Reconciling top-down and bottom-up energy/economy models: a case of TIAM-FR and IMACLIM-R

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Abstract

Recent global economic and environmental forecasts consistently show a trend of continuous decline in natural resources, degradation of environmental quality, increasing vulnerability of economic growth as a result of environmental stress, competition for land and natural resources, soaring energy prices and climate change. These forecasts partly rest on significant efforts by the scientific community over the past three decades to improve knowledge of the interactions between economic growth and the environment; particularly modelling methods have developed to become increasingly applied to the assessment of the environmental and economic consequences of various energy demand and greenhouse gas policies. However, the significantly diverging viewpoints of models developed by energy engineers, or 'bottom-up' (BU) models, and those developed by economists, or 'top-down' (TD) models, hinder effective dialogue and mutual understanding between researchers from different academic backgrounds. The purpose of this paper is to promote a constructive dialogue between modellers from each side of the modelling paradigms, based on a comparative critique of the BU TIAM-FR model and the TD IMACLIM-R model. The comparison terms extend from the theoretical foundations of each model to their structure and specifications, and applicability to policy assessment. Preliminary numerical simulations are developed to demonstrate the relevance of linking the two models, while the technical challenges and methodological limitations of coupled simulations are addressed.

1- Introduction

Since the beginning of the 1990's and the rise of the climate change concern, policymakers have been increasingly interested in a better understanding of the efficiency and cost of policies whose purpose is to shift energy systems toward more environmentally desirable technology paths. The scientific community has responded this interest by many tools which lie in between two polar approaches, the bottom-up and top-down models (IPCC, Chap. 8, SAR and TAR). Bottom-up (BU) models are energy sector models characterised by a rich description of the current and prospective energy supply and end-use technologies. They picture energy systems evolutions as resulting from myriad of decisions on technology adoption, *i.e.* follow a bottom-up methodology to forecast energy systems. They mostly are optimisation models concerned with the cost minimisation of satisfying energy service demands, under a set of pre-determined constraints that can range from technology mandates to energy efficiency or GHG emission targets. Their main shortcoming lies in their partial equilibrium nature, *i.e.* their inability to consider feedbacks from markets beyond the energy market — the primary production factors (labour, capital, natural resources) and the overall general equilibrium effects (income, saving).. These could however substantially modify the conclusions of any prospective study. For instance, the massive investment flows necessary to the paradigm shifts compatible with pledged 2050 decarbonisation targets cannot indeed but impact on the cost of capital.

Conversely, Top-Down (TD) models focus on the interactions between the energy systems and the rest economy at cost of a more aggregate description of these systems, hence the label 'top-down'. They rely on descriptions of the economy based on national accounting data (in monetary values). They describe the reactions between energy and the economy through econometric techniques applied to data on consumption, prices, incomes, and factor costs to model the supply and demand for goods and services. The TD models applied to energy and climate prospective are frequently of the computable general equilibrium (CGE) family. CGE models base their representation of economic behaviour on microeconomic principles. They typically simulate markets for primary factors of production (mainly labour, capital and natural resources), domestic and imported goods and services that are brought into equilibrium by price adjustments. Compared to BU models, their major limitation is that they reduce techniques to instantaneous trade-offs between aggregated production inputs or consumption goods. Particularly, capital costs are treated by default as the remainder of value-added once labour costs and natural resource rents subtracted. They are thus structurally ill-equipped to explore the potential for a decoupling of economic growth and energy demand, which arguably requires disaggregated analysis of energy technologies (Nakata, 2004).

The TD/BU debate first came to prominence during the efficiency-gap debate of the 1980's and 1990's (Grubb *et al.*, 1993). On the one hand, TD modellers (notably CGE modellers) generally work with model forms that assume that competitive markets automatically trade off production inputs and consumption goods efficiently. This economic perspective *a priori* denies the existence of an energy efficiency gap — that some energy efficiency measures could be profitably implemented, but are not. On the other hand, BU models suggested that there were significant "no-regrets" possibilities for increasing energy efficiency in the economy; although of obvious importance to energy and carbon policymaking, this divergence of views is still not completely resolved.

When policymakers need to make decisions about the magnitude and timing of energy-environment targets, and about the best policy packages to achieve them, they need information both on the technical feasibility of these targets and on their impacts in terms of GDP levels, competitiveness, employment, finance and households' purchasing power. Neither the BU nor the TD modelling perspective is able to give comprehensive and robust guidance on these requirements. Thus the differences between their results are rooted in a complex interplay among the differences in purpose, structure, and input assumptions. A common practice is to utilise them in parallel in policy processes but sometimes at cost of the internal consistency.

One way of bridging the gap between the two modelling approaches is to develop 'hybrid' models aiming at combining the advantages of both categories of models, starting from either of the 2 paradigms and amending it to approach the other (Hourcade *et al.*, 2006). It is not our purpose here and we rather explore the potential for coupling two constituted models, the TIAM-FR and IMACLIM-R models. TIAM-FR, a declination of the TIMES model, is a typical BU model that has been widely used to assess sectoral and global energy and climate policy from both developed and developing countries perspective (see for example Assoumou and Maïzi, 2011; Bouckaert *et al*., 2012; Dubreuil *et al.*, 2012; Ricci and Selosse, 2013; Selosse and Ricci, 2013). IMACLIM-R, the recursive version of IMACLIM, is a multi-regional multi-sector TD model that has been developed by CIRED to assess the long-term global economic impacts of climate policy (Guivarch *et al*., 2009; Mathy and Guivarch, 2010; Rozenberg *et al*., 2010; Giraudet *et al*., 2011; Hamdi-Cherif *et al*., 2011). Our aim is to provide insights on how to make constructive dialogue between modellers from each side of the modelling paradigms, based on a comparative critique of TIAM-FR and IMACLIM-R, respectively understood as representative of the BU and TD approaches. The comparison draws on model architecture and structure, theoretical foundation and applicability in the light of policy assessment. Preliminary numerical simulations have been implemented to examine the consistency of linking TIAM-FR and IMACLIM-R models. In perspective, we discuss the relevance and mathematical and technical challenges in the prospects for developing coupled models as well as policy implications.

The next section describes the architecture and economic rationale of TIAM-FR and IMACLIM-R models. Section 3 discusses the models' features and usefulness for informing policy making. Section 4 explores the ways of coupling TIAM-FR/IMACLIM-R and presents preliminary results as well as limitations of coupled simulations. Section 5 concludes and provides research perspective.

2- Modelling paradigms and economics rationales

As a member of the TIMES family, TIAM-FR is a dynamic, linear programming, optimisation model that proposes a BU description of energy systems. It is based on a detailed description of existing and future energy technologies, which correspond to alternative pathways of all energy carriers from their sources to end-uses, through a wide array of conversion technologies. TIAM-FR computes a partial equilibrium on energy markets, in the sense that, at each time period, energy demand and supply are made to match (energy markets clear). This equilibrium feature is present at every level of the energy system: primary, secondary and final energy forms, and energy services.

The optimisation problem formulation in the TIAM-FR model mobilises four types of entities (adapted from Loulou 2008), (i) decision variables: endogenous quantities to be determined by the optimisation; (ii) the objective function: the criterion to be minimised or maximised; (iii) constraints: equations or inequalities involving the decision variables that must be satisfied by the optimal solution; and (iv) parameters entered by modellers as regards processes, technologies, *etc*. All TIAM-FR runs configure the energy system over a certain time horizon in such a way a total net present value of the stream of annual costs is computed for each region, and discounted to a user selected reference year. These regional discounted costs are then aggregated into a single total cost constituting the objective function to be minimized under a number of constraints (Loulou, 2008). The net present value (NPV) of the total energy system costs for all regions is the sum of all annual costs *per* region r and year t, $AC_{r,t}$, discounted at a $d_{r,y}$ general rate:

$$NPV = \sum_{r=1}^{R} \sum_{t \in T} \left(1 + d_{r,t}\right)^{t_0 - t} AC_{r,t} \tag{1}$$

Where: t_0 is the reference year for discounting; T is the set of years for which costs are incurred, which includes all years in the model horizon,[2] plus past years (before the reference year t_0) if costs have been defined for past investments, plus a number of years after the end of the planning period where some investment and dismantling costs are still being incurred, as well as the salvage value of fixed capital; R is the set of TIAM-FR regions. An important feature is that investment decisions are made in each period with full knowledge of the future cost and demand trajectories. In other words, the decision makers are assumed by the model to operate globally with the benefit of full information and perfect foresight (clairvoyance of energy planner).[3]

TIAM-FR formulates and computes its projection of optimal energy systems based on the Linear Programming approach. It can be summed up as follows:

$$Min\ c \cdot X \tag{2}$$

subject to

$$\forall t \in [1, T]\ \forall i \in [1, I] \sum_{k=1}^{K} Q_{k,i}(t) \geq D_i\,(t) \tag{3}$$

and

$$B \cdot X \geq b \tag{4}$$

where X is the vector of all variables with associated discounted cost vector c, I the number of demands categories for energy services; $Q_{k,i}(t)$ the capacities of end-use technologies k susceptible of addressing service demand i at time t; $D_i(t)$ the exogenous demand for energy service i to be satisfied at time t; B and b vectors or matrixes of exogenous parameters (echoing emission contents and potential caps, energy contents and energy efficiency mandates, technology mandates, *etc.*). Expression (2) defines the total discounted cost to be minimised. Expression (3) formulates the set of demand satisfaction constraints. Expression (4) synthesises the set of constraints weighing on the cost minimisation, a large number of which express the physical and logical relations that must be satisfied in order to properly depict the energy system (Loulou, 2008).

In terms of policy assessment, TIAM-FR is a powerful tool for energy planning, energy technology penetration analysis and emission mitigation (technical) costs evaluation at regional and nationwide level. The model can inform policymakers on the opportunity to trade off different energy technologies, thus approaching an optimal allocation of resources, which is crucially important for resources saving and GHG mitigation portfolio design.

[2] More precisely, the time horizon of the model may range from one year to many decades and is usually split into several periods representing points where investment decisions may be taken and where the activity and flow variables may be considered as average values. Additional years are used to consider capacity installations that took place before the beginning of the model horizon, the *past years.* The investment and dismantling costs are computed for each year of the horizon (and beyond if needed) and transformed into streams of annual payments (Loulou *et al.*, 2005). All cost parameters in the objective function are inter/extrapolates to the individual years of the model as part of calculating the annual cost details (TIMES Version 2.5 User Note).

[3] The hypothesis of competitive markets with perfect foresight can be relaxed in versions of TIMES based on stochastic programming, to account for risk and uncertainty (Loulou and Labriet, 2008).

Compared to TIAM-FR, IMACLIM-R is a recursive general equilibrium model of the TD family[4] (Sassi *et al.*, 2009): "recursive" in the sense that it is solved in sequential (yearly) time steps, linked through time by capital accumulation based on exogenous savings rates, *i.e.* on a generalised assumption of imperfect foresight (myopic economic agents) quite contrary to TIAM-FR; "general equilibrium" in the sense that it provides a consistent, comprehensive description of factor and goods markets where consumers, among which public administrations, and producers, among which energy producers, interact through domestic and international trade. This multiplicity of agents comes along with decentralised decision making, another major contrast to TIAM-FR.

On the side of households, behaviour specifications are partly rooted in microeconomic theory (*i.e.* 'micro-founded'): at each simulation year and in each of the 12 regions modelled (for convenience we drop time and region subscripts in the following equations), households maximise utility as a (Stone-Geary) function of consumption C_i of n goods above basic-need levels $\overline{C_i}$, a mobility service S_m, and housing services S_h above a basic-need level $\overline{S_h}$. A salient feature of the model is that this maximisation is not only conditional to a standard budget constraint, but also to a time constraint: the time T_i spent in each of 4 i-indexed alternative mobility modes (a function of the passenger-km performed and the relative congestion of modes) is equal to a mobility-time budget T_m set at 1.1 hours *per* person *per* day across regions and times. This assumption is supported by numerous studies with fairly close outcomes ranging from 50 minutes to 1.3 hours *per* day (Zahavi and Talvitie, 1980; Bieber *et al.*, 1994; Schaefer and Victor, 2000; Vilhelmson, 1999). The consumption program synthesises as:

$$\underset{C_1,\ldots,C_n,S_m,S_h}{Max}\ U(C_1-\overline{C_1},\ldots,C_n-\overline{C_n},S_m,S_h-\overline{S_h}) \tag{5}$$

subject to

$$\sum_{i=1}^{n} p_{Ci}\, C_i + p_{Sm}S_m + p_{Sh}\, S_h = R \tag{6}$$

and

$$\sum_{i=1}^{4} T_i = T_m \tag{7}$$

with self-explanatory price notations.

