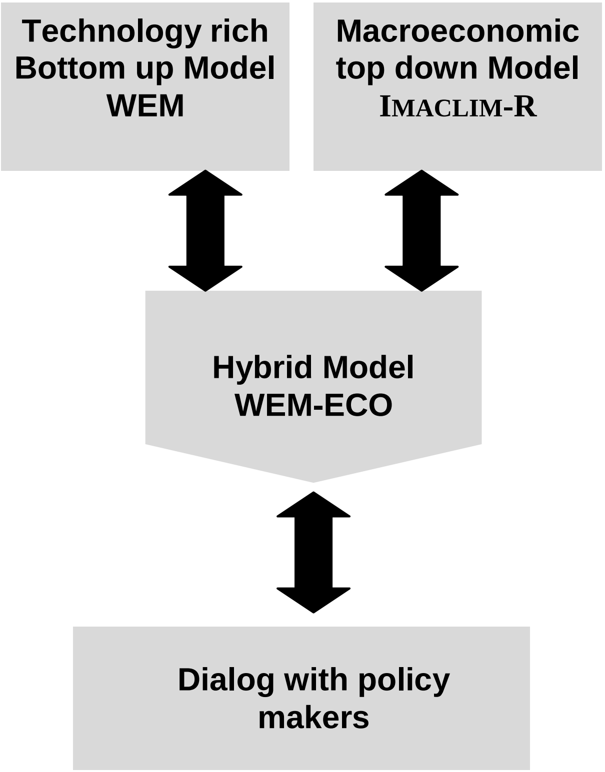

Figure 2 : The WEM-ECO model as an integrator of different expertise

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[2] Centre International de Recherche sur l’Environnement et le Développement.

Beyond the traditional dichotomy between bottom-up and top-down models, there is therefore a need for a representation of reality that rests on the use of support variables on which the different communities of engineers, economists and decision makers can interact. These goals lead to a modelling effort underpinned by twin objectives: (i) to construct an integrated hybrid model whose structure would facilitate the incorporation of expert judgment through interaction with technical experts from the IEA and the energy community; and (ii) to offer a modular and flexible architecture which would make it possible to use either an aggregated or a fully-integrated version of the model, depending on the type of policy question that would need to be addressed by the modelling exercise and the depth of analysis that would be required. This modelling effort produced the WEM-ECO model that results from the coupling of the WEM model with the IMACLIM-R CIRED's recursive general equilibrium model.

As the integration of a large bottom-up model with a general equilibrium model is a technical challenge, this paper details the coupling technique but also aims to detail how such a modelling architecture can be used in the particular context of the IEA to capture the knowledge embodied in the organisation's experts around a common unified tool for dialogue. We aim to stress how such hybrid architecture can facilitate convergence towards a common set of consistent scenarios by channelling the debate around a set of concrete variables and their interactions. In the specific context of the IEA, the paper describes the development of the model as a learning process through which various communities of experts interact and learn from each other. The paper shows that beyond the development of a set of integrated and consistent scenarios, the major achievement of this process is that the model specific architecture makes it possible to capture and formalise analytically the expert knowledge embodied in the IEA organisation and network.

The next section describes successively the architecture of the bottom-up WEM model and the top-down IMACLIM-R model, emphasising the rationale behind their architecture. The third section describes the experience with the coupling procedure between the two models and details the different levels at which the hybridisation can take place. The final section takes a more social science perspective and analyses the benefits of the WEM-ECO modelling framework to incorporate the expert judgment embodied in an organisation like the IEA, and provides some concrete examples of the learning process that accompanied the development of the model

2 The sectoral (WEM) and the general equilibrium (IMACLIM-R) models

2.1 The IEA World Energy Model (WEM)

The World Energy Model (WEM) has been developed internally to the IEA since 1993 and is now in its 10th version. Most of the data are obtained from the IEA's own databases of energy and economic statistics, and are complemented from a wide range of external sources.

World Energy Model Structure

WEM is an energy sector partial equilibrium model which provides short- to medium-run energy demand and supply projections. It is made of 21 regional or country blocks (c.f. Appendix 1). Contrary to optimisation models (like MARKAL type models), the WEM model is a simulation model with a yearly step based on a modular structure. This architecture choice is grounded in the short- to medium-term time horizon (2030), and reflects the willingness to have a modelling tool facilitating the interaction with the many experts of the IEA through multiple run iterations, and taking advantage of the rich IEA databases. The WEM is made up of six main modules: *final energy demand, power generation, refinery and other transformation, fossil fuel supply,* CO_2 *emissions, and investment*. Figure 3 provides a simplified overview of the model's structure.

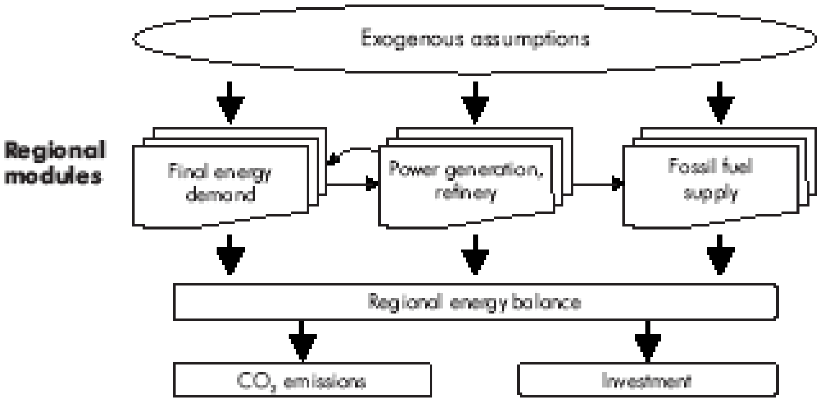

Figure 3 : World Energy Model Overview

The main *exogenous assumptions* concern economic growth, demographics, international fossil fuel prices and technological developments. Electricity consumption and electricity prices dynamically link the final energy demand and power generation modules. The refinery model projects throughput and capacity requirements based on global oil demand. Primary demand for fossil fuels serves as input for the supply modules. Complete energy balances are compiled at a regional level and the CO_2 emissions and energy-supply investment of each region are then calculated using derived carbon factors. ***Other possibility:*** Complete energy balances are compiled at a regional level and the CO_2 emissions are then calculated using carbon factors.

