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NEW EMISSIONS SCENARIOS

Exploration of long run carbon-intensive pathways with IMACLIM-R

ENSEMBLES Project
Task 7.1b

February 2007

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1 Introduction

This report deals with the research undertaken for the ENSEMBLES European Project at SMASH-CIRED, under the Research Theme 7 ‘Scenarios and policy Implications’, precisely to fulfill Task 7.1b.

Task 7.1 was first focused on the assessment of SRES scenarios, which provided the clear answer that SRES trajectories were still a valid set of reference scenarios to explore the range of uncertainties about non-intervention future pathways (Tol, O’Neill, van Vuuren, 2005; Vuuren and O’Neill, 2006). SMASH was involved in the updated task 7.1b that was to compute some new emissions scenarios that could bring further insights beyond the materials and lessons from SRES. The SRES exercise was a unique attempt to provide a set of scenarios explicitly designed to explore the uncertainties, both from models and from our ignorance of the future. This kind of exercise demands a rigorous coordination scheme, stringent transparency on modeling assumptions, numerous iterations among experts and modelers, and numerous model runs. Therefore, both for scientific and for pragmatic reasons, the research presented in this report do not pretend to provide a new, updated, comprehensive set of trajectories, but rather intend to focus on a specific question.

One major challenge is to reinforce the internal consistency of long run scenarios, through an endogenous representation of the interactions between macroeconomic, technological and structural variables. The Imacim-R model aims precisely at allowing a representation detailed enough as to reinforce the plausibility of the simulated trajectories, and facilitating the dialog between modellers, experts, and stakeholders. Two research issues are at stake in this innovative modelling approach:

- (i) On one side, a stronger consistency could probably limit the uncertainty of emission trajectories, if some combinations of exogenous trends are deemed to be impossible,
- (ii) On the other side, the modelling of endogenous mechanisms instead of exogenous trends should in principle lead to more robust assessments of the impact from energy and climate policies, owing to an explicit modelling of more numerous possible feedbacks.

We chose to apply this approach to try and explore scenarios that could be in the upper bound of carbon-intensive pathways. This choice stems from two facts in the current research community:

- (i) In many studies, we observed that the multi-scenario approach is somehow abandoned in favor of a single medium reference trajectory, which we think very harmful for policy-oriented as academic research;

- (ii) Recent trends of energy and carbon intensity led to a strong increase of emissions that follows the upper bound of the SRES scenarios, in spite of the ETS, the Kyoto Protocol and the plausibility of future stringent GHG regulations. This means that some deep forces – growth, technology or development styles – actually push emissions upwards and are likely to do so during the following decades more than sometimes expected *on average*.

Understanding what are the forces behind a carbon-intensive scenario could play a significant role in the design of appropriate policies in due time, to counterbalance these forces and lead the economy on a decarbonization path.

The report is divided in two parts: first it presents the Imaclim-R model, its rationale and its detailed specifications; second it presents a set of emission scenarios computed with Imaclim-R thanks to the most recent developments. The new scenarios explore what could be the energy and non-energy drivers of high emissions trajectories. We focus our analysis on the link between trajectory uncertainty and the interactions between global growth regimes, price signals, technology potentials and development styles.

2 The Imaclim-R framework

The risk of non sustainable development stems ultimately from the joint effect of issues as diverse as climate change, energy and food security, land cover changes or social dualism in urban and rural areas. These issues in turn depend on the dynamics of consumption and technologies in sectors such as energy, transportation, construction or food production and on the hazards caused by shortages of primary resources or by the transformation of our global environment. The challenge is thus to integrate sector-based analysis in a common economic framework capturing their interplay in a world experiencing very rapid demographic and economic transitions.

The IMACLIM-R structure presented in this paper tries and meets this challenge through an integrated modeling approach (Weyant et al., 1996). Its primary aim is to provide an innovative framework that could organize better the dialogue between economics (to capture the general interdependences between sectors, issues and policy decisions), demography (to represent a major driver of the world economic trends), natural sciences (to capture the feedbacks of the alteration of the ecosystems) and engineering sciences (to capture the technical constraints and margins of freedom).

We first present the rationale of the IMACLIM-R structure; the following part contains the technical description of its static and dynamic components.

2.1 Rationale of the IMACLIM-R modeling blueprint

The overall rationale of IMACLIM-R stems from the necessity to understand better, amongst the drivers of baseline and policy scenarios, the relative role of *(i) technical parameters* in the supply side and in the end-use equipments, *(ii) structural changes* in the final demand for goods and services (dematerialization of growth patterns), *(iii) micro and macroeconomic* behavioral parameters in opened economies. This is indeed critical to capture the mechanisms at play in transforming a given environmental alteration into an economic cost and in widening (or narrowing) margins of freedom for mitigation or adaptation.

The specific way through which IMACLIM-R tries and reaches this objective derives from a twofold diagnosis about the challenges for designing more useful baseline scenarios:

- The increasing recognition that endogenizing technical change to capture policy induced transformation of the set of available techniques should be broadened to the endogeneization of *structural* change. As noted by Solow (1990) indeed, the rate and direction of technical progress depend not only on the efficiency of

physical capital on the supply side but also on the structure of the final households' demand. Ultimately they depend upon the interplay between consumption styles, technologies and localization patterns. The point is that drastic departures from current trends possibly required by sustainability targets cannot but alter the very functioning of the macroeconomic growth engine.

- Although computable general equilibrium models represented a great progress in capturing economic interdependences that are critical for the environment-economy interface; their limit is to study equilibrated growth pathways, often under perfect foresight assumptions, whereas sustainability challenges come primarily from controversies about long term risks. These controversies and the delay in perceiving complete impacts cannot but inhibit their internalization in due time and trigger higher transition costs necessary to adapt to unexpected hazards. This makes it necessary to describe an economy with disequilibrium mechanisms fueled by the interplay between inertia, imperfect foresights and 'routine' behaviors. For instance, an economy with structural debt or unemployment and submitted to volatile energy prices will not react in the same way to environmental shocks or policy intervention as an economy situated on a steady state growth pathway.

2.1.1 A Dual Vision of the Economy: an easier dialogue between engineers and economists

IMACLIM-R is based on an explicit description of the economy both in money metric values and in physical quantities linked by a price vector¹. The existence of explicit physical (and not only surrogate) variables comes back to the Arrow-Debreu axiomatic. In this context, it provides a dual vision of the economy allowing to check whether the projected economy is supported by a realistic technical background and, conversely, whether the projected technical system corresponds to realistic economic flows and consistent sets of relative prices. It does so because its physical variables allow 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. This information encompasses (i) engineering based analysis about economies of scale, learning by doing mechanisms and saturations in efficiency progress (ii) expert views about the impact of incentive systems, market or institutional imperfections and the bounded rationality of economic behaviors.

¹ For the very subject of climate change mitigation, which implies the necessity to account for physical energy flows, modellers use so-called 'hybrid matrices' including consistent economic input-output tables and physical energy balances (see Sands et al., 2005). In Imacim-R we aim at extending physical accounting to other non-energy relevant sectors such as transportation (passenger-kilometres, ton-kilometres) or industry (tons of steel, aluminium, cement).

One major specificity of this dual description of the economy is that it no longer uses 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 robustness², their main limit, when representing technology, is that they resort to the Sheppard's lemma to reveal 'real' production functions, after calibration on cost-shares data. And yet, 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 of time, result from an optimal response to the current price vector³ 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 issues⁴. Even more important, the use of such production functions prevents from addressing the path-dependency of technical change.

The solution retained in IMACLIM-R is based on the 'belief' that it is almost impossible to find tractable functions with mathematical properties suited to cover large departures from reference equilibrium over one century and flexible enough to encompass different scenarios of structural change resulting from the interplay between consumption styles, technologies and localization patterns (Hourcade, 1993). Instead, the productions functions at each date and their transformation between t and $t+n$ are derived from a recursive structure that allows a systematic exchange of information between:

- An annual static equilibrium module, in which the equipment stock is fixed and in which the only technical flexibility is the utilization rate of this equipment. Solving this equilibrium at t provides a snapshot of the economy at this date: a set of relative prices, levels of output, physical flows, profitability rates for each sector and allocation of investments among sectors;

² Having assessed one thousand econometric works on the capital-energy substitution, Frondel and Schmidt conclude that "*inferences obtained from previous empirical analyses appear to be largely an artefact of cost shares and have little to do with statistical inference about technology relationship*" (Frondel and Schmidt, 2002, p.72). This comes back to the Solow's warning that this 'wrinkle' is acceptable only at an aggregate level (for specific purposes) and implies to be cautious about the interpretation of the macroeconomic productions functions as referring to a specific technical content' (Solow, 1988, p. 313) .

³ "Total-factor-productivity calculations require not only that market prices can serve as a rough-and-ready approximation of marginal products, but that aggregation does not hopelessly distort these relationships." (Solow, 1988, p. 314)

⁴ Babiker, M.H., J.M. Reilly, M. Mayer, R.S. Eckaus, I. Sue Wing and R.C. Hyman (2001). « The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Emissions, Sensitivities and Comparison of Results. Massachusetts Institute of Technology ». *Joint Program on the Science and Policy of Global Change report #71* (http://web.mit.edu/globalchange/www/MITJPSPGC_Rpt71.pdf)

- 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, computes the reaction of technical systems and send back this information to the static module in the form of new coefficients for calculating the equilibrium at $t+1$.

Each year, technical choices for new equipments are flexible; they modify at the margin the factors and overall productivity embodied in the existing equipments that result from past technical choices. This general putty-clay⁵ assumption is critical to represent the inertia in technical systems and how the economy adapts not only to the level and direction of economic signals but also to their volatility.

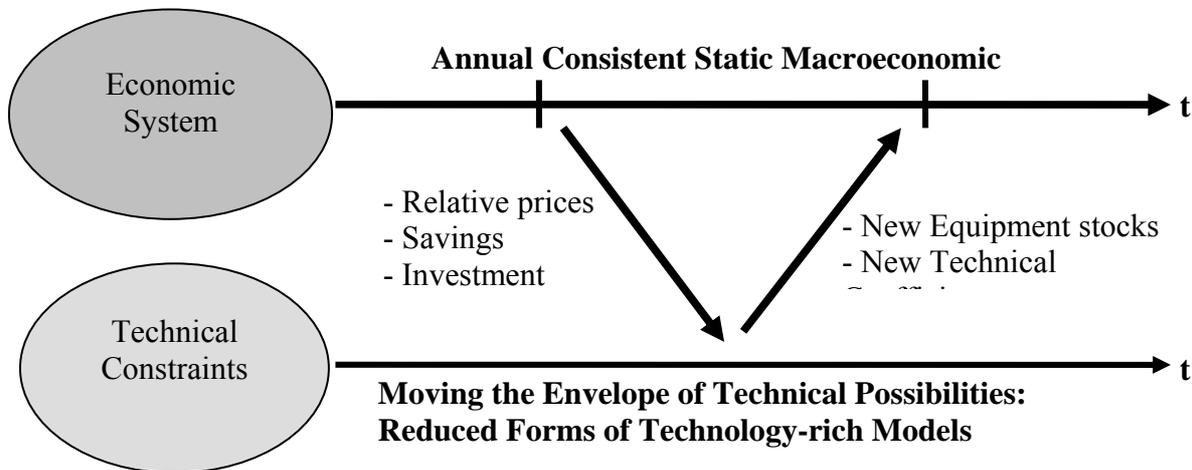


Figure 1: Iterative Top-down / Bottom-Up dialogue in IMACLIM-R

This modular structure allows to couple a rather aggregated static equilibrium with sector-specific bottom-up reaction functions (transportation, energy, land-use) that capture explicit and tangible drivers of structural and technical changes in a compact way⁶. These reduced forms are calibrated to approximate the response of bottom-up models to a set of economic parameters (price signals, investments). The level of sector aggregation and the compactness of bottom-up modules can thus be adapted in function

⁵ Doing this we neglect the existing possibilities of ‘retrofitting’ existing capital from one technology to an other one, or from one sector to an other sector. This can be modified easily in the modules describing capital dynamics. In the current version of the model our choice is to represent somehow the upper bound of inertia.

⁶ Building these ‘compact’ bottom-up reaction functions avoids us the daunting and perhaps useless task of building general equilibrium structures with as many product categories as in engineering based descriptions of the energy systems.

of the objective of the modeling exercise. One benefit of this modeling strategy is to test the influence of the various assumptions about decision-making routines and expectations (perfect or imperfect foresight, risk aversion...).

2.1.2 A growth engine allowing gaps between potential and real growth

IMACLIM-R's growth engine is conventionally composed of exogenous demographic trends and labor productivity changes and is fuelled by regional net investment rates and investments allocation among sectors. The specificity of this engine is to authorize endogenous disequilibrium so as to capture *transition* costs after a policy decision or an exogenous shock. Retaining endogenous disequilibrium mechanisms comes to follow Solow's advice (1988) that, when devoting more attention to transition pathways, economic cycles should not be viewed as "optimal blips in optimal paths in response to random variations in productivity and the desire for leisure [...] and the markets for goods and labor [...] as frictionless mechanisms for converting the consumption and leisure desires of households into production and employment". We thus adopted a "Kaleckian" dynamics in which investment decisions are driven by profit maximization under imperfect expectations in non fully competitive markets⁷. Disequilibria are endogenously generated by the inertia in adapting to changing economic conditions due to non flexible characteristics of equipment vintages available at each period. The inertia inhibits an automatic and costless come-back to a steady-state equilibrium. In the short run the main available flexibility lies in the rate of utilization of capacities, which may induce excess or shortage of production factors, unemployment and unequal profitability of capital across sectors. Progress in computational capacity now allows to run disequilibrium models that incorporate features that avoid the drawback of Harrod-Domar's knife-edged growth with structural (and unrealistic) crisis, and this without resorting to the "wrinkle" (Solow, 1988) of the production function which tended to picture frictionless return to the steady state. The growth pathways generated by IMACLIM-R always return to equilibrium in the absence of new exogenous shock, but after 'some' transition.

