# The IMACLIM-R Model:

## Infrastructures, Technical Inertia and the Costs of Low Carbon Futures under Imperfect Foresight[*]

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**Abstract.** This paper analyzes the transition costs of moving towards a low carbon society when the second-best nature of the economy is accounted for. We emphasize the consequences on mitigation costs of considering the interplay between *a*) technical systems inertia, including slow infrastructure turnover in transportation and construction; and *b*) imperfect foresight influencing investment decisions. To this end, the hybrid general equilibrium modeling framework IMACLIM-R is employed as it allows for transitory partial adjustments of the economy and captures their impact on the dynamics of economic growth. The modeling exercise quantitatively emphasizes the *i)* specific risks that the interplay between inertia and imperfect foresight leads to high macroeconomic costs of carbon abatement measures; *ii)* opportunities of co-benefits from climate policies permitted by the correction of sub-optimalities in the reference scenarios. The article draws insights for the framing of future climate architectures by studying the role of measures that act complementarily to carbon pricing in the transport sector. In particular, reallocating public investment towards low-carbon transport infrastructure significantly reduces the overall macroeconomic costs of a given GHG stabilization target and even creates the room for long-term net economic benefits from climate policies.

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# 1. INTRODUCTION

Economic analysis of climate policy faces a paradox. The literature suggests that the macroeconomic cost of achieving stringent GHGs concentration targets would be moderate[1], but most countries remain reluctant to adopt ambitious climate policy. This may be because the few percentage points of GDP losses, translated in billion dollars, represent a prohibitive cost for decision makers; but part of the paradox may also lie in an often disregarded caveat of the IPCC report:

> "Most models use a global least cost approach to mitigation portfolios and with universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century" (IPCC, 2007, Box SPM.3).

This caveat actually points out the deficit of information about the transition to a low-carbon future in a second-best world. One can argue that imperfect foresight, incomplete markets and institutional failures will lead to higher costs that those reported so far, or, conversely, that non optimal baselines offer opportunities for relative gains under climate policy. This is the major finding of Barker and Scrieciu (2010) with the macroeconometric E3MG model, calibrated on past trends.

The IMACLIM-R model (Sassi et al., 2010) contributes to this debate by incorporating some features of second-best economies in a Computable General Equilibrium model, able to represent important structural and technical change over a century. Its main specificity is to endogenize transitory adjustments of an economy constrained by the interplay between choices under imperfect foresight and the inertia of technical systems. Imperfect foresight is a consequence of *a*) uncertainty about future relative prices, final demand and investments profitability, *b*) "noises" coming from signals other than energy prices (informal economy, prices of land and real estate) and *c)* non-economic determinants of public decisions in transportation and urban planning. Of little importance in a flexible world, imperfect

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[1] The IPCC (2007) reports costs between small GDP gains and lower-than-5.5% losses of global GDP in 2050 for stabilization targets between 445 and 535 ppm $CO_2$-eq (Table SPM.6). The ADAM project (Edenhofer et al., 2010b), extends the estimates to 2100 and finds aggregate costs below 2.5% of global GDP for 400 ppm $CO_2$-eq targets.

foresight becomes crucial when non-optimal choices cannot be corrected frictionless because of inertias on capital stocks and behavioral routines.

The objective of this paper is to show how this interplay between imperfect foresight and inertia explains the peculiar shape of the mitigation cost profiles found by IMACLIM-R compared to those in most models, including WITCH and REMIND in the RECIPE project (Edenhofer et al, 2010a; Luderer et al, 2010a). Section 2 sums up the overall rationale of the IMACLIM-R model and insists on the specific role of infrastructures, a typical case of rigid capital stock. Section 3 shows out the major economic reasons for high short term climate policy costs, specifically in emerging economies, and for potential long run benefits. Section 4 investigates how cost profiles change with a richer climate policy package including complementary measures to carbon pricing, specifically infrastructure policies that affect the transport sector.

## 2. RATIONALE OF THE IMACLIM-R MODELING STRUCTURE

The IMACLIM-R model is a recursive, dynamic, multi-region and multi-sector Computable General Equilibrium (CGE) model of the world economy.[2] It describes growth patterns in second best worlds (market imperfections, partial uses of production factors and imperfect expectations) through a hybrid and recursive dynamic architecture. A detailed algebraic description of this model is given in the Supplementary Electronic Material and we herein outline only those of its features that matter for the purpose of this paper.

### 2.1. A growth engine with gaps between natural and effective growth

IMACLIM-R incorporates exogenous assumptions of regional labour productivity growth and active population growth (see Supplementary Material), which determine the exogenous 'natural' growth rate.[3] Effective growth rates are endogenously driven by labour allocation across regions and sectors at each point in time, given relative productivities and short-term rigidities (capital stock inertia, frictions in reallocating labour and wage rigidity). Aggregate

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[2] The version of the IMACLIM-R model used in this study divides the world in 12 regions (USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle-East, Africa, Rest of Asia, Rest of Latin America) and 12 sectors (coal, oil, gas, liquid fuels, electricity, air transport, water transport, other transport, construction, agriculture, energy-intensive industry, services & light-industry).

[3] A large strand of literature has emerged after Solow (1956) that traditionally represents growth trajectories on the basis of this "natural" growth rate, which boils down to representing the global economy as characterized by a unique composite production sector operating at full employment.

capital accumulation is controlled by exogenous saving rates like in Solow (1956), and IMACLIM-R represents investment decisions under imperfect foresight. At a given date, agents have limited information about the future and shape their expectations on the basis of past and current trends (adaptive expectations). Under such semi-myopic foresight, installed capital resulting from past investment decisions may not be adapted to future economic settings. However, it cannot be renewed overnight due to inertias and acts as a constraint on the adaptability to variations of economic conditions (activity levels and prices).

### 2.2. A recursive and modular architecture to endogenize technical change

The general equilibrium model IMACLIM-R model endogenizes the rate and direction of technical change by representing the bottom-up impact of investment decisions on the deployment of technical systems. The consistency of the top-down/bottom-up conversation is guaranteed by a hybrid structure representing the economy in money values and physical quantities (Hourcade et al, 2006). This dual accounting, following the Arrow-Debreu axiomatic (Arrow and Debreu, 1954), ensures that the projected economy is supported by a realistic technical background (in the engineering sense) and, conversely, that projected technical systems correspond to realistic economic flows and consistent sets of relative prices. In climate policy analysis, this approach has for long been claimed as crucial for the energy goods to represent explicitly their carbon-to-energy ratio (Malcolm and Truong, 1999; Sands et *al.*, 2005). IMACLIM-R extends it to transportation as another key sector of climate analysis.

A recursive structure then organizes a systematic exchange of information between a top-down annual static equilibrium providing a snapshot of the economy at each yearly time step, and bottom-up dynamic modules informing on the evolution of technical parameters between two equilibria (Figure 1).

*[Figure 1 about here]*

The annual static equilibrium determines relative prices, wages, labour, value, physical flows, capacity utilization, profit rates and savings at date *t* as a result of short term equilibrium conditions between demand and supply on all markets, including energy. Utility-maximizing households base their consumption choices on both income and time constraints; the former is the sum of wages, capital returns and transfers whereas the latter controls the total time spent in transportation. Firms adapt their short term production considering fixed input-output coefficients (the average of techniques embodied in their capital stock) and decreasing static returns when capacity approaches saturation[4]. They determine their prices with a margin rate over production costs (mark-up) to capture the effect of imperfect competition.[5]

Total demand for each good (the sum of households' consumption, public and private investments and intermediate uses) is satisfied by a mix of domestic production and imports.[6] All intermediate and final goods are internationally tradable. Domestic as well as international markets for all goods are cleared (i.e. no stock is allowed) by a unique set of relative prices and this determines the utilization rate of production capacities.[7] The equilibrium values of all variables are sent to the dynamic modules to serve as a signal for agents' decisions affecting technical coefficients at *t*+1.