Contrary to consumption, production does not follow any explicit optimisation behaviour: each year, producers set prices by applying an exogenous mark-up that merges capital amortisement and profits to the production costs imposed by fixed cost structures (the Leontief assumption), then adapt to demand. However, feedbacks on costs are accounted for by mechanisms that echo a 'second best' economic setting quite distinct from the first-best setting (perfect foresight on competitive energy markets) of TIAM-FR. Notably, the capital and labour endowments are suboptimally used: both unemployment and a below-100% utilisation rate of production capacities are possible, with a deflatory impact on labour costs. Also, capital accumulation through time is modelled under a 'putty-clay' assumption, with rigid (Leontief) specific cost structures embedded in successive capital vintages. In this general framework, economic growth results mainly from the exogenous drivers of population and labour productivity dynamics.

[4] Section 3 dwells on the fact that it is also hybridised to approach a BU description of energy supply and demand systems.

IMACLIM-R's rationale stems from the necessity to understand better, amongst the drivers of energy-economy prospective trajectories, the relative role of (i) technical parameters in the supply side and in end-use equipments, (ii) structural changes in the final demand for goods and services (dematerialisation of growth patterns), (iii) micro and macroeconomic behavioural parameters in open economies. This is indeed critical to capturing the mechanisms in the transformation of a given environmental alteration into an economic cost and in the widening or narrowing margins of freedom for climate mitigation or adaptation.

3- Main modelling specification

3-1 - Modelling scope and scale

The structure of TIAM-FR is defined by variables and equations extracted from and calibrated on data input, both qualitative and quantitative, from authoritative sources as the International Energy Agency (IEA) for energy balances, and from literature or expert knowledge (IPCC reports, US-Environmental Protection Agency, IEA-Energy Technology Perspectives, US-Department of Energy, US Geological Survey, World Energy Council) for the characteristics of the technologies and reserves of primary energies. The qualitative data includes lists of energy carriers, available technologies (across regions and time periods), as well as environmental externalities that are to be tracked. The quantitative data group the technological and economic parameter values specific to each technology for each region and time period. Indeed, in the case of multi-region models, a technology often may be available for use in distinct regions; however, cost and performance assumptions may be different (Loulou and Labriet, 2008). This information collectively defines each TIAM-FR regional model database and the resulting mathematical representation of the Reference Energy System (RES) for each region (Figure1).

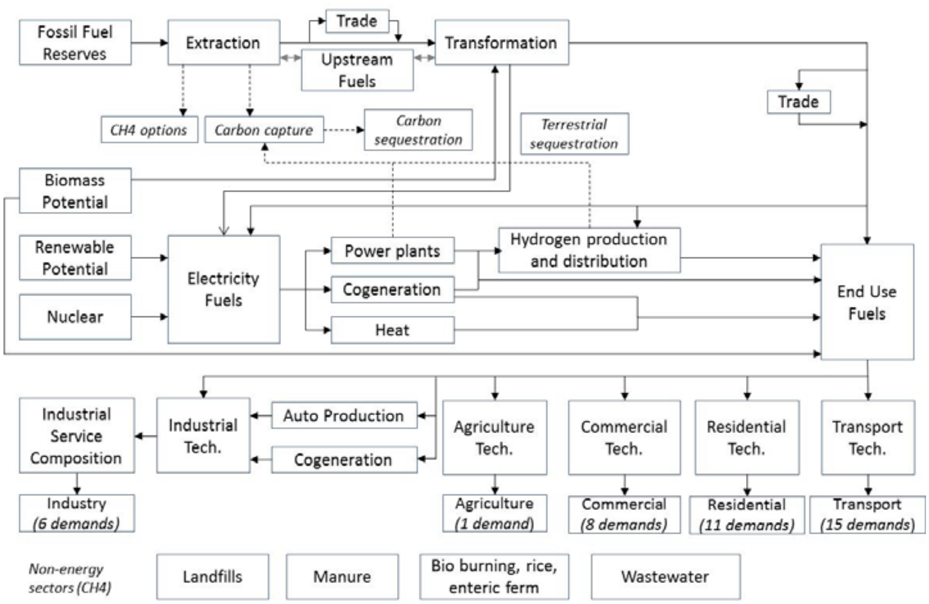

Figure 1 - The reference Energy System of TIAM-FR
Source : adapted from Loulou and Labriet, 2008

The RES network links commodities to several thousand existing and future technologies characterised by economic and technological parameters in all sectors of the energy system (agriculture, industry, commercial, residential and transport; taking into account the conversion and electricity sectors). The system includes the extraction, transformation, distribution and trade of various energy forms, and end-uses.

TIAM-FR is geographically aggregated in 15 world regions (Table 1). It covers the time horizon from 2005 to 2100, year generally selected to properly reflect the long-term nature of the climate constraint. Indeed, a climate module computes the change in CO_2 concentrations in three reservoirs, the total change in atmospheric radiative forcing from anthropogenic activities and the temperature change in two reservoirs relative to the pre-industrial period. Note that the climate module does not induce retroaction on energy services demands, which remain unchanged. More generally, TIAM-FR computes CO_2, CH_4 and N_2O emissions from energy consumption.

Index	**Region**
AFR	Africa
AUS	Australia and New Zealand
CAN	Canada
CHI	China (including Honk Kong, excluding Taiwan)
CSA	Central and South America
EEU	Eastern Europe
FSU	Former Soviet Union (inc. Baltic States)
IND	India
JPN	Japan
MEX	Mexico
MEA	Middle-East (inc. Turkey)
ODA	Other Developing Asia (inc. Taiwan and Pacific Islands)
SKO	South Korea
USA	United States of America
WEU	Western Europe (EU-15, Iceland, Malta, Norway and Switzerland)

TIAM-FR is driven by 42 exogenous end-use energy demands grouped into six sectors: transport (15 demands), residential (11 demands), commercial (8 demands), agriculture (1 demand), industry (6 demands) and other segments (1 demand) (Figure 2). Each energy demand is calibrated exogenously by the modeller for the base year, and then follows a trend induced by some exogenous driver, *i.e.* regional economic and demographic projections, such as the evolution of GDP, population or sectoral outputs over the time horizon (Figure 2). These drivers are obtained from accepted external sources (Loulou and Labriet, 2008) or from other modelling experiments. Indeed, ETSAP-TIAM (another model of the TIMES family) partly derives them from a coupling experiment with the GEMINI-E3 model (Drouet *et al.*, 2008) — which we examine in a further section. Demands are associated to their drivers through time- and region-specific elasticities that can reflect decoupling (elasticities smaller than 1, to account for saturations) or accelerated penetration assumptions (elasticities larger than 1).

The model must satisfy these demands in each time period, by using the existing capacity and/or by implementing new capacity for end-use technologies. Thus, based on a set of coherent assumptions about the future pathways of demands drivers (demand side) and of technological characteristics and resources potentials (supply side), the model explores possible long-term energy futures on a given time horizon, under potential policy constraint, using linear programming to minimise the discounted costs of the global energy system (Reisman, 1997; Chen *et al.*, 2007) (see section 3.2 for a detailed description of costs).

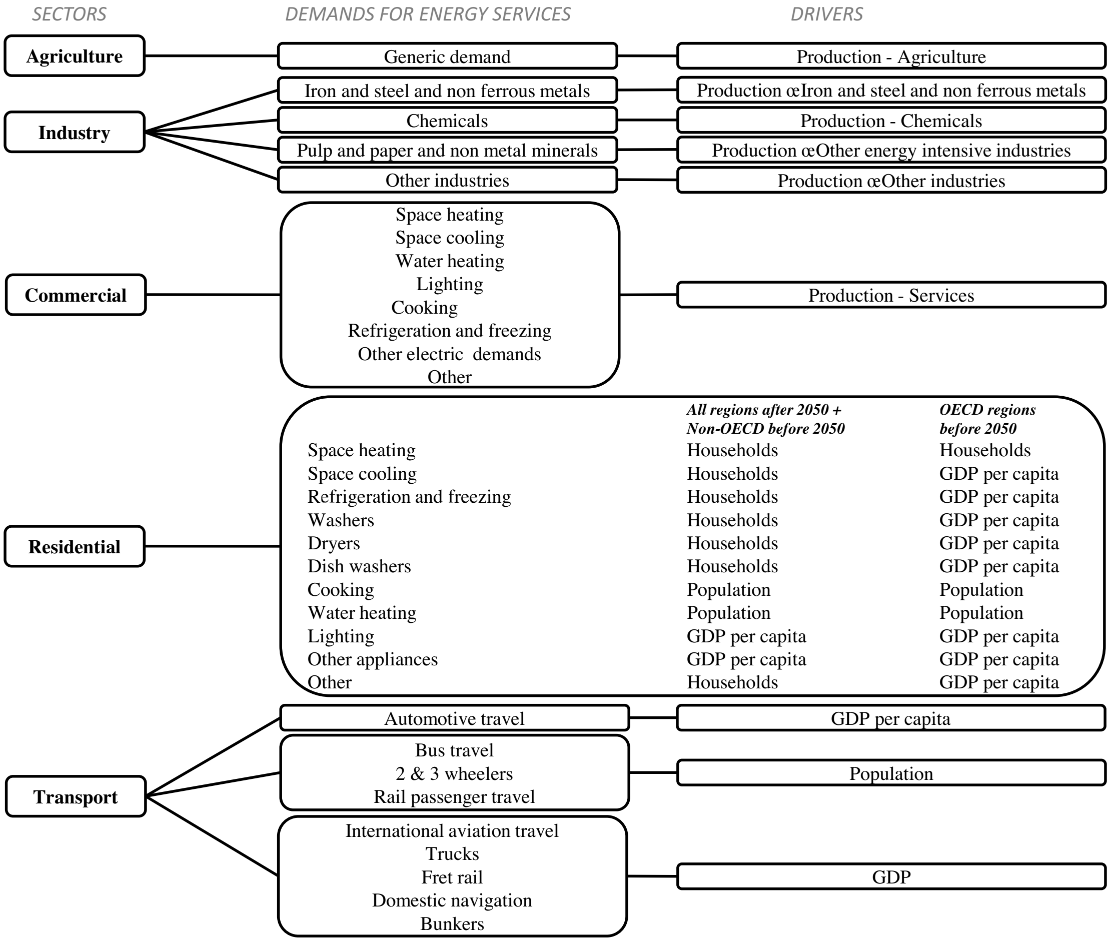

Figure 2 - Demands for energy services and their drivers in TIAM-FR

As expected considering its top-down characteristics, IMACLIM-R provides a more aggregated view of global economic activity, which it divides into 12 regions and 12 sectors (Table 2). The base year of the model (2001) builds on the GTAP-6 database, a balanced Social Accounting Matrix (SAM) of the world economy. The original GTAP-6 dataset is however modified to (i) aggregate regions and sectors according to the IMACLIM-R mapping, and (ii) accommodate the 2001 IEA energy balances, in an effort to base IMACLIM-R on a set of hybrid energy-economy matrixes (Cassen *et al.*, 2010; Rozenberg, 2010; Sassi *et al*., 2010).

Through this hybrid calibration, the modelling architecture specifically aims at an easy incorporation of technological information coming from BU models and experts' judgements into its prospective scenarios. These are thus defined both in money-metric terms and in physical quantities, with the two dimensions linked by a price vector. This guarantees a realistic technical background to the projected economy or, conversely, a realistic economic background to any projected technical system.