⁷ We are encouraged in this direction by the Stiglitz's remark that some results of neo-classical growth model incorporating costs of adjustment "have some semblance to those of the model that Kaldor (1957, 1961) and Kalecki (1939) attempted to construct" which "may be closer to the mark than the allegedly "theoretically correct" neoclassical theory" (Stiglitz 1993, pp 57-58)

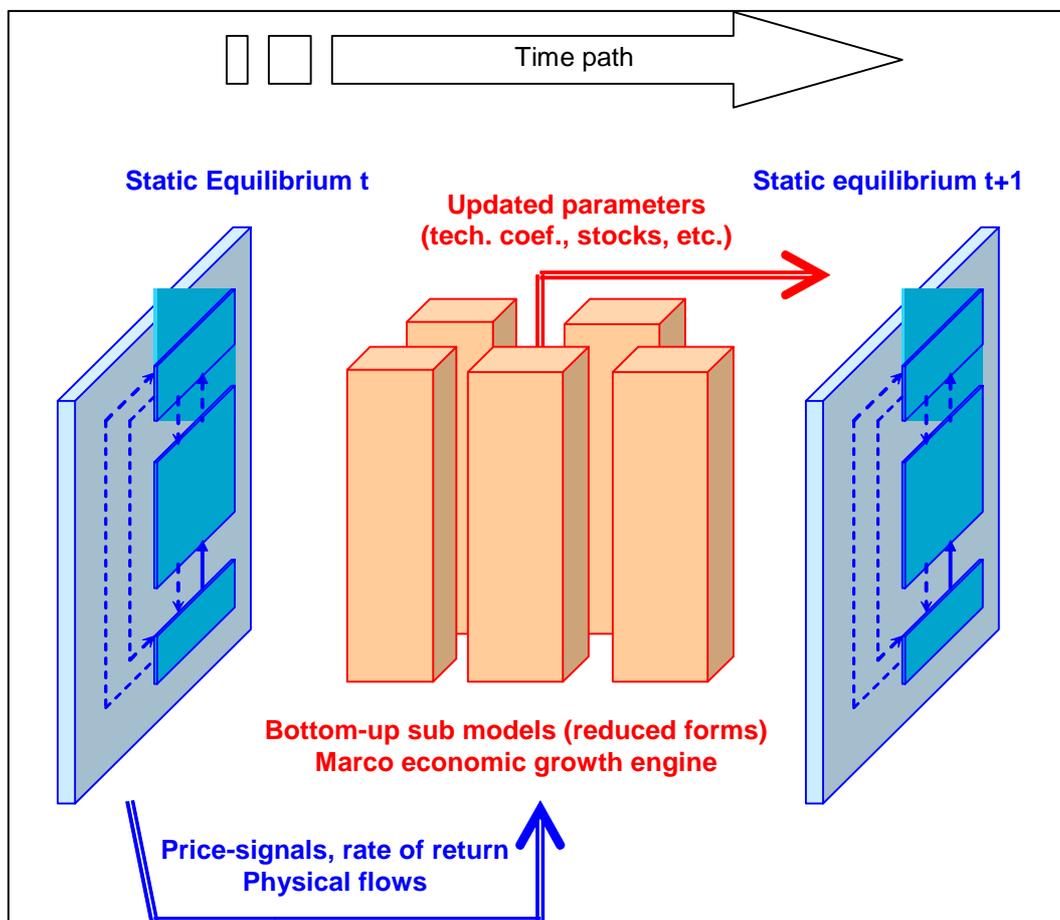


Figure 2 : The recursive dynamic framework of IMACLIM-R

2.2 Technical Description

2.2.1 Aggregation scheme and Data

IMACLIM-R is a multi-sector multi-region dynamic recursive growth model. The time-horizon of the model is 2100. The model is run for a partition of the world in twelve regions and twelve economic sectors. The model is calibrated on economic data from the GTAP 6 database (benchmark year is 2001), physical energy data from ENERDATA 4.1 database and passenger transportation data from (Schafer and Victor, 2000).

The mapping of regional and sector aggregation of the original regions⁸ and sectors⁹ of GTAP 6 can be found in the following tables.

IMACLIM-R 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.

Table 1 : Regional aggregation

⁸ For a comprehensive description of GTAP 6.0 region see : https://www.gtap.agecon.purdue.edu/databases/v6/v6_regions.asp

⁹ For a comprehensive description of GTAP 6.0 sectors see : https://www.gtap.agecon.purdue.edu/databases/v6/v6_sectors.asp

Imaclim-R sectors	GTAP sectors
Coal	Coal
Oil	Oil
Gas	Gas
Refined products	Petroleum and coal products
Electricity	Electricity
Construction	Construction
Air transport	Air transport
Water transport	Sea transport
Terrestrial transport	Other transport
Agriculture and related industries	Paddy rice, Wheat, Cereal grains nec, Vegetables, fruit, nuts, Oil seeds, Sugar cane, sugar beet, Plant-based fibers, Crops nec, Cattle, sheep, goats, horses, Animal products nec, Raw milk, Wool, silk-worm cocoons, Forestry, Fishing, Meat, Meat products nec, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Food products nec, Beverages and tobacco products.
Energy-intensive Industries	Minerals nec, Textiles, Wearing apparel, Leather products, Wood products, Paper products, publishing, Chemical, rubber, plastic prods, Mineral products nec, Ferrous metals, Metals nec, Metal products, Motor vehicles and parts, Transport equipment nec, Electronic equipment, Machinery and equipment nec, Manufactures nec.
Other industries and Services	<i>Rest of sectors</i>

Table 2 : Sector aggregation

In the following pages, we describe the equations of the static equilibrium that determine short-term adjustments, and the dynamic modules that condition the motion of growth. Index k refers to regions, indexes i and j refer to goods or sectors, index t refers to the current year and t_0 to the benchmark year 2001.

2.2.2 Static Equilibrium

The static equilibrium is Walrasian in nature: domestic and international markets for all *goods* are cleared by a unique set of relative prices. On the production side, whereas total investment flows are equilibrated, the utilization rate of production capacities can vary and there is no guarantee that the labor force is fully employed. Those mechanisms depend on the behaviors of representative agents on the demand and supply sides. They derive from (i) the maximization of a households' representative utility function under budget constraints, (ii) the choice of the utilization rate of installed production capacities, (iii) the decision routines in government policies, (iv) the adjustments of commercial and capital flows, (v) the allocation of investments among sectors. The calculation of the equilibrium determines the following variables: relative prices, wages, labor, quantities of goods and services, value flows. At the equilibrium, all are set to satisfy market clearing conditions for all tradable goods under budget constraints of agents and countries while respecting the mass conservation principle of physical flows.

2.2.2.1 Households demand of goods, services and energy

Consumers' final demand is calculated by solving the utility maximization program of a representative consumer¹⁰. The distinctive features of this program come from the arguments of the utility function and from the existence of two budget constraints (income and time).

Income and savings

Households income is equal to the sum of wages received from all sectors i in region k (non mobile labor supply), dividends (a fixed share $div_{k,i}$ of regional profits) and lump-sum public transfers, as shown in equation [1]. Savings are a proportion ($1-ptc_{k,i}$) of this income, set as a scenario variable which evolves in time in function of exogenous assumptions that translate views about how saving behaviors will change in function of the age pyramid¹¹.

¹⁰ Here we follow (Muellbauer, 1976) who states that the legitimacy of the representative consumer assumption is only to provide 'an elegant and striking informational economy', by capturing the aggregate behavior of final demand through a utility maximization. This specification remains valid as long as the dispersion of individual consumers' characteristics is not evolving significantly (Hildenbrand, 1994).

¹¹ A full endogeneisation of the saving rates over the long run would require a better description of the loop between demography and economic growth. Advances in that direction will be undertaken in collaboration with the INGENUE 2 model (CEPII, 2003).

$$Income_k = \sum_j wages_{k,j} + \sum_j div_{k,j} \cdot profits_{k,j} + transfers_k \quad [1]$$

$$Savings_k = (1 - ptc_k) \cdot Income_k \quad [2]$$

Utility function

The arguments of the utility function U are (i) the goods $C_{k,i}$ produced by the agriculture, industry and services sectors (ii) mobility service $S_{k,mobility}$ (in passenger-kilometers pkm) (iii) housing services $S_{k,housing}$ (in square meters). Basic needs of each good or service are noted bn .

$$U = \prod_{\substack{\text{goods } i \\ (\text{agriculture,} \\ \text{industry,} \\ \text{services})}} (C_i - bn_i)^{\xi_i} \cdot (S_{\text{housing}} - bn_{\text{housing}})^{\xi_{\text{housing}}} \cdot (S_{\text{mobility}} - bn_{\text{mobility}})^{\xi_{\text{mobility}}} \quad [3]$$

First note that energy commodities are considered only as production factors of housing services and mobility: they are not directly included in the utility function. They will impact on the equilibrium and welfare through the associated energy bill. Energy consumption for housing is derived from the physical stock of lodging and from efficiency coefficients characterizing the existing stock of end-use equipments 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-motorized. Due to differences in amenities delivered by each mode and to regional particularities, the transport modes are assumed imperfect substitutes. The amounts of passenger-kilometers pkm_{mode} in the different modes are nested in a single index of mobility service, within a constant-elasticity-of-substitution function.

$$S_{k,mobility} = \left(\left(\frac{pkm_{k,air}}{b_{k,air}} \right)^{\eta_k} + \left(\frac{pkm_{k,public}}{b_{k,public}} \right)^{\eta_k} + \left(\frac{pkm_{k,cars}}{b_{k,cars}} \right)^{\eta_k} + \left(\frac{pkm_{k,nonmotorized}}{b_{k,nonmotorized}} \right)^{\eta_k} \right)^{-\frac{1}{\eta_k}} \quad [4]$$

The advantage of not entering energy in the utility function is to allow an explicit representation of the end-use efficiency. The final energy demands from households are derived from the levels of $S_{k,housing}$ and $pkm_{k,cars}$ through equation [5]:

$$C_{k,Ei} = pkm_{k,cars} \cdot \alpha_{k,Ei}^{Cars} + S_{k,housing} \cdot \alpha_{k,Ei}^{m^2} \quad [5]$$

where α^{cars} are the mean energy consumption to travel one passenger-kilometer with the current stock of private cars and α^{m^2} is the consumption of each energy product per square meter of housing. These parameters are held constant during the resolution of the static equilibrium and are adjusted in the residential module (see 0) that describes the changes in nature of end-use equipments and their energy requirements.

Maximization program

In order to capture the links between final demand and the availability of infrastructures and equipments, IMACLIM-R considers that consumers maximize their utility under two constraints:

(i) A **disposable income constraint** which imposes that purchases of non-energy goods and services $C_{k,i}$ and of energy (induced by transportation by private cars and end-use services in housing) are equal to the income available for consumption (equation [6]), for a given set of consumers prices $pC_{k,i}$,

$$ptc_k \cdot Income_k = \sum_i pC_{k,i} \cdot C_{k,i} + \sum_{Energies\ E_i} pC_{k,E_i} \cdot (pkm_{k,cars} \cdot \alpha_{k,E_i}^{cars} + S_{h,housing} \cdot \alpha_{k,E_i}^{m^2}) \quad [6]$$

(ii) A **time budget constraint** which imposes an upper limit to the average time people can (or are willing to) devote to daily transportation. This rests on the so-called Zahavi's law (Zahavi et Talvitie, 1980), stating that the average daily travel time of households in a large panel of cities remains constant over decades. The choice between different transportation modes depends not only on their relative prices but also on their relative marginal travel time efficiency τ_{k,T_j} i.e. the time needed to travel one additional kilometer by the mode T_j . Each mode is characterized by a specific *travel time efficiency* which decreases with the utilization rate of its infrastructures. The more one approaches the capacity limit $Captransport_{k,T_j}$ of its infrastructures (expressed in kilometers of road or rail, or seat-kilometers), the less each mode will be time-efficient because of congestion (Figure 3). The Zahavi constraint reads¹²:

$$Tdisp_k = \sum_{means\ of\ transport\ T_j} \int_0^{pkm_{k,T_j}} \tau_{k,T_j} \left(\frac{u}{Captransport_{k,T_j}} \right) du \quad [7]$$

Obviously, as explained in section 0, this capacity limit will change over time according to the amount of investment devoted to each type of infrastructure.

¹² Assuming a 1.1 hour per day traveling, the total annual time devoted to transportation is given by $Tdisp_k = 1.1 \cdot 365 \cdot L_k$ where L_k is the total population.

2.2.2.2 Production constraints and supply curves

At each point in time producers are assumed to operate under constraint of a fixed production capacity $Cap_{k,i}$, defined as the maximum level of physical output achievable with installed equipments. However the model allows short-run adjustments to market conditions through modifications of the utilization rate $Q_{k,i}/Cap_{k,i}$. This represents a different paradigm from usual production specifications, since the ‘capital’ factor is not always fully operated. It is grounded on three broad set of reasons: (i) beyond a certain utilization rate, static diminishing return cause marginal operating costs to become higher than the market price; (ii) security margins are set in case of technical failures or of unexpected selling opportunities, (iii) the existence of economic cycles contrast with the fact that capital intensive industries calibrate their capacity expansion over long periods of time and then undergo ups and downs of their revenues.

Supply cost curves in IMACLIM-R thus show static decreasing returns: production costs increase when the capacity utilization rate of equipments approaches one (Figure 3). In principle these decreasing return may concern all the intermediary inputs and labor. However, for simplicity sake and because of the orders of magnitude suggested by the work of (Corrado and Mattey, 1997) on the link between utilization rates of capacities and prices, we assume that the primary cause of higher production costs consists in higher labor costs due to extra hours with lower productivity, costly night work and more maintenance works. We thus set (i) 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 labor; (ii) a decreasing return parameter $\Omega_{k,i} = \Omega(Q_{k,i}/Cap_{k,i})$ on wages only, at the sector level¹³ (see [9]).

Actually this solution comes back to earlier works on the existence of short-run flexibility of production systems at the sector level with putty-clay technologies (Marshall, 1890, Johansen, 1959) demonstrating that this flexibility comes less from input substitution than from variations in differentiated capacities utilization rates.

¹³ The treatment of crude oil production costs is an exception: the increasing factor weighs on the mark-up rate, to convey the fact that oligopolistic producers can take advantage of capacity shortages by increasing their differential rent.

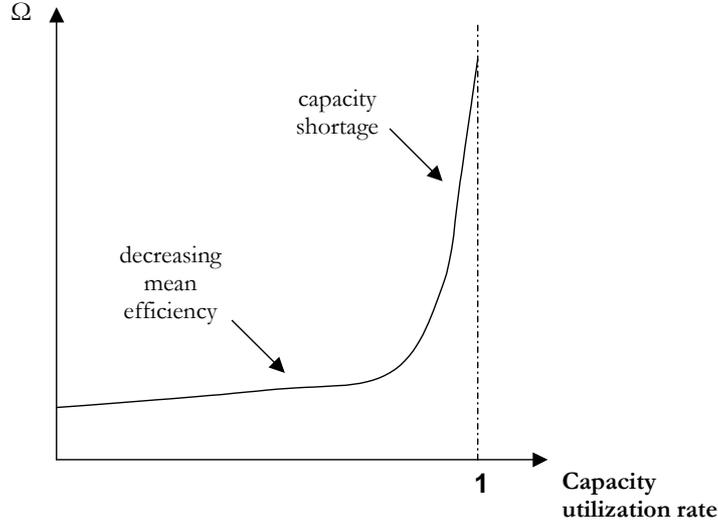


Figure 3: Static decreasing returns

We derive an expression of mean production costs $Cm_{k,i}$ (equation [8]), depending on prices of intermediate goods $pIC_{j,i,k}$, input-output coefficients $IC_{j,i,k}$ and $l_{k,i}$, standard wages $w_{k,i}$, and production level through the decreasing return factor $\Omega_{k,i}$ applied to labor costs (including payroll taxes $tax_{k,i}^w$).

$$Cm_{k,i} = \sum_j pIC_{j,i,k} \cdot IC_{j,i,k} + (\Omega_{k,i} \cdot w_{k,i}) \cdot l_{k,i} \cdot (1 + tax_{k,i}^w) \quad [8]$$

Producer prices are equal to the sum of mean production costs and mean profit. In the current version of the model, all sectors apply a constant sector-specific mark-up rate $\pi_{k,i}$ so that the producer price is given by equation [9]. This constant markup corresponds to a standard profit-maximization for producers whose mean production costs follow equation [8] and who are price-takers, provided that the decreasing return factor can be approximated by an exponential function of utilization rate.

$$p_{k,i} = \sum_j pIC_{j,i,k} \cdot IC_{j,i,k} + (\Omega_{k,i} \cdot w_{k,i}) \cdot l_{k,i} \cdot (1 + tax_{k,i}^w) + \pi_{k,i} \cdot p_{k,i} \quad [9]$$

This equation represents an inverse supply curve; it shows how the representative producer decides its level of output $Q_{k,i}$ (which is included in the $\Omega_{k,i}$ factor) in function of all prices and real wages.