The dynamics of the economy is governed by endogenous descriptions of capital accumulation and technical change, given the exogenous 'natural' growth assumptions. At each year, regional capital accumulation is given by firms' investment, households' savings, and international capital flows[8]. On that basis, the across-sector distribution of investments is governed by expectations on sector profitability and technical conditions as described in sector-specific reduced forms of technology-rich models (referred to as Nexus modules and extensively described in the Supplementary Material).

The Nexus modules represent the evolution of technical coefficients resulting from agents' microeconomic decisions on technological choices, given the limits imposed by the innovation possibility frontier (Ahmad, 1966). They embed *a*) sector-based information of economies of scale, learning-by-doing mechanisms and saturation in efficiency progress, and *b*) expert views about the asymptotes on ultimate technical potentials, the impact of incentive

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[4] Following (Corrado and Mattey, 1997), decreasing returns reflect the higher labor costs associated to extra-hour operations, costly night work and increasing maintenance works when capacity approaches saturation.

[5] The mark-ups are exogenous except in energy sector where they are endogenous to reflect (a) the market power of fossil fuel producers (b) specific pricing principles in the power sector (e.g., mean cost pricing), and (c) the different margins over the three inputs for liquid fuels production (oil, biomass, coal).

[6] For non-energy goods, we adopt Armington specifications (Armington, 1969) to capture the partial substitutability between domestic and foreign goods, while physical accounting for energy goods (in MToe) makes them fully substitutable.

[7] The partial utilization rate of production capacities allows representing operational flexibility through early retirement of those capacities which, although installed, are not used for actual production because not competitive in current economic conditions.

[8] In absence of explicit interest rate, we assume a gradual correction of current imbalances, as a standard proxy for the complex determinants of international capital flows in energy forecasting exercises (Edmonds et al, 2004; Paltsev et al., 2005).

systems, and the role of market or institutional imperfections. The new investment choices and technical coefficients are then sent back to the static module in the form of updated production capacities and input-output coefficients to calculate the $t+1$ equilibrium.

This structure comes to adopt a standard putty-clay representation with fixed technical content of installed capital, which allows distinguishing between short-term rigidities and long-term flexibilities (Johansen, 1959).

### 2.3. A specific treatment of the transport sector

The potentials of the IMACLIM-R structure have been exploited to make explicit the specifics of the transport sector and its impact on energy demand. This sector, vital for economic and human development, is characterized by a strong path dependency of options, by the influence of non-energy determinants in the collective and individual behaviors (for example the spatial setting *via* location choices of both firms and households) and by the dependence upon long-lived infrastructure investments.

The IMACLIM-R model represents the specific role of *i*) the attractiveness of alternative modes influencing the modal choice of individuals, *ii*) households' mobility needs constraining average distances of travel and commuting, and *iii*) the spatial organization of production determining freight transport needs:

*i.* The relation between transportation infrastructure, mobility demand and modal choices is captured in the maximization of households' utility where saturation of infrastructures cause speed decreases when normal load conditions are exceeded. Then, investments in transport infrastructures determine the efficiency of the different transport modes and, hence, the allocation of travel time budget across modes of different efficiencies.

*ii.* The utility demand for mobility is dependent upon agents' localization choices through households' constrained mobility for commuting and shopping (Grazi et al., 2008). It does so through a "basic need' level which is not directly sensitive to fuel prices variations but rather capture location and infrastructure constraints (residential areas, work centers, transport infrastructures), including urban policies aimed at limiting urban sprawl.

*iii.* The freight transport content of production processes is represented by explicit input-output coefficients. The absence of decoupling between production and transport (constant input-output coefficient) corresponds to pursuing current trends of transport-intensive production; in alternative scenarios we also consider a progressive decrease of the freight content of production in a way to represent changes in producers' choices on the supply chains, relocation of production infrastructures (more vertically integrated, and spatially closer to markets) and a moderation of "just-in-time" processes.

## 3. TIME PROFILES OF CLIMATE POLICY COSTS

We herein analyze the specifics of cost profiles of a global climate policy in IMACLIM-R. In section 3.1, we test their robustness to parameter uncertainty. In section 3.2, we use a simple analytical demonstration to clarify the economic determinants of costs in second-best settings. In section 3.3, we demonstrate why the long distance race between technical change and inertia is the major cause of important short-term losses and allows for long-term catch-up of baseline levels (and even some benefits).

To conduct these analyses, our numerical experiments will encompass (see Appendix)

A. three assumptions on *Oil and Gas supply :* (A-1) assumes moderate limitations on medium-term oil supply in line with conservative estimates on the amount and distribution of oil reserves, whereas (A-2) considers lower oil reserves. We add a third variant, an even more pessimistic case, where not only are resources low, but also geological constraints on capacity deployment forces to an accelerated decline of global production (A-3).

B. two assumptions on the *Substitutes to oil*: *(*B-2) corresponds to a faster and deeper market diffusion of substitutes to oil (biofuels and Coal-To-Liquid) than (B-1).

C. two assumptions on *Demand side technological change* : (C-2) refers to a faster diffusion of decarbonization and energy efficiency technologies than in (C-1).

Using the same assumptions on regional natural growth, we obtain very similar mean GDP growth under all combinations of parameter assumptions defining the $3 \times 2^2 = 12$ 'BAU' scenarios for the 2010-2100 period.[9] These scenarios feature a wide dispersion of $CO_2$ emissions from 30 to 69 $GtCO_2$ in 2100 (see Table 1), which lie in the middle of the 15-135 $GtCO_2$ range of the SRES and post-SRES scenarios, in 2100 (Barker et al., 2007, Figure TS7).

*[Table 1 about here]*

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[9] Note that the reference scenario from the RECIPE model comparison exercise (Luderer et al, 2010a) is not included within these BAU scenarios. Indeed, specific exogenous forcing of the model were introduced in the model comparison exercise in order to make the reference scenarios comparable across models. For example, an exogenous oil price trajectory was used, but is not used in the BAU scenarios from this article.

Since the objective is to analyze the mechanisms of cost formation, we worked under an identical $CO_2$ emission trajectory for all stabilization scenarios over the period. We thus set aside the question of the intertemporal flexibility for allocating emission reductions for the same carbon budget that could affect near-term mitigation costs by postponing emission reductions (“when flexibility”). The trajectory is chosen in category III of IPCC scenarios corresponding to a stabilization target of 440-485 ppm $CO_2$: global $CO_2$ emissions peak in 2017 and are decreased by 20% and 60% with respect of 2000 level in 2050 and 2100, respectively (Barker et al., 2007, Table TS2). For the purpose of this exercise, we also exclude international redistribution of tax revenues[10] and the model endogenously calculates the world carbon tax to be imposed to meet the emissions constraint at each point in time.