Economic growth assumptions for the short- to medium-term are based on those prepared by the Organisation for Economic Co-operation and Development, the International Monetary Fund and the World Bank. Over the long-term, growth in each region is assumed to converge to an annual long-term rate, which depends on demographics, macroeconomic conditions and pace of technological change. Rates of population growth for each region are based on projections from the United Nations (2004). And as a prominent scenario driver, average retail prices of each fuel used in final uses, power generation and other transformation sectors are derived from assumptions about the international prices of fossil fuels.

Final Energy Demand

Total final energy demand is the sum of energy consumption in each final demand sector. In each sub-sector or end-use, at least six types of energy are shown: coal, oil, gas, electricity, heat and renewables. However, this level of aggregation conceals more detail. For example, the different oil products are modelled separately as an input to the refinery model. The OECD regions and the major non-OECD regions are modelled in greater sectoral and end-use detail than other non-OECD regions for which data are less available. Within each sub-sector or end-use, energy demand is estimated as the product of an energy intensity variable and an activity variable.

- *Industry Sector*

The industrial sector is split into five sub-sectors: *iron and steel, chemicals and petrochemicals, non-metallic minerals,, paper and pulp* and *other industry*. The energy intensity of each sub-sector output and end-use fuel shares are projected on an econometric basis with a specific incorporation of experts' views. The output level of each sub-sector is modelled separately and is combined with projections of its energy intensity to derive the consumption of total energy by sub-sector. This allows more detailed analysis of the drivers of demand and of the impact of structural change on energy consumption trends. The increased disaggregation also facilitates the modelling of alternative scenarios, where output levels, energy intensities and end-use shares are changed to analyse in detail the impact of alternative policies or different choices of technology.

- *Residential and Services Sectors*

The residential sector's energy consumption in OECD regions is split into five end uses: space heating, water heating, cooking, lighting and appliances. The energy consumption related to each end use is computed as the product of an intensity and an activity variable such as the housing surface area or the stock of appliances. For each end use, the intensity variable and fuel shares are projected on an econometric basis and are linked with average end-use energy prices. In developing countries, the residential sector also includes projections of traditional biomass consumption, which are linked to GDP per capita and the urbanisation rate. In the services sector, energy consumption is projected on an econometric basis as a function of the value added of the sector.

- *Transport Sector*

The WEM fully incorporates a detailed bottom-up approach for the transport sector in all regions. Transport modes are split between road (which includes passenger car, bus, truck and 2- and 3-wheelers), aviation, rail (freight and passenger), sea and pipeline transport. The road transport module also projects a gasoline/diesel fuel split. Activity levels are either accounted in passenger-kilometres or tonne-kilometres and their evolution are related to transportation prices, population and GDP changes through econometrically estimated functions for all modes, except for passenger buses and trains and inland navigation that do not include a price reaction. For light duty vehicles, buses and trucks, the related technical change includes an analysis of the contribution of different vehicle technologies to fuel economy improvements, using projections on the evolution of energy efficiency. The module incorporates an evaluation of the potential available from several technology options, as well as the likelihood of their market penetration.

Due to their key roles in transportation dynamics, the stock of private vehicles is split into vintages and its evolution is related to GDP growth through the use of an S-shaped Gompertz function (Dargay *et al.*, 2006) that allows the mimicking of regional differences in car ownership: namely the saturation level (assumed to be the maximum per capita vehicle ownership of a country/region) and the speed at which the saturation level is reached with the increase in per capita income. The estimation of these two parameters is based on several country/region-specific factors such as population density, urbanisation and infrastructure development.

Transformation sectors

The transformation sectors comprise the power generation module and the refinery module. The power generation module computes the amount of electricity generated by each type of plant to meet electricity demand, the amount of new generating capacity needed, the type of new plants to be built, the fuel consumption of the power generation sector, and electricity prices. The structure of the power generation module is described in Figure 4. For each region, electricity generation is calculated by adding the electricity demand projection to electricity used by power plants themselves and network losses. Base year existing capacities are based on a database of all world power plants. For each region, a load curve is assumed. New generating capacity is computed as the difference between total capacity requirements and plant retirements. Plant lives vary by technology and by region (from 45 years up to 60 years). When new fossil fuel plant is needed, the model chooses between different fossil fuel options on the basis of total electricity generating costs, which combine capital, operating, and fuel costs over the whole operating life of a plant, using lifelong generating costs based on the levellised cost modelling approach.