From equation [9] we derive immediately wages and profits in each sector:

$$wages_{k,i} = (\Omega_{k,i} \cdot w_{k,i}) \cdot l_{k,i} \cdot Q_{k,i} \quad [10]$$

$$profits_{k,i} = \pi_{k,i} \cdot p_{k,i} \cdot Q_{k,i} \quad [11]$$

2.2.2.3 Governments

Governments' resources are composed of the sum of all taxes. They are equal to the sum of public administrations expenditures $G_{k,i}$, transfers to households $transfers_k$ and public investments in transportation infrastructures $InvInfra_k$ ¹⁴. Public administrations expenditures are assumed to follow population growth. Decisions to invest in infrastructures hang on behavioral routines detailed in 0. As $G_{k,i}$ and $InvInfra_k$ are exogenously fixed in the static equilibrium, governments simply adjust transfers to households to balance their budget (equation [12]).

$$\sum taxes_k = \sum_i G_{k,i} \cdot pG_{k,i} + transfers_k + InvInfra_k \quad [12]$$

2.2.2.4 Labor market

For each sector the output $Q_{k,j}$ requires a labor input $l_{k,i} \cdot Q_{k,i}$. In each region, the unemployment rate is given by the difference between total labor requirements and the current active population L_k^{act} :

$$z_k = \frac{L_k^{act} - \sum_j l_{k,j} \cdot Q_{k,j}}{L_k^{act}} \quad [13]$$

The unemployment rate z_k impacts on all standard wages $w_{k,i}$ according to a wage curve (Figure 4)¹⁵. Effective wages in each sector depend both on the regional level of employment (through the wage curve) and on the sector utilization rate (through the decreasing return factor Ω).

¹⁴ We assume that road infrastructures are funded by public expenditure and by public commitments vis-à-vis equipment and building industries.

¹⁵ For a comprehensive discussion about the meaning and the robustness of the wage curve, see (Blanchflower and Oswald 1995).

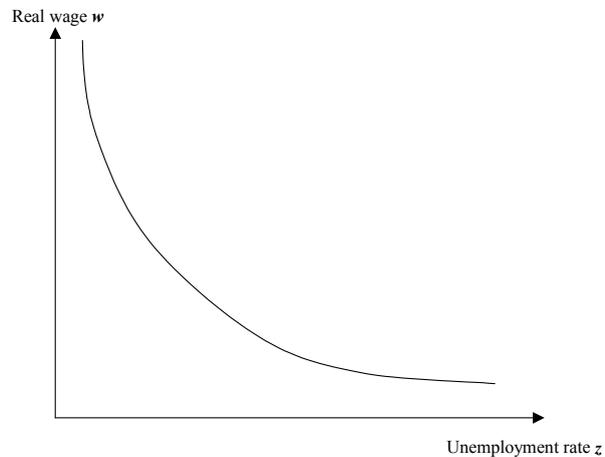


Figure 4: Wage curve

2.2.2.5 *Capital flows and investments*

Regional and international allocation of savings

In the real world, capital flows, savings and investment depend on various factors such as real interest rates, risk attitudes, anticipations or access to financial markets for individuals, and monetary and fiscal policies, national debt and openness to foreign direct investment at the aggregate level. In spite of the difficulties to represent so complex interactions in a global model, it is crucial to seize how financial flows impact the very functioning of the growth engine and the spread of technical change. As stressed by (McKibbin et al., 1998), the assessment of global energy or climate policies cannot neglect the impact of large shifts in commercial flows (variations of energy flows, exchanges on carbon markets, changes in product competitiveness) on current accounts, on investments and eventually on relative prices. In an attempt to seize these crucial interactions, we adopted the following modeling options:

- Available domestic financial resources for investment are given by the sum of savings and the share of profits that is not redistributed to households.
- Producing sectors formulate anticipations on the investment requirements to expand their production capacity; they do so under imperfect foresight about future prices, profitability rates and demands. In each region the sum of all sectors investment needs represents a global demand for financial resources.
- We then compare the available financial resources in each region and this global demand. Regions showing a surplus of financial resources become net capital exporters and feed an international capital pool, which is then allocated to other

regions that experience a deficit of financial resources. In addition to nominal return they take into account durable country-risks that hamper foreign direct investment.

- The resulting net available financial resources are allocated among sectors proportionally to their investment needs. Investment is used in each sector to build new production capacities with a new set of technologies, which requires the purchase of different goods – most of them from the construction and industry sectors (see below 0).

Eventually, the capital balance is defined as the difference between capital exports and capital imports. Capital balance and commercial balance compensate for each other, as a result of the conservation of value flows between all agents in each region¹⁶. Any shift in capital or commercial flows will be counterbalanced by a shift in each region's relative prices, and the subsequent instantaneous modifications of exports and imports¹⁷.

Purchase of investment goods

The total amount of money $InvFin_{k,i}$ available for investment in sector i in the region k allows to build new capacities $\Delta Cap_{k,i}$ at a cost $pCap_{k,i}$ (equation [14]). The cost $pCap_{k,i}$ depends on the quantities $\beta_{j,i,k}$ and the prices $pI_{k,j}$ of goods j required by the construction of a new unit of capacity in sector i and in region k (equation [15]). Coefficient $\beta_{j,i,k}$ is the amount of good j necessary to build the equipment¹⁸ corresponding to one new unit of production capacity in the sector i of the region k . In order to be consistent with shifts to more or less capital intensive techniques, these parameters are modified according to the characteristics of the new sets of techniques embodied in new capacities. They capture both the structure of the demand for investment goods and the *capital deepening* associated to technical change.

Finally, in each region, the total demand of goods for building new capacities is given by equation [16].

$$\Delta Cap_{k,i} = \frac{InvFin_{k,i}}{pCap_{k,i}} \quad [14]$$

¹⁶ But this accounting rule is met without considering other parameters that would modify the current account in the real world such as variations of money stocks of central banks.

¹⁷ Since short run growth fluctuations are very sensitive to current account variations (and the policy intervention to control them) we did not want to retain the closure rule of current accounts being constant or converging to zero.

¹⁸ In practice, due to sector aggregation in this version of the model, building a new unit of capacity only requires construction and industry goods (for the other inputs, i.e. energy and transportation goods, β coefficients are null).

$$pCap_{k,i} = \sum_j (\beta_{j,i,k} \cdot pI_{k,j}) \quad [15]$$

$$I_{k,j} = \sum_{\text{sectors } i} \beta_{j,i,k} \cdot \Delta Cap_{k,i} \quad [16]$$

2.2.2.6 Goods' markets and international trade

All goods can be traded internationally and each component of total demand is composed of both imported and domestic goods. In order to avoid tracking bilateral flows, which is not crucial for the purpose of our simulations, all trade flows go in an international pool which re-allocates them. For each good, international trade is then characterized by two parameters: (i) the share of domestic ($shareC_{k,i}^{dom}$) and imported ($shareC_{k,i}^{imp}$) goods in each region for households, government, investment and intermediary consumption (denoted C, G, I and IC respectively) and (ii) the share of exports of each region on the international markets ($MS_{k,i}^X$).

A well-known modeling issue is how to translate that products are not perfect substitute. The most usual practice is to adopt an Armington (1969) specification, based on the assumption that the same goods produced in different regions are not perfect substitutes, but can be aggregated in a single quantity index (typically a CES index). We adopt it for all non-energy goods. It enables to represent markets in which domestically produced goods keep a share of domestic markets even though their price is higher than the world price wp_i , 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, this Armington specification has the major drawback of not allowing to sum up international trade flows in physical terms. Although this modeling choice can be maintained for generic “composite goods”, where quantity units are indexes that are not used directly to analyze the economy-energy-environment interfaces, it cannot be used to track energy balances in real physical units. Therefore, for energy goods we assume a perfect substitutability, but, to avoid that the cheapest exporter takes all the market, we follow a mere market sharing formula. The international pool buys energy at different prices and sells at a single mean world price to importers. Shares of exporters on the international market and regional shares of domestic versus imported energy goods depend on relative export prices, export taxes and on ‘market fragmentation’ parameters calibrated so as to reproduce the existing markets’ structure¹⁹.

¹⁹ The market fragmentation parameters encompass regional specificities such as the commercial networks, delivery costs, consumer preferences for nationally or regionally produced goods.

For all goods, import prices p^{Imp} include the world price wp_i , export taxes or subsidies $tax_{k,i}^{imp}$, and mean transportation costs ($wp_{it} \cdot nit_{k,i}$) (equation [17]). Then energy prices impact on transportation costs and eventually on commercial flows and industrial localization patterns.

$$p_{k,i}^{Imp} = wp_i \cdot (1 + tax_{k,i}^{Imp}) + wp_{it} \cdot nit_{k,i} \quad [17]$$

2.2.2.7 Equilibrium constraints on physical flows

Equations [18] and [19] are market closure equations which secure physical balance respectively for domestic and imported goods for all kind of goods.²⁰ For each good, the volume of the international market X_i is equal to the demand for imports summed over all the regions (equation [20]). Exporters supply the international markets with shares MS^X as shown in equation [21].

$$Q_{k,i} = shareC_{k,i}^{dom} \cdot C_{k,i} + shareG_{k,i}^{dom} \cdot G_{k,i} + shareI_{k,i}^{dom} \cdot I_{k,i} \\ + [\sum_j Q_{k,j} \cdot IC_{i,j,k} \cdot shareIC_{i,j,k}^{dom}] + X_{k,i} \quad [18]$$

$$M_{k,i} = shareC_{k,i}^{imp} \cdot C_{k,i} + shareG_{k,i}^{imp} \cdot G_{k,i} + shareI_{k,i}^{imp} \cdot I_{k,i} \\ + [\sum_j Q_{k,j} \cdot IC_{i,j,k}^{imp} \cdot share_{i,j,k}^{imp}] \quad [19]$$

$$X_i = \sum_k \left(shareC_{k,i}^{imp} \cdot C_{k,i} + shareG_{k,i}^{imp} \cdot G_{k,i} + shareI_{k,i}^{imp} \cdot I_{k,i} + \sum_j shareIC_{i,j,k}^{imp} \cdot IC_{i,j,k} \cdot Q_{k,j} \right) \quad [20]$$

$$X_{k,i} = MS_{k,i}^X(t) \cdot X_i \quad [21]$$

2.2.2.8 Choice of a numeraire

The static equilibrium consists in a full set of quantities and relative prices fulfilling all equations above. The absolute level of prices is not determined by the model, which is completely homogenous in prices. One price has to be fixed as a numeraire and we chose to set the price of the composite good in the USA equal to one.

²⁰ Note that for energy goods the two equations can be summed in a unique balance constraint, whereas it is not feasible for Armington goods.

2.2.2.9 Greenhouse gas emissions

IMACLIM-R computes CO₂ emissions from fossil fuel burning, thanks to consistent energy balances and emission coefficients by fuels. The ongoing work on detailed descriptions of industry (see 3.6) and land-use will allow to encompass emissions from industrial processes and land-use management, and for other greenhouse gases. The impact of CO₂ emissions on climate is computed by a compact climate model developed earlier at CIRED (Ambrosi et al., 2003).

2.2.3 Dynamic Linkages: Growth engine and technical change

In IMACLIM-R, the rate and direction of economic growth are governed by (i) a macroeconomic growth engine that determines the potential rate of growth at each period in time (ii) the energy-related technical change in each region that encompasses the evolution of energy supply and the dynamics of energy consuming equipments (iii) the induced structural change resulting from the evolution of the composition of households' demand, of intersectoral relationships and of sector-specific labour productivity.

Ultimately, the real economic growth of a region in a given scenario results from the interplay between these three sets of drivers and from the interdependence mechanisms that links this region to other world regions.

2.2.3.1 The growth engine: demography, productivity and investment

The IMACLIM-R growth engine is made up of (i) exogenous demographic trends, (ii) labor productivity growth, (iii) capital deepening mechanisms and (iv) hypothesis about the evolution of saving rates.

Exogenous assumptions for demographic trends are derived from UN scenarios corrected with migration flows capable to stabilize populations in low fertility regions, such as Europe. Both active and total populations are concerned: the former drives the available working force in the economy, the latter determines the levels of consumption for a given equipment ratio.

Labor productivity growth follows a constant long term rate for the most advanced economy and catching-up assumptions for other regions. More precisely, the baseline trajectory is based on the hypothesis that (i) the United States remain the world productivity leader and their mean labor productivity follows a steady growth of 1.65% per year, (ii) other countries productivity dynamics are driven by a partial catch-up of productivity gaps, the parameters of which are calibrated on historic trajectories (Maddison, 1995) and 'best guess' of long-term trends (Oliveira-Martins et al., 2005). For policy scenarios, two different specifications were tested in order to focus on endogenous technical change (Crassous et al., 2006): labor productivity was either exogenous or dependent on cumulated regional investment. The latter case allows to test the crowding-out effect of climate policies on total investment and then productivity growth.

In combination with these long-run drivers, both the availability of investments and their allocation are control variables of the effective growth. The amount of

investment in each sector drives the pace of productive capacity expansion and the pace of embodied technical change. Productive capacity follows a usual law of capital accumulation with a constant depreciation rate, except Electricity and Industry sectors for which both vintages and equipment lifetimes are fully represented. Sub-sector allocation of investments among technologies is treated in a specific module for each sector, when relevant. The IMACLIM-R architecture currently includes five detailed dynamic modules concerning either supply or final demand for energy: fossil fuel extraction, electricity generation, residential energy uses, transportation and industry.

2.2.3.2 *Energy-related technical change*

As previously explained, all technical change parameters are driven by the cumulated effect of economic choices over the projected period. Because of the embodiment of technical change in equipments, endogenous technical change captured in IMACLIM-R has to be interpreted as encompassing both R&D and learning-by-doing. We describe hereafter the sub-modules that simulate this putty-clay dynamics on both energy supply and energy demand sectors.