### 3.1. ‘Carbon price-only’ policy: a time profile robust to uncertainty

The left-hand panel in Figure 2 displays global GDP variations in stabilization scenario targets compared to the Business As Usual (BAU) situation, the bold black line giving the average costs of these scenarios[11]. The right-hand panel of Figure 2 compares the average growth rates in BAU and stabilization scenarios.

*[Figure 2 about here]*

With a 3% discount rate, discounted mitigation costs over the period 2010-2100 range from 1% to 4.6% across scenarios, but this aggregated value masks critical issues revealed by the time profile of costs. Actually, despite differences in the magnitude of GDP variations across scenarios, four phases of GDP losses (Figure 2, left panel) and carbon price (Figure 3) can be identified for all of them:

*(i)* substantial transitory costs during the first two decades of stabilization with lower growth rates than in reference scenarios (but never an absolute decrease of GDP in any region).[12] These costs are associated with a sharp initial increase of the carbon price.

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[10] The RECIPE project investigates the consequences of regional differences in carbon tax (Jakob et al, 2010) and the effects of alternative rules for quota allocation among regions (Luderer et al, 2010b)

[11] This average value attributes equal importance to each ‘future world’ and should not be intended as a best-guess estimate. It is displayed to identify the general trends of the variables under consideration, independently of their variability across scenarios.

[12] IPCC reports global GDP losses between 0.2% and 2.5% in 2030 (IPCC, 2007, Table SPM.4), whereas we obtain a range between 1% and 9.5%, with the average value around 4% (see Figure 2).

*(ii)* a medium-term (about fifteen years) GDP catch-up with higher growth rates under a climate policy than in the reference scenario; this phase is associated with a decline in the carbon price ending around 2045,

*(iii)* a second phase of significant GDP loss in the stabilization scenario from 2045 to 2070 associated with a second phase of steep carbon price increase,

*(iv)* a long-term regime in which, on average, the continuous increase of average carbon prices do not trigger significant GDP loss, as if the economy were adapted to a regime with ever increasing carbon prices. In fact, this average stabilization of GDP losses hides a divergence across scenarios, between optimistic scenarios with a slow economic catch-up towards baseline levels and pessimistic ones with continuing departures from these levels.

*[Figure 3 about here]*

The magnitude of the above mechanisms features some significant regional difference, since the costs remain moderate in developed countries, but are extremely high in the rest of the world (Figure 4 and Table 2). This is particularly true in the short-term, in which developing countries face, on average, as high as 10% transitory losses around 2030 (against only 1% at the same time horizon in developed countries).

*[Figure 4 about here]*

*[Table 2 about here]*

## 3.2. Drivers of mitigation costs: an analytical detour

The economic drivers of these non conventional time profiles can be derived from a stylized model which incorporates the core specificities of the static equilibrium of the IMACLIM-R model. To this aim, we consider an economy producing a composite good *Q* with energy and labour as input factors, a mark-up price equation to represent imperfect competition and a wage-curve to capture labour market imperfections.

A simple analytic derivation of production variations $\Delta Q$ when a tax on energy $\tau_E$ is levied (see the Supplementary Material for a detailed presentation) gives a proxy for mitigation costs:

$$\frac{\Delta Q}{Q_0} = \frac{z_0}{1-z_0} \cdot \left[ 1 - \left( 1 - \frac{p_E . e}{w_0 l} \tau_E \right)^{-\frac{1}{\alpha}} \right] \quad (1)$$

In equation (1), $e$ and $l$ are the unitary energy and labour requirements for production, $p_E$ the price of energy, $w_0$ and $z_0$ the wage rate and unemployment level in the absence of taxation and $\alpha$ is the elasticity of the wage curve (the higher $\alpha$, the more flexible the labor markets). The remarkable lesson of equation (1) is that the energy parameters are not the only drivers of the costs induced by a given level of carbon taxation. Part of the magnitude of the costs is driven by the macroeconomic effects on labour markets controlled by the elasticity of the labor market $\alpha$ and the unemployment rate $z_0$ [13]. Another part is driven by the energy costs / labor costs ratio $\left(\frac{p_E.e}{w_0 l}\right)$: the countries the more adversely affected by higher energy prices are those in which the energy share in production costs is high and the salaries share is low.

The dynamic effect of the carbon tax depends on the interplay between the pace of a) changes in labour markets driving wage adjustments, b) technical change favouring lower labour and energy inputs for production, c) energy price and carbon tax evolutions. This justifies why we can obtain high short-term losses but more moderate costs in the long-term.

Over the short-term, the decline of the energy costs / labor costs ratio is constrained by the absolute increase of wages and inertias on the evolution of the ratio *e/l*, which globally enhance the costs according to equation (1).

Over the long term, induced technical change accelerates the decline of the energy content of production and slows down the increase of energy costs; labour costs increases thanks to wage adjustments (in particular in developing countries during their catch-up period); and the decline of energy demand due to carbon taxation triggers a significant drop of energy prices with respect to the baseline. These effects combine to reduce long-term costs[14].

### 3.3. A long distance race: technical change versus inertia

Let us now analyze in more detail how the above mechanisms work during the four phases of our time profiles.

*(i)* During the 2010-2030 period, the particularly high GDP losses of climate policy found with IMACLIM-R are due to the sharp increase of carbon prices $\tau_E$ (Figure 3) and inertias in the decrease of *e/l*. Under adaptive expectations indeed, investment choices can be

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[13] These effects are analyzed more in-depth in (Guivarch et al.,2010)

[14] To demonstrate why those long-term costs can even be negative, it is necessary to represent the imperfect allocation of investments under baseline, which brings about considering a multisectoral model at the expense of analytical solvability.

redirected only with high carbon prices whereas, under perfect foresight long-term prices are internalized in short term decisions which makes high short-term prices unnecessary. These carbon prices trigger increases of production costs, final prices and households' energy bills because the decrease of the carbon-intensity of the economy is limited by inertias on installed capital and on the renewal of households' end-use equipment (residential appliances, vehicles). These effects combine to undermine households' purchasing power, generate a drop in total final demand, a contraction of production, higher unemployment (under imperfect labour markets) and an additional weakening of households' purchasing power through lower wages.

These mechanisms are more pronounced in emerging and developing countries because their industrial catch-up is based on a high share of energy-intensive basic industries with a high ratio $e/l$ and low wages $w$. The GDP losses caused by these structural characteristics are enhanced by the negative effect of a unique carbon price on the international competitiveness of these carbon-intensive economies (Figure 4 and Table 2).

Unsurprisingly, more optimistic assumptions on technological change limits short-term losses, since fast technical change partly counterbalances the inertia on the renewal of installed capital and makes decarbonisation easier: the energy intensity of production decreases, the carbon price necessary to trigger decarbonisation is lower, and those two effects combine to reduce GDP losses (Case C-2 in Figure 5). In addition, transitory costs are much lower where low oil reserves impose high short-term oil prices further accelerating technical change (Case A-3 in Figure 6).

