Mitigation costs in second-best economies: time profile of emission reductions and sequencing of accompanying measures

Meriem HAMDI-CHERIF[*, ‡, 1], Henri WAISMAN[*], Céline GUIVARCH [*, #], Jean-Charles HOURCADE [*]

** Centre International de Recherche sur l'Environnement et le Développement (CIRED, ParisTech/ENPC & CNRS/EHESS) – 45bis avenue de la Belle Gabrielle 94736 Nogent sur Marne CEDEX, France.*

[#] École Nationale des Ponts et Chaussées—ParisTech, 6-8 avenue Blaise Pascal – Cité Descartes, Champs sur Marne, 77455 Marne la Vallée CEDEX 2, France.

[‡] Chair Modeling for Sustainable Development, ParisTech

Abstract

This article revisits the role of the time profile of carbon emission reductions in the design of climate policies. Using the CGE energy-economy model Imaclim-R, we demonstrate that the emission profile does not significantly change the time profile and the magnitude of mitigation costs. Recycling carbon tax revenues towards lower labor taxes and an early action on long-lived infrastructures offer very important reductions of mitigation costs. These complementary measures are as an important determinant of mitigation costs as the time profile of emissions and the sequencing of these options is closely related to the intertemporal tradeoff on emission reduction.

Keywords: Mitigation cost, when flexibility, second best, fiscal reform, infrastructure policy

JEL Classification: D58, E62, H29, H54, Q5

[1] Author for correspondence: *Phone*: +33 1 4394 7374; *Fax*: +33 1 4394 7370; *Email*: hcmeriem@centre-cired.fr.

I. Introduction

The debates about climate policies largely focus on the definition of a stabilization objective that would limit the risks linked to climate change and still be acceptable regarding the costs of the decarbonisation process. The latest report of the Intergovernmental Panel on Climate Change (IPCC, 2007) summarizes the findings about alternative options and concludes that mitigation costs remain limited (lower than 3% GDP reductions in 2030) even under the most ambitious reductions limiting the temperature increase at +2°C. These assessments provide a normative vision based on three main assumptions: optimal functioning of economic interactions (perfect markets, intertemporal optimization), perfect implementation of mitigation measures through carbon pricing and least-cost trajectories of emissions reductions as summarized in an often disregarded caveat:

> "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).

In these exercises, the time schedule of emissions reductions results from the optimization of economic functioning under a stabilization objective. Hammitt et al. (1992) and Wigley et al. (1996) show that delaying action reduces mitigation costs for three reasons: (1) the delay leaves time for technologies to develop, therefore when measures are implemented more efficient and cheaper technologies are available; (2) this allows to benefit from greater uptake of CO2 by the carbon sinks such as the oceans and the biosphere; (3) future costs weigh less due to discounting. Their arguments have been confirmed by the analysis of EMF-14 (Richels et al., 1999), but other authors, including Azar (1998), Azar and Dowlatabadi (1999), Ha-Duong et al. (1997) and Grubb (1997) showed that their conclusion could be reversed depending on the assumptions on discounting, inertia, uncertainty and technical change. A review of the arguments developed in this controversy over the economic benefits or costs of delaying mitigation actions can be found in Toman et al. (1999). A few years later, the controversy was revisited in the light of induced technical change mechanisms, like learning-by-doing or R&D, which give an incentive for early action (for example Goulder and Mathai, 2002; Manne and Richels, 2004).

The basic intuitions of this paper are that (1) the time profile of emission reduction will result from a political decision that may depart from economic optimization, which forces to consider the emission objective as an exogenous constraint on the economy rather than part of economic optimization, and (2) the timing of emission reductions is all the more important when considering the second-best nature of economic interactions where inertias and imperfect expectations drive economic dynamics away from its optimal trajectory. In this sense, this paper reverses the approach of carbon emission reductions by assuming that it is imposed as an exogenous constraint on the second-best economy with ambiguous effect on socio-economic trajectories. On the one hand, as an additional constraint, it may reinforce the sub-optimality of economic adjustments and enhance the costs with respect to the "first-best" case. But, on the other hand, it may help to correct some suboptimalities of the baseline case and hence contribute to accelerate economic activity.