2.2.3.2.1 *Supply of energy*

Fossil fuels: resources depletion and production costs

This module seizes the main constraints on fossil fuels production and details the drivers of their prices. Coal and gas extraction costs are depicted through reduced forms of the energy model POLES (Criqui, 2001), linking extraction costs to cumulated extraction, while crude oil is subject to a detailed treatment which deserves more explanations. The equation [9] sets oil price as the sum of production costs and of a mark-up:

- *Production costs* captures the differentiated characteristics of oil slicks (conventional vs. unconventional oil) as oil reserves are classified in 6 categories according to the cost of putting a barrel at producer's disposal (including prospecting and extraction). The decision to initiate the production of a given category of resources is made when the current world price of oil reaches a threshold level. This threshold defines at which price level the producer considers that the exploitation becomes profitable, taking into account both technical production costs and non-prices considerations (security, investment risks).
- *The mark-up π* applied by producers depends on the short-run pressure on available production capacities: it increases when the ratio of current output to

total production capacity approaches unity. The availability of crude oil production capacities is not only constrained by the amount of previous investments, but also by geological and technical factors that cause time lags in the increase of production (a slick existing in the subsoil is not entirely and immediately available for extraction)²¹. Therefore for a given category of resource in a given region, the available capacity of production is assumed to follow a ‘Hubbert’ curve. This curve is interpreted as resulting from the interplay of two contradictory effects: the information effect _finding an oil slick offers information about the probability of existence of other ones_ and the depletion effect _the total quantity of oil in the subsoil is finite_ (Rehrl and Friedrich (2006))²².

The unequal allocation of reserves is captured by an explicit description of available resources in each region; endogenous decision routines can mimic the decision to run or not new capacities in OPEC countries – that currently own between 40% and 50% of the world total production capacities – and the subsequent market power. IMACLIM-R is then able to capture the impact of strategic behaviors and geopolitical scenarios: for instance, the freeze of production capacities decided by producers can be used to mimic oil crisis

Electricity generation

The electric sector can not be represented as other producing sectors as electricity is not a commodity and cannot be stored easily: the so-called “load curve” associated with an electrical grid plays a central role in the choice of suitable technologies. The methodological issue is then to model realistically the production of electricity that mobilizes installed producing capacities according to a non-flat load curve.

The electric supply module in IMACLIM-R represents the evolution of electric generating capacities over time. When describing annual investment decisions within the electric sector, the model anticipates, ten years forward, the potential future demand for electricity, taking into account past trends of demand. The module then computes an optimal mix of electric productive capacities to face the future demand at the lowest cost given anticipations of future fuel prices. The optimization process sets not only the total capacity of the plants stock but also its distribution among 26 different power plant technologies (15 conventional including coal-, gas- and oil fired, nuclear and hydro and 11 renewables) which characteristics are calibrated on the POLES energy model. The

²¹ Note that this time lag between exploration decisions and commercial decisions allows to include any other type of constraint on the deployment of capacities.

²² Note that this physical interpretation of the ‘Hubbert’ curve at the ‘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.

share of each technology in the optimal capacity mix results from a classical competition among available technologies depending on their mean production costs. Moreover, this competition also includes constraints linked with the differentiated cost structure of the technologies: technologies with high fixed costs and low variable costs such as nuclear power are more competitive for base load capacities whereas technologies with low fixed costs and high variable costs are likely to be chosen for peak production.

This modeling structure also allows to account for the physical constraints - in the absence of competitive technology for electricity storage - that hamper the extensive deployment of renewable capacities within the electrical grid due to their intermittent production, especially for solar or wind technologies. Once the optimal mix of productive equipment for year $t+10$ has been computed, the model accounts for the time constraints in the deployment of capacities: the new capacity built at year t results from a minimization of the gap between the mix of capacity currently installed and the mix of capacity that is expected to be optimal to face the demand at year $t+10$. This minimization is run under the constraint of the actual amount of investment allocated to the electric sector. This process of planning with imperfect foresight is repeated at every period and expectations are adapted to changes in prices and demand.

2.2.3.2.2 Demand of Energy

For the evolution of demand-side systems, we distinguish specific mechanisms for residential, transportation and industry consumptions.

Residential energy end-uses

Total household energy demand for residential end-use is disaggregated in seven main end-uses whose characteristics are described separately: space heating, cooking, water heating, lighting, space cooling, refrigerators and freezers, and other electrical appliances.

For each of these seven end-uses, the final energy service SE_i depends on the total number of households H_i (or the number of residential square meters for space heating and space cooling), their equipment rate λ_i and the level of use of the equipment e_i . For each energy carrier j , the subsequent final energy demand DEF_j depends on the shares of the energy mix for each end-use sh_{ij} , and on the mean efficiency of equipments ρ_{ij} .

for each energy

$$\left\{ \begin{array}{l} DEF_j = \sum_{end-use i} sh_{ij} \cdot \frac{SE_i^{COM}}{\rho_{ij}} \end{array} \right. \quad [22]$$

The evolution of the shares of the energy mix for each end-use is modeled by a logit function on prices of the energy services, to describe households' choices on inhomogeneous markets. The evolution of the efficiency of equipments can be made dependent on past experience and prices.

The lodging surface per person evolves correlatively to the real disposable income per capita. This is also the case for end-use equipments, but the utilization intensity of these equipments is driven by both the real disposable income per capita and the energy prices, with elasticities depending on the end-use (distinguishing basic needs and comfort uses), the region considered and the absolute level of use of the equipment. The corresponding demand curves are bounded by asymptotes, representing minimum levels (or subsistence levels) and saturation levels which translate views about future 'development styles'.

Some more explanation has to be given on traditional biomass energy. Its contribution is often neglected as it mainly belongs to the informal sector. Therefore, we split up the final energy service SE_i^{TOT} into the energy service supplied by "commercial" energy sources (coal, gas, oil and electricity) SE_i^{COM} , and the energy service provided by traditional biomass SE_i^{BIO} . In equation [23], θ_i represents the share of the population relying on traditional biomass for the energy service considered. To include a link between development indexes and endogenous characteristics of the population (mainly disposable income and inequalities in the distribution of revenues described through a Gini index), we assume that this share of the population using traditional biomass is the share of the population earning less than 2\$ a day (IEA, 2002).

for each end – use

$$\begin{cases} SE_i^{COM} = H_i \cdot (1 - \theta_i) \cdot \lambda_i \cdot e_i^{COM} \\ SE_i^{BIO} = H_i \cdot \theta_i \cdot \lambda_i \cdot e_i^{BIO} \\ SE_i^{TOT} = SE_i^{COM} + SE_i^{BIO} \end{cases} \quad [23]$$

Transportation

The transportation dynamic module alters the constraints applied to the transportation demand formation in the static equilibrium: transportation's infrastructure, households' car equipment, vehicles energy efficiency and evolution of the freight content of economic activity.

Transportation's infrastructure evolves accordingly to the investment decisions. Various investment policies can be tested through different routines. For personal

vehicles, the building of transportation infrastructure follows the evolution of modal mobility. It induces a change in the travel time efficiency (Figure 5). For the ‘other transports’ sector (which gathers road and rail transportation, excepted personal vehicles) and air transport, capacity indexes follow the variations of the productive capacity of those sectors.

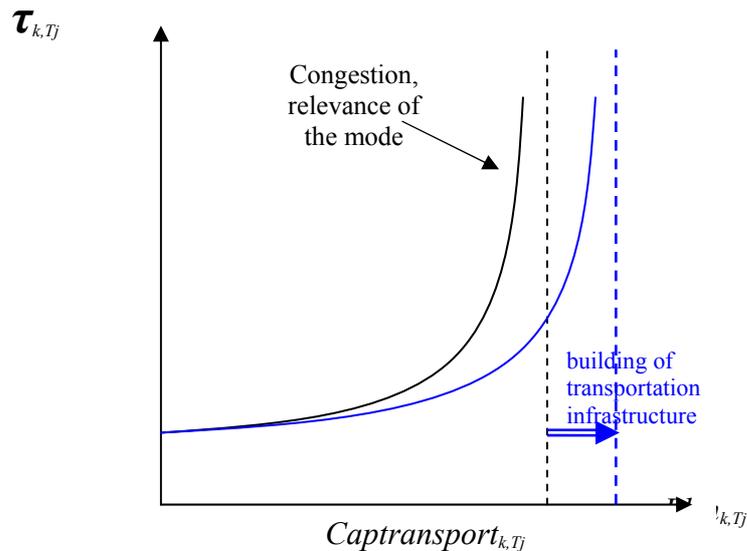


Figure 5: Marginal time efficiency of the mode Tj

Total households’ time dedicated to mobility evolves correlatively to the total population. The motorization rate is related to the evolution of per capita disposable income with a variable income-elasticity. Indeed, for very poor people, the access to motorized mobility rests on public modes and income-elasticity remains low. Households with a medium per capita income have access to private motorized mobility and the motorization rate becomes very sensitive to variations of income. Finally, for higher per capita income level comparable to OECD’s, saturation effects appear and the income elasticity of the motorization rate declines.

The evolution of the energy intensity of the automobile fleet is related to final energy prices through a reaction function calibrated on the energy sector model POLES. This function encompasses induced energy efficiency gains for conventional vehicles and the penetration in the fleet of advanced technologies such as electric, hybrid or fuel cells cars.

As for the freight dynamics, the evolution has to be described in a different manner. It is driven by the capacity indexes (encompassing infrastructure disponibility), the energy input-output coefficients of ‘other transports’ and the freight content of

economic growth. The evolution of the energy input-output coefficients of ‘other transports’, triggered by final energy prices variations, accounts for both energy efficiency gains and shifts between road and rail modes. This evolution results from a compact reaction function also calibrated on bottom-up information from POLES.

Eventually, the evolution of the freight content of the economic growth, which is represented by the transportation input-output coefficients of all the productive sectors in the economy, is an exogenous scenario’s variable. Indeed it is unclear to assess how energy prices will affect firms’ choices of localization and production management, but these parameters are likely to play a central role in cost-effective mitigation policies (Crassous et al, 2006).

Agriculture, Industry and Services

By default, supply-side energy consumption in these three sectors changes according to global energy efficiency improvements and shifts of the energy mix for new vintages of capital. Both are driven by relative prices of energies. On the demand-side, income elasticities of consumption of industrial and agricultural goods are assumed to decline when per capita income increases, in order to represent saturations. It mechanically leads to an endogenous dematerialization.

Nevertheless, the examination of sustainable trajectories representing large departures from baseline trajectories because of dramatic decarbonization or/and dematerialization trends pointed out that the description of industry dynamics should be improved. We indeed need to assess potential reductions of emissions, energy or materials’ consumption not only in industrial processes themselves, but also those allowed by potential changes in end-use material consumption elsewhere in the economy. As stressed in (Gielen and Kram, 2006), material policies are likely to represent significant low-cost abatement potentials, thanks to dematerialization or trans-materialization. A current research project aiming at exploring the implications of a division by four of GHG emissions in 2050 in Europe for glass, cement, steel, aluminum and refining industries recently led to the development of (i) a bottom-up description of the demand for each of these five products and (ii) reduced forms of detailed model describing technological change in these sectors, that incorporate technical asymptotes, recycling potentials and limitations in energy substitution. Finally, changes on the supply and demand sides for those industrial sectors are re-aggregated to modify the characteristics of the industry sector as a whole in the static equilibrium, in order to ensure full macroeconomic consistency of trajectories.

Structural change

Imaclin-R does capture structural change as resulting from the simultaneous evolutions of household final demand, technologies in the energy sector, input-output matrices and labor productivity. For example, assuming that households' housing demand is inelastic, a scenario in which productivity gains are far lower in the construction sector than in the composite sector will lead to a higher share of this sector in total output. This share will be lower, for the same productivity assumptions, in a scenario in which housing demand is more elastic.

To this respect, an interesting feature of Imaclin-R is the representation of structural change triggered by transportation dynamics. Indeed thanks to the fact that the households' optimization program under double constraint allows to represent the induction of mobility, structural change is made dependent upon both infrastructure policies and technical change. Dynamically, investments targeted to transportation networks will lower congestion of transportation and increase its time-efficiency, while more efficient vehicles will lower fuel costs. Thus for the modes in which congestion has been released, mobility demand will increase, even at constant income and time budget. Then the share of transportation in the total GDP will not only depend on the price effect of lower transportation costs but also on the volume effect of the induction by infrastructures.

An other interesting example, the numerical importance of which is demonstrated in (Crassous et al., 2006), is the critical evolution of freight transportation. Indeed if the input-output coefficients of transportation services in all sectors are assumed to remain stable or to increase, because efficiency gains in transportation modes are outweighed by the generalization of 'just-in-time' logistics and the spatial extension of markets, then an activity which now represents a minor share of total output will tend to increase steadily over time.

3 Long-run emission scenarios

However these two ambitious objectives require a numerical implementation if one wants to go beyond the aesthetical framework. This is the objective of the fourth and last part of this report. It presents a case study on a set of scenarios combining hypotheses on the potential economic growth (demography and labour productivity growth rates), on development styles (« energy intensive » versus « energy sober») and on the technical progress potential in the energy sector (« slow and limited » or « rapid and deep »). Eight variants are obtained by combining the three sets of hypotheses. This exercise permits to stress how the macroeconomic impacts of technology transformations can significantly modify the trajectories: rebound effect on the economic activity, on the mobility, on the fuel prices and on the energy mix.

Before presenting the analysis of results, we describe hereafter the hypotheses chosen for each variant as well as their modelling translation in Imacim-R model.

3.1 Assumptions

3.1.1 The growth engine

3.1.1.1 *Demography transition: slow vs. rapid and extended*

The main demography uncertainty is how rapid and broad will the demography transition in the developing countries be.

The high population hypothesis extrapolates the past trends up to the end of the XXIst century. The fertility rates are supposed to converge in the long run towards the level which provides a stable population. Industrialized countries would have a very slow population growth, while Asian population would be stable during the second half of the century and the rest of the world at the end of the century. The total population grows to 9.4 billions in 2050, and then more slowly to 10 billions in 2100.

The low demography trajectory results from hypotheses of lower rates both for fertility and mortality, so that the demography transition is completed earlier in developing countries. The distinct feature of this hypothetical trajectory is that the global population peaks at 8.7 billions around 2050, before it decreases to 7 billions in 2100.

Our first (high) trajectory chosen is the median one from the United Nations (UN, 1998) (and it was also chosen in the B2 SRES scenarios). The low trajectory we retained was proposed as the low projection from Lutz (1996) (again retained by the A1 and B1 SRES scenarios). The recent publication by (Vuuren and O'Neill, 2006) does not modify them much.

The following table gives a summary of these trajectories.