Regions	Sectors
USA	Coal
Canada	Oil
Europe	Gas
OECD Pacific (JP, AU, NZ, KR)	Liquid fuels
Former Soviet Union	Electricity
China	Air transport
India	Water transport
Brazil	Land transport
Middle-East	Construction
Africa	Agriculture
Rest of Asia	Energy-intensive industries
Rest of Latin America	Composite (remainder)

Table 2 Regional and sectoral disaggregation of the IMACLIM-R model

To fully exploit the potential of this dual representation requires abandoning the use of conventional aggregate production functions that, after Berndt and Wood (1975) and Jorgenson (1981), were admitted to mimic the set of available aggregate production techniques and thus the technical constraints impinging on an economy. It is indeed arguably impossible to find mathematical functions flexible enough to encompass all the contrasted scenarios of structural changes plausibly resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade, 1993), for small as well as for large departures from the reference equilibrium. This accounts for the already reported absence of formal production functions in IMACLIM-R. This absence is compensated for by a recursive structure that allows for a systematic exchange of information between (Figure 3):

- The annual static equilibrium module with Leontief production functions (fixed equipment stocks and intensities of intermediary inputs, especially labour and energy) — but flexible utilisation rates of the labour and capital endowments, which principles were described Section 2 above. Solving this equilibrium at some year *t* provides a snapshot of the economy: information about relative prices, output levels, physical flows and profit 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, most of which assess the reactions of technical systems to the previous static equilibria. These reactions are then reintroduced into the static module in the form of updated input-output coefficients to calculate year $t + 1$ equilibrium.

Between two equilibria, technical choices are fully flexible for new capital only: each equilibrium's input-output coefficients are modified at the margin, to account for the fixed techniques embodied in existing equipment and resulting from past technical choices. This general 'putty-clay' assumption is critical to representing the inertia in technical systems and the perverse effect of volatility in economic signals (Rozenberg *et al*, .2010). Technically speaking, the goal of the dynamic modules is to modify the technical constraints applying to the economy in static equilibrium. Such modifications concern the structures of production costs in the sectors as well as the stocks of household energy end-use equipment and their efficiencies (Rozenberg *et al.*, .2010).

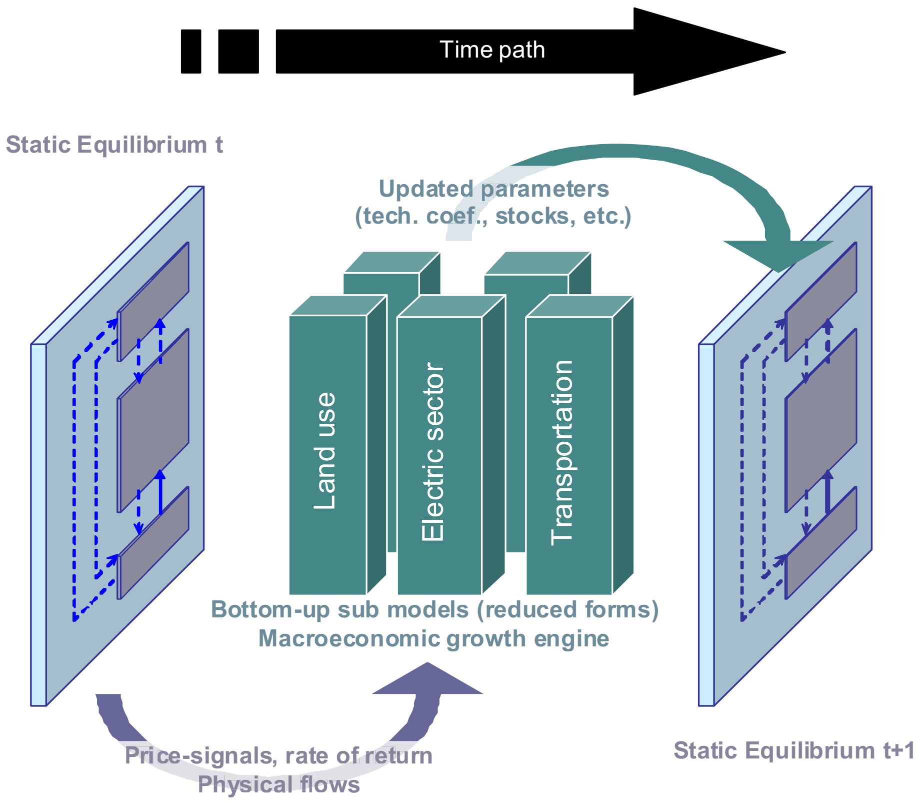

Figure 3 - Static equilibrium and dynamic nexus coupling in IMACLIM-R

From a mathematical point of view, the successive static equilibria of IMACLIM-R boil 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, $i \in [1, n]$, a set of variables (as many as equations), z_i, $i \in [1, m]$, a set of parameters and f_i, $i \in [1, n]$, a set of functions, some of which 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 economic system is properly balanced; the other subset translates various 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 (*e.g.* households' consumption trade-off). It is these constraints that ultimately reflect, in the flexible architecture of IMACLIM-R, a certain economic 'worldview' — notably, the equations describing household consumptions derive from the first-order conditions of maximisation of their postulated utility function (*cf. infra*).

Among the accounting constraints, a set of market clearing conditions balance the physical uses and resources of all goods. It is programmed under the standard assumption that all goods are consumed the year they are produced, *i.e.* no stocks are modelled; demand and supply are equilibrated by a vector of prices in the Walrasian fashion. In each region and for each good i, total resource Y_i (either the sum of domestic production and imports or a non-linear Armington aggregate of them) is then equal to the sum of intermediate use, domestic final consumptions (by households C_i, by public administrations G_i and for investment I_i)[5] and exports X_i.

$$\forall i \in [1,12] \quad Y_i = \sum_{j=1}^{12} \alpha_{ij} Y_j + C_i + G_i + I_i + X_i \tag{8}$$

where α_{ij} is the intensity of production j in good i — the α_{ij} define the input-output matrix.

Another accounting constraint regards public budgets: governments finance their expenditures G_i at prices $p_{i,G}$, net transfers to households T_H, and infrastructure investments I_G, with fiscal income F:

$$F = \sum_{i=1}^{12} p_{i,G} G_i + T_H + I_G \tag{9}$$

3-2 - production costs and prices

As already explained, the objective function of TIAM-FR is the sum over all regions of the total annual cost of the energy system of region r at time t, $AC_{r,t}$, discounted to a user-selected reference year. This total annual cost is the sum over all technologies, all demand segments, all pollutants, and all input fuels of the various costs incurred, namely: annualised investments and annual operating costs, minus revenue from exported energy carriers, minus salvage values, plus taxes on emissions (Loulou *et al.*, 2004). More precisely, each year, the total energy system costs include the following elements (adapted from Loulou *et al.*, 2005 and Loulou, 2008):

- The capital costs incurred for the investment in supplemental capacity and some dismantling processes (*e.g.* the costs of decommissioning nuclear power plants). These investments variables are spread into streams of annual payments, computed for each year of the horizon, and beyond, for the investments undertaken in the later periods and in the case of dismantling costs. The number of years over which this spread is performed follows an economic rationale echoing amortisement over the economic life of processes.
- The fixed and variable operation and maintenance (O&M) costs, and other costs occurring during the dismantling processes.
- The costs incurred for the domestic production and the import of energy resources.
- The delivery costs for the fuel required by processes.
- The taxes and subsidies associated with energy sources, technologies, and emissions. Taxes and subsidies on investments are treated exactly as investment costs in the objective function.

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[5] The final consumption of crude oil is nil in all regions and at all time periods. That of coal is nil in Latin America and the Middle East for all time periods.

- The salvage value of processes and embedded commodities at the end of the planning horizon. This value represents the unused portion of the technical lives of investments, which commonly exceed their economic lives, when they also exceed the model's horizon. The salvage value applies to several types of costs: investment costs, sunk material costs, as well as decommissioning costs and surveillance costs. It is reported as one single lump sum accruing precisely at the end of the horizon, and then discounted to the base year like all other costs. Note that the salvage value is assigned to the single year following the end of the time horizon (Loulou *et al.*, 2005).

TIAM-FR models technology investment on the basis of the technical cost of energy supply, based on a central assumption of marginal cost pricing by energy suppliers. This pricing formulation implies that energy markets are perfectly competitive (no producer may charge an extra profit above the marginal cost), while the transactions costs of technology shifts are disregarded.

Indeed, the primal solution of TIAM-FR provides the optimal values for the decision variables of the primal problem (*e.g.* activity levels, energy flows, capacity additions, *etc.*). According to the duality theory of linear programming, there is a dual variable for each constraint of the TIAM-FR programme. Also called the constraint's shadow price, it corresponds to the marginal change of the objective function *per* unit increase of the constraint's right-hand-side and provides additional information in terms of marginal costs. The price of a commodity is thus in fact equal to its marginal cost.[6] For example, in the case of some upper CO_2 emission constraint, the dual solution describes the marginal cost expected from a unit decrease of CO_2 emissions below the threshold enforced (Remme *et al.*, 2009). In the mathematical economics literature, whenever the price is derived from the marginal value of a commodity, the qualifier 'shadow' can be used to distinguish the competitive market price from the price observed in reality, which may be different, as is the case in regulated industries or in sectors where market power is exerted (Loulou *et al.*, 2005).[7]

All these prices and costs are expressed in 2001 US dollars in all regions and time periods. The fact that all extraction and technology costs are constant in this unit implies that any feedbacks from the energy system on the cost structure of the various economic activities producing these services and equipments are ignored, including indeed the impact on capital markets of the potentially high investment requirements of the energy system trajectories depicted. This is one of the main aspects in which IMACLIM-R departs from TIAM-FR, as it endogenously models the prices of all goods and primary factors at the static general equilibrium of each projected year. In this way the model accounts for the retroaction on prices of many macroeconomic variables as well as climate policies. More specifically, in each region the producer price of each good i (*cf.* the list of sectors/goods Table 2 above), p_{Yi} , is the sum of input purchases $p_{CIji}\,\alpha_{ji}$, labour costs $\Omega_i\, w_i\,(1+t_i^w)\, l_i$, and a remainder of value-added blending amortisements and profits $\pi_i\, p_{Yi}$:

[6] The conditions of particularly non-competitive markets as the international oil market are thus mimicked through the adjustment of trading costs (see further section 3.4).

[7] It is important to note that marginal value pricing does not imply that suppliers have zero profit. Profit is exactly equal to the suppliers' surplus, and it is generally positive. Only the last few units produced may have zero profit, if, and when, their production cost equals the equilibrium price, and even in this case zero profit is not automatic as production may exhibit decreasing returns (*ibid.*).

$$p_{Yi} = \sum_{j=1}^{n} p_{CIji}\, \alpha_{ji} + \Omega_i\, w_i \left(1 + t_i^{w}\right) l_i + \pi_i\, p_{Yi} \quad (10)$$

where Ω_i is a function of the utilisation rate of production capacity Y_i / Q_i, *i.e.* embodies a decreasing returns assumption. Equation (10) is thus essentially an inverse supply curve (or the cost dual of a production function) that fixes how costs increase with output, from a static point of view — utilisation rates are independent through time. Section 3.3 below comments on the status and dynamics of the α and l input-output coefficients, particularly those of the energy sectors, which are the closest approximation to a technology in the TD framework of IMACLIM-R' yearly equilibria. The benchmark mark-up π is calibrated in 2001. For the fossil fuels production, π is endogenised, i.e. varying with energy prices each year in the dynamic module. For most non energy sectors, π is quasi-constant during the whole period.

In the current version of IMACLIM-R, coal and gas extraction mark-ups are indeed functions of cumulated extraction calibrated as reduced forms of the POLES energy system model (Criqui, 2001). Crude oil is subject to a detailed treatment that deserves a longer development.

To capture the different characteristics of oil sources (conventional *vs.* unconventional oil), oil reserves are indeed explicitly modelled in a dedicated technical module. They are classified in six categories of full cost of a barrel (including prospecting and extraction expenses). The decision to initiate the production of a given resource follows a simple profitability criterion, comparing total production costs and the current world price of oil. The profit rate applied by producers depends on the short-run pressure on available production capacities. In other words, the mark-up rate π increases when the ratio of current output to total production capacity approaches unity. A specificity of crude oil is that the availability of production capacity is not only constrained by the amount of previous investments, but also by geological and technical factors that cause intrinsic inertias in the increase of production. Therefore, for a given category of resource in a given region, the available capacity of production is assumed to follow a 'Hubbert curve'. Rehrl and Friedrich (2006) argue that this curve results from the interplay of two contradictory effects: the information effect (finding an oil reserve delivers information about the probability of existence of other ones) and the depletion effect (the total quantity of oil in the subsoil is finite). Interestingly, this physical interpretation of the 'Hubbert curve' at a field level is not equivalent to empirically assuming the occurrence of a peak of world oil production sometime in the 21st century, which is still controversial.