The article proceeds as follows: We start by presenting the methodology and the scenarios used to conduct the analysis in the Section II, we then investigate the effects of alternative emission profiles deciding the pace of the decarbonization process in the Section III. The last section before conclusion explores the interplay between the time profile of carbon abatements and the complementary measures that act at different time horizons (*Reforming the fiscal system* in Section IV.1 and *Early action on transport infrastructures* in Section IV.2). Finally, the Appendix describes the methodology used to build the emission pathways used in this article.

II. Methodology and Scenarios

1. The baseline scenario

The analysis of economic interactions is conducted with the multi-region and multi-sector Computable General Equilibrium (CGE) model IMACLIM-R (Waisman et al, 2012). From its calibration date 2001, IMACLIM-R describes dynamic trajectories in one year steps through the recursive succession of static equilibria representing the second-best nature of economic interactions (including market imperfections and underuse of production factors) and dynamic modules representing the evolution of technical and structural constraints. This structure adopts adaptive anticipations so that agents take investment decisions according to the extrapolation of past and current trends; the gap between these expectations and real market outcomes conditions growth trajectory and their position with respect to their natural rate given by demographic and productivity trends. . A detailed algebraic description of this model is given in the Supplementary Electronic Material of Waisman et .al (2012).

The baseline scenario ignores any type of climate policy measures. Economic activity remains sustained during the whole century with average growth rates around 2%, mostly due to fast growth in emerging economies. Energy efficiency diffuses largely with an average global increase around 2% over the period 2010-2100 and particularly high rates for emerging economies such as China and India (Table 1). CO2 emissions from fossil fuel combustion increase from 24 Gt in 2001 to 38.5 in 2035 to stabilize around 37 Gt in 2100, and total carbon budget for the period 2001-2100 amounts to 946 GtC. This emission trajectory belongs to the lower class of the large SRES and post-SRES emissions range (IPCC, 2007)

	World	USA	Europe	Chine	Inde
mean annual growth (2001-2100)	1.7%	1.2%	1.90%	2.8%	2.9%
mean annual growth (2010-2050)	2.1%	0.9%	2.10%	3.7%	3.8%
mean annual growth (2010-2100)	1.9%	1.3%	2.00%	2.7%	2.9%

Table 1: Mean annual growth of the energy efficiency in the baseline scenario

A climate policy is represented by a carbon price associated to carbon emissions from the production and use of fossil energies (coal, oil and gas). It thus increases the cost of final goods and intermediate consumption according to the carbon content of the fuel used. At each date, the carbon price value is endogenously calculated to curve carbon emissions according to a prescribed objective. The analyses carried in this paper consider four options for carbon emission trajectory and six groups of macroeconomic and sectoral measures adopted in the context of climate policies to go with carbon pricing.

2. Climate policy scenario: carbon emission trajectory

For the sake of clarity, we limit our analysis to a unique stabilization objective expressed as the total radiative forcing in 2100, as for the Representative Concentration Pathways developed for the fifth IPCC Assessment Report (van Vuuren et al., 2011). The target chosen is 3.4W/m2 in 2100, with a possibility of overshoot of the target during the 21st century. This target corresponds to the radiative forcing in 2100 from the pathway developed by IMAGE model in Energy Modeling Forum 24 study as an intermediate scenario between the Representative Concentration Pathway 3 Peak&Decline (RCP-3PD) and the RCP 4.5 from RCP database[2].Although less restrictive than the RCP 3PD target, this objective is still ambitious and is adapted to the "when flexibility" analysis because it provides a certain leeway to deal with the timing of emission reductions.