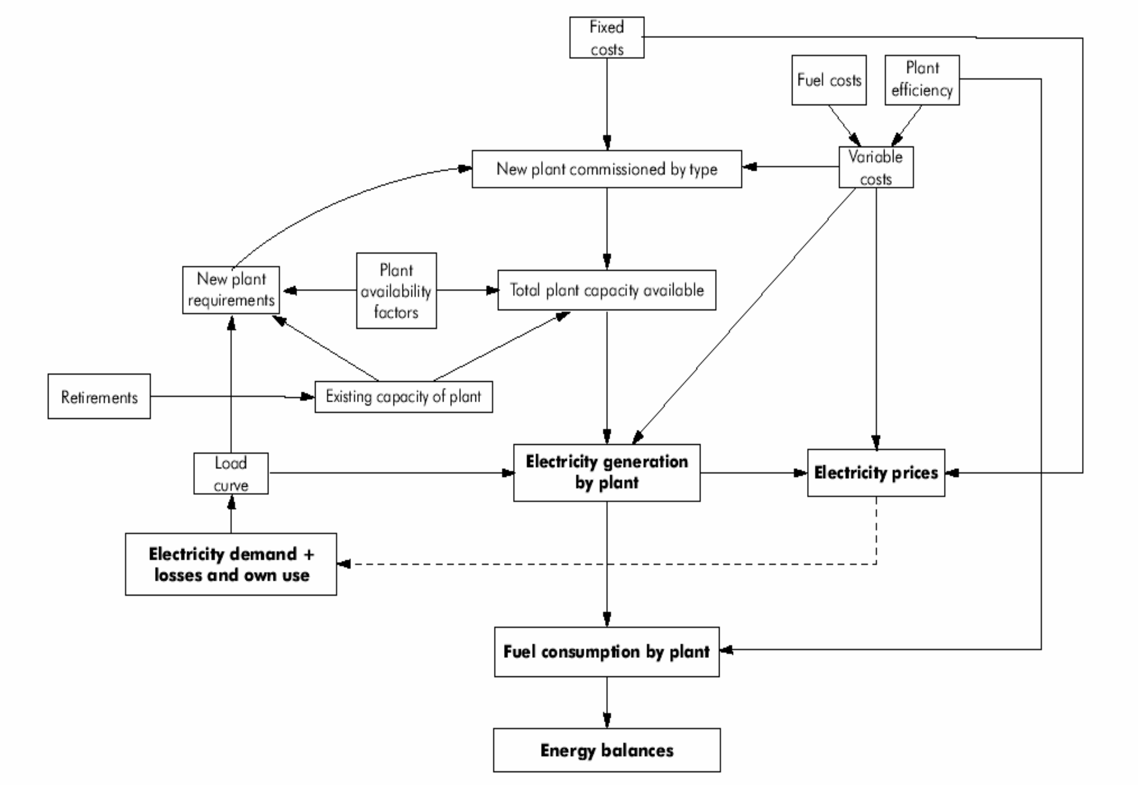

Figure 4: Structure of the WEM Power Generation Module

The projections for renewable electricity generation, combined heat and power (CHP), distributed generation (DG) and nuclear power are derived in separate sub modules, which are based on an assessment of government plans and the relative competitiveness of these technologies with fossil fuel generation technologies, taking into account global and regional learning effects. The combined heat and power option is considered for fossil fuel and biomass plants. The CHP sub-module uses the potential for heat production in industry and buildings together with heat demand projections, which are estimated econometrically in the demand modules. The distributed generation sub-module is based on assumptions about market penetration of DG technologies.

The development of renewables is based on an assessment of the potential and costs for each source (biomass, hydro, photovoltaics, solar thermal electricity, geothermal electricity, on- and off-shore wind, tidal and wave) in each of the twenty one world regions. By defining financial incentives for the use of renewables and non-financial barriers in each market, as well as technical and societal constraints, the model calculates deployment as well as the resulting investment needs on a yearly basis for each renewable source in each region (Resch *et al.*, 2004). The model uses a database of dynamic cost-resource curves to capture the learning potential of such technologies.[3]

Fossil Fuel Supply

The oil, gas and coal supply modules are based on an assessment of resource curves. The oil and gas modules can model strategic behaviour from dominant producers.

Oil production is split into three categories, Middle East and North African countries (MENA), non-MENA, and non-conventional oil production.[4] In the Reference Scenario, OPEC producers are assumed to be the residual suppliers such that MENA conventional oil production fills the gap between total world oil demand that is computed as the sum of regional oil demand, world bunkers and stock changes; and non-MENA added to non-conventional oil production. A field-by-field analysis study is the main source of information for the main parameters (*WEO-2005*). The database comprises 200 fields in the MENA region which are analysed according to a two-step methodology: *i)* a supply curve analysis, then *ii)* judgment and modifications based on existing or planned projects for a specific field. This analysis was used for both oil and gas fields, and was expanded in *WEO-2006* to major non-OECD oil and gas producing countries.

The derivation of non-MENA production of conventional oil (crude and natural gas liquids) uses a long-term approach. This approach involves the determination of production according to the level of ultimately recoverable resources and a depletion rate estimated by using historical data and industry sources. Ultimately recoverable resources depend on a recovery factor. This recovery factor reflects reserves growth, which results from, among other things, improvements in drilling, exploration and production technologies. The trend in the recovery rate is, in turn, a function of the oil price and of a technological improvement factor. Non-conventional oil supply is determined mainly by the oil price. Higher oil prices bring forth greater non-conventional oil supply over time.

Gas fields in MENA countries and in key non-OECD countries are analysed based on the field by field analysis described above for oil. Gas output projections are based on the level of ultimately recoverable resources and a depletion rate. There are some important differences with the oil module. In particular, three regional gas markets are considered — America, Europe and Asia — whereas oil is modelled as a single international market. Two country types are modelled: net importers and net exporters. Once gas production from each net-importing region is estimated, taking into account ultimately recoverable resources and depletion rates, the remaining regional demand is derived and then allocated to the net-exporting regions, again according to recoverable resources and depletion rates. Production in the net-exporting regions is subsequently calculated from their own demand projections and export needs. Trade is split between LNG and pipelines according to: (i) the terms of

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[3] The concept of dynamic cost-resource curves in the field of energy policy modelling was originally devised for the research project Green-X, a joint European research project funded by the European Union's fifth Research and Technological Development Framework Programme – for details see www.green-x.at.

[4] MENA and non-MENA production includes crude oil, NGLs and condensates.

existing long-term contracts and the pattern of LNG and pipeline projects under construction or being built; (ii) the less costly option; and (iii) a minimisation process of transportation distances.

The coal module is a combination of a resources approach and an assessment of the development of domestic and international markets, based on the international coal price. Production, imports and exports are based on coal demand projections and historical data, on a country basis. Three markets are considered: coking coal, steam coal and brown coal. World coal trade, principally constituted of coking coal and steam coal, is separately modelled for the two markets and balanced on an annual basis.

2.2 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.

2.2.1 Model structure

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[5], it remains the case that, whatever their

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[5] 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*

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). 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 for calculating 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 representing the inertia in technical systems and the role of volatility in economic signals.