*[Figure 5 about here]*

*[Figure 6 about here]*

*(ii)* Between 2030 and 2045, the economic catch-up observed in Figure 2 is due to two major positive effects of early carbon prices, which lowers the weight of energy in the production process, $p_E.e$. First, moderation of oil demand in stabilization scenarios delays Peak Oil and the associated oil price increase (reduction of energy prices $p_E$). Second, the accumulation of learning-by-doing favours the diffusion of carbon-free technologies over this time horizon, with the co-benefit of enhanced energy efficiency (lower $e$). The mitigation costs are further moderated at this time horizon by the decrease of carbon price $\tau_E$ between 2030 and 2045, permitted by the abundance of mitigation potentials below 50\$/tC$0_2$ in the

residential, industrial and power sectors (see (Barker et al., 2007, Figure TS27)). Those effects can be interpreted as a partial correction, *via* carbon pricing, of sub-optimal investment decisions in the BAU scenarios thanks to the steady increase of fossil energy costs (carbon price included) which partly compensates for the imperfect anticipation of increases in oil prices in the BAU scenario. It forces short-sighted decision-makers to progressively internalize constraints in fossil fuel availability, and accelerate the learning-by-doing in carbon-saving techniques. This yields a virtuous macroeconomic impact through a lower burden of imports in oil importing economies and reduced volatility of oil prices. In this sense, a carbon price is a hedging tool against the uncertainty on oil markets (Rozenberg et al., 2010).

This virtuous effect is stronger in the case of slow technical change leading to high oil dependency (scenario C-1 in Figure 5). In this case indeed, economies are more vulnerable to Peak Oil in the BAU scenario. The GDP catch-up is also more important in the case of high reserves. In the Scenario A-1 (Figure 6) indeed, oil-free technical change is for long discouraged by low oil prices and the high economic burden imposed by Peak Oil period is significantly reduced by early carbon pricing.

*(iii)* Around 2050, a new phase of increasing mitigation costs starts as a consequence of a sharp increase of carbon prices $\tau_E$ from around 100$/tCO2 in 2045 to around 300$/tCO2 in 2070. Indeed, at this time horizon, most of the low cost mitigation potentials in the residential, industrial and power sectors have been exhausted, and the essential of emission reductions has to come from the transportation sector. A fast increase of carbon prices is then necessary to ensure emission reductions despite the weak sensitivity of the transportation sector to carbon prices and the trend of increasing carbon-intensive road-based mobility. This context is generated by the concomitance of four effects: a) the massive access to motorized mobility in developing countries, b) the absence of targeted policies to control urban sprawl, which tends to increase the dependence on constrained mobility c) the abundance of investments in road infrastructure, which decrease road congestion and favor the attractiveness of private cars at the expense of other transportation modes, d) the rebound effect on mobility demand consecutive to energy efficiency gains, which offsets

approximately 25% of the emissions reductions that would have resulted from technical energy efficiency improvement.[15]

In addition the diffusion of Coal-To-Liquid (CTL) as a mature substitute to oil after 2050 makes passenger mobility particularly carbon intensive. During this post-Peak Oil period, the assumptions about the degree of maturation of CTL are one key determinant of overall costs. Mitigation costs are high with a rapid deployment of CTL in the BAU scenario, making very high carbon prices necessary to limit its penetration (Case B-2 in Figure 7)

*[Figure 7 about here]*

*(iv)* After 2070, an increase of carbon price is still necessary to control emissions in the transportation sector since most other mitigation potentials have already been exploited (up to 600\$/t$CO_2$ in 2100). However, contrary to the first period, high carbon prices do not necessarily induce significant GDP losses. Indeed, they apply to a low-carbon economy and, at that time horizon, the share of labor costs has increased drastically in currently developing regions, making the critical energy-to-labor cost ratio $\left(\frac{p_E.e}{w_0 l}\right)$ far lower.

The race between increasing mobility needs and technical change in the transport sector is thus critical to explain discrepancies across scenarios over the century. In this race, the diffusion of Electric Vehicles is a key parameter (given almost carbon-free power generation). Optimistic assumptions for the market potential of electric vehicles accelerate its diffusion, decrease the energy cost $p_E.e$ and allows for a final phase of GDP catch-up (C-2 in Figure 5). Conversely, if the diffusion of electric vehicles is limited, the transportation sector remains fossil fuel intensive and further emission reductions come at as slightly increasing cost (C-1 in Figure 5).

## 4. Beyond carbon pricing: the role of investments in long-lived infrastructure

The time profile of mitigation costs obtained with a worldwide carbon price in Section 3 highlights two major concerns.

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[15] This order of magnitude of the rebound effect is in the range of empirical measures reported in the literature (Greening et al., 2000).

First, the necessity of high short-term carbon prices is detrimental to most economies and triggers high transitory losses (especially in developing countries). The sensitivity of short-term mitigation costs to technological change parameters, as discussed in Section 3.3 (i), suggests that support schemes to low-carbon technologies may be an appropriate complementary measure to foster early investments and endogenous improvements of low-carbon technologies (Kverndokk and Rosendahl, 2007) and to lower carbon prices (see Bosetti et al., 2009).[16]

Second, the high short-term carbon prices may be insufficient to limit long-term losses, notably because of the very specific dynamics of the transportation sector (Jaccard, 1997) where energy prices are swamped by other determinants (e.g., real estate markets, political bargaining behind infrastructure policies and just-in-time processes in the industry). In this section, we test a design of climate policy where carbon pricing is complemented by measures aimed at controlling the long-term dynamics of transport-related emissions. In this exploratory exercise, we represent spatial planning-related policies and changes in investment decisions for long-lived infrastructure in a synthetic way through three main sets on assumptions[17].

*(i)* a shift in the modal structure of investment in transportation infrastructure favoring public modes against private cars. Instead of assuming that the allocation of investments follows modal mobility demand, we consider public policies that reallocate part of them from road to low-carbon transportation infrastructure (rail and water for freight transport, rail and non-motorized modes for passenger transport).

*(ii)* a progressive relocation of buildings infrastructure that allows for a reduction of households' constrained mobility (essentially commuting) from the 50% of total mobility as previously considered to 40% .

*(iii)* changes in the production/distribution processes allowing to reduce transport needs (we considered a 1% decrease of the input-output coefficient between transport and industry to be compared with a constant coefficient in the previous case).

Replicating the numerical experiments for the 12 above BAU scenarios, we find that the reduction of mobility needs and the shift towards low-carbon modes allows meeting the same

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[16] These schemes are not investigated explicitly in this paper, but are implicitly captured by the assumption on technological change.

[17] Given the absence of reliable and comprehensive data on the cost of implementation of these measures, we assume a redirection of investments at constant total amount and neglect side costs and benefits.

climate objective without a steep rise of carbon prices over the long run (Figure 8) and with far more moderate GDP losses (Figure 9).

*[Figure 8 about here]*

*[Figure 9 about here]*

Another important finding is that these positive effects become especially important only after 2050, which is the logical outcome of the inertias in deploying new infrastructures. However, the complementary measures do not change drastically carbon prices before 2050, their impact on GDP losses is already visible between 2025 and 2050 in the form of an acceleration of the GDP catch-up with its BAU level and negligible losses around 2050 (Figure 9). The alternative infrastructures are not fully deployed but they begin to have an influence on the demand for gasoline (constraining the rebound effect) at the very moment when other sources of decarbonization start to become exhausted. This reduction of gasoline demand has a significant impact on the dynamics of the oil market and yields a deeper 'peak oil avoidance.

In the short run, the effects of complementary policies is less important, but non negligible; as GDP losses being reduced by 20% in 2025 with respect to the carbon-price only policy. But, because of the inertia of transportation infrastructures, the bulk of the transition problem has to be addressed through other policies (fiscal policies, differentiated tariffs, subsidies for energy efficiency in the residential sector, etc.) targeted to avoid a full transmission of the carbon price to householders' energy bill, especially in developing countries.