We build a family of four carbon emission trajectories (T-1, T-2, T-3 and T-4) over the period 2010-2100, which differ in terms of date of (and level of) the emissions peak and of long-term stabilization level but which all lead to the same radiative forcing in 2100 (see Figure 1). T-1 is the trajectory where the most important mitigation efforts have to be done at the beginning of the period (early action). T-4 is the one where the mitigation efforts are concentrated at the end of the period (delayed action). T-2 and T-3 are two intermediate trajectories between T-1 and T-4. These trajectories are elaborated by using a three-reservoir (atmosphere, biosphere + ocean mixed layer, and deep ocean) linear carbon cycle model calibrated on the IMAGE model (Ambrosi at al., 2003). The methodology to build this family of emissions trajectory is described in the Appendix.

[2] http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about#

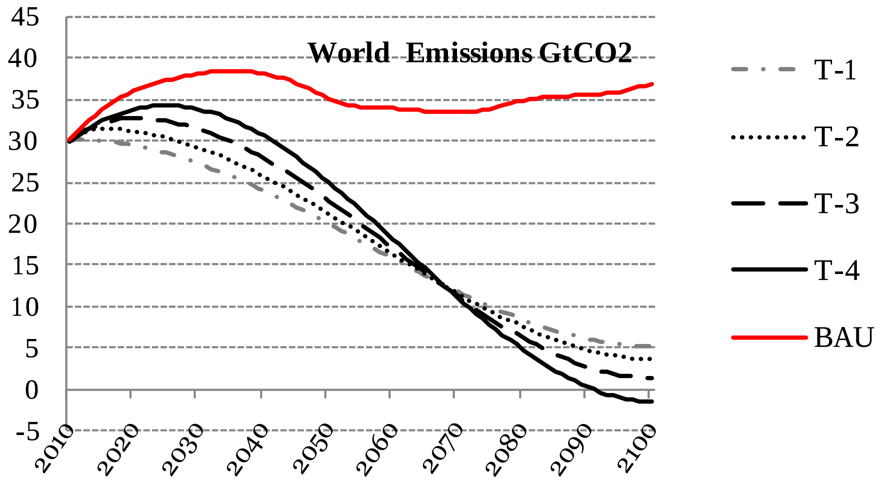

Figure 1: Global CO_2 emissions (energy only)

3. Climate policy scenario: carbon price and accompanying measures

The model endogenously calculates the global carbon tax to be imposed at each point in time to satisfy the emission trajectory imposed. For the sake of simplicity, we consider a uniform carbon tax (i.e., identical for all sectors, households and regions).

The revenues of this carbon tax are perceived by the government. We limit our analysis to two standard possibilities according to the way these revenues are recycled: either fully redistributed to households in the form of a lump-sum transfer (*Hsld*) or used as a decrease of the pre-existing labor taxes (*Labor*).

We also consider the possibility that measures aiming at controlling transport-related emissions through actions on the determinants of mobility may be adopted as complementary measures to carbon pricing.

Let us notice that the two groups of accompanying measures considered in our analysis, ‘Carbon fiscal system’ and ‘Long-lived infrastructure policies’, have complementary effect on mitigation costs. Revenue recycling affects economic adjustments in the short- and medium-term and may essentially play a role in the course of the transition to soften adjustment costs on labour markets. Transport infrastructure policies are more important in the long-term because they concern long-lived capital, which cannot be modified overnight, but will be active at a long-term horizon when, once exhausted least-cost mitigation potentials in the residential, industry and power sectors, it becomes necessary ro reduce sensibly transport-related emission trends.

III. Mitigation costs and time profile of emissions reductions

In this section, we start by considering the benchmark case of climate policies, in which nor fiscal reform nor infrastructure policies is adopted as accompanying measure to carbon pricing.

We start by investigating the dependence of aggregated mitigation costs over the time profile of emission reductions. by comparing the discounted costs for different values of the discount rate. We analyse more specifically results obtained with 7%, 3%, 1% discount rates representing respectively a short-term, medium-term and long-term vision since the discount factor is below ½ after 10, 25 and 70 years respectively.