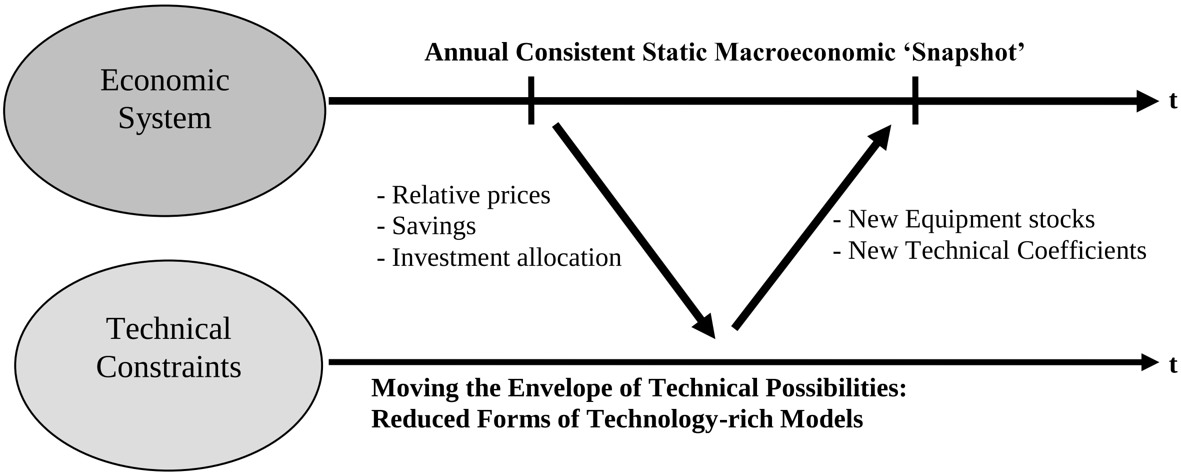

Figure 5 : Iterative Top-down / Bottom-Up dialogue in IMACLIM-R

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and have little to do with statistical inference about technology relationship" (Frondel and Schmidt, 2002, p.72).

Technically, the IMACLIM-R model generates an economic trajectory through the solving of 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 $\Omega_{k,i}$) weights 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:

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

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 passenger-kilometres *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.

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

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.

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

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-kilometre 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.

3 Improving the consistency of energy scenarios using the WEM-ECO hybrid toolbox

The willingness to build a modelling framework resulting from the coupling of two pre-existing models rests on the recognition that both approaches are complementary, such that the hybrid model resulting from the coupled architecture should gather the advantages from the two pre-existing models.

3.1 The different levels of interaction of the two models

As a partial equilibrium model of the world energy sector, WEM guaranties a very detailed representation of specific mechanisms that drive energy trends and especially those resulting from the associated technological changes. Nevertheless the overall dynamic of the model rests on exogenous assumptions on population, on the growth and structure of GDP, that determine the evolution of various *activity variables*. These activity variables are used to compute the demand for specific energy services, the production of which requires the consumption of final energy depending on the technical characteristics of related energy equipment. Although a price elasticity is often used to represent the feedback of price variation on the formation of energy demand, the general consistency between (i) macroeconomic assumptions (growth and structure of the GDP) (ii) changes in energy prices and (iii) evolution of technological characteristics of the energy sector is not guaranteed by such a framework. On the other hand, IMACLIM-R, as a general equilibrium model, generates economic trajectories which present a strong internal consistency between economic and energy trends. Nevertheless the detail of the energy sector remains poor, especially for technological parameters.

The WEM-ECO model, resulting from the coupling of WEM and IMACLIM-R, is built on an iterative exchange of information between the two models (Figure 6). IMACLIM-R feeds WEM with detailed sectoral activity variables and energy prices. In return, WEM computes technical reactions from the energy sector to this changing context. A scenario is considered harmonised when this iterative procedure converges to a stationary solution in which energy related technical reactions from WEM no longer modify the activity variable and prices trends generated by IMACLIM-R and used as exogenous drivers in WEM.

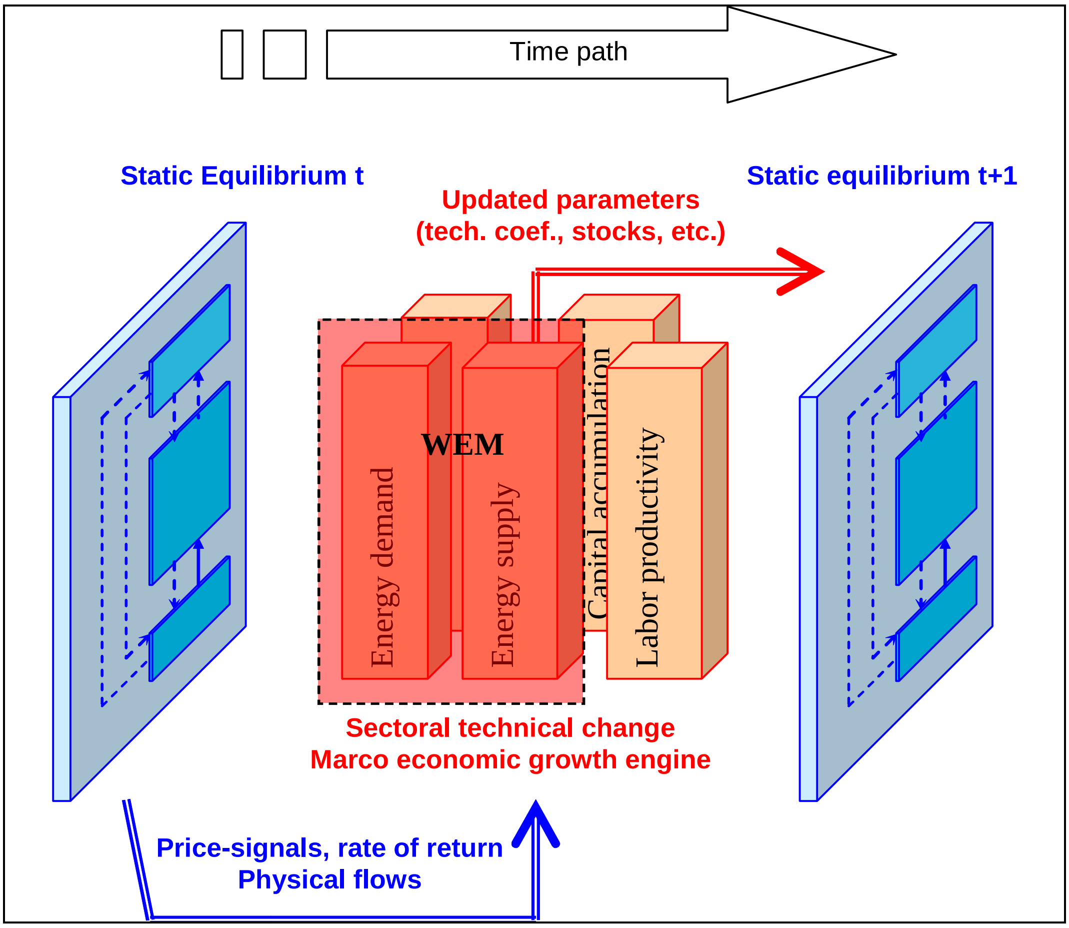

Figure 6: The recursive dynamic framework of WEM-ECO

From an analytical point of view, running WEM requires a set of assumptions on technological parameters and exogenous economic drivers which can be divided into three subsets:

- A set of assumptions on *activity variables*, noted {AV} ;
- A set of assumptions on *energy prices*, noted {PE} ;
- A set of *parameters* driving the various sectoral modules, noted {*ps*}.