Moreover, IMACLIM-R can capture the impact of various geopolitical scenarios or market behaviours: endogenous routines can mimic the decision to exploit or not to exploit new capacities in the Middle-East region and the subsequent gain in market power, depending on strategic objectives formulated as either price or market-share targets.[8] For a given year, Middle-East production capacity is still bounded by the bell-shaped Hubbert curve but its actual level can be below this limit if the chosen strategy requires a restriction of production. Conversely, all other regions are supposed to be motivated by short-term return on investments and put reserves into production as soon as it becomes

[8] These objectives can also be adjusted to reflect assumptions on the solidity of the OPEC cartel (Rozenberg *et al.*, 2010).

profitable to do so (that is when the oil price on international markets exceeds the total cost of exploration and exploitation). These producers are referred to as 'fatal producers'.

Downstream from producer prices,

- consumer prices are derived from producer and import prices by adding sales taxes (at rates constant through time), through specifications that differentiate between energy and non-energy goods. The prices of the former are simply weighted averages of the domestic and international prices, which are themselves weighted averages of export prices. For the latter, consumer prices are constant elasticity of substitution (CES) prices of domestic and import-based prices, reflecting an Armington assumption of imperfect substitutability (*cf.* section 3.4 below).
- Export prices add to each region's producer prices export taxes or subsidies and international transportation costs (a weighted average of the bilateral costs detailed by the GTAP database). This allows taking into account the impact of increasing energy prices on transportation costs and eventually on commercial flows and industrial localisation patterns.

3-3 - Technology choice and technology portfolio dynamics

As pointed out by Nakata (2004), a main distinction between the TD and BU approaches is how behaviour is endogenised and extrapolated over the long run. TD and BU models also have different assumptions and expectations on the efficiency improvements from current and future technologies. BU models often focus on the engineering energy-efficiency gains evident at the microeconomic level and on the detailed analysis of the technical and economic dimensions of specific policy options. They picture technology in the engineering sense: a given technique related to energy consumption or supply, with a given technical performance and lifecycle cost.

The optimisation objective being to minimise the total discounted cost, the model chooses the least costly combination of technologies that satisfies the specified demand and the different constraints of the model that allow depicting the associated energy system. The least costly technology will be first used up to its maximum penetration potential. At the margin, one technology will probably be used at less than its maximum if this contributes to minimizing the overall cost. Technologies are thus selected in least-cost order up to the point where the constraints are satisfied. Maximum market penetration and allowable levels of emissions are examples of constraints that limit the use of a technology. In the same manner, the modeller can force the use of some technologies at their full potential. Due to the way in which the linear program operates and the constraints that are to be satisfied, the optimal combination of technologies may include both of two technologies with very little difference of cost, or none of them.

The future evolution of technological parameters depends on time and on the cumulative investment decision of the model, *i.e.* technological learning is endogenous (Loulou *et al.*, 2004, 2005). In that sense, investment costs of technologies are linked to cumulative investments as follow:

$$INVCOST_t = a \cdot C_t^{-b} \tag{11}$$

where $INVCOST_t$ is the unit investment cost of a technology at time t, C_t the cumulative investment in that technology up to time t, a the initial unit investment cost (when C_t is equal to 1) and b the learning index expressing the learning speed. With the building up of experience, *INVCOST* decreases making investments more attractive. To detect the advantage of investing early in learning technology and to accept making initially non-profitable investments, agents have to be farsighted and not only consider the initial unit investment cost which is higher. In this case, they can benefit from the investment cost reduction. In TIMES models, a Mixed Integer Programming (MIP) formulation is implemented due to the non-linear mathematical optimization resulting in the above formulation (Loulou *et al.*, 2005; Loulou and Labriet, 2008). The total investment cost, TC_t, is then obtained by integrating $INVCOST_t$:

$$TC_t = \int_0^{C_t} a \cdot y^{-b} * dy = \frac{a}{1-b} \cdot C_t^{-b+1} \qquad (12)$$

TC_t is a concave function of C_t, and equals the quantity that should appear in the objective function for the investment cost of a learning technology in period ***t***. Adding precision and realism to the cost profile can affect the technology choice dynamics. For example, a lead-time can exist between the beginning and the end of the construction of some large processes, as for some other processes the investments in new capacity can occur progressively over several years, so TIAM-FR spreads the investments over several years. Economic life may be different from the technical life of the process, so the payment of any capital cost is annualised at a different rate than the overall discount rate. Note that additional constraints are used to control the penetration trajectory of learning technologies, as upper investment or capacity bounds along the time trajectory. These constraints allow avoiding unrealistically large investments in some learning technologies in early periods, which could be motivated by long term gains in future periods (investing early allowing the unit investment cost to drop).

In IMACLIM-R, both the majority of technology choices (with the exception of the transport modal choice synthesised in section 3.1) and all technology dynamics are decentralised in the various technology modules that alter, year after year, (i) the Leontief structure (of the 12 productions of the aggregate economic balance of each region, and (ii) the energy intensity of the housing and transportation services consumed by households. This short-term rigidity of techniques, together with the already introduced putty-clay treatment of both productive and end-use capital dynamics, are central to the model's stance on technology dynamics. Long-term substitution possibilities are determined according to dynamic changes in the input-output structure reflecting technological change.

Some of the underlying mechanics are close to TIAM-FR's specifications, *i.e.* rely on cost minimisation over some finite horizon, although generally at a more aggregate scale than TIAM-FR, and under imperfect anticipations — it is particularly the case for the power sector and for residential end-use equipments, or for the costs of the 5 synthetic private car technology options, which decrease with cumulative sales.

Some other technical change mechanisms are modelled in a much less explicit manner, partly for lack and in the waiting of more detailed specifications. First and foremost, exogenous, region-specific labour productivity improvements impact all production sectors. Together with population increase they are the major source of economic growth; their endogenisation is probably beyond the scope of IMACLIM'R's sustainable development focus. Secondly, the energy intensity of transport activities and the transport intensity of all productive sectors autonomously improve, following parameters that are central scenario variables meant to reflect energy efficiency improvements in railways, trucks and planes, and shifts in the logistical organisation of economies.

3-4- International energy markets

In the real economy, the market behaviour of energy producers has direct repercussions on energy prices and hence energy investment decisions and the market share of technologies, but also ultimately on household income and economic growth. Specifically, oil and gas markets are notoriously non competitive, with the resources unevenly distributed across the globe, which prompts producers to constitute oligopoly and exert pricing power.

In TIAM-FR, the specifics of these energy markets are projected through the introduction of additional constraints — for instance, on the investment dynamics of some technologies, on technology mandates, *etc*. However, energy markets are not explicitly modelled and energy prices depend on technical extraction and transport costs and final demands, which in turn are defined exogenously. Incidentally, natural gas prices are differentiated across three regional ensembles: USA, Japan and Europe, whereas crude oil prices are structured according to OPEC and non-OPEC regions with specific extraction costs for each step of each category of supply. TIAM-FR allows endogenous trade of several energy forms: coal (2 forms – lignite and hard coal – declined in 4 resources according to characteristics as costs), natural gas (gaseous and liquefied, declined in 11 resources), crude oil (4 forms — heavy oil, oil sands (mined-synthetic and in situ-ultra heavy), shale oil) declined in 21 resources), gasoline, heavy fuel oil, distillates and naphtha. Some precisions are integrated in trade *via* specific bilateral transportation costs (Loulou *et al*., 2008). In the model, biomass is characterized by manifolds sources (6 forms – solid biomass, industrial wastes, municipal wastes, crops, biogas (landfill) and biofuels (liquids) – declined in 8 resources) but biomass is not traded between regions.

In IMACLIM-R, international trade is considered for all produced goods: in each region the total demands for each good are composed of both imported and domestic varieties. To avoid tracking bilateral flows (thought of as not crucial to energy-environment forecasts, notwithstanding their 'energy security' importance), all trade flows transit by good-specific international pools. For each good international trade is thus characterised by two parameters: the share of each region's exports in the international pool, and the share of the domestic and the imported variety in each region's consumptions.

At the high level of sectoral aggregation of IMACLIM-R, products are composite goods and cannot be, as such, perfect substitutes. One usual way of addressing this issue in TD models is to adopt an Armington (1969) specification, which amounts to aggregate domestic and imported products in a single quantity index (typically a CES index). This allows representing markets in which higher-priced goods keep a share of domestic and international markets. IMACLIM-R adopts this representation for all non-energy goods.

While ensuring the closure of domestic and international markets in money-metric terms, the Armington specification has the major drawback of not allowing to sum up international trade flows in physical terms — the relationship between the Armington index and its constituents being non linear. This is hardly acceptable for energy goods in any analysis of the economy-energy-environment, as it is not compatible with the need to track energy balances expressed in real physical units. For the international markets of oil, coal, gas and electricity, IMACLIM-R thus rather assumes perfect substitutability. However, to avoid that the cheapest exporter would supply all the market, the model follows a market sharing formula. The international market buys energy exports at different prices and sells at a single average world price to importers. The shares of exporters in the international pool and the shares of domestic *vs.* imported energy goods depend on relative export prices and on market fragmentation parameters that are calibrated to reproduce the existing markets structures.

4- A «soft-linking» experiment of TIAM-FR and IMACLIM-R

This last section explores a preliminary soft-linking experiment between the TIAM-FR and IMACLIM-R models.

4-1- The model-linking challenge

As can be gathered from the contrasted presentations of the TIAM-FR and IMACLIM-R rationales, any successful linking of BU and TD models requires operating on 3 axes (Figure 4).

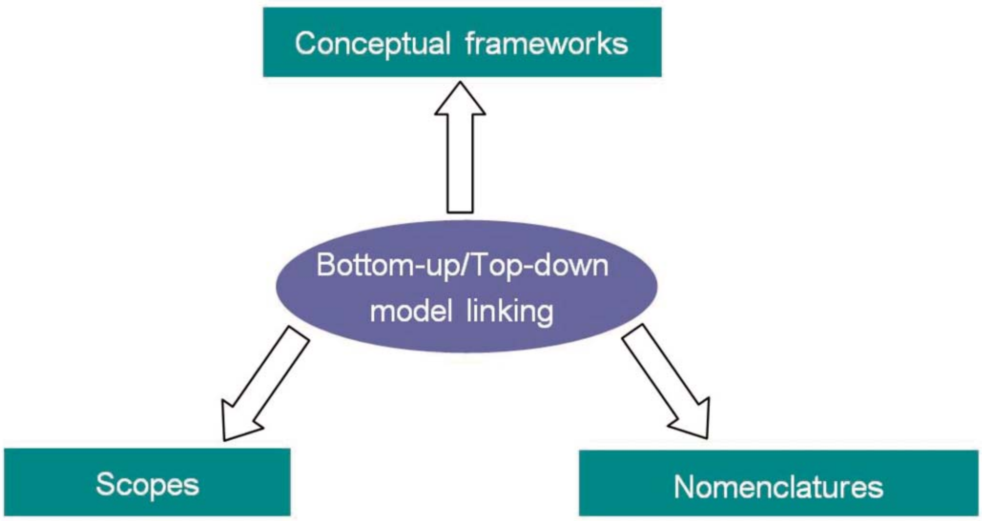

Figure 4 3 axes to the challenge of coupling BU and TD models

First and foremost, the conceptual frameworks of the two candidate models must somehow be conciliated. This is particularly challenging in the case of TIAM-FR and IMACLIM-R, considering their optimisation *vs.* recursive approach of time dynamics. In essence, the optimisation results of TIAM-FR are 'normative' in the sense that they describe cost-minimising investment and consumption trajectories under perfect foresight. Conversely, the simulation results of IMACLIM-R are 'positive' economic trajectories that embark some inefficiencies stemming from the fragmented nature of decision making and the assumption of myopic or imperfect anticipations. The bridge between these seemingly irreconcilable approaches can somewhat be gapped by introducing a set of constraints in TIAM-FR that could emulate some of the sub-optimal features of real economies tentatively modelled by IMACLIM-R. Typically, trade on strategic international markets as that of crude oil can be exogenously constrained, and the rents on crude oil markets represented by increased trading costs. Another possible way of conciliating the two approaches is by simply accepting that a part of the economic system, the part regarding the supply of energy and end-use energy equipments, could be governed in a much more centralised and rational manner than the rest of economic activity. Despite the decentralised nature of energy demand decisions this case could be made considering the extent of policy intervention in energy matters, both on the supply and the demand side of markets. The core divergence remains, however, that TIAM-FR operates under perfect foresight, notwithstanding any additional constraint aimed at controlling its trajectories.