## 5. CONCLUSION

This paper analyzes the macroeconomic effects of a worldwide carbon price with the IMACLIM-R model. The profiles of GDP costs differ significantly from those found in a first best economy, because the model captures key features of second- best economies (non fully flexible labor markets, imperfect competition, adaptive foresight) and represents the inertia of technical systems.

Over the short term (2020-2030), the absence of perfect foresight makes high carbon prices necessary and causes high GDP losses. Technical inertia limits the pace of decarbonization and the high carbon prices increase production costs; these costs are transmitted to the selling prices and combine with higher household's energy bill to undermine consumers' purchasing power. These mechanisms are more important in emerging economies because of their higher labor-to-energy costs ratio, driving particularly important losses. In the medium term (2030-

2050), the climate policy has important co-benefits by reducing the reduced vulnerability to Peak Oil and accelerating learning-by-doing in fossil-free techniques. This favors higher growth rates in the policy trajectories and a catch-up of the BAU GDPs. Over the long-term (2050-2100), there is the recurrence of significant costs notably because of the necessity to control transport-related emissions. In the absence of very optimistic assumptions on biofuels or electrical cars, high carbon prices are necessary to outweigh increasing trends of motorized mobility and drive steady losses in the long-term.

This lock-in can be avoided by specific measures triggering an early redirection of investments in favor of modal shifts towards public modes, moderation of urban sprawl, and curtailment of the transport intensity of production. Based on this diagnosis, we investigate the role of infrastructure dynamics in the formation of cost profiles and investigate a climate architecture where carbon pricing is complemented by measures designed to control transport-related emissions. The adoption of such measures proves to significantly reduce the policy costs, particularly in the long term, and even creates room for negative costs in the long-term.

This result contributes to the debate on the assessment of climate policies in second-best economies by demonstrating that absolute gains of climate policy can exist even in case of important departures from current trends. Here, these gains are obtained because the shifts of investments in long-lived infrastructures help to control the structural change towards energy-intensive mobility.

This analysis has direct policy implications for the design of climate policy in that it sheds light on the role of infrastructure investments as complementary policies to carbon pricing. More detailed insights could be obtained by disaggregating these measures in a set of agglomeration-specific policy measures, and complementary initiatives at alternative spatial scales, that may shed light on different behavioral responses, in terms of relocation of production and consumption activities.

# Appendix: Numerical assumptions and variants of scenarios

## A. Numerical assumption on oil and gas supply

The three crucial determinants of the 'oil supply' Nexus are the amount of ultimate resources (and their regional distribution), the inertia on capacity deployment and the decision of Middle-East producers acting as "swing producers".

Most estimates of proved oil reserves converge around 2.2 Tbbl (BP, 2011) including past production. To reflect controversies about the amount of reserves to be discovered, we adopt two assumptions for ultimate resources $Q_\infty$: 3.3 Tbbl and 3.8 Tbbl. The lower bound reflects a conservative assumption on resource additions, in line with estimates from the Association for the Study of Peak Oil (ASPO). The higher bound considers higher resource potentials, corresponding to median estimates by (USGS, 2000; Greene et al., 2006; Rogner, 1997).

The intensity of constraints on production growth due to geological constraints is captured by the slope parameter $b$[18]. For conventional oil, we adopt the econometric estimate from Rehrl and Friedrich (2006): $b_C$=0.061/year. Given uncertainty on large scale production of non-conventional oil, we consider either the same value than conventional oil, $b_{NC}$=0.061/year, or more pessimistic assumption of a slower deployment with $b_{NC}$=0.04/year. For Middle-East producers, we impose in addition a cap on the annual increase of production capacity, $\Delta Cap_{ME}$.

The deployment of production capacities in Middle-East countries is decided by the price objective $p_{obj}$. A benchmark for oil price setting is a continuous increase towards a medium-term stabilization around 80$/bbl, reflecting the progressive loss of influence of Middle-East producers. Given uncertainties, especially in the geopolitical context, we also consider the possibility that Middle-East producers are able to expand their production capacities to bring oil price at their pre-2004 level, 40$/bbl. This market flooding option is possible only for the more optimistic assumption on reserves. This exercise of the market power ends up when the finiteness of the resource forces a decline of production. For the sake of simplicity, we assume that it happens once a share $sh_D$ of their reserves remains underground, and consider two values (50% or 25%) to reflect the uncertainties on the stock of resource in Middle-East countries.

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[18] a small (high) $b$ means a flat (sloping) production profile to represent slow (fast) deployment of production capacities.

Finally, the 'gas supply' NEXUS represents indexation of gas markets on oil markets with a 0.68 elasticity of gas to oil price, as calibrated on the World Energy Model (IEA, 2007). But, in order to represent the possibility that gas scarcity triggers faster price increases, we consider an alternative where this indexation disappears when oil prices exceed a threshold level $p_{oil/gas}$ (chosen at 80$/bbl). In this latter case, gas prices are driven by the increased margins for gas producers.

These numerical assumptions are grouped in three variants summarized in Table A-1

Table A-1: Numerical assumptions for the three variants on oil and gas supply

| | *Unit* | **A-1** | **A-2** | **A-3** |
|---|---|---|---|---|
| $Q_\infty$ | *Tb* | 3.8 | 3.3 | 3.3 |
| $p_{obj}$ | *$/bl* | 40 | 80 | 80 |
| $b_{NC}$ | $Year^{-1}$ | 0.061 | 0.04 | 0.04 |
| $\Delta Cap$ | *Mbl/y* | 0.8 | 0.7 | 0.7 |
| $sh_D$ | *%* | 25 | 25 | 50 |
| $p_{oil/gas}$ | *$/bl* | 80 | ∞ | ∞ |

# B. Numerical assumption on substitutes to oil

The 'alternatives to oil' Nexus considers two large-scale substitutes to oil for liquid fuels production: biofuels and Coal-To-Liquid.

The supply curves, $S_{bio}(t,p)$ give biofuels production, given competition with oil, and are taken from IEA (2006). They assume maximum biofuels production at 14 EJ/year in 2030 and, thanks to technical progress, at 42 EJ/year in 2050. These assumptions are quite conservative with respect to recent estimates about biofuels potential (Chum et al, 2011, Figure 2.23(b)) and we introduce an alternative, more optimistic, assumption allowing 20 EJ/year in 2030 and 60EJ/year in 2050. The diffusion of biofuels is in addition submitted to the constraint of a time delay, $\Delta t_{bio}$, which captures inertia on the deployment of raw products (biomass) and of refining capacity.