In turn, the set of assumptions that are required to run the IMACLIM-R can be divided into three subsets:

- A set of assumptions regarding *technical coefficients'* evolution for the energy sector, noted {TCE};
- A set of assumptions on the exogenous evolution of *non energy drivers* (e.g. population, labour productivity…), noted {MC} ;
- A set of *parameters driving non energy sectoral modules*, noted {*pmnes*}.

The coupling procedure consists of an iterative modification of the drivers of each model using the information coming from the other. For WEM, the assumptions gathered in the subsets {AV} and {PE} can be modified by the coupling process, while those from {*ps*} remain constant. In the IMACLIM-R model, {TCE} can be modified by the coupling process, while {MC} and {*pmnes*} remain constant.

The ultimate goal of the coupling procedure is to produce scenarios in which the common outputs of the two models, i.e. the energy flows and uses, are identical. These scenarios can then be considered harmonised and account for the specific feedbacks and constraints existing in both of the models. In theory the “natural” way to exchange information between a BU and TD model would see the TD model providing activity variables and energy prices to the BU model, which would in return inform the TD model on the technical reaction of the energy sector. In practice, however, the use of such theoretical procedure is limited by the fact that in the WEM model – like in many other BU models – all energy uses are not necessarily related to explicit technical coefficients. Indeed for many specific requirements, the amount of energy consumption is computed through the use of an econometric equation using elasticities to prices and to an aggregated activity variable such as the regional GDP. This process does not disentangle the channel that links a sectoral activity variable to requirements of energy services, and finally to energy consumption through an aggregated value of energy equipments’ efficiency. In such cases, the coupling procedure must be designed in practice so as to overcome this barrier, *e.g.* by coupling the two models at a more aggregated level.

Two different coupling procedures were therefore developed in preparation for the *World Energy Outlook 2007*, depending on the degree of precision of technical coefficients that could be extracted from WEM. The first procedure is intended to draw some information at an aggregated level from the coupling exercise. It was designed to be used when some technical coefficient could not be extracted from WEM. The exchange of information between WEM and IMACLIM-R takes place at the level of energy consumption and does not concern technical coefficients. The second procedure is more straightforward and rests on a more classical dialogue between the two models, IMACLIM-R producing activity variables and energy prices, and WEM generating the technical reaction of the energy sector. The next section presents in greater details the first procedure and its benefits in the context of economic-energy scenario construction at the IEA. The second procedure is explored in the last section of the paper.

3.2 A systematic coupling technique minimising computational resources requirements

In the specific IEA context, the benefits resulting from a greater degree of integration of the two models have to be balanced against the time devoted to this hybridisation procedure. A full integration of the two models is more demanding in computational and human resources and would have significantly slowed down the iterative process of simulations in preparation to the *World Energy Outlook 2007*. Moreover, in the specific IEA context, where ‘expert judgement’ is incorporated into the modelling through an adjustment process requiring many model runs, the first procedure of integration has the advantage not to increase significantly the computational time. In this case, the benefits in terms of precision of the results resulting from a deeper integration of the two models were largely outweighed by the greater precision that could be achieved through doing more runs of a faster model integrated at a more aggregated level.

The coupling procedure as it is used in the current version of WEM-ECO starts with the choice of values for the subset of parameters that will not be modified during the coupling process. As the default parameterisation of the IMACLIM-R model is not fine-tuned for the short- and medium-run, the economic growth assumptions from the WEM *Reference Scenario*[6] are used to calibrate the growth drivers the IMACLIM-R model (i.e. changes in labour productivity and active population). This calibration determines a *potential* growth, the realisation of which will be endogenous and

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[6] The *Reference Scenario* assumes that there are no new energy-policy interventions by governments as off mid-2007. This scenario is intended to provide a baseline vision of how global energy markets are likely to evolve if governments do nothing more to affect underlying trends in energy demand and supply, thereby allowing alternative assumptions about future government policies to be tested (IEA, 2007).

considered as a result of the coupling process. The parameterisation of the IMACLIM-R model is also modified to reflect expert views on macroeconomic patterns that underpin the basic WEM parameters and the *Reference Scenario* storyline. These assumptions mainly concern the future pattern of globalisation, market opening and capital flows associated with the evolution of the current major macroeconomic disequilibria. For *WEO-2007*, the parameterisation of international trade elasticities was set in order to reflect a pursuit and increase of the globalisation process. With regard to capital flows that compensate trade imbalance in the base year of the model, it is assumed that imbalances tend to zero over the long run, reflecting the belief that these imbalances cannot last indefinitely and some mechanisms will appear to counterbalance current driving forces.

The coupling procedure consists of an exchange of information between the two models. As there is no hard link between the two models, the exchange of information actually consists in an exchange of scenarios. The challenge when using such aggregated coupling technique is to design a framework in which the exchange of information from WEM to IMACLIM-R does not reduce to an exchange of parameters. Indeed, IMACLIM-R receives from WEM detailed energy balances that are used to iteratively calibrate the corresponding technical coefficients in IMACLIM-R. The detail of the procedure can be structured as follows:

1. Run WEM with default values for $\{AV_0\}$, $\{PE_0\}$ and $\{ps_0\}$ and get results for energy flows for the whole energy sector (final demand, transformation and supply).