The second axis of research that must be investigated in coupling experiments is that of the modelling scopes. Beyond the obvious fact that a BU model is restricted to energy matters while a TD model extends to all economic activities, the precise coverage of any two candidate models must be thoroughly analysed. From a TD perspective, the treatment of decentralised energy productions is problematic. IMACLIM-R does not indeed model traditional biomass, nor is it well equipped to describe decentralised power production, for the reason that the energy consumptions deriving from these technologies are not backed by market transactions, *i.e.* escape current national accounting conventions on which TD models base their description of economies. From an aggregate point of view, decentralised power production can be modelled as a substitution of capital to energy consumption — but this is true also of any improvement of the energy efficiency of end-use equipments, and the two effects should probably be decoupled; Drouet *et al.* (2009) provide some insightful answers to this challenge (Box 1). Turning to TIAM-FR, the question is that of the availability of any economic information beyond energy markets. Any constraint on investment capacities that could reflect capital market issues? Its explicit representation of end-use equipments, and most importantly building construction & retrofit and personal cars, implies that TIAM-FR reaches beyond energy demand to depict the demand for different equipment sectors. Implicit assumptions on international trade and exchange rates.

The third axis of any coupling experiment is a comparative of nomenclatures. The shared parts of the respective scopes of two candidate models can indeed be organised in quite different manners, considering how the national account logics of TD models differs from the energy balance logics of BU energy models. On the supply side of energy markets, the manifold cost structures of electricity production depicted in TIAM-FR are synthesised in one aggregate sector by IMACLIM-R. Barring a costly disaggregation, in any coupling experiment the capital intensity of this unique sector will have to reflect the various impacts of the penetration of renewable alternatives and the politically-driven future of nuclear electricity, while it will also have to translate the anticipated infrastructure developments — the investment costs of smart-grid deployment; its gas and refined petroleum products intensities shall translate the evolution of fossil-fuel based electricity, while its intensity in agricultural products will be asked to reflect any biomass penetration. On the demand side of energy markets, the broad end-use categories of TIAM-FR's energy balances, particularly the transport, residential and commercial buildings end-uses, aggregate energy consumptions that are dispersed across all the economic agents of IMACLIM-R (the various production sectors and the aggregate household). In some instances the disaggregation of TIAM-FR allows for a more precise connexion to

IMACLIM-R sectors: fuel consumptions from aviation transport can safely be attributed to the aerial transport sector of IMACLIM-R; energy consumptions from bus and rail transport can similarly be attributed to the ground transport sector of IMACLIM-R; the fuel consumptions of trucks and personal cars, however, are much harder to dispatch, first between households and sectors then amongst sectors. Considering the connexion in the other direction, *i.e.* from IMACLIM-R to TIAM-FR, raises yet additional issues: as already hinted, the energy consumptions of the 3 transport sectors of IMACLIM-R aggregate transport and non-transport uses, such as the consumptions required by the heating and cooling of the many commercial buildings necessary to their operation.[9]

Drouet *et al.* (2008, 2009) detail an extensive coupling of the version of TIAM maintained by the ETSAP programme, ETSAP-TIAM, and the TD GEMINI-E3 model. The coupling is performed through an iterative exchange of inputs and outputs playing on the complementarity of the 2 modelling approaches. From ETSAP-TIAM, GEMINI-E3 derives:

- The share of fossil fuels *vs.* electricity and the fossil fuel mix of all its productions and of the consumption of its representative household. These are forced into GEMINI-E3 by downgrading the initial CES production and utility 'nests' into Leontief functions with fixed coefficients, whose trajectories are thus set.[10]
- Evolutions of the global energy intensity of all productions that aggregate (1) energy efficiency improvements; (2) decreases in 'market' energy intensity caused by the penetration of renewable and nuclear energy, which are compensated by increases of either capital intensity or intensity in the agriculture good (biomass).[11]
- Adjustments specific to each energy consumption of all productions that translate the energy requirements of hydrogen production as described by ETSAP-TIAM; these are distributed across sectors *pro-rata* hydrogen consumption following ETSAP-TIAM.
- Adjustments to the specific capital and carbon intensity of electricity production to account for the capital cost of carbon capture and storage.
- Regional prices of the 3 fossil energies. These are again forced into GEMINI-E3 by downgrading the initial CES nest where natural resources (fix factors) appear into a Leontief structure, and adjusting the natural resource coefficient to match ETSAP-TIAM prices.

Conversely, ETSAP-TIAM derives from GEMINI-E3 all its demand drivers (except demography, a preliminarily harmonised exogenous driver to both models).

The iterative exchange of this information between the 2 models is stopped when demand variations between two consecutive runs drop below some choice threshold.

Box 1 The ETSAP-TIAM/GEMINI-E3 coupling experiment

We can now confront the results of this 3-axis exploration with the coupling options. Dwelling on Drouet *et al.* (2008) and Bauer *et al.* (2008) we identify 3 such options:[12]

[9] The share of non-transport uses is statistically relevant: in 2011 the dominant French railway company SNCI devoted 12.4% of its total ton-of-oil equivalent energy consumption to buildings (SNCF, 2011).

[10] For productions, consistency with the original GEMINI-E3 database is guaranteed by reporting any discrepancy on the labour expenses. Similar adjustments on the consumption budget of households are not reported.

[11] The two effects impact different but homogeneous variables of GEMINI-E3.

[12] Drouet *et al.* inventory two supplemental symmetric options that do not apply to the linking of two existing models: (1) extending the TD framework to BU specifications in some of its parts, typically the description of the power sector as do Charles River Associates (1997), Böhringer (1998, 2008), McFarland *et al.* (2004), Bosetti *et al.* (2006), *etc.*; (2) extending a BU model with a reduced macroeconomic growth model, as do Manne and Richels (1992) or Messner and Schrattenholzer (2000).

1. An exchange of information, relying on the complementarity of the inputs and outputs of the two modelling approaches. If the exchange is restricted to exogenous parameters of both models it can be performed without modification of their specifications (*cf. e.g.* Hoffman and Jorgenson, 1977; the 'harmonisation' option of Drouet *et al.*, 2008). To enhance the consistency of modelling results it is however necessary, considering the unavoidable overlap of variables, to 'unplug' some specifications and replace them with exogenous assumptions imported from the other modelling system (*cf.* Drouet *et al.*, 2008, 2009, synthesised Box 1).
2. A calibration of some of the TD model's specifications on results of the BU model (*e.g.* Schäfer and Jacoby, 2006; the 'soft link' option of Bauer *et al.*, 2008): the energy model is used to simulate a large set of investment and consumption trajectories. Some behavioural parameters of the TD model are adjusted to approach the aggregate price and quantities relationships emerging from this simulation set. This option was indeed implemented between the POLES model of energy markets and the IMACLIM-S model, a stripped down version of the IMACLIM-R model (Ghersi *et al.*, 2003; Ghersi and Hourcade, 2006).
3. The fusion of the two models in one single structure. This last option has the obvious advantage of maximising the consistency of the two approaches. The 'hard link' option of Bauer *et al.* (2008), or Böhringer and Rutherford (2005, 2006) explore this option. However, they operate it on schematised models with a view of assessing its theoretical operability. To the best of our knowledge it has never been performed on full-fledged pre-existing models.

Concerning TIAM-FR and IMACLIM-R, the third, theoretically most appealing option is indeed barred by the many dimensions of the nomenclature correspondence problem — notwithstanding the practical difficulties of interfacing two different programming platforms. Although it benefits from the POLES/IMACLIM-S precedent, we must also set aside the calibration of reduced form: considering the level of disaggregation of the IMACLIM-R model and its recursive nature, it would imply calibrating 12 production functions and one household utility function over the time horizon, at the cost of too-great a number of TIAM-FR runs — and based on methodological considerations that cannot be straightforwardly imported from Ghersi *et al.* (2006) and remain to be pinpointed. The natural decision is thus to follow the first option and more specifically Drouet *et al.* (Box 1), not only by default, but also considering how close the macroeconomic core of IMACLIM-R and TIAM-FR are from the GEMINI-E3 and ETSAP-TIAM models.

4-2 - One preliminary numerical exercise

At this first stage, a 'soft' linking may be considered. That is, running first IMACLIM-R model to obtain the primary economic indicators (GDP and sectoral activity levels), which will be subsequently taken by TIAM-FR as drivers of energy demand. This requires preliminary aggregation of the regional distribution of IMACLIM-R, to come closer to that of TIAM-FR; and a disaggregation of IMACLIM-R's heavy industry output, to correspond with the industrial demand sectors of TIAM-FR.

The main outputs of TIAM-FR are future investments and activities of technologies at each time period and in each region. Furthermore, the structure of the energy system is given as an output, *i.e.* type and capacity of the energy technologies, energy consumption by fuel, emissions, energy trade flows between regions, a detailed energy system costs, and marginal costs of environmental measures as GHG mitigation targets. By comparison, IMACLIM-R's outputs cover a range of macroeconomic variables such as GDP, real wages, employment, prices besides investment in energy sectors, energy supply and carbon emissions (Table 3).

Model	Main inputs	Main outputs
TIAM-FR	Evolution of population GDP growth Sectors outputs Lifecycle costs of energy supply and end-use technologies Extraction costs of primary resources Reserves or potential of primary resources	A set of investments in all technologies The operating levels of all technologies The imports and exports of each type of tradeable energy forms The extraction levels of each primary energy form The flows of each commodity into and out of each technology The emissions of CO_2, CH_4 and N_2O by each technology, sector, and total The change in concentration of the GHG The radiative forcing induced by the atmospheric concentration of GHG in the atmosphere The change in global temperature induced by the change in radiative forcing
IMACLIM-R	Population Active population Labour productivity Savings rate Substitution elasticities of household consumption Substitution elasticities of international trade Extent of primary resources	GDP Output (12 productions) Intermediate and final demands (12 goods) inc. final energy demand Producer and consumer prices CO_2 emissions Investment in energy producing capacity GHG emissions

Table 3 *Main inputs and outputs of the TIAM-FR (adpated from Loulou and Labriet, 2008) and IMACLIM-R models*

As these two models existed before the exercise, it is difficult to modify their structures and their resolution methods. But this has to be thought for the further step, where some technical issues must be resolved a priori, and where iteration process may be set up to revise TIAM-FR's expectations (e.g. every 5 years) and feed inputs back to IMACLIM-R to recalculate the new equilibrium prices in each year.

To keep this primary exercise in a tractable manner, our analysis is focused on the simulations of prospects for economic growth, energy demand and carbon emissions. The modelling horizon is 2100. The comparison of TIAM-FR and IMACLIM-R's modelling will highlight world results.

More precisely, we firstly ran IMACLIM-R model to simulate a two contrasting scenarios: business as usual (BAU) and a climate policy scenario, i.e. an atmospheric concentration of CO_2 limited at 450 ppm in 2100 corresponding to a global climate policy designed to achieve the consensual 2°C objective. This allowed us to obtain a variety of macroeconomic indicators which were then integrated into TIAM-FR as drivers of final energy demand through the modelling horizon. Note that

IMACLIM-R and TIAM-FR use the same data and scenario with regards to the growth of population. These data come from United Nations sources. Since the global geographical division in IMACLIM-R and TIAM-FR does not match exactly each other, we have reprocessed the simulation outcome of IMACLIM-R and re-aggregated in accordance with the 15 regions defined in TIAM-FR. Further details of the disaggregation are available upon request.