Coal-To-Liquid is treated as a backstop technology, which enters the market as soon as liquid fuel selling price exceeds its total cost, $p_{CTL}$, including production processes and risk premium. This backstop technology is submitted to capacity constraints in the form of a delay $\Delta t_{CTL}$ between investments and production. Given uncertainty on large-scale CTL production, we consider two possibilities, depending whether CTL is a mature technology (low threshold oil price at 120$/bbl and no inertia in the deployment) or it is submitted to constraints slowing down its deployment (high threshold oil price at 200$/bbl and significant time-lag in the deployment)

These numerical assumptions are grouped in two variants summarized in Table A-2

Table A-2: Numerical assumptions for the three variants on oil and gas supply

| | *Unit* | **B-1** | **B-2** |
|---|---|---|---|
| $S_{bio}(t,p)$ | *Mtoe/y* | $\underline{S_{bio}}(t,p)^{(*),}$ | $1.5^{*}\ \underline{S_{bio}}\ (t,p)$ |
| $\Delta t_{bio}$ | *Years* | 6 | 4 |
| $p_{CTL}$ | *$/bl* | 200 | 120 |
| $\Delta t_{CTL}$ | *Years* | 8 | 0 |

$^{(*)}$*exogenous trend from (IEA, 2006)*

## C. Numerical assumptions on demand-side technical change

The ‘Power generation’ Nexus represents investment choices in new power generation technologies according to a minimization of mean production costs. Technical change is then dependent upon the decrease of capital costs, along with the learning process controlled by technology-specific learning rates $\gamma$ (it measures the percentage decrease of capital costs for each doubling of experience). Learning does not affect standard technologies due to saturation of experience, but potentially contributes to important costs decreases in more recent or prospective technologies, including wind energy and Carbon Capture and Storage. Due to uncertainties on the technical potentials of these technologies, we represent either fast learning through high learning rates (7% for wind *vs* 13% for CCS) or constrained learning with low learning rates (3% for wind *vs* 7% for CCS). Note that we consider lower learning rates for wind units than for CCS to represent that the former is a more mature technology, with less remaining progress potential.

In addition, the 'Power generation' Nexus represents the constraints that may affect the diffusion of carbon-free power plants by an exogenous maximum market share, with different dynamics for already existing and new technologies. In the former group, we explicitly represent Nuclear and Wind Energy and assume their maximum shares $Sh_{Nuke}$ and $Sh_W$ as constant-over-time. We adopt rather conservative assumptions on the long-term potential of Nuclear and consider a maximum market share at 40% to capture limitations for social acceptability reason (20% in a more constrained vision). For wind energy, we consider a benchmark case where it is limited to 15% of production to capture implicitly constraints imposed by intermittent production and additional integration costs at higher shares. This assumption is in line with the median estimate of the 164 global scenarios reviewed by the IPCC (Wiser et al, 2011, Figure 7.25). But, a growing body of work has evaluated higher levels of deployment, around 20% or more, provided that cost and policy factors are favourable. To treat this case, we also consider a higher limit on wind's market share, at 25%. In the latter group, we consider Carbon Capture and Storage (CCS), and the maximum share $Sh_{CCS}$ increases over time to represent its progressive deployment, ranging from zero at the starting year ($t_{0,CCS}$) up to its long-term market potential $Sh_{max,CCS}$. During the early years, inertia limits the deployment of this new technology as captured by a slow increase of the maximum share during a 'bottleneck period' of length $\Delta t_{CCS,}$ followed by an accelerated increase once the technology is mature.

In the 'Industry and services' Nexus, energy prices affect the selection of new production capacities but do not influence existing ones. This putty-clay assumption implies that changes in final energy use are dependent on their lifetime Δtind. This is an important variable, since it conditions both the turnover of productive capital (and hence the speed of technical change) and investments needs. We take 20 years as a benchmark case, whereas 30 years reflects a more constrained context on investment imposing delayed retirement of production capacities.

In the 'Housing and Buildings' Nexus, the baseline trends of energy consumption per square meter, $\alpha_{res}(t)$ are taken from outcomes of the POLES model. They feature a relative decrease of unitary energy demand in developed regions thanks to energy efficiency, while strong increases in developing countries are due to the access to energy services along with wealth increase. In addition, the energy mix is orientated towards electricity and gas at the expense of coal and oil. We consider also more energy-intensive pathways with proportionally higher unitary energy consumption due to lower efficiency gains (for technical constraints or lack of investments) and/or a more prominent access to energy services in developing countries.

In the ‘Freight transportation’ Nexus, the energy intensity of vehicles is driven by an exogenous trend $\mu_f\,(t)$ and a short-term fuel price elasticity $\varepsilon_f$ to capture autonomous and endogenous energy efficiency gains as well as short-term modal shifts, respectively. The long-term price response of the fleet then results from the sequence of those short-term adjustments.

The ‘Passenger Transportation’ Nexus represents the crucial determinant of energy efficiency and modal choices. Energy efficiency in private transportation is mainly dependent on the constraints on the diffusion of Electric Vehicles (EV). They are captured by an exogenous maximum $Sh$ on their market share, which ranges from zero in the first year ($t_{0,EV}$) to $Sh_{max,EV}$ as it achieves its long-term market potential. During the early years, inertia limits the deployment of this new technology, as captured by a slow increase in the maximum share during a ‘bottleneck period’ of length $\Delta t_{EV,}$ followed by an accelerated increase once the technology has matured.

Modal allocation of mobility demand is affected by investments in infrastructure, which determine the relative efficiency of the different modes. Instead of the default assumption that investment is allocated proportionally to modal mobility demand, alternative decisions may trigger a re-allocation from road to low-carbon transportation infrastructure (public and rail transport for passengers and rail and water transport for freight).

These numerical assumptions are grouped in two variants summarized in Table A-3.

Table A-3: Numerical assumptions for the three variants on oil and gas supply

| | | *Unit* | **C-1** | **C-2** |
|---|---|---|---|---|
| *Nuclear* | $Sh_{Nuke}$ | % | 20 | 40 |
| *Wind energy* | $Sh_W$ | % | 15 | 25 |
| | $\gamma_W$ | % | 3 | 7 |
| *Carbon Capture and Storage* | $t_{0,CCS}$ | *Date* | 2015 | 2010 |
| | $\Delta t_{CCS}$ | *Years* | 10 | 7 |
| | $Sh_{max,CCS}$ | % | 70 | 100 |
| | $\gamma_{CCS}$ | % | 7 | 13 |
| *Electric* | $t_{0,EV}$ | *Date* | 2020 | 2010 |

|  |  |  |  |  |
|---|---|---|---|---|
| *Vehicles* | $\Delta t_{EV}$ | *Years* | 8 | 3 |
|  | $Sh_{max,EV}$ | % | 50 | 80 |
|  | $\gamma_{EV}$ | % | 10 | 20 |
| *Freight transport* | $\mu_f(t)$ | - | 1 | $\underline{\mu_f}(t)$ (**) |
|  | $\varepsilon_f$ | - | -0.35 | -0.4 |
| *Buildings* | $\alpha_{res}(t)$ | *Toe/m*$^2$ | $1.2 * \underline{\alpha_{res}}(t)$ | $\underline{\alpha_{res}}(t)$ (**) |
| *Industry* | $\Delta t_{ind}$ | *Years* | 30 | 20 |