2. Proceed to iterative runs of the IMACLIM-R model with the calibrated values for $\{pmnes_0\}$ and $\{MC_0\}$ and moving the values of $\{TCE\}$ to produce a scenario in which the energy flows (accounted in real physical quantities) match the corresponding WEM values. This process eventually produces a new set of sectoral activity variables $\{AV_1\}$ and energy prices $\{PE_1\}$

3. Run WEM with new values for sectoral activity variables and energy prices $\{AV_1\}$, $\{PE_1\}$. Get results for energy flows for the whole energy sector.

4. Repeat stages 3. and 4. and stop using the criterion defined by Eq. 1 and 2
   $abs(max(\{AV_{k+1}\}-\{AV_k\}))<epsilon$ {1}
   $abs(max(\{PE_{k+1}\}-\{PE_k\}))<epsilon$ {2}

When the process reaches its stationary solution, there is a complete similarity between the energy flows represented in WEM and the IMACLIM-R model. A run of WEM using the activity variables and energy prices produced by IMACLIM-R gives energy balances that are similar to those produced by the IMACLIM-R model.

3.3 Methodological issues and advantages of the WEM-ECO architecture

When trying to organise a link between a bottom-up and a top-down model, the obstacles encountered are numerous and have been detailed in the existing literature (Hourcade *et al.*, 2006). From the perspective of the WEM-ECO model, the first issue concerns the difference in regional and sectoral aggregation between the two pre-existing models. These differences can be overcome through the use of aggregation and disaggregation procedures to make the exchange of information possible between the two models.

The second and most important issue lies in the intrinsic capability of one model to easily embark information coming from the other one and more fundamentally to share overlapping modelling areas where dialogue between the two models is possible. This issue is particularly problematic when coupling a CGE model with a partial equilibrium model of the energy sector. Indeed, most general equilibrium models use pre-determined production functions to represent the sectors' set of available producing techniques. The information provided by the BU model is used to produce a better calibration of these functions. As an example, Schaffer and Jacoby (2005) used a BU model of the transportation sector to improve the calibration of the elasticity of substitution and autonomous energy efficiency gains that parameterise transportation energy consumption within the EPPA model. This work can hardly be reproduced at a more generalised level because of the constraints resulting from the mathematically predetermined form of the production functions that are used in such a model.

The implementation of an aggregated or mixed coupling technique such as the one previously described relies on a complete user's control on energy technical coefficients within the CGE. The specific structure of the IMACLIM-R framework allows this procedure to be easily implemented. First, this structure gathers a general equilibrium framework and a detailed description of the energy sector for final demand, transformation and primary supply. Energy flows are expressed in physical terms and energy commodities are not traded under Armington assumption that allows (i) to maintain physical energy conservation when importing or exporting and (ii) to have better exogenous control on energy trade flows in order to take on board information from WEM's runs. Each energy sector (either for transformation or primary supply) is associated with regional productive capacity, the evolution of which can be easily controlled on a yearly step and linked with the corresponding investment requirements. These productive capacities find their exact correspondences in WEM and thus are ideal coupling variables within the set {TCE}.

Similarly, the production of energy services for final consumption for households or productive sectors is not represented through any predetermined production function and the same is true for the transformation process of primary into final energy. The production technology is instead modelled through the use of input output coefficients, the evolution of which is controlled in the dynamic module on a yearly basis. These technical coefficients are then iteratively modified during the coupling process to adjust to the amount of energy consumption generated by WEM, thereby revealing the technical evolution underlying the WEM's energy trend.

4 Hybrid modelling as a tool for exchange and an integrator of expert judgment

The WEM-ECO model was used to generate the *Reference* and *High Growth*[7] scenarios of the *World Energy Outlook 2007*. This section details how such a modelling architecture can be used in the particular context of the IEA to capture the knowledge embodied in the organisation's experts around a common unified tool for dialogue. This section details the development of the model as a learning process through which various communities of experts interacted and learned from each other. We

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[7] The *High Growth Scenario* is based on the assumption that GDP growth in China and India is on average 1.5 percentage points per year higher than in the *Reference Scenario*. This results in an average growth rate to 2030 of 7.5% for China and 7.8% for India. For China, the main driver of growth in this scenario is sustained high investment and continued rapid productivity gains, as the government pushes ahead with reforms to increase the role of the private sector and to open up the economy to foreign investment. For India, the main drivers are acceleration and deepening of structural and institutional reforms, combined with faster infrastructure development (*WEO-2007*).

aim to stress how such hybrid modelling architecture can facilitate convergence towards a common set of consistent scenarios by channelling the debate around a set of concrete variables and their interactions. Beyond the development of a set of integrated and consistent scenarios, the major achievement of this process was that the model-specific architecture made it possible to capture and formalise analytically the expert knowledge embodied in the IEA organisation and network.

4.1 Incorporating macroeconomic feed backs into energy-environment scenarios

Despite the use of a simplified coupling procedure at an aggregated level, the coupling between WEM – an energy sector partial equilibrium model – and IMACLIM-R – a general equilibrium model – provided an integrated framework to take into account macroeconomic feedbacks in energy scenarios. The WEM-ECO model produces consistent energy-economy scenarios in which the changing patterns of the energy sector impact aggregated economic variables. Because of the detailed sectoral description of energy consumption that underpins the integration of the two models, the macroeconomic feedback accounts for direct and transferred (between regions) macroeconomic effects associated with changes in energy prices or technical paths. The direct effect represents the gross impact of energy changes on regional welfare and holds for (i) productive sectors where energy spending impacts production costs and sectoral profitability and for (ii) household budgets where energy consumption crowds out demand for other goods and services. The transfer effect is related to positive or negative income transfers between regions resulting in a change in the energy context. These transfers are first related to the trade of energy goods but also to terms of trade effects associated with the differentiated impact of energy changes on production prices across regions. The information drawn from the WEM-ECO model allows the level of activity variables driving the WEM energy scenarios to be modified to take into account the feedbacks from energy sector changes. These activity variables can be either very aggregated such as GDP levels or at a more detailed level such as sectoral output or household transportation demand.