Millions		2000	2025	2050	2075	2100
World	High	6086	7972	9296	9942	10227
	Low	6086	7826	8555	8137	6904
Europe	High	593	604	577	564	581
	Low	593	626	624	587	554
North-America	High	315	373	391	399	405
	Low	315	381	431	471	513
Japan-Austrasia	High	204	205	192	147	91
	Low	204	215	212	200	188
CIS	High	277	280	275	261	253
	Low	277	291	287	264	235
Latin America	High	518	695	817	872	898
	Low	518	684	756	720	612
Middle East	High	174	267	341	394	431
	Low	174	278	357	390	365
Africa	High	815	1503	2163	2630	2855
	Low	815	1415	1808	1903	1648
The rest of Asia	High	887	1120	1265	1260	1203
	Low	887	1107	1178	1064	844
India	High	1021	1416	1691	1823	1896
	Low	1021	1414	1579	1474	1150
China	High	1281	1510	1584	1592	1613
	Low	1281	1415	1322	1064	794

Table 3 : Total populations, millions of inhabitants, 2000-2100

In order to assess the active population, which is determining the labour force in the scenarios, we define it as:

- The population from 18 to 64 years old in developing countries;
- The population from 15 to 64 years old in industrialized countries.

This is an oversimplification, especially as it does not give an account of the complex dynamics of the formal-informal categories and of the female access to work. It nevertheless provides a robust idea of the magnitude and it shows the following tendencies:

(i) In the high population variant,

- An active population growing less rapidly than the total population all along the century for North America, and even decreasing for Europe, Japan and Australia ;
- An active population growing more rapidly than the total population for Africa, along the century ;
- An active population growing more rapidly than the total population for the other developing countries in the early century before the active population decreases after 2010 in China and 2030 in the rest of DC ;
- A more unique pattern in the CIS region: the total population decreases while the active population increases up to 2010 and strongly decreases afterwards.

(ii) In the low population variant,

- An active population growing less rapidly than the total population all along the century for North America, and even decreasing for Europe, Japan and Australia ;

- For all developing countries, the trajectory goes more or less rapidly through the four stages: (1) an active population growing more rapidly than the total population, (2) and then less rapidly, (3) before a decrease of the active population is combined to a slow growth of the total population, (4) before the active population itself also decreases more rapidly than the total population. Thus the active population decreases in China from 2010 on, in America Latina from 2040 on, in India from 2050 on, in Africa from 2065 on; while the total population begins to decrease in China from 2030, in America Latina and India from 2055 on and in Africa from 2070 on.

In both scenarios, these evolutions of age composition are apt to have an impact on the saving behaviour and to induce structural financing issues, either for the retired persons in industrialized countries, or for the high potential growth and infrastructure needs in developing countries.

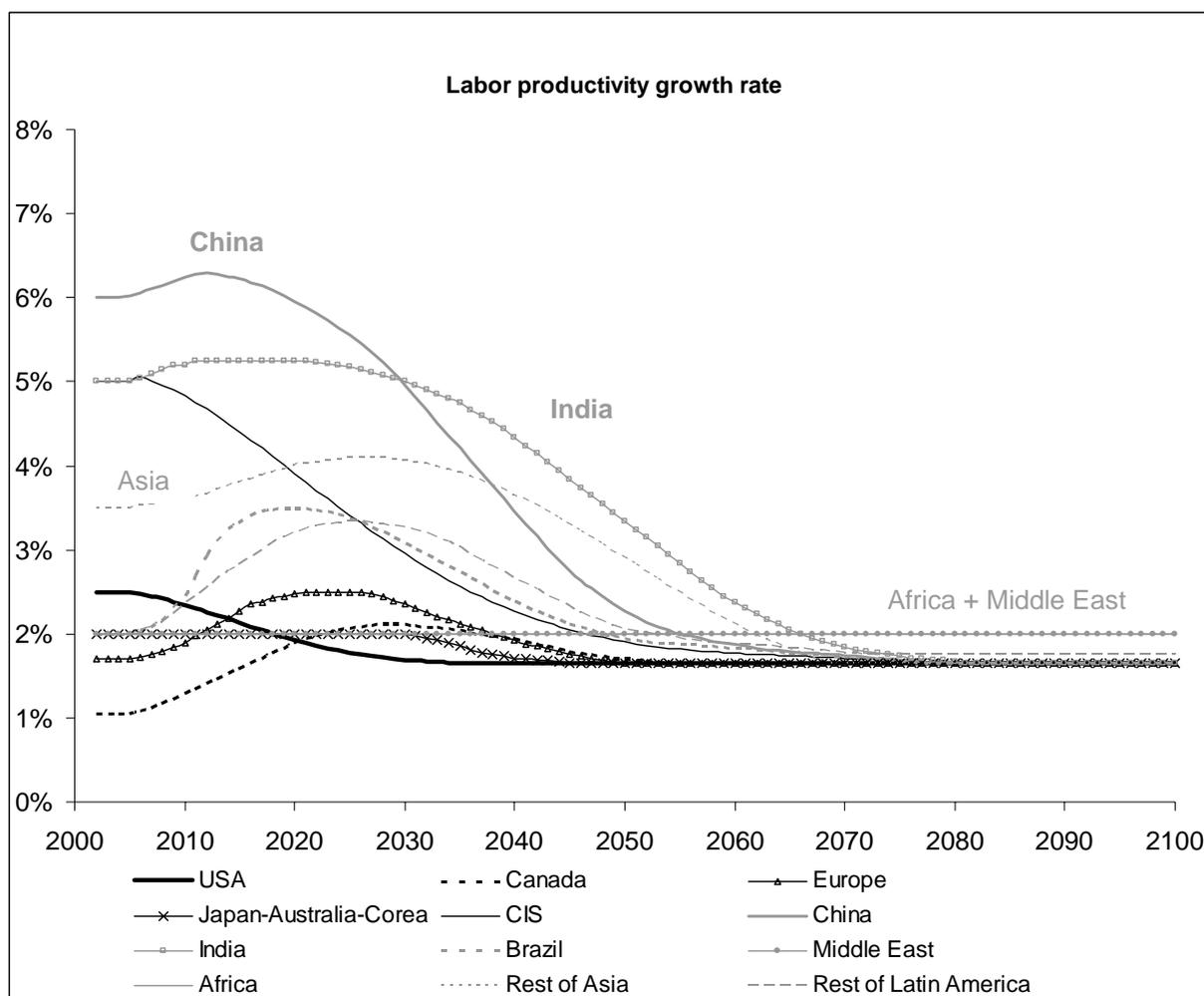
3.1.1.2 *Labour productivity: North American leadership but a variant on the long run growth rate.*

In both variants, the trajectory chosen for the labour productivity gains rests on two converging studies, one on the past trends by A. Maddison (1995), and the other on the future trends by Oliveira Martins (2005).

Thus the high variant represents:

- A long run adjusted growth rate of 1.65% per year derived from the CEPII (INGENUE, 2005) which takes into account the intergenerational flows (savings, pension, heritage) ;
- A combination of three assumptions: a catching up trend by developing countries with higher labour productivity rates, combined to a high capital output ratio and to a substitution of labour with capital as it happened in the XXth century industrialized countries.

We assume that the *absolute levels* of productivity in DC are partially catching up with IC ones. The CIS region and 5 out of 7 developing regions are involved in such a catching up during most of the century. We assume exogenously that the CIS region and China and India among other developing countries have already begun this catching up phase (for different reasons) whereas Latin America would join them some time in the first half of the century. For the Middle East and for Africa, we have not assumed such a catching up, because of political instability and of other obstacles (i.e. the non optimal use of oil income, or '*Dutch disease*'). The IMF statistics have however assumed a 2% projected labour productivity growth rate per year for the century.



Graph 1: Hypotheses on the labour productivity growth rates

The low variant corresponds to a homothetic trajectory with annual rates decreased by 10%, that is to say a long run growth trend put down to 1,485 % and a less rapid catching up. Both variants imply the assumption of a strong technical progress diffusion across regions, that corresponds to a continued globalization and integration process.

3.1.2 Development styles: « energy intensive » vs « energy sober »

The high (energy intensive) variant corresponds to the generalisation of the American way of life, characterized by the urban sprawl resulting from a preference for large individual houses. It requires to heat and air-condition these large areas, and to invest in a large set of home equipments and private cars.

The low (energy sober) variant represents the dense urban pattern based on collective buildings with a high residential density. It induces less everyday mobility needs as well as a greater role for collective transport. Electric equipments for households are less spread out in this variant.

Each variant is characterized by quite different « saturation levels » (with regards to the home size and durable good home equipment). Nevertheless, development styles can't be

summarised by a mere expression of saturation levels of equipment rates and households demand. Consumptions behaviours depend on existing room for manoeuvre; therefore there is a direct link between the evolution of equipment rates and the growth of income per capita. The parameterisation of this link strongly influences the transitional profile of development pathways.

Let us note that we did not contrast the variants on parameters concerning long distance mobility needs (air transport) and fret transport. The reason is that both are highly increasing components in the context of global trade development and are not dependent on the low versus high choice concerning the urban and territory planning variants.

In practical terms, the contrasted development styles are represented by the following assumptions on parameters:

- Concerning lodging, the asymptotic values and the income elasticities for the residential area per head are increased respectively by 20% and 30% in the high variant as compared to the low variant ;
- Concerning the home equipment, the asymptotic values and the income elasticities are also increased respectively by 20% and 30% in the high variant as compared to the low variant ;
- Concerning the transport, we have chosen to encapsulate the whole option in one single parameter, namely the “household motorization ratio”. The asymptotic ratio values of the private car per capita are 0.7 in the high variant as against 0.6 in the low variant case. Furthermore we opt for a higher income elasticity of the private car investment in the high variant, which means a larger number of cars for a given growth trajectory in developing countries ;
- The material intensity of household consumption is represented by the final demand level to the industry sector. We assume that the saturation level of this final demand in the high variant case is twice the low variant case level.

3.1.3 Energy and technology variables: variants on technical progress and on the speed of technology diffusion

We have decided to represent two technical progress variants in the final demand sectors (transport, residential) and in the productive sectors, in which exist the larger energy efficiency potential gains. However there are also uncertainties on the market imperfections inertia and on the consumer and industrial producer behaviours, which induces an uncertainty on the speed of the diffusion of more efficient technologies. That is the reason why our variants bear on both the asymptotic energy efficiency but also on the diffusion speed to its attainment. The low variant targets a higher energy efficiency and a more rapid technical progress than the high variant. Thus we make the twin hypotheses that the sooner the technical progress, the deeper it will go in the long run.

However let us note that in both variants we took a rather conservative view on the potential technical progress. We assume no fundamental technological breakthrough, for instance in the case of hydrogen to electricity. Also concerning the fossil fuel reserves we have made only one hypothesis, and a rather optimistic one²³.

²³ The fossil resource parameterization was done on the basis of the results of the POLES model, which in turn was calibrated on the data published by the *Institut Français du Pétrole (IFP)*.

The parameters chosen to represent both energy efficiency variants in the model are as follows:

- Concerning transports, we assume that in 2100 the efficiency frontier is 60% lower and the efficiency price elasticity is twice higher in the low energy variant than in the high energy variant.

- Concerning the residential sector, the variants differ by a slow or rapid rate of progress on the energy efficiency of equipments.

- Concerning the productive sectors, variants differ by a slow or rapid AEEI (Autonomous Energy Efficiency Improvement).

3.1.4 Eight alternative scenarios

Combining the two variants on the three hypotheses above, we get eight alternative scenarios, which are denominated as follows in the rest of this report.

Development styles:

- D0 : low variant, energy sober development style;
- D1 : high variant, energy intensive development style ;

Technology variables :

- T0 : low variant, rapid and deep technical progress ;
- T1 : high variant, slow and more limited technical progress ;

Growth engine :

- M0 : low variant, low population and labour productivity growth rate;
- M1: high variant, median population and high labour productivity growth rate.

These eight scenarios do **not** include **any explicit climate change policy**. However the frontier between a business as usual and a climate policy has become blurred. The uncertainty element is inherent in BAU scenarios because of the uncertain knowledge that we have on the future, say on the real oil reserves or on the possible technological breakthroughs. The uncertainty also results from a sequence of collective and individual choices all along the trajectory of evolution of future technical and socio-economic systems. What is at stakes behind the development style concept is the fact that collective decisions on spatial planning schemes, on urban and transport infrastructures etc open or close the margin for individual choices. Even a scenario including a consistent set of factors reducing the private car mobility can be seen as a BAU scenario, provided this orientation is considered independently from the climate change challenge, otherwise it would rather be seen as a “policy” scenario in which infrastructural policies reinforce the emission abatement potential.

Instead of the distinction BAU scenarios vs. climate policy scenarios, we prefer to say that the aforementioned scenarios share the common feature of a zero carbon price.

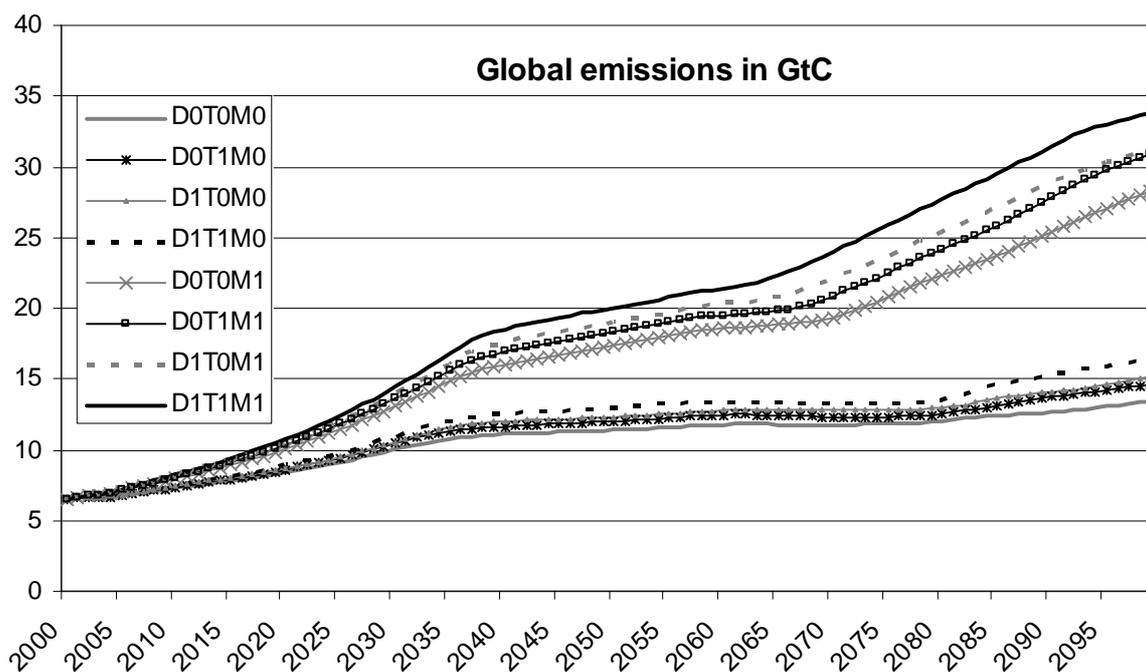
3.2 Emission scenarios

3.2.1 What risks of a high carbon future?

Our eight emission scenarios give an uncertainty interval in 2100 going from 13 to 33 gigatons of Carbon (that is from 47 to 120 gigatons of CO₂). Our interval stands clearly above the SRES interval going from 5 to 21 GtC.