(**)*exogenous trend from the POLES energy sectoral model(LEPII-EPE ,2006)*

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# Figures

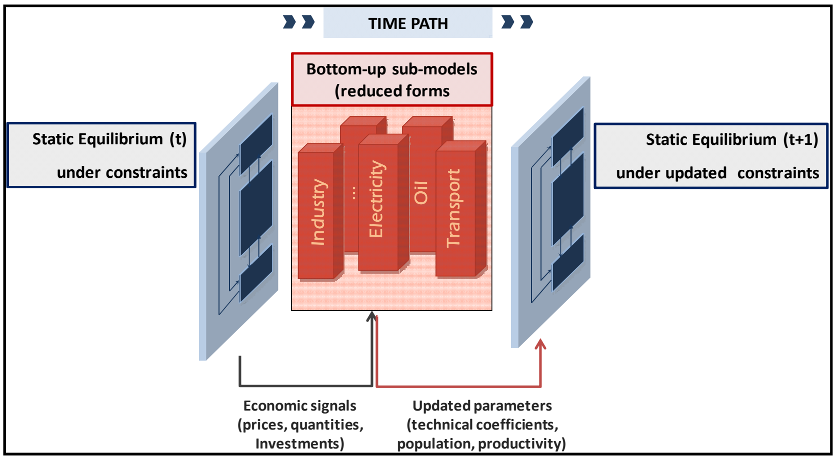

Figure 1: The recursive and modular structure of the IMACLIM-R model

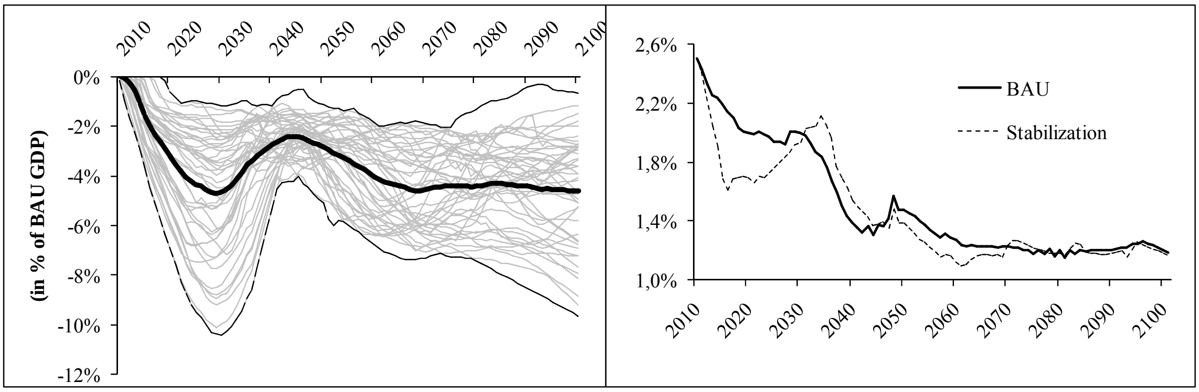

Figure 2: Global GDP variations between stabilization and BAU scenarios, over the 2010-2100 period [left-hand panel]; Average GDP growth rate across all BAU (solid line) and stabilization (dotted line) scenarios [right-hand panel]

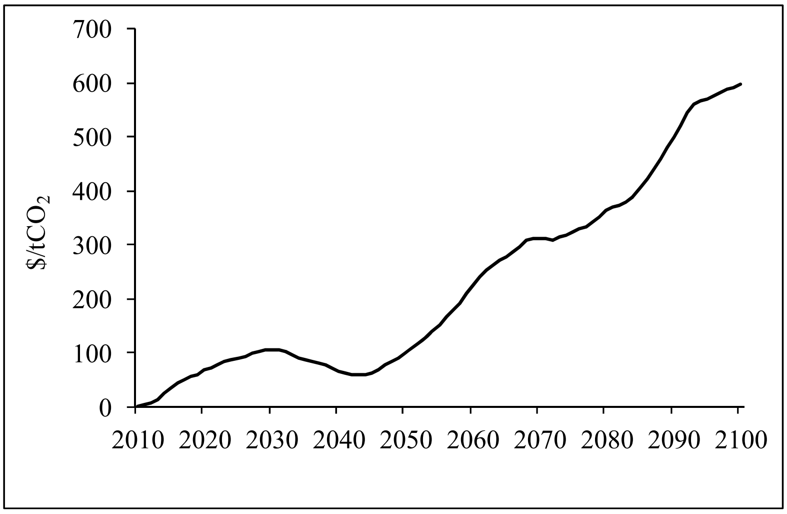

Figure 3: Average carbon tax

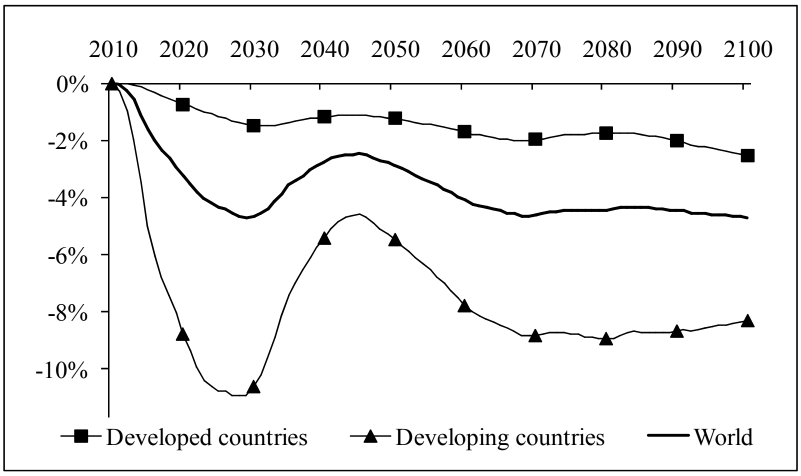

Figure 4: Average GDP variations between stabilization and BAU scenarios in developed countries, developing countries and the world, over the period 2010-2100

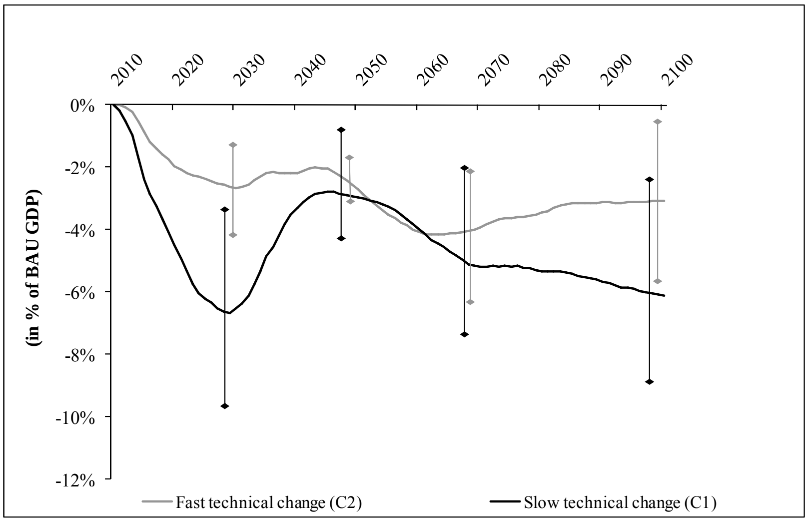

Figure 5: Average GDP variations between stabilization and BAU scenarios with slow (black) and fast technical change (grey). Note: Vertical bars give the range of values across scenarios at some dates.

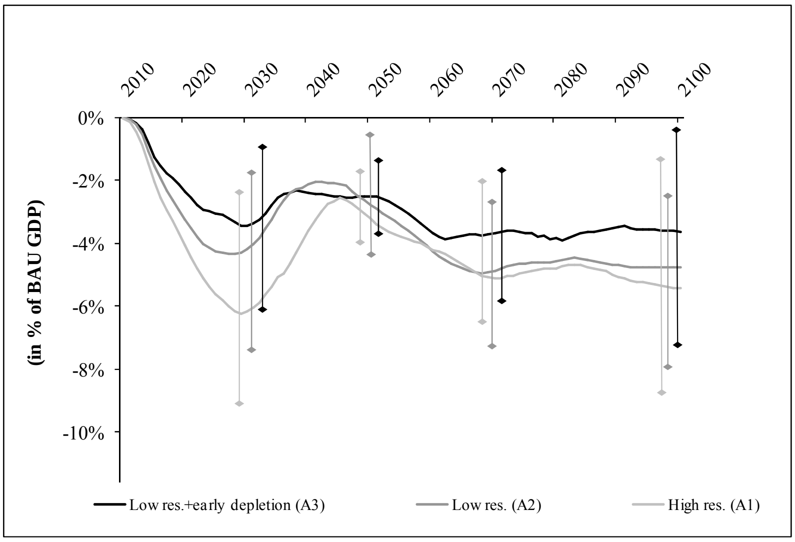

Figure 6. Average GDP variations between stabilization and BAU scenarios with the three assumptions on oil and gas supply. Note: Vertical bars give the range of values across scenarios at some dates.