For *WEO-2007*, WEM-ECO was used to determine how the economy and energy consumption in each region of the world may be affected by higher GDP growth assumptions in China and India (by 1.5 percentage points as compared to the RS). Higher growth in China and India affects the economies of the rest of the world through its impact on international commodity prices and on overall trade in all types of goods and services. The higher GDP growth rates assumed in the *High Growth Scenario* result in faster growth of energy demand in both countries. Higher growth in energy demand, combined with supply-side constraints (limited investment response by major oil and gas producers), drives up international energy prices. WEM-ECO was used to recalculate the global equilibrium for international trade in energy and non-energy goods and services, and for energy and other commodity prices in the rest of the world by major region. The average IEA crude oil import price – a proxy for international oil prices – increases by 40% in 2030, natural gas prices rise by the same proportion, while increased coal demand drives the price up 19% higher than in the Reference Scenario.

Higher economic growth in China and India affects the world economy as a whole through different intertwined channels. On the one hand, higher demand for energy and raw materials, combined with supply-side constraints, leads to a tightening of commodities markets. This adversely affects economic growth in commodity-importing countries, but boosts growth in exporting countries. On the other hand, larger volumes of trade associated with higher demand in China and India (and to a lesser degree in energy-exporting countries) draw in additional imports from the rest of the world and, therefore, stimulate economic activity in other countries. The latter effect is partly offset by losses in market share for tradable goods produced in other regions, because of increased exports by

China and India. The net effect varies. Most regions – Canada, Brazil, the rest of Latin America, the Middle East, Russia and other transition economies – enjoy a net increase in GDP in 2030. But the United States, the European Union, OECD Pacific and other developing Asian countries as a whole see marginal reductions in their GDP (Table 1). Overall, world GDP grows faster, by 4.3% per year on average compared with 3.6% in the Reference Scenario, as the "demand-pull" effect offsets the depressive impact of higher commodity prices.

	Average annual growth rate, 2005-2030	Difference from Reference Scenario	
		Average annual growth rate, 2005-2030	Level of GDP in 2030
OECD	**2.1%**	**-0.06%**	**-1.4%**
North America	2.4%	-0.02%	-0.4%
United States	*2.3%*	*-0.04%*	*-1.0%*
Europe	1.9%	-0.10%	-2.4%
Pacific	1.8%	-0.07%	-1.8%
Japan	*1.3%*	*-0.07%*	*-1.7%*
Transition economies	**3.6%**	**0.02%**	**0.4%**
Russia	3.5%	0.03%	0.6%
Developing countries	**6.2%**	**1.06%**	**30.2%**
Developing Asia	6.9%	1.28%	37.3%
China	*7.5%*	*1.50%*	*45.2%*
India	*7.8%*	*1.50%*	*45.1%*
Middle East	4.4%	0.41%	10.9%
Africa	4.0%	0.05%	1.4%
Latin America	3.3%	0.06%	1.4%
Brazil	*3.1%*	*-0.00%*	*-0.1%*
World	**4.3%**	**0.61%**	**16.3%**
European Union	*1.9%*	*-0.10%*	*-2.4%*

Table 1 : World Real GDP Growth by region in the High Growth Scenario

4.2 Facilitating dialogue with experts and conceptualising judgement in energy scenarios

The specific design of the WEM-ECO model attempts to facilitate dialogue with experts. Two main challenges can be distinguished when incorporating sectoral experts' judgments within a world energy scenario.

First, a sectoral expert that gives his view on a given future evolution has in mind an implicit specific vision of the future state of the word. Incorporating expert judgment to improve an energy scenario is possible only if the expert and the scenario designer share the same implicit vision about the future economic context. In this respect, the description of the energy sector in WEM helps to provide a better understanding and representation on the general context in which the energy scenario is incorporated. This context is either materialised through the choice of assumptions (on economic or demographic growth for example) or through the level of energy prices that reveal the underlying views on the level of tension on energy markets. Thanks to the comprehensive description of the whole economic system it provides, the WEM-ECO model can be used to make explicit some underlying assumptions driving the energy scenario. The representations of the complete structure of international trade or households' consumption are key information that help to harmonise views about the future general economic context in which the sectoral experts express their judgement.

Second, the use of this coupling technique allows technical mechanisms that underpin the formation of energy use in WEM to be disentangled. This is particularly relevant for sectors in which energy consumption is modelled through an econometric regression. In such cases, the WEM-ECO model actually reveals the underlying evolution of energy efficiency and sectoral activity. These two sets of variables that are shadowed in WEM become explicit in WEM-ECO and can be subjected to sectoral experts' checking. The regional distribution of sectoral productive capacities detailed in the WEM-ECO model is also submitted to experts' control. WEM-ECO is here used to make explicit some key sectoral variables that underlie WEM energy trends. The evolutions of these variables are then submitted to experts' checking and the recursive structure of WEM-ECO allows new scenarios including the experts' views on the evolution of specific coefficients to be produced.

As an example, Figure 7 disentangles the evolution of the ratio of energy consumption from the industry sector to GDP for the European region. This aggregated indicator is broken down into (i) pure energy efficiency gains associated with technical changes (ii) and structural changes that affect the sectoral activity level. The WEM-ECO framework therefore makes it possible to decouple the two trends and to submit them to expert scrutiny. Even if the methodological gains are robust, the numbers presented in Figure 7 do not pretend to be realistic and are only drawn from very preliminary results. Particularly, the dematerialisation trend that is endogenously modelled in the WEM-ECO model might be underestimated.

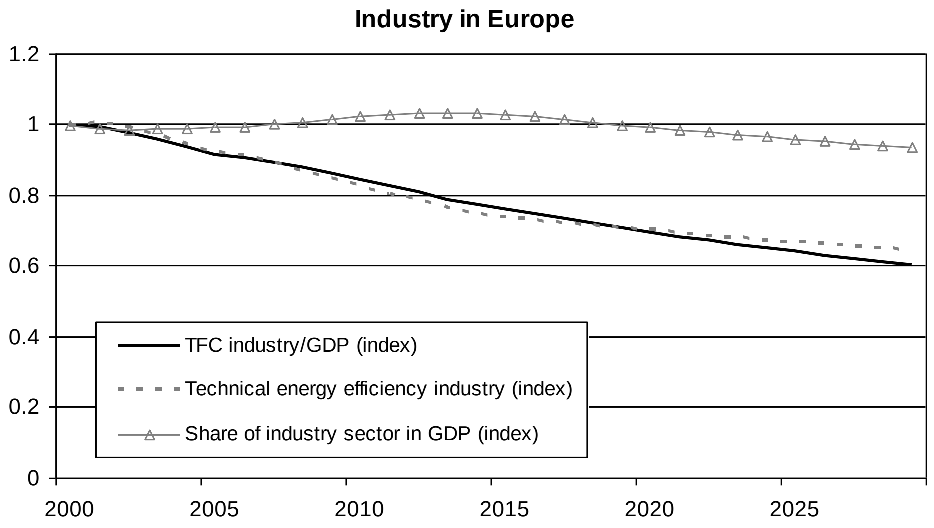

Figure 7 : Disentangling the apparent evolution of GDP intensity of industry sector energy final consumption.