At a global level, the sensitivity of GDP losses to the emission profile depends on the time horizon considered, as captured by the discount rate (Table 2). At a medium-term horizon (3% discount rates), costs are rather insensitive to the emission profile, whereas they are widely dispersed according to the emission trajectory for both short-term and long-term visions. In a short-term perspective (7% discount rate), more rapid decarbonization efforts unsurprinsingly enhance the costs, as in scenario T-1, whereas delayed emission reductions almost halves the cost, as in scenario T-4. Conversely, , when a long term perspective is adopted (1% discount rate), the higher aggregated GDP losses are observed under the stabilization trajectory T-4, i.e. the case where the most important efforts have to be done at the end of the period. In that case, the global discounted losses reach 11.1%.

	Dsicount rate		
	1%	**3%**	**7%**
T-1	-9.6%	-6.8%	-3.2%
T-2	-9.7%	-6.5%	-2.7%
T-3	-10.0%	-6.3%	-2.1%
T-4	-11.1%	-6.6%	-1.8%

Table 2: Global GDP variations between stabilization and reference scenarios (for the different emissions targets)

The discounted values analyzed above give interesting pictures of the mitigation costs, but they hide some critical dynamic mechanisms. To go beyond this aggregated picture and enter into the mechanisms driving the time profiles of mitigations costs, we consider the temporal profiles of these costs (Figure 2) and of carbon prices (Figure 3).

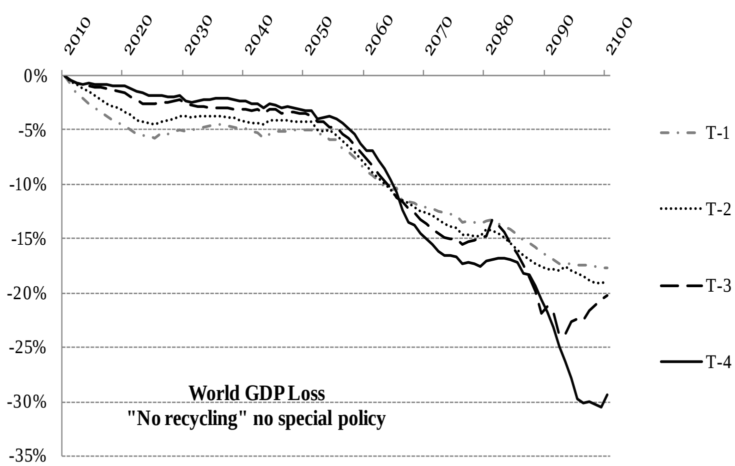

Figure 2: Global GDP variations between stabilization and reference scenarios (for the different emissions targets)