The macroeconomic indicators in terms of annual growth rate comprise the following elements:

- Annual growth rate of GDP;
- Sectoral activities:
  - Heavy industry output where the growth index from IMACLIM-R's industry sector is disaggregated into four subsectors:
    - Chemicals;
    - Iron & steel and non-ferrous metals;
    - Non-metal minerals and paper;
    - Other energy intensive manufacturing.
  - Services output.
  - Agricultural output.
  - Buildings and construction:
    - Residential floor space (for space heating and cooling);
    - Construction sector.

Secondly, the macroeconomic indicators were integrated into the TIAM-FR model to drive the energy service demand and, from it, determine the energy system in an optimisation framework.

We then ran the TIAM-FR model with the macroeconomic indices coming from IMACLIM-R to calculate the optimal outcome of the energy supply system and carbon emissions trajectories at the world level. We have investigated a set of configuration based on the two contrasting scenarios, i.e. the reference scenario (BAU) and the climate scenario (CLIM), whose drivers are detailed in the following table.

		Drivers – Growth indices from:	
		BAU scenario in IMACLIM-R	**CLIM scenario in IMACLIM-R**
Scenario in TIAM-FR	**BAU**		
	CLIM_dCLIM		
	CLIM_dBAU		

Table 2 Scenario investigation

More precisely, BAU scenario from TIAM-FR is based on macroeconomic indicators extracted from the BAU scenario of IMACLIM-R. Concerning the climate scenario, CLIM_dBAU and CLIM_dCLIM refers to two different trajectories consistent with the 450ppm target in 2100 for CO_2 emissions. CLIM_dBAU is derived from simulation based on the BAU growth indices in IMACLIM-R, whereas CLIM_dCLIM is driven by growth indices from the 450 ppm scenario in IMACLIM-R.

As mentioned above, we have dropped the price elastic energy demand functions in running TIAM-FR as the prices have not been harmonized between the two models. For CLIM_dBAU, energy service demands equal the BAU ones and carbon emissions reduction is totally relying upon the supply side technologies in that the 450 ppm target can be achieved. In comparison, it follows from the utilization of the growth indices of IMACLIM's 450 ppm scenario, a lower level of energy services demands in the climate scenario CLIM_dCLIM reflecting the retroactions of prices. (Energy services demands by sector are presented in Appendices).

Here we present briefly the first results of the modified version of TIAM-FR according to macroeconomic indicators from IMACLIM-R. Comparing these results constitutes an interesting ground for discussion about the sense of harmonization.

CO_2 emissions paths induced by climate constraints are reported in the Figure 7. CO_2 emissions in 2100 would need to be cut by more than 3 in the world to comply with the 450 ppm constraint. In the BAU scenario, global CO_2 emissions would double in 2050 compared to 2000 and would increase to more than 61 Gt in 2100. In CLIM_dBAU and CLIM_dCLIM, the target of 450 ppm allows to reduce the CO_2 emissions until the level of 19 Gt. But it is interesting to note that, for the latter scenarios, the paths are different due to different level of energy demands. Indeed, while the CO_2 emissions pursue its growth in the CLIM_dBAU until 2040 and gradually slow down until the 2100 target, the CO_2 emissions in the CLIM_dCLIM stop growing from 2012 (excepted in 2050, what could be explained by the level of energy demands induced by the drivers).

The comparison of CLIM_dBAU and CLIM_dCLIM pathway shapes illustrates again the divergence between TIAM-fr and IMACLIM-r in terms of modelling philosophy. Under an intertemporal optimized abatement trajectory (CLIM-dBAU), emissions may keep growing by 2040 then slightly drop until 2060 before declining sharply. By contrast, as agent cannot see this *optimal* abatement pathway in the IMACLIM-r therefore the pricing signal must be very strong (which reflects the degree of 450ppm constraint) to curtail the fossil-fuel dependent goods and services demand, as a consequence the growth indices would be much lower than in the case of the *optimal* growth in the short and mid-term. However, in the long run, there would be more flexibility for emission to grow in CLIM-dCLIM than CLIM_dBAU as the economy will be largely decarbonized and thus offers more rooms for emission increase. We can conclude that TIAM-fr and IMACLIM-R will suggest different timing and arbitrage for emission abatement for a given climate target.

At this stage, we should run TIAM-FR with elastic demand in order to compare when we isolate the effect of the implicite elasticities of IMACLIM-R. Giving the emission paths of IMACLIM-R, we also can isolate the impact of how IMACLIM-R manages supply.

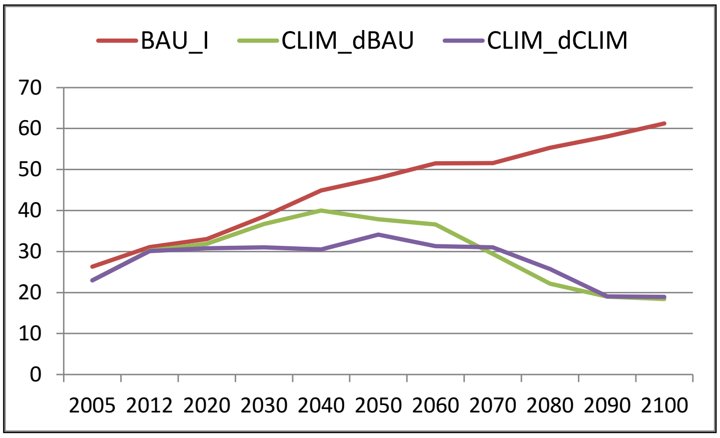

Figure 7 World CO_2 emissions (Gt)

On the other hand, even if whatever the level of the energy demands, sectors being primarily decarbonized to reach the CO_2 emissions mitigation target are the electricity sector, followed by industry, the distribution of the CO_2 emissions by sector varies somewhat according to CLIM_dBAU and CLIM_dCLIM, as showed in the figure 8.

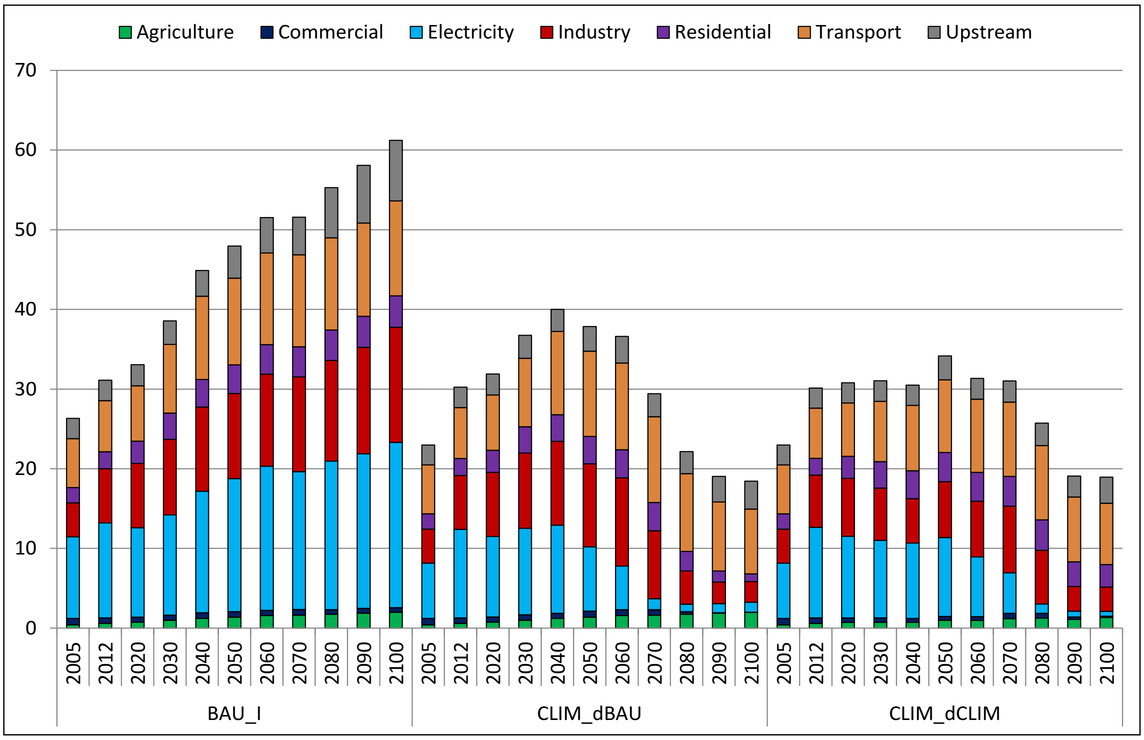

Figure 8 World CO_2 emissions by sector (Gt)

More precisely, in CLIM_dBAU, the CO_2 emitted by the electricity sector decreases from around 7 Gt in 2005 to 1.2 in 2100. CO_2 emissions reach 0.6 Gt in 2100 in the CLIM_dCLIM scenario. CO_2 emissions represent near to 21 Gt in 2100 in the BAU. The share of electricity sector in the total of CO_2 emissions moves from 30% in 2005 to 7% and 3% respectively in CLIM_dBAU and

CLIM_dCLIM. While CLIM_dCLIM appears more stringent in terms of decarbonization for the electricity sector, it is interesting to note that the CO_2 emissions mitigation in the industry is more important in CLIM_dBAU than in CLIM_dCLIM with 2.6 Gt of CO_2 emitted in 2100 in the former against 3 Gt of CO_2 emitted in the latter scenario (14.5 Gt of CO_2 emitted in the BAU in 2100). CO_2 emissions in industry represent in 2100 14% in CLIM_dBAU and 16% in CLIM_dCLIM of the total CO_2 emissions (24% in BAU) against 19% in 2005.

Another sectors impacted by the climate policies implemented in scenario are commercial and residential. In the BAU, these sectors account for 1 and 6% respectively of the CO_2 emissions in 2100 (3% and 7% in 2005). In CLIM_dBAU, they represent near to zero and 5% respectively for commercial and residential sectors in 2100 and 1% and 16% respectively in CLIM_dCLIM at the same period. The CO_2 emissions in commercial sector move from 0.8 Gt in 2005 to 0.007Gt in 2100 (0.1 Gt in CLIM_dCLIM and 0.5 Gt in BAU) in 2100. Note that in the BAU, the CO2 emissions from commercial sector are less high in 2100 than in 2005. As regard the CO_2 emissions in residential sector, they move from 1.9 Gt in 2005 to 0.9 Gt in 2100 (2.8 Gt in CLIM_dCLIM and 3.9 Gt in BAU) in 2100.

These results suggest that transport sector be the most difficult sector to decarbonize. Indeed, impact on the transport sector is less important and the CO_2 emissions mitigation in the climate scenarios is quite limited compared to the BAU, with an ever increasing path of CO_2 emissions in climate scenario even if slower than in BAU. On the other hand, the decarbonization of the other sectors involves than the CO_2 emissions from transport sector represent more than 40% in 2100 in the climate scenarios by comparison with 19% in the BAU.

a. Primary and final energy consumption

World primary energy consumption in the BAU scenario increases by 1.1% per year between 2005 and 2100 reaching a level 2.9 times higher at the end of the period. The world consumption is higher in the CLIM_dBAU scenario in 2100 due to technological substitution to comply with CO_2 mitigation constraints. Conversely, it is interesting to note the effect of the lower level of end-use demand, due to drivers taking into account the policy effect, in the CLIM_dCLIM scenario where the world primary energy consumption represents around 82% of the one in BAU and 77% of the one in CLIM_dBAU.

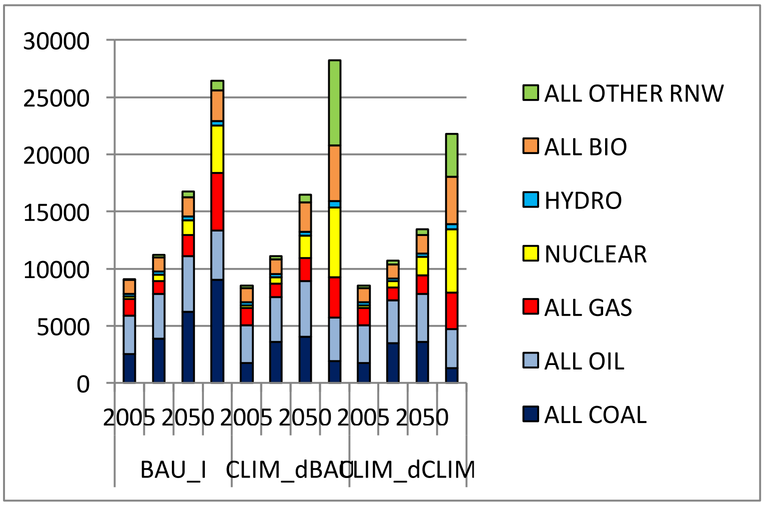

Figure 9 World primary enregy supply (mtoe)

In all the three scenario, the primary energy mix is still dominated by fossil fuel until 2050, as showed in the figure 9. In 2100, constraint falls more heavily and renewables energies are more developed, as nuclear.