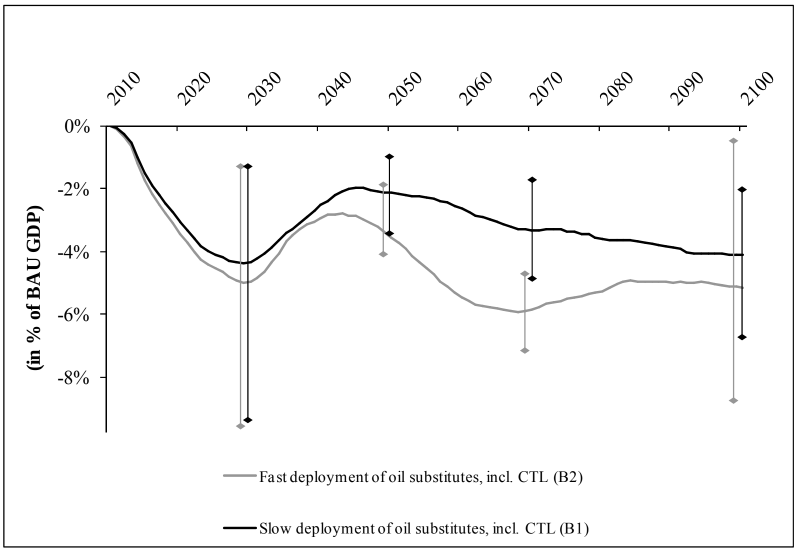

Figure 7. Average GDP variations between stabilization and BAU scenarios with slow (black) and fast (grey) deployment of oil substitutes [upper right-hand panel]; Note: Vertical bars give the range of values across scenarios at some dates.

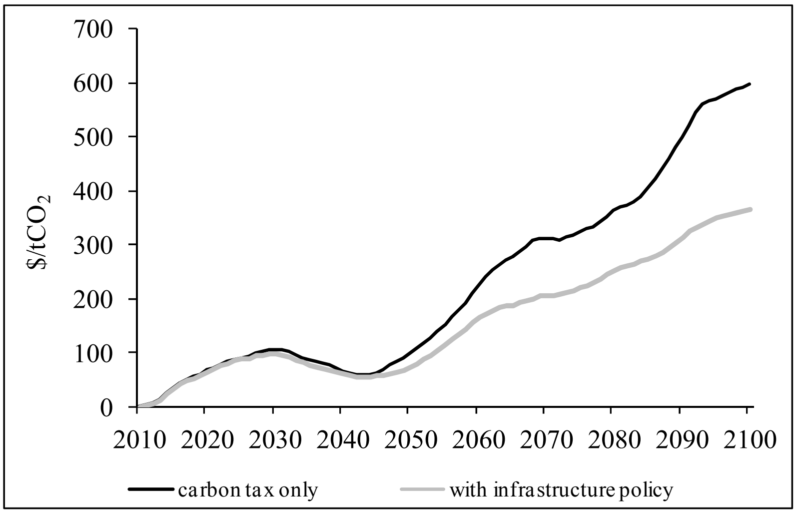

Figure 8: Average carbon price for a 'carbon price-only' policy (black) or with complementary infrastructure policies (grey).

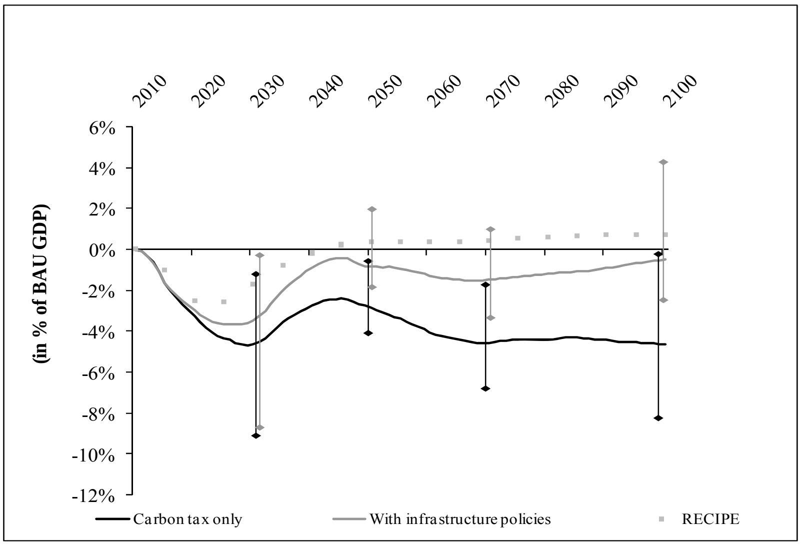

Figure 9: Average GDP variations between stabilisation and BAU scenarios for a 'carbon price only' policy (black) or with accompanying infrastructure policies (grey). Note: Vertical bars give the range of values across scenarios at some dates; squares represent GDP variations between the stabilisation and the BAU scenario in the RECIPE project.

# Tables

| | world | USA | Europe | China | India |
|---|---|---|---|---|---|
| **mean annual growth (2010 – 50)** | **2.1** *[2.0 - 2.2]* | **1.7** *[1.6 - 1.8]* | **1.6** *[1.4 - 1.7]* | **4.0** *[3.8 - 4.1]* | **4.3** *[3.8 - 4.5]* |
| **mean annual growth (2010 – 2100)** | **1.7** *[1.6 - 1.7]* | **1.8** *[1.7 - 1.8]* | **1.4** *[1.3 - 1.4]* | **2.4** *[2.3 - 2.5]* | **2.9** *[2.7 - 3.0]* |

Table 1: Mean annual real GDP growth in BAU scenarios, for the world and a selection of regions and countries (average values in bold, full range of variations across scenarios into brackets).

| | 2030 | 2050 | 2100 |
|---|---|---|---|
| **USA** | **1.2** *[0.1 - 2.4]* | **1.4** *[-0.1 - 2.4]* | **2.3** *[0.2 - 5.3]* |
| **Europe** | **0.8** *[-0.4 - 2.4]* | **0.7** *[-0.8 - 1.8]* | **1.6** *[-0.7 - 4.5]* |
| **China** | **16.8** *[5.3 - 33.9]* | **6.9** *[4.5 - 12.1]* | **10.5** *[-3.9 - 21.4]* |
| **India** | **13.5** *[3.6 - 21.6]* | **7.5** *[4.0 - 15.0]* | **10.9** *[0.8 - 21.2]* |

Table 2: GDP losses (a negative value represents an actual gain) between stabilization and BAU scenarios for a selection of major countries and regions, in 2030, 2050 and 2100 (average values in bold, full range of variations across scenarios into brackets).