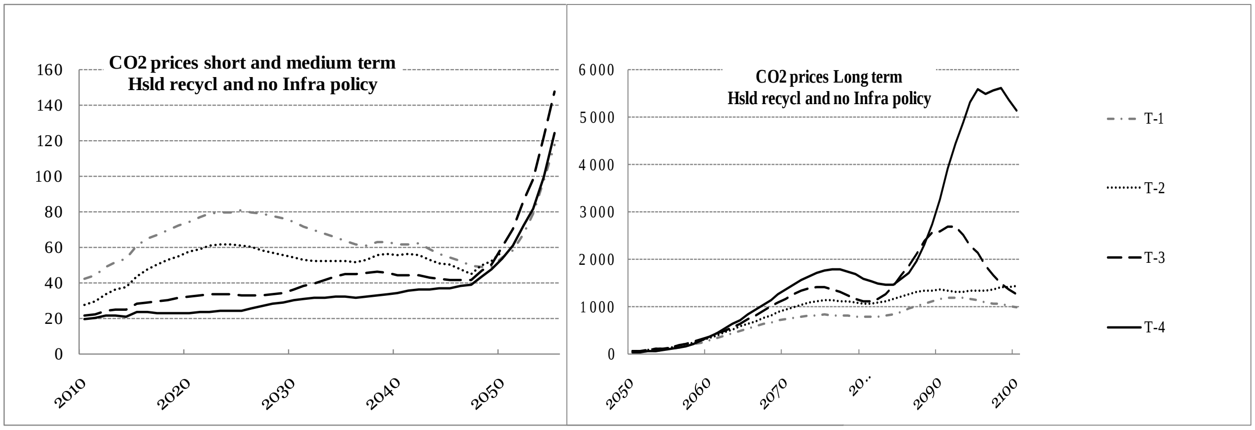

Figure 3: Carbon tax

Despite differences in the magnitude of the effects according to the emission trajectory, mitigation costs feature common general trends that can be grouped in four phases

(i) Transitory costs during the first fifteen years of stabilization with lower growth rates than in reference scenario (but never an absolute decrease of GDP in any region). These costs are associated with a sharp increase of the carbon price. These costs are obviously more important under the T-1 scenario, which forces fast decarbonisation and hence particularly high carbon prices (80$/tCO2 in 2025).

(ii) a stabilization of losses and even small GDP catch-up with close or higher growth rates under the climate policy than in the reference scenario; this phase is associated with a decline in the carbon price ending around 2050.

(iii) a second phase of increasing GDP loss in the stabilization scenario from 2050 to 2080 associated with a second phase of fast carbon price increase.

(iv) Finally, a long-term regime that starts around 2080, in which carbon price trajectories diverge sensibly according to the long-term emission constraint. Under scenario T-4 with the lowest emission objectives in 2100, very high carbon prices are necessary and trigger very important losses; on the contrary, under T-1 in which the bulk of emission reduction have already been done, carbon prices stabilize and GDP losses stagnate (which means that growth rates are identical between the baseline and the policy cases).

We observe that the classification of emission trajectories in terms of mitigation costs follows exactly the emission profiles, with enhanced costs at the periods where marginal reductions are the more important..The higher GDP losses on this period are obtained under the more constrained trajectory (T-1) where they reach 5.7% in 2025, which corresponds to the point where the carbon price is at his higher level across the different trajectories during this first period. The less constrained trajectory on this period (T-4) entails much more moderate levels of losses, which hardly exceed 3% in 2050.

We then observe a drastic increase of the costs after this first period with a crossing point in 2066 (all the losses amount to 10.7%) corresponding to the crossing point of all the emissions trajectories (Figure 1). After this point the emissions profiles' order reverses and the carbon prices and costs order too. At the end of the period, in the case of very low emissions target, such as T-3, or T-4 where there are some negative emissions, the carbon prices shoot up and rise levels that greatly exceed 1000$/tCO2. This leads to very high levels of GDP losses: they reach 24% for T-3 in 2092 and 30% in 2100 for T-4. These costs amounts are high in absolute terms, but they are all the more when compared to the two other cases (T-1 and T-2), which even if increasing continuously, don't exceed 20% in 2100.

Based on this general picture, let us now analyze in more detail what is happening during the four phases described above.

(i) During the 2010-2025 period, the GDP losses of the climate policies are due to the increase of carbon prices and of the energy-to-labor cost ratio. Under adaptive expectations indeed, investment choices can be redirected only with high carbon prices. 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.

The magnitude of these effects depends on the assumption made on technological change, which determines the pace of low-carbon technical change, since fast technical change partly counterbalances the inertia on the renewal of installed capital and makes decarbonisation easier:

the energy intensity of production decreases and the carbon price necessary to trigger decarbonisation is not so high. However, transitory costs are not as low as we could expect even under relatively fast energy efficiency (up to - 12% relatively to baseline in 2030, see Figure 4), because technical progress is insufficient to compensate carbon price increases in the total energy costs.