4.3 Ensuring the internal consistency of scenarios

Beyond the need to include neglected macroeconomic feedbacks in energy scenarios and facilitate interaction with sectoral experts, the WEM-ECO model has been designed to increase the internal consistency of scenarios produced by WEM that rely on a partial equilibrium representation of the economic system. This task requires the adoption of a more in-depth coupling procedure between the two models. The challenge for future improvements of WEM-ECO is to achieve a deeper integration of the two models along the lines of the second procedure detailed previously, while limiting the computing time increase resulting from the coupling procedure, such that many model runs can be made. Work is in progress on both WEM and IMACLIM-R models to facilitate and speed up the integration of the two models.

The forthcoming version of WEM allows us to plan for a more ambitious integration with IMACLIM-R. Indeed, a key driver of the update of WEM is to provide a detailed representation of sectoral energy consumption by systematically disentangling the evolution of a sectoral activity variable from energy intensity trends. This allows for a systematic computation of technical coefficients either for sectoral final energy demand or for transformation processes. These complete sets of technical coefficient and activity variable can then be iteratively exchanged between the two models thus leading to a harmonisation of scenarios at a more accurate level of coupling. Keeping the same format as in section 3.2, the coupling procedure becomes:

1. Run WEM with default values for $\{AV_0\}$, $\{PE_0\}$ and $\{ps_0\}$ and get results for sectoral energy technical coefficients $\{TCE_0\}$ and energy flows for the whole energy sector (final demand, transformation and supply).

2. Run the IMACLIM-R model with the calibrated values for $\{pmnes_0\}$ and $\{MC_0\}$, and constraint the evolution of $\{TCE\}$ to $\{TCE_0\}$. This produces a new set of sectoral activity variables $\{AV_1\}$ and energy prices $\{PE_1\}$.

3. Run WEM with new values for sectoral activities variables and energy prices $\{AV_1\}$, $\{PE_1\}$. Get results for sectoral energy technical coefficients $\{TCE_1\}$.

4. Repeat stage 2 and 3 and stop using the criterion defined by Eq. 1 and 2.

This coupling procedure exhibits new constraints deriving from the macroeconomic need to ensure balanced budgets for households or productive sectors and cleared markets for goods and production factors such as capital. These constraints guarantee that the projected energy uses and technical evolution within the WEM are supported by realistic economic flows and consistent set of prices. This analysis requires to use as dialogue variables between the two models sectoral activity variables and explicit technical coefficients for specific energy uses, the evolution of later being associated with investment needs either on the supply and demand side that enter the capital market modelled within the general equilibrium framework of the IMACLIM-R model. Work is underway to use this deeper integration procedure of the two models in preparation for the *World Energy Outlook 2008* scenarios.

5 Conclusion

The growing focus on *short-term* actions to mitigate climate change and energy security threats and the need for more communication with experts and policy makers creates a twin challenge for economic-energy-environment modellers. First, the focus on short-term mitigation strategies requires the integration of expert judgement on short-term trends within longer-term scenarios. Second, the modelling framework should be constructed so as to facilitate the interaction with both decision makers and a large variety of sectoral and technology experts.

This paper presented recent efforts at the IEA to develop a flexible hybrid model (WEM-ECO) by coupling the bottom-up technology-rich WEM model with the top-down general equilibrium model IMACLIM-R. The model architecture was specifically designed to facilitate the incorporation of expert judgement and facilitate convergence towards a common set of internally consistent scenarios – particularly through a dual representation of physical (energy) and economic (money) flows. The paper detailed the iterative coupling procedure that can be implemented at different aggregation levels depending on the time horizon considered and the uncertainty about technological and economic parameters.

WEM-ECO was used to produce the *High Growth Scenario* of the *World Energy Outlook 2007* focusing on China and India. The paper drew some lessons from the interaction process between the various experts and showed how WEM-ECO played a central role as an integrator of different approaches within a consistent view of the future. The paper detailed how some specific modelling architecture choices were made taking into account the particular context of the IEA as an organisation grouping diverse communities of experts. The development of the WEM-ECO model was described as a learning process whose major achievement was to enable the formalisation of the expert knowledge embodied in the IEA organisation and network and to facilitate the convergence towards an internally consistent set of scenarios.

6 Appendix: Regional details of WEM-ECO

WEM-ECO Regions	***GTAP regions***
USA	*USA*
CAN	*Canada*
EUR	*Austria, Belgium, Denmark, Finland, France, Germany, United Kingdom, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, Switzerland, Rest of EFTA, Rest of Europe, Albania, Bulgaria, Croatia, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania.*
OECD Pacific	*Australia, New Zealand, Japan, Korea.*
FSU	*Russian Federation, Rest of Former Soviet Union.*
CHN	*China*
IND	*India*
BRA	*Brazil*
ME	*Rest of Middle East*
AFR	*Morocco, Tunisia, Rest of North Africa, Botswana, South Africa, Rest of South African CU, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Rest of SADC, Madagascar, Uganda, Rest of Sub-Saharan Africa.*
RAS	*Indonesia, Malaysia, Philippines, Singapore, Thailand, Vietnam, Hong Kong, Taiwan, Rest of East Asia, Rest of Southeast Asia, Bangladesh, Sri Lanka, Rest of South Asia, Rest of Oceania.*
RAL	*Mexico, Rest of North America, Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America, Central America, Rest of FTAA, Rest of the Caribbean.*

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