Our scenarios in the high end of the interval illustrate that the abundant availability of coal could make these global emission levels possible in a future world with a zero carbon price (no carbon constraint). Emission could go beyond the SRES upper bound even for scenarios which assume a good technology progress and an energy sober development style.

These high scenarios share a common element, i.e. the Coal-To-Liquid technology, which is all the more justified as the coal price do not increase much as compared to the other liquid fuels, including the bio-fuels, and to electricity. Within this set of energy hypotheses, the main factor determining the long run emissions pattern is the growth engine²⁴, which cumulates the demography and labour productivity growth, this growth relying on an increasing role played by coal and its derivatives. The coal role in the energy mix will be dealt with later.



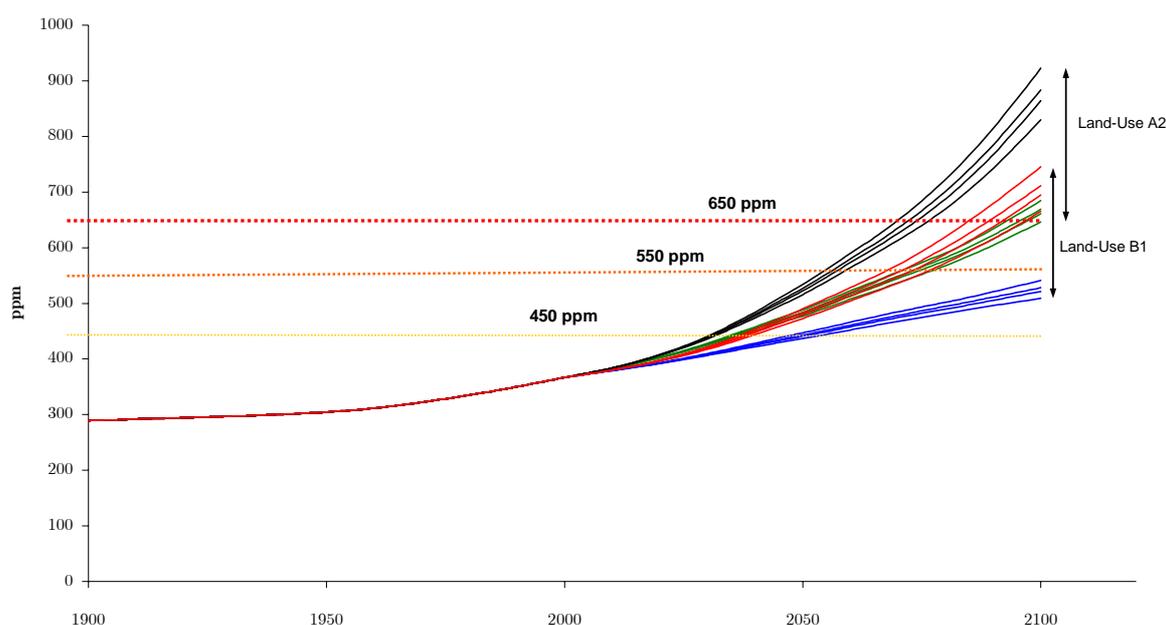
Graph 2 : Global emissions (in GtC) for our eight scenarios

These emission trajectories are bound to have a potentially significant impact on the climate system. By feeding Imaclim-R fossil fuel emissions into OSCAR, a carbon cycle model (Gitz, 2004) developed at CIRED, we have calculated the concentration profile

²⁴ It would be unfounded to extrapolate this remark to the totality of possible scenarios. We have explored here only the variants pertaining to the efficiency parameter intervals and not to the possible availability of some technical breakthroughs. Without a C-T-L route or with a strong potential for hydrogen, this overwhelming determining role of the macro-economical factor would probably no longer be true, albeit it would remain crucial for the emissions

obtained for each of the eight scenarios (Graph 3), by combining them with two contrasted land use scenarios chosen from the SRES (A2 and B1 based on IMAGE giving a very detailed land use). Two observations are worth mentioning:

- Our scenarios without a carbon constraint do not allow a stabilization level below 650 ppm CO₂ that is at least 750 ppm for all GHG. Even the scenarios combining a low growth and a low deforestation (in blue), would go beyond the 650 ppm ceiling without emission mitigation policies. The upper emission bound (in black) is set between 800 and 920 ppm in 2100 and displays a very high emission growth rate.
- The land use uncertainty is comparable to the fossil fuel uncertainty, as shown by the black arrows.



Graph 3 : CO₂ atmospheric concentrations for the eight scenarios and two polarized land use scenarios (SRES B1 et A2)

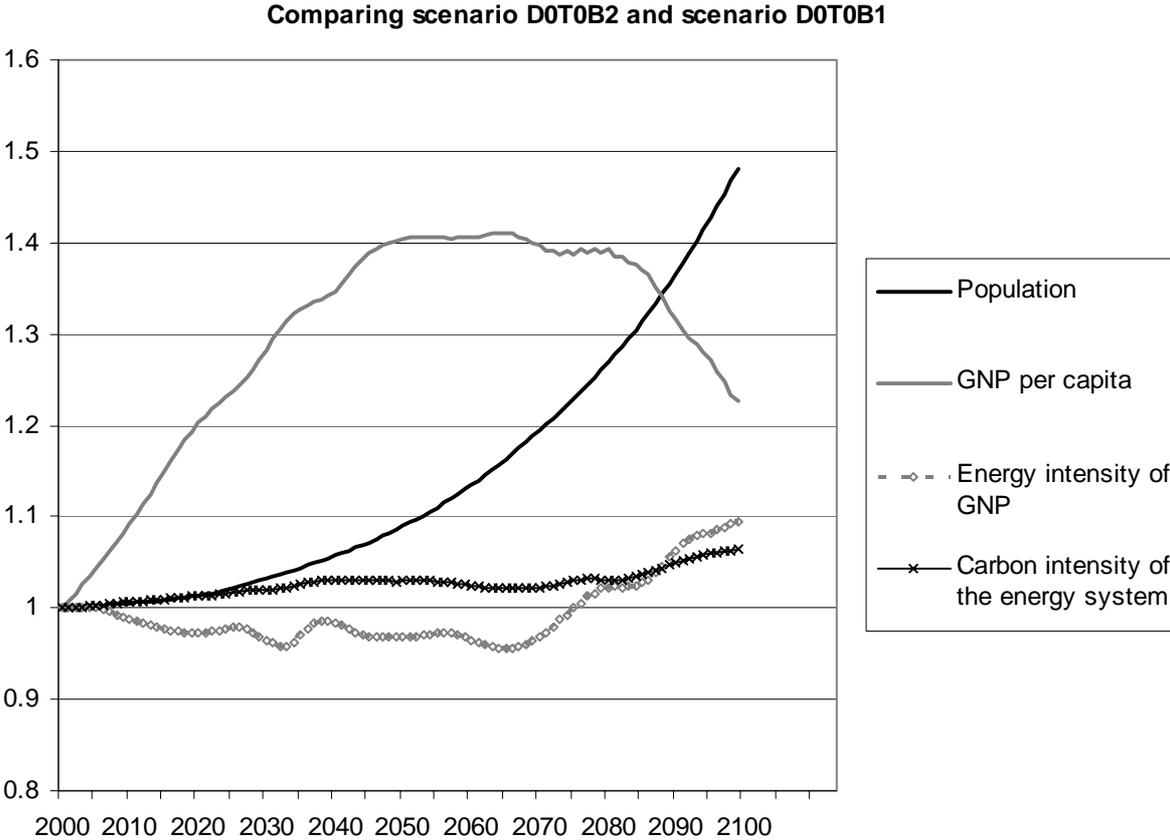
3.2.2 The « Kaya » decomposition revisited ex post

In the first part of our report, we have shown that adding up the uncertainty on each element of the « Kaya » decomposition can overestimate the combined uncertainty for lack of taking into account the strong correlations between economic growth, energy efficiency and carbon intensity. After having tried to explicitly represent the uncertainty mechanisms and give their assumed parameter interval, we come back *ex post* to the « Kaya » decomposition as an analysis filter for the trajectories simulated by Imaclim-R.

In support to the argument that aggregated variables inside the “Kaya” identity do not follow independent dynamics, let us compare two scenarios which only differ on the growth engine factor. The Graph 11 shows the relative evolution of Kaya indicators of the high growth engine scenario D0T0M1 compared to the low growth engine scenario D0T0M0. Clearly the modification of macroeconomic parameters has an effect on the energy intensity of the GNP (+10% in 2100) as well as on the carbon intensity of the energy system (+6% in 2100).

The energy intensity of the GNP is first lower in the high growth engine (M1) scenario, in a transitory phase with a higher energy efficiency progress rate due to the macroeconomic effects: the higher economic growth induces an increased use of energy, therefore forcing higher the fuel prices, themselves inducing technology progress. This global effect is combined to the usual effect: the higher the GNP growth (in M1), the higher the investment in new capital, the younger is the average capital age, the better its average energy efficiency. On the contrary, the economic growth in developing countries is accompanied by a strong industrialisation, structural change which has an effect on aggregated energy intensity of the GNP contrary to the previous, as industry is more energy intensive than agriculture or services. At the end of the century, the energy intensity of the GNP becomes higher in M1 under the combined effect of this structural change effect and of the convergence of energy efficiency levels in both scenarios, as they stand on the same hypothesis for technical asymptotes.

The carbon intensity of the energy system is higher in the scenario D0T0M1 than in the D0T0M0 all along the trajectory, because the increased growth largely rests on the use of fossil fuels. From 2040 to 2070 the penetration of biofuels allows a partial stabilisation of the carbon intensity index, whereas the (M1/M0) index increases later in the century because the coal share increases as coal and its derivative CTL become then the main fuel to cope for a higher growth.

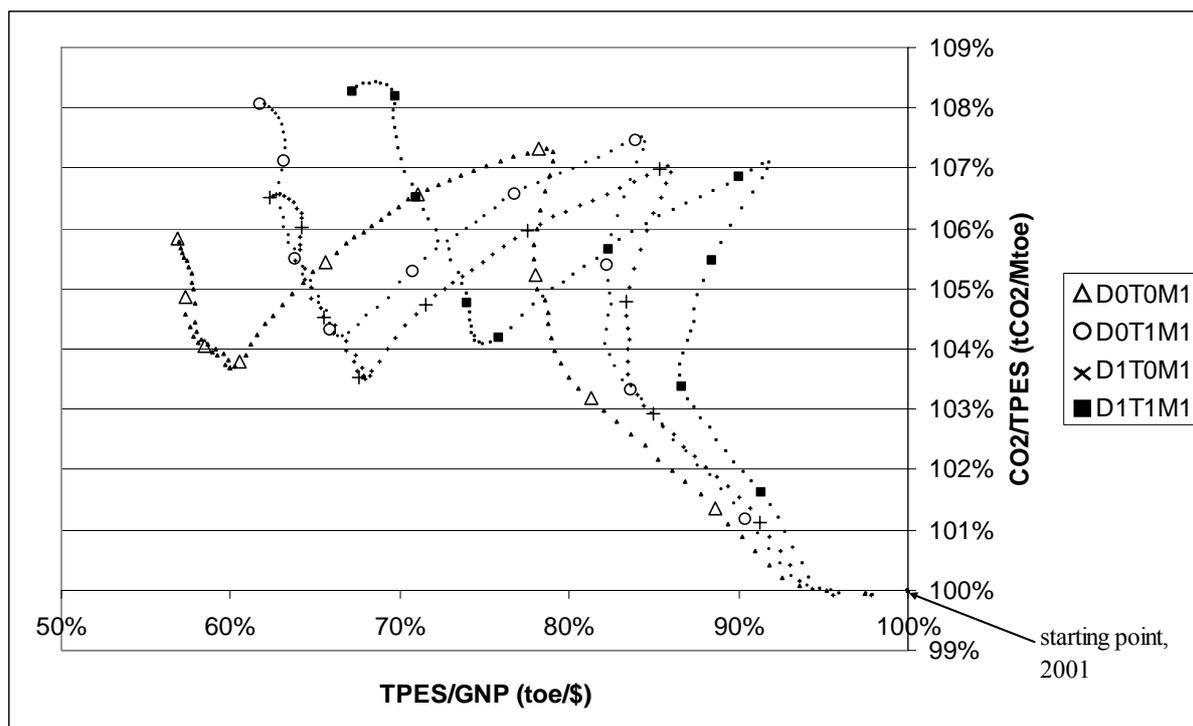


Graph 4 : Comparing the Kaya decomposition factors between the D0T0M0 and D0T0M1 scenarios.

To go beyond this demonstration on a particular case showing that indicators from the Kaya decomposition are correlated, let us examine the joint evolutions of energy intensity and carbon intensity in the eight scenarios produced. This examination is symptomatic of the understanding difficulties emerging from the fact that Kaya identity gives only a very aggregated view of the mechanisms underlying emission trajectories.

The Graph 5 puts together the global trajectories of the four scenarios sharing the high growth engine (M1) variant. All the M1 scenarios display rather comparable trajectories including four distinct phases of the underlying structural and energy dynamics along the XXIst century:

- (i) From 2005 to 2020, the four scenarios exhibit substantial energy efficiency gains, ranging from 10% to 20% as compared to the 2001 reference, but growth rests largely on fossil energy resources, owing to their moderate prices, which triggers a 3% growth of the carbon intensity;
- (ii) From 2020 to 2040, the marginal energy efficiency gains per year across all sectors are more than compensated by a rapid and wide structural change in the developing countries. The industrialization process in the large emerging economies is based on a growing share of the GNP going to energy intensive sectors, which mechanically increases the average energy intensity of the world GNP, even though the energy efficiency is improving from year to year in all sectors. The fossil resources keep being competitive and accessible, so that the average carbon intensity increases by 4% per year during that phase ;
- (iii) From 2040 to 2060 (or 2080 depending on the scenario), a sudden bifurcation brings an era of high energy efficiency gains and of energy de-carbonization. It results from the combination of various factors: (i) the accelerated oil and gas price increases induce accelerated efficiency gains, (ii) the bio-fuels become competitive and take a growing share of liquid fuels, and (iii) the industrial growth rate in developing countries slows down considerably.
- (iv) The end of the century brings a new turn of trajectories. A slow down of energy efficiency gains is due to the asymptote hypothesis: the nearer you get to the ceiling, the slower you move to it, whereas the demography and the labour productivity assumptions lower the GNP growth rate. The decarbonisation effect is being stopped as the bio-fuels can no longer grow due to its physical limits, whereas the coal-to-liquid road becomes competitive.



Graph 5 : World trajectories of the 4 high growth engine scenarios exhibiting respectively the total primary energy supply (TPES) to GNP ratio and the carbon to TPES ratio.

Each point corresponds to a year; larger symbols stand for each decade.

These evolutions provide a straightforward explanation of why CO₂ emission can reach up to 110 gigatons of CO₂ (30 gigatons of carbon) in 2100 : a strong GNP growth, between 30 to 40% of energy efficiency progress, but a continued dependence on competitive fossil fuels, which do not induce any straightforward decarbonisation.