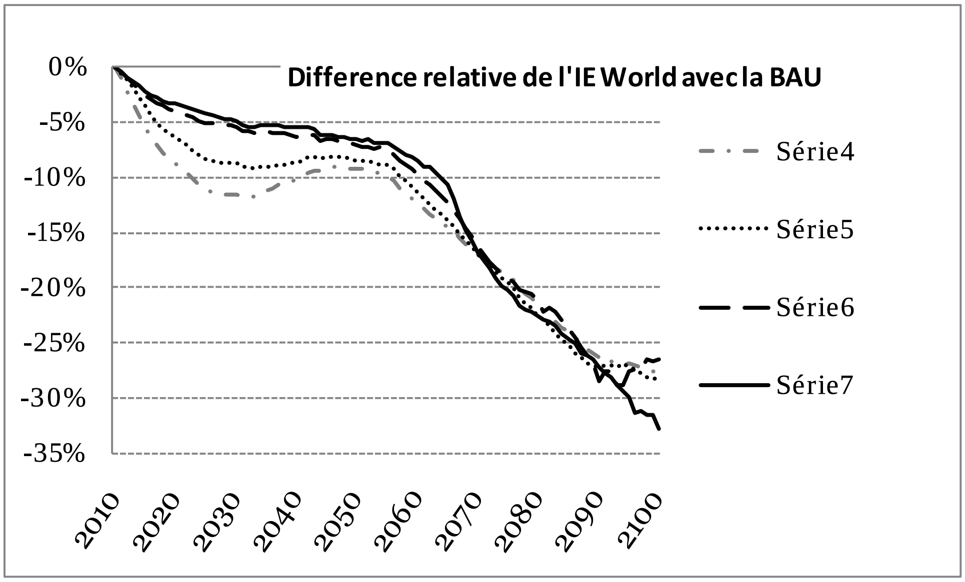

Figure 4: Global energy efficiency gap between climate scenarios and the baseline

(ii) Between 2025 and 2050, the satbilization of mitigation costs in Figure 2 is due to two major positive effects of early carbon prices, which lowers the weight of energy in the production process. First, we observe a moderation of oil demand in the stabilization scenario and the associated oil price increase (reduction of energy prices). 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. The mitigation costs are further moderated at this time horizon by the stabilization of carbon price towards around 40$/tCO2, which is a sufficient level to reach most mitigation potentials 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).

(iii) From 2050 to 2080, a new phase of increasing mitigation costs starts as a consequence of a sharp increase of carbon prices. 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.[3] These effects are particularly sensible in the T-4 scenario for which this period corresponds to the bulk of emission reductions with a division by 5 of total emissions between 2050 and 2080.

(iv) Finally, over the very-long term the crucial determiannts of mitigation costs becomes the diffusion of power generation plants with biomass and CCS, since they are the only type of technologies enabling negative emissions. This possibility is crucial for the emission trajectories with very low or even negative emission levels in the long-term (T-3 and T-4), in which very hiugh carbon prices are necessary to accelerate the progress on this technology and hence its diffusion on the markets. This effect also happens under T-1 and T-2 scenarios, but BioCCS

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

technologies are less important, since targeted emission levels can be reached with only a marginal contribution of negative emissions

We have observed that the more constrained carbon trajectory on the short term generates the higher costs in this period. This question of short-term costs is of the most importance, since it can create high social and political obstacles for implementing a climate policy. We could think that if we want to solve this issue, i.e. to reduce these high short term costs, we can delay the action of mitigating emission. But we have shown that doing this implies a persistence of the issue on the long term. Indeed, delaying the action on the short term allows reducing the early costs, but it makes things worse on the long term, generating higher economic losses than in the case of an early action. So we can shift the issue from short to long term, but it appears quite clearly that the question of “when flexibility” alone cannot solve the problem. It is thus necessary to rethink the question of “How to implement climate change policies?”, or more precisely, to think about complementary instruments that must be mobilized to reduce the costs of a mitigation target going beyond the simple timing of the action.

IV. Climate policies and accompanying measures

1. Reforming the fiscal system: a way to reduce the short and middle term effects of the mitigation policies

In the analysis carried out is section III, the carbon revenues perceived by the government are redistributed to households in a lump-sum manner. This sub-section investigates the effect of an alternative approach, according to which they