The share of renewable energies (excluded hydro), nuclear energy and biomass accounts respectively for 26%, 22% and 17% of the primary energy demand in 2100 in CLIM_dBAU and 17%, 26% and 19% in CLIM_dCLIM. The environmental scenarios have a real impact on the primary energy mix. Demand for biomass and renewable energies increases significantly compare to the BAU while demand for coal and oil decreases sharply. Fossil fuels represent 33% and 36% of the primary consumption, respectively in the CLIM_dBAU and the CLIM_dCLIM scenario, by comparison with BAU where coal, oil and gas account for 69% of the primary mix.

World final energy consumption increases by 0.9% per year between 2005 and 2100 in BAU reaching a level 2.4 times higher at the end of the period. Fossil fuels account for 67% of the final mix in 2005 and 56% in 2100. Renewables increase strongly in the period but they still represent 16% and 17% respectively in 2005 and 2100 of the final energy consumption (Figure 10).

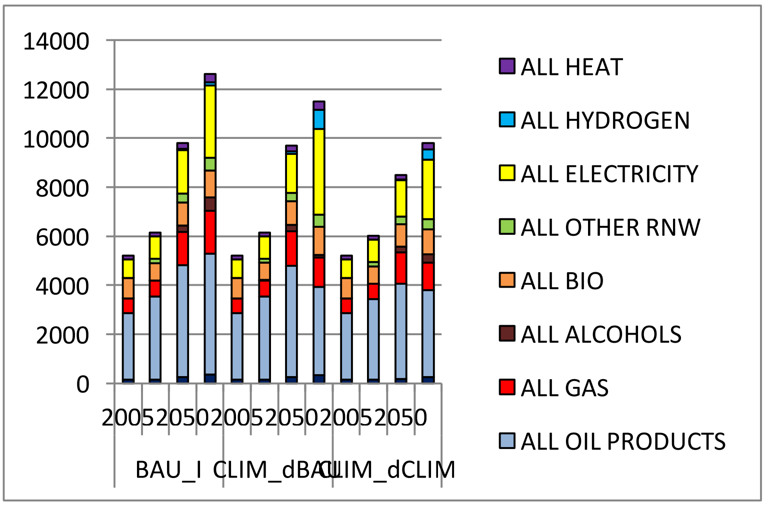

Figure 10 World final energy consumption (mtoe)

Electricity consumption grows by 296% from 2005 to 2100. This growth is higher in CLIM_dBAU, with an increase of 367% in the same period but lower in CLIM_dCLIM, with 223%, reflecting the effect on the demand. In 2100, electricity account for 30% and 25% respectively in CLIM_dBAU and CLIM_dCLIM, relative to BAU where it represents 23%. No large structural change in the final energy final has to be note between the BAU and the climate scenario during the time period. Modifications occur rather in the electricity mix.

b. Electric power generation

Power has been one of the most contributing sectors of carbon emissions. The implementation of environmental policies creates a dazzling deployment of low-carbon emitting sources (nuclear, hydro; renewable and biomass), their contribution in the electricity production being 75% and 83% in 2100 respectively in CLIM_dBAU and CLIM_dCLIM, relative to 47% in BAU. Since 2050, they account more than fossil to the generation of electricity in the climate scenarios. The share of coal and gas drastically decreases with the implementation of an environmental policy constraint and is integrated in the carbon capture technologies deployment which developed strongly in 2100, accounting for 25% and 17% respectively for CLIM_dBAU and CLIM_dCLIM.

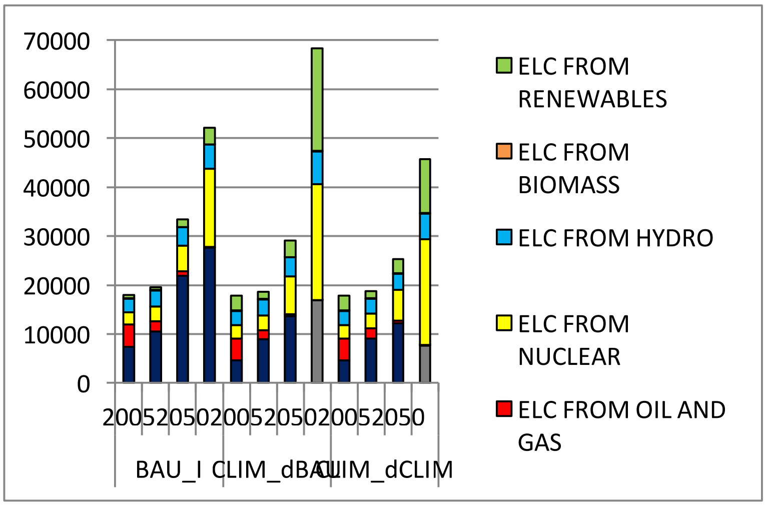

Figure 11 World power generation (TWh)

Figure 11 also describes the strong development of renewables, especially in the scenario CLIM_dBAU where they account for 31% of the power generation. They deployment is less important in the scenario CLIM_dCLIM while nuclear production of electricity is similar in both climate scenarios. It results a share of nuclear reaching 47% in CLIM_dCLIM relative to 35% in CLIM_dBAU.

5- Conclusions and perspective

This paper proposed a new energy modelling framework by coupling two types of energy models for addressing policy issues raised in energy security and climate change mitigation research. In general, TD models such as IMACLIM has richer information on the whole economy with the representation of factor markets (capital, labour). On the other hand, the technology richness of the BU models represents better the technologies available in a specific bounded economy for a given time. It is argued that it is necessary to direct the modelling research towards a hybrid approach through coupling different types of models for environmental policy assessment in a consistent modelling framework. Our simulations show that coupled TD and BU may produce policy relevant simulations results such as carbon abatement and energy supply strategies in the areas of national/global climate policy implementation. However, the applied methodology presents some limitations in terms of indicators harmonization and prices consistency and results should be interpreted with care.

From microeconomic point of view, a major difference residing in TD and BU models is that the behaviours of both energy suppliers and end-users may affect significantly the general equilibrium and underlying prices on the different markets; which in turn will have repercussions on the investment and savings decisions across regions. Also, the government's fiscal policies play a central role in boosting or slowing the economic growth and influence all the institutions of the market.

In summary, Model coupling should take into account the level of linkage, scientific significance and research contribution. It is necessary to couple economic and technology models to respond relevant long term energy and climate policy questions. Our coupling tentative shows that modellers can benefit from information on the whole economy with the representation of factor markets (capital, labour) represented in Macro model on the one hand, and combined with technology richness of the BU models which represent better the technologies available in a specific bounded economy for a given time on the other hand. Nevertheless, the models do not necessarily converge due to the difference in structural design and modelling paradigm. Some technical and mathematical challenges need to be addressed to provide insights into policy recommendations.

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7- Appendix: Energy services demands

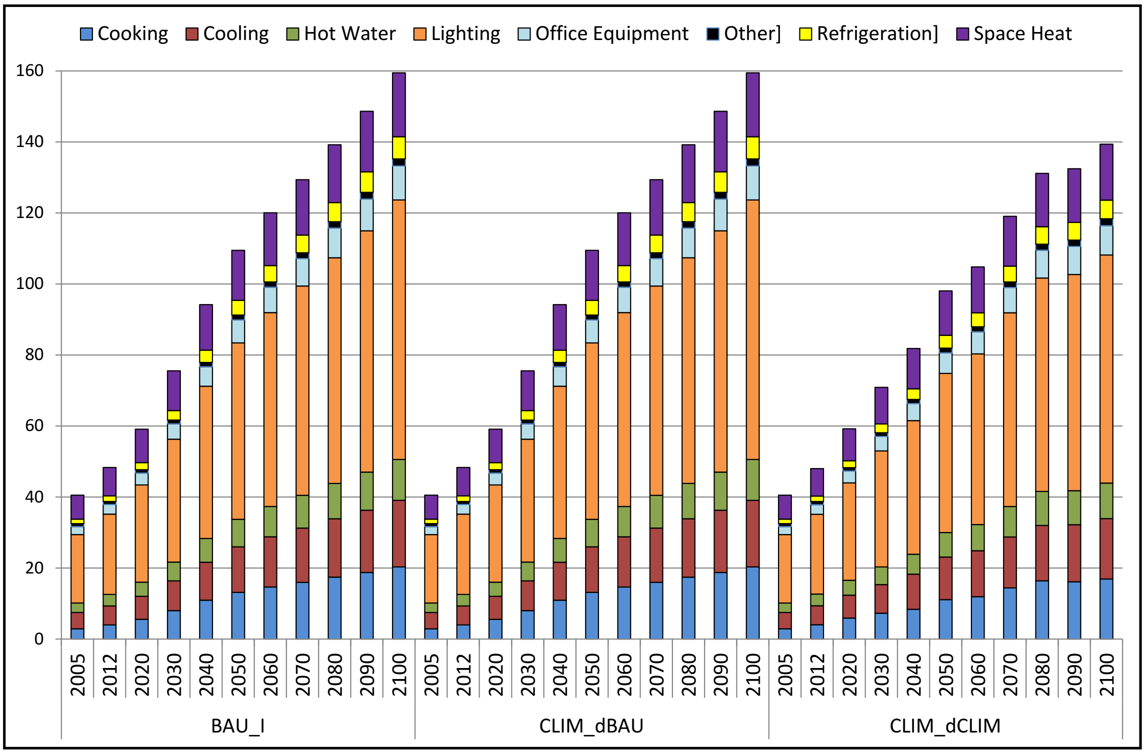

Figure 12. Demands for energy services in commercial sector (EJ)

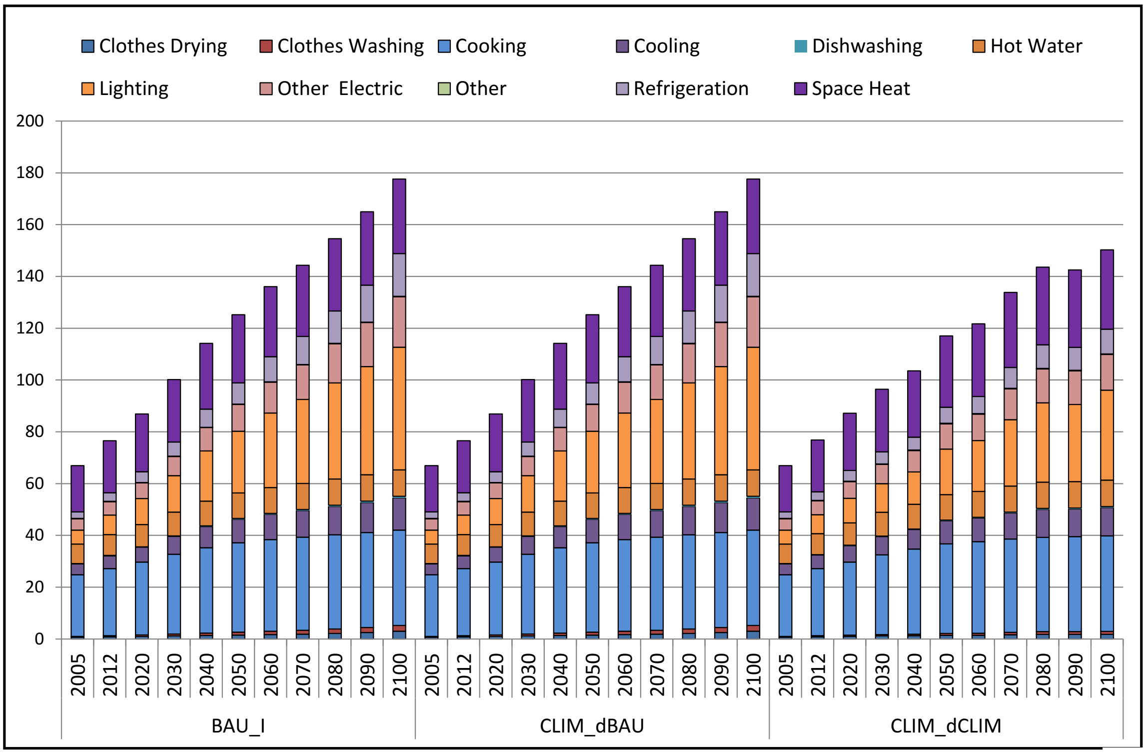

Figure 13. Demands for energy services in residential sector (EJ)