Three mechanisms at work in our scenario dynamics deserve some more detailed explanations: the rebound effects, the effect of developing countries industrialisation, and comeback of coal as a competitive fuel.

3.2.3 The rebound effects

The rebound effect concept refers to the case of a consumption (or an activity) increase following an energy efficiency improvement. The rebound effects combine direct, indirect and macro-economic effects triggered by an energy efficiency progress.

- Direct effects – The consumer opts to re-use the saved expense to consume more. For instance, someone getting access to a more efficient car (saving on the specific fuel use per kilometre) can opt for increasing one's car use. This direct effect is limited as the average transport time remains bounded (around 1.1 hour per day, as given by empirical observations: the so-called "Zahavi" rule).

- Indirect effects – The consumer can opt to re-use the saved expense in consuming more of other goods, which in turn induce additional energy consumption. For instance, a household can save money owing to a more efficient heating system and use it to buy more durable goods for the home equipment.

- Market effects – Less demand for a resource lowers its price, which allows marginally more competitive uses. For instance, the electricity has been initially used for lighting in the residential sector, but its decreasing price allowed its use for many other home equipments.

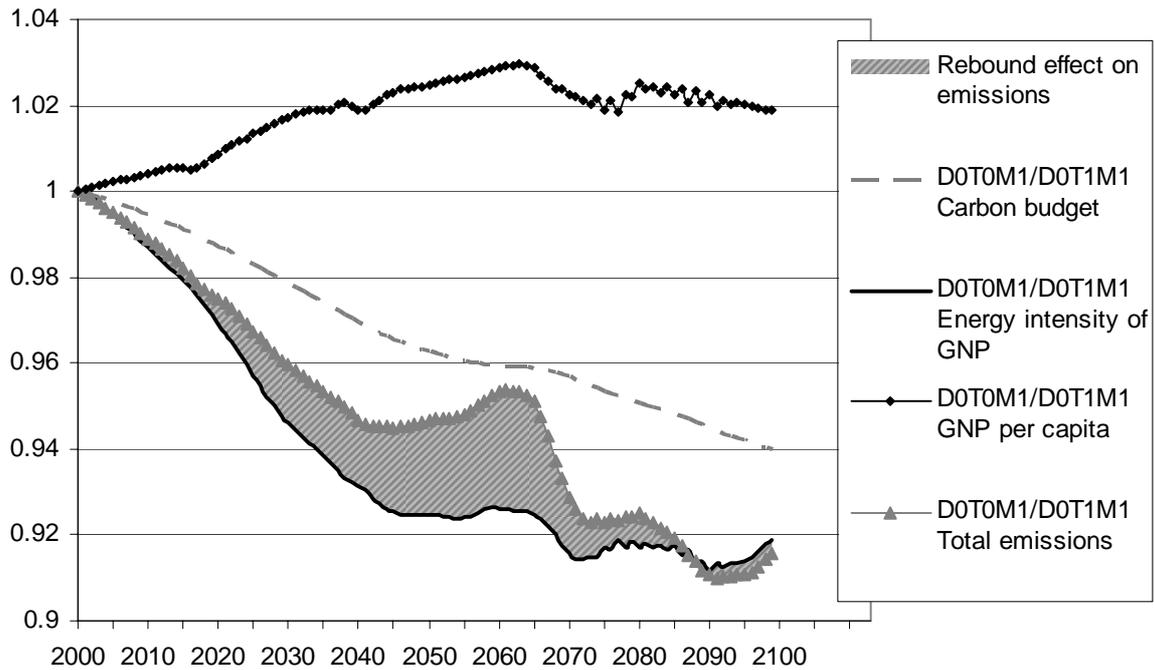
When talking about emissions, the rebound effect corresponds to the difference between the emission reduction projected (by mere transposition of efficiency gains) and the real reduction due to an increased energy efficiency. Indeed, 30% improvement of energy efficiency won't lead to 30% reduction of energy expenses nor 30% emissions reduction; the difference between these 30% of "potential" emissions reduction and real reduction is the rebound effect.

Of course this doesn't mean the rebound effect rules out all benefits of energy efficiency improvements on emissions, but it truly limits their impact, as we will illustrate with two examples of results given by the model.

3.2.3.1 The rebound effect of the technical progress on the GNP

As the technical progress saves part of the energy expenses for a given energy service, it allows a higher activity level and thus again an increased energy demand which cuts on the initial energy saving.

Let us compare for instance D0T0M1 and D0T1M1 scenarios, which share the same development style D0 and the same high growth engine M1, but have different technical progress variant. A more rapid technical progress in the D0T0M1 scenario decreases the energy intensity of the GNP for a given date (see Graph 6). However the level of activity, represented here by the GNP, is higher because of the redeployment of part of the saved energy expenses. The net effect on the emission saved is smaller than the gross direct effect. The effect is magnified on the carbon budget (i.e. the cumulated emissions) and therefore on the climate.



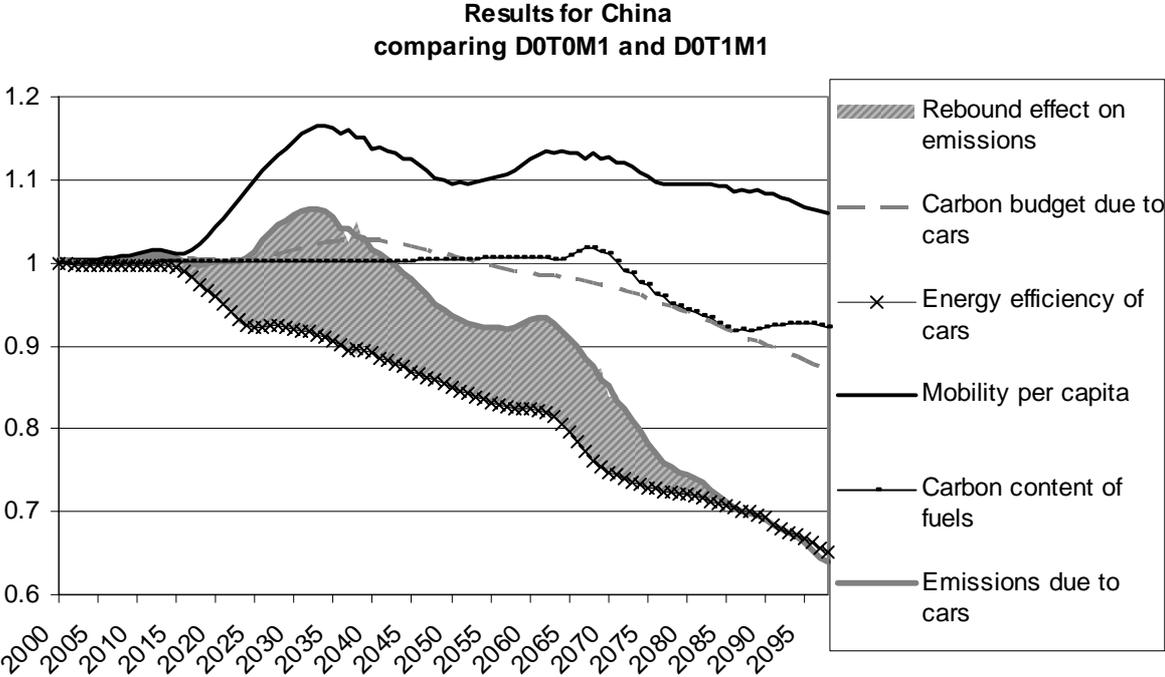
Graph 6 : The rebound effect of the technical progress on the GNP and the carbon budget. Comparing the scenarios D0T0M1 and D0T1M1.
Index 1 for the scenario D0T1M1.

3.2.3.2 *The rebound effect of the technical progress on the mobility*

The rebound mechanism described previously has been publicized mostly in the transport case. As explained previously, progress in cars efficiency hides partly increases of oil prices and induces more mobility (income effect on the mobility in the households' utility function). Additionally to this income effect, efficiency improvement can induce changes in the modal shares as the efficiency gains and the weight of energy in the kilometre cost are not homogenous in the different modes. The emission reductions expected may thus be counterbalanced partly by mobility increase and modal transfer on more energy intensive transportation modes.

Coming back to the comparison between the D0T0M1 and D0T1M1 scenarios, which share the same development style D0 and the same high growth engine M1, but are distinguished on the technical progress variant, the rebound effect on mobility can be highlighted. The trajectories for China (see Graph 7) display more mobility in the more energy efficient scenario (D0T0M1). The total emissions due to cars are the product of the four factors: (i) the carbon content of fuels, (ii) the specific fuel use per kilometre (energy efficiency of cars), (iii) the mobility per head and (iv) the population (identical for the two scenarios under scrutiny here). The carbon content in the D0T0M1 scenario is slightly higher than in the D0T1M1 scenario because the more efficient route determines a lower cumulated fossil fuel demand and thus lower prices, which slows down the entry of bio-fuels. Later in the century, the efficient route (T0) can still rely on the bio-fuels, whereas the less efficient scenario (T1) has saturated the bio-fuel potential and is bound to go more on the coal-to-liquid route.

In the end private transport emissions are not mechanically discounted by the ratio of progress on the specific fuel use in the T0 scenario as against the T1. Emissions can even be higher in the transition phase (here from 2025 to 2045) because the higher technical progress is assumed to induce a strong modal shift in favour of the private car option.

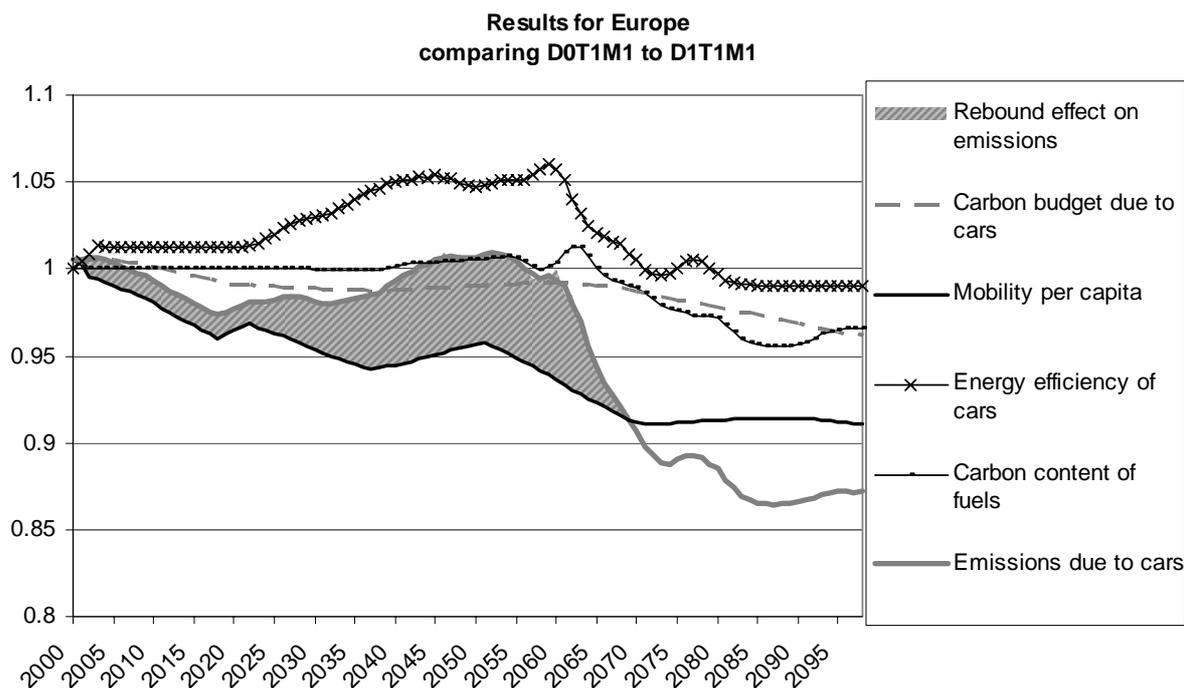


Graph 7 : The rebound effect of the technical progress on the mobility and the carbon budget. Comparing results for China: D0T0M1 compared to D0T1M1.
 Index 1 is set for the scenario D0T1M1

3.2.3.3 *Effect of the development style on the technical progress*

Again the energy technical progress can induce a feedback effect through price in the case of the development style variant. As in the rebound effect case, the direct emission difference is partly compensated: a less energy intensive development style determines a lower cumulated oil and gas demand and thus a lag in the world price increase. In turn it determines less induced technical progress or less induced energy resource substitution, for instance towards bio-fuels. The projected technical progress penetration effect is reduced as compared to the theoretical energy efficiency gain.

This effect is not visible in the Graph 5 because it is negligible as compared to the energy need difference between both development styles. But a detailed D0T1M1 and D1T1M1 comparative analysis can illustrate the compensation mechanism. On Graph 8, the D0T1M1 contains less mobility need, and thus less oil price increase. Therefore it induces less technical progress and a lagged bio-fuels penetration. In total the emission projection does not reflect the totality of the gross effect of a lower mobility need determined by a denser space planning.