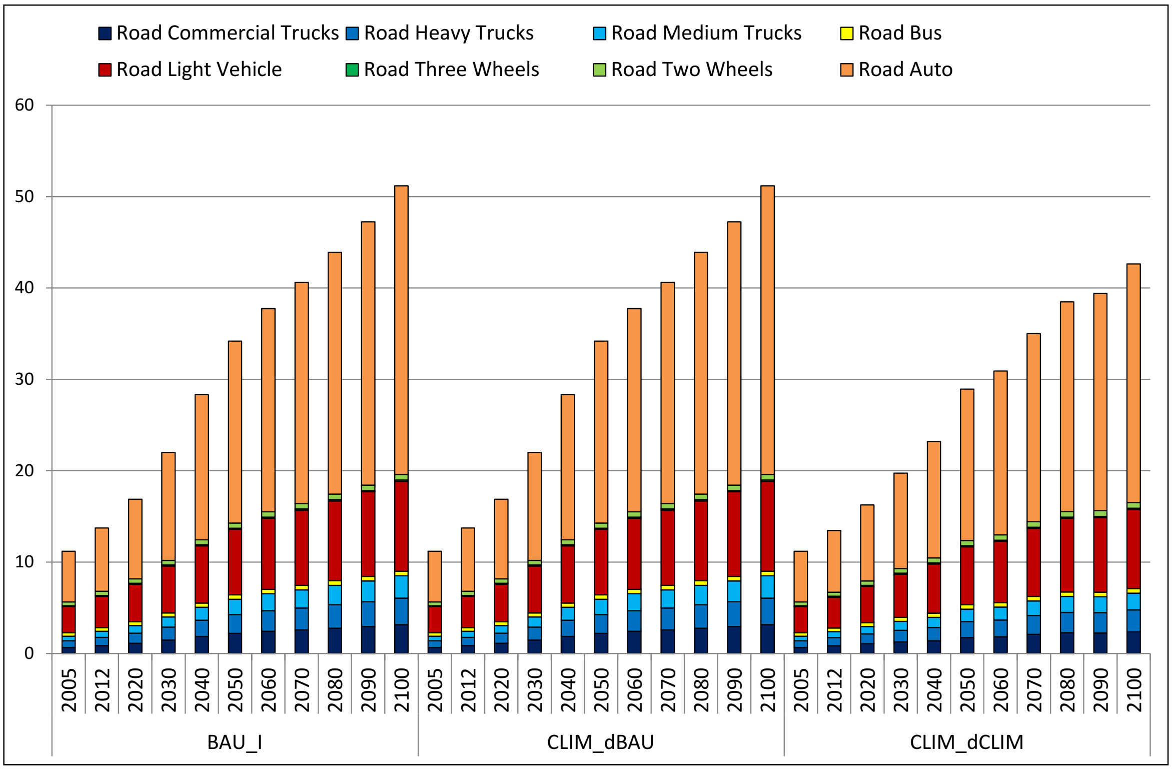

Figure 14. Demands for energy services in transport sector (road transportation) (Bv/km)

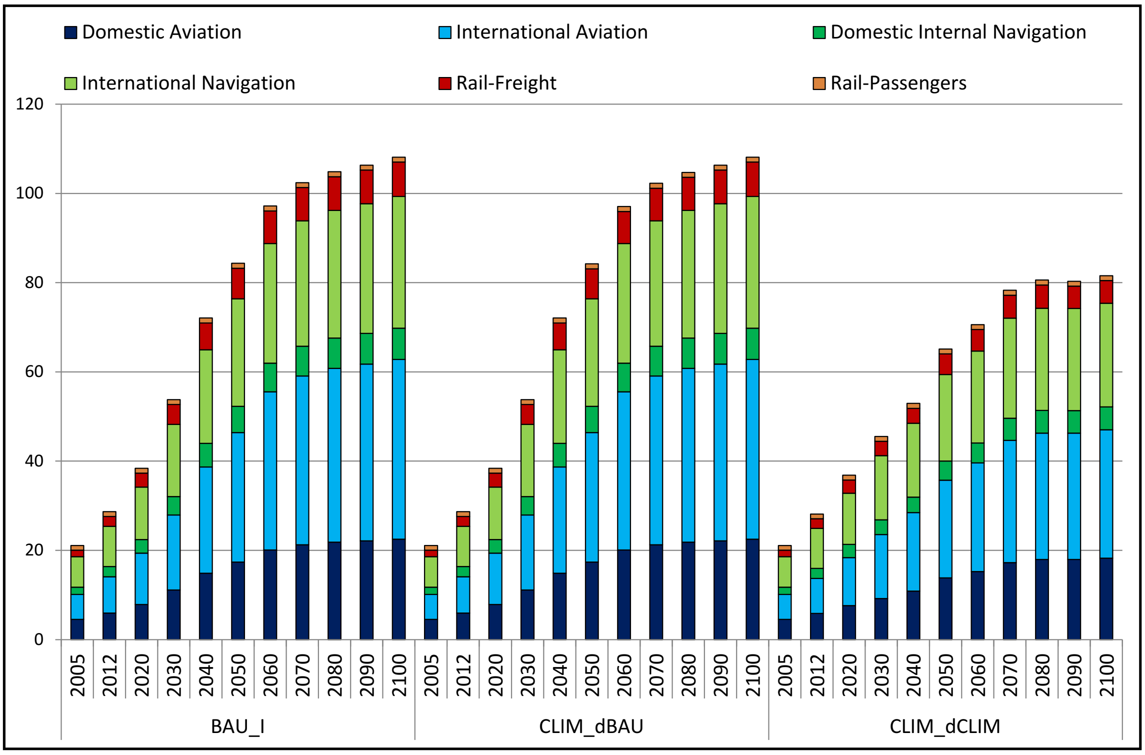

Figure 15. Demands for energy services in transport sector (excl. road transportation) (EJ)

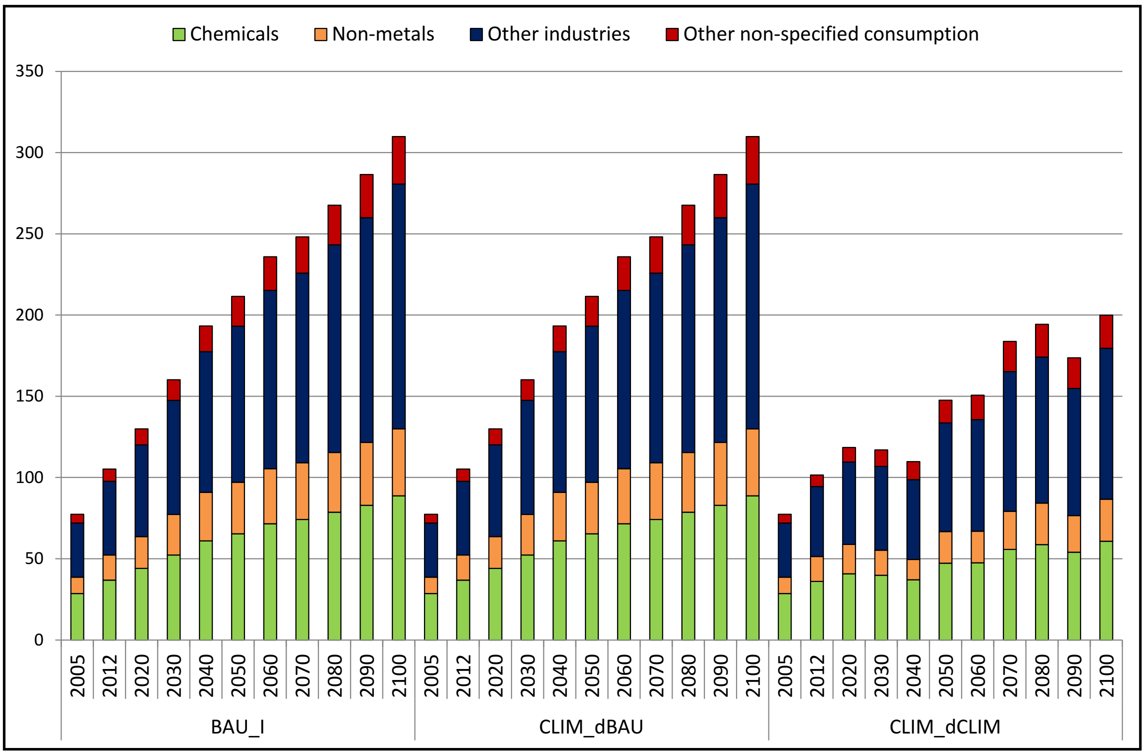

Figure 16. Demands for energy services in industry sector (EJ)

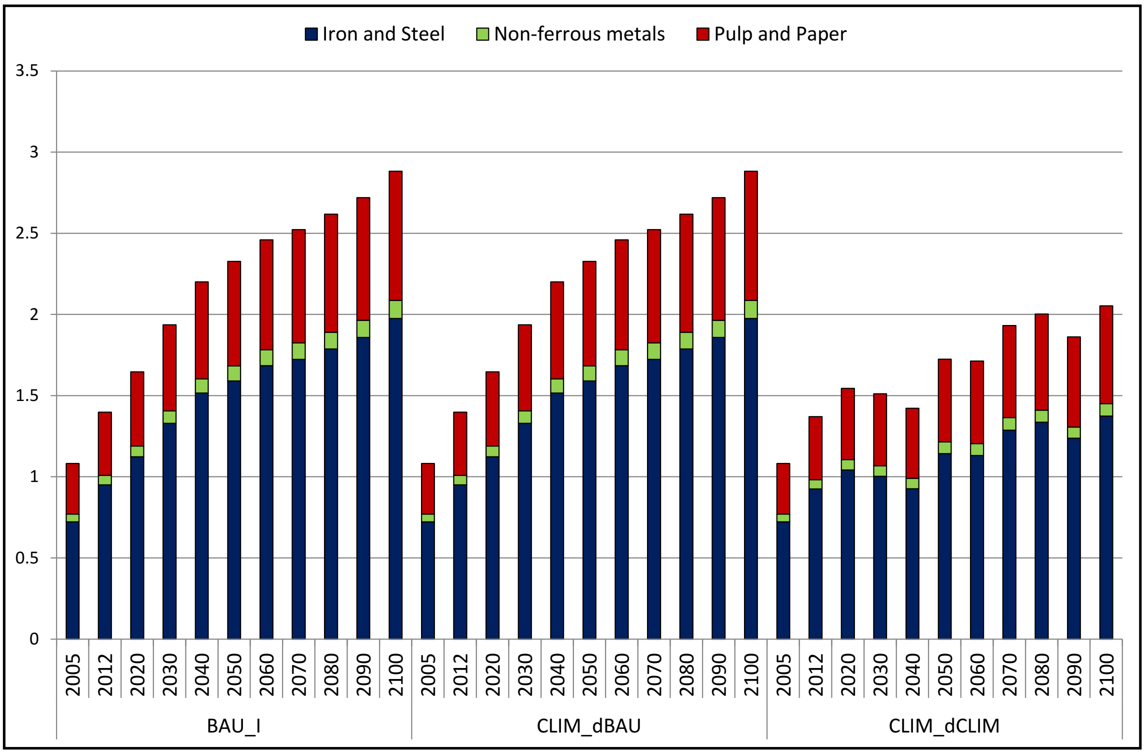

Figure 17. Demands for energy services in industry sector (Mt)

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