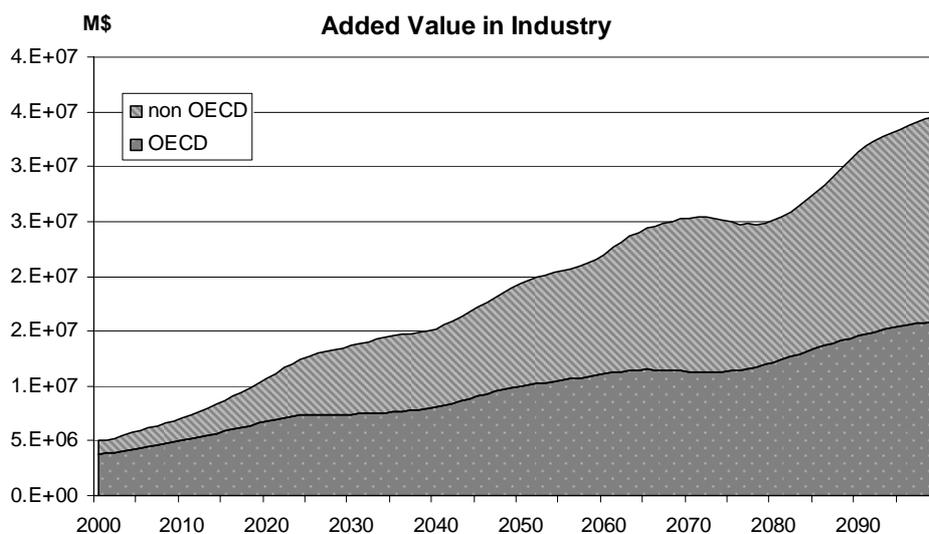


**Graph 8 : The fossil price feedback effect and the carbon budget.
The D0T1M1 - D1T1M1 comparison for Europe.**
Index 1 = D1T1M1 scenario

3.2.4 The structural change in the developing countries

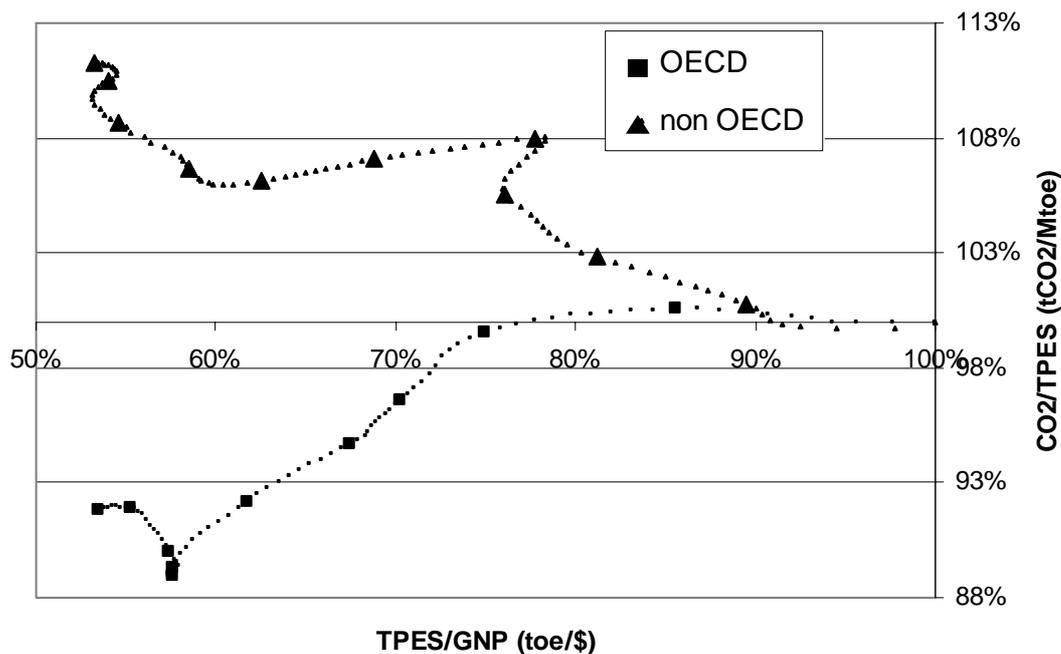
The CO₂ emission per capita in developing countries is much below what it is in industrialized countries, even with comparable geographical or climatic areas. Therefore the catching-up which is assumed as the central trend of the next century means that the developing countries will be weighting more and more on the world average all along the century. Thus we can see on the Graph 5 that the developing countries industrialization catching-up weights as much as to be able to slow down (or even reverse) the global trend of an ever declining global energy intensity into a temporary increase from 2020 to 2040.

The Figure 17 illustrates the OECD and non OECD differing trajectories. OCDE countries, where the expansion of the service sector is continuous over the whole trajectory, see a strong decrease of the energy intensity (around 45% in 2100 as compared to 2000). This decrease of energy intensity goes along with a slow decarbonisation due to progressive penetration of nuclear and renewable energies for electricity generation. One should note that these two trajectories, presented on the same graph, may be misleading: the starting point in 2000, represented here by the ratio 100%, doesn't correspond to the same absolute values for OECD and non OECD countries. The latter remain, in our scenarios, less efficient than the OECD average. Therefore, the energy intensity world average will be raised by the growing share taken by non OECD countries in the world GNP (from 20% to 40% between 2000 and 2100 in scenario D1T1M1).



Graph 9 : OECD and non OECD industry added value in scenario D1T1MI

This effect that we may call « aggregation effect » is visible when we compare the world trajectory (as in figure 11) to the regional trajectories (as in figure 17). Beyond the precise data presented here, there lies a fundamental issue. Will the catching up effect in favour of developing countries share in the world industry (and GNP) be dominated by a leapfrogging effect towards the efficiency frontier or will it still be combined to a strong heritage of the efficiency gap from the starting period. In the end the global energy trajectory is differing very significantly. The factors bearing on it are as follow: the capacity to finance “clean” technologies on productive capital or final equipment, the inertia of existing less efficient capital, the relative prices of energy compared to domestic prices in developing countries, etc.

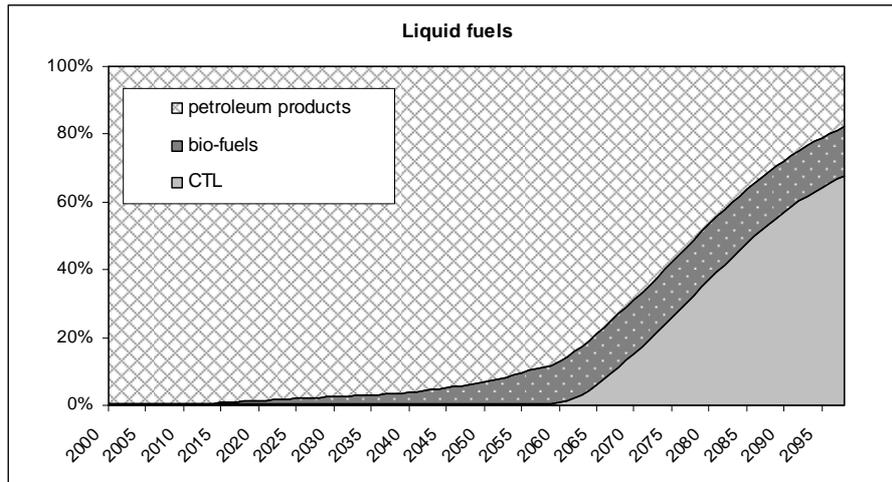


Graph 10 : OECD and non-OECD trajectories for the scenario D1T1M1.

3.2.5 The comeback of coal

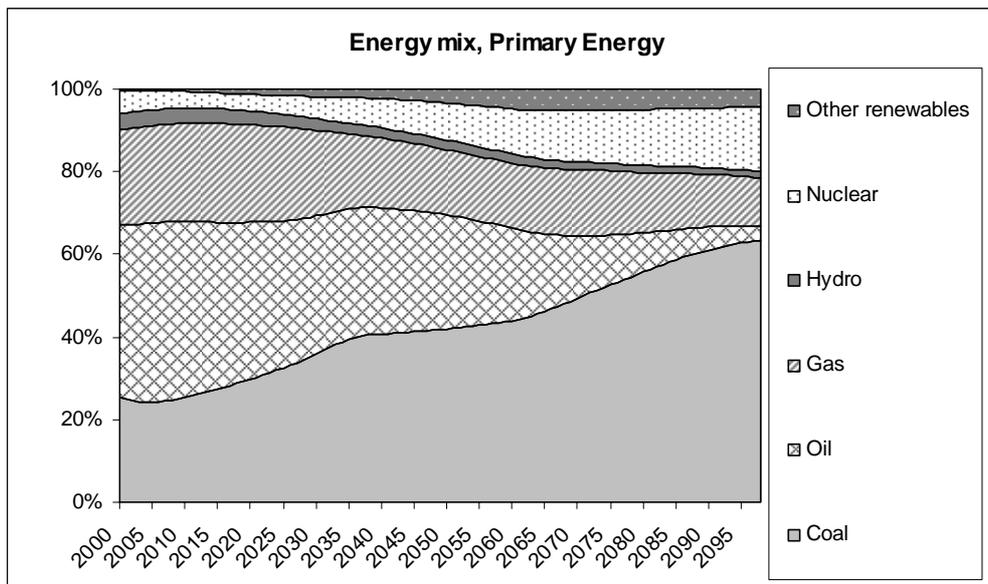
On the Graph 2, there is a noticeable slow down on the emission growth trajectory, beginning around 2035 up to 2065 or 2085 according to the scenario, before a steeper slope up to the end of the century. This sequence reflects the physical impact of the penetration of bio-fuels from around 2035 on and their saturation between 2065 and 2085 giving room to the coal-to-liquid route. This coal comeback is inevitable in a zero carbon price world with a coal-to-liquid technology available and becoming the least cost option. It carries a strong risk of an emission explosive trajectory before the end of the century.

More precisely, this “comeback of coal” occurs when remaining oil resources and bio-fuels are not sufficient to satisfy demand for liquid fuels. The Imaclim-R model thus does not make the hypothesis of a « backstop » technology, i.e. a technology apt to penetrate after the price increase gets above its competitive price and then to provide an unlimited supply of a perfect substitute to the exhausted oil reserves and then to the saturated bio-fuels. As the existence of such a backstop technology does not seem assured today, it seemed to be nor necessary nor robust to make such assumption for our simulations.



Graph 11 : The shares of liquid fuels in the scenario D1T1M1.

The bio-fuel potential is limited by the land use constraints, the competition with food land allocation, and the agricultural yield. We have fed into our model the bio-fuel supply potentials as published in the International Energy Agency (IEA, 2006). We do not assume a drastic modification of the agricultural system, as we are modelling a reference scenario with no carbon policy. The bio-fuel global upper limit is nevertheless set at 1400 Mtoe, which is about equivalent to the current OPEP oil production. Finally, the capture and geological sequestration of CO₂ would only save the potential emission during the coal-to-liquid process and not the emission which inevitably happens during the engine combustion itself. The impact of the comeback of coal on emissions wouldn't be tempered significantly by capture and sequestration.



Graph 12 : The primary energy mix evolution in the D1T1M1 scenario.

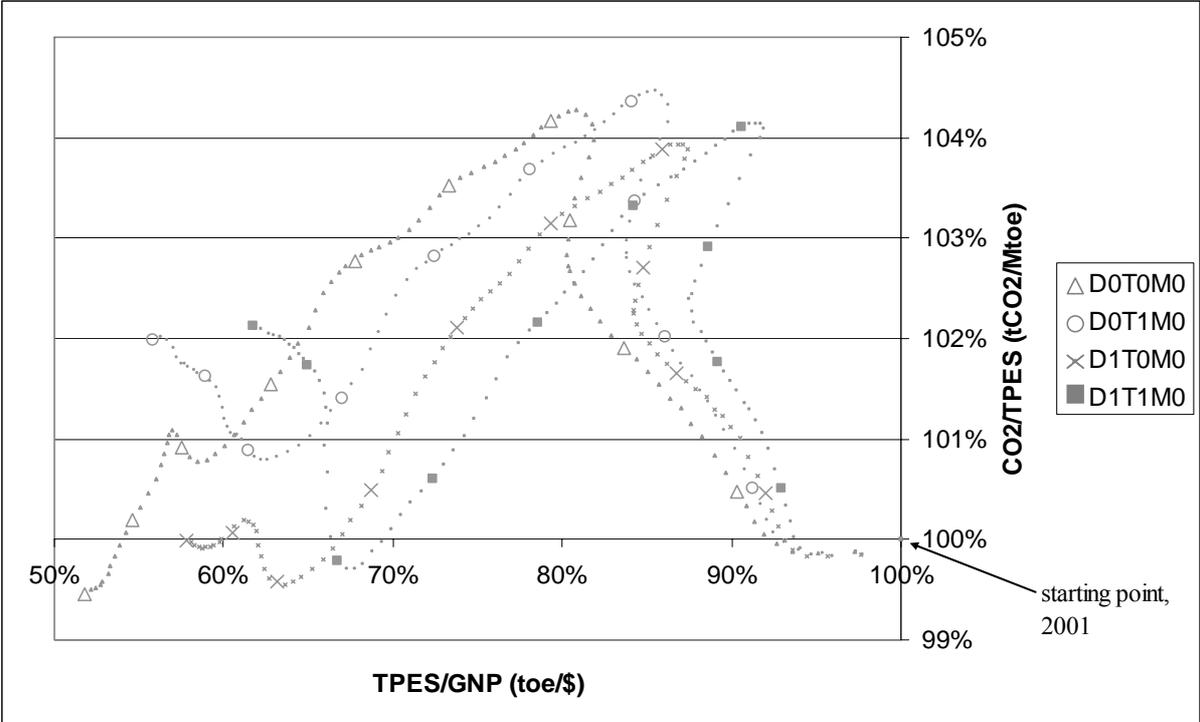
In the mix of the total primary energy supply, the renewable energy share increases only at a very slow pace, whereas the coal remains much more competitive. Only the increase

of nuclear in the generation and the shift to electricity of the energy system allows to decrease the fossil energy share in the energy mix, as shown Graph 12.

3.2.6 Impact of growth variants on the fossil content of trajectories

The Graph 5 presents the trajectories of the four highest emission scenarios. The impact of moderate growth on « Kaya » trajectories stems directly from analysis detailed so far. Nevertheless, we may comment on salient features shown in the Figure 20:

- The carbon intensity increases by around 4% instead of 8% in the M1 scenarios;
- An energy efficiency quite comparable in 2100 resulting from a slightly lower technical progress and less rebound effects as well as less industry growth ;
- The postponement of the recourse to the coal-to-liquid option in the scenarios with the “sober” development style variant, which benefit from a postponed oil and gas exhaustion.



Graph 13 : Trajectories for 4 scenarios of low growth engine (M0): the energy intensity of GNP index and the world carbon intensity of energy index.
 Each point represents one year and larger symbols stand for decades.

3.3 Conclusion

In this exercise, we formulate independent assumptions on the economy growth engine and on the energy technical progress. Therefore the growth impact on the energy efficiency gains is only a second order mechanism through the speed of equipment replacement or the cumulative extraction of fossil resources, which in turn have a bearing on the technological package all along the trajectory. Nevertheless it widely recognized that the birth, the development and the diffusion of innovative technologies are directly correlated to the economic growth, for at least two reasons: first, growth is a precondition to finance the

R&D investments; second technical progress may be induced by the anticipations that agents make on the potential gains of expected progress, and those anticipations depend notably on the growth rate, on the energy price and on the expected fossil reserves. Both factors support the interdependence view that the higher the GNP growth expected, the higher the technical progress. Previous work with an earlier and more compact version of the IMACLIM-R model was especially focused on this topic of induced technical change, but not with a perspective of exploring uncertainty.

This sounds like a reminder of what was answered by modellers to Castles and Henderson's criticism against the overestimated growth rates for the catching up of developing countries GNP expressed in current exchange rates. Nakicenovic and al. (2003) stressed that the emission estimation of SRES was still correct because the effect of overestimated growth rates for developing countries may somehow be compensated by the higher technical progress growth rates as a corollary to the high GNP growth rates. McKibbin and al. (2004) tested this intuition with the G-Cubed model and showed that emissions are not systematically over-estimated because of higher catching-up growth rates of GNP with the use of market exchange rates.

If we lend credibility in the intuition that GNP and technical progress growth rates are correlated, we should examine more in depth the assumptions behind the most contrasted scenarios, i.e. D0T0M0 and D1T1M1, to test their self-consistency. We cannot decide for sure whether they are still within the uncertainty for crossed intervals on growth and technical progress, or whether we miss here a strong link. In that case, it would mean that the four scenarios (D*T1M1, D*T0M0) can not be considered as consistent, and the most contrasted scenarios would become D0T1M0 and D1T0M1. The initial uncertainty interval between the eight scenarios of 13.4 to 33.8 GtC, would then decrease to 14.6-31.3 GtC, that is an interval reduced by 19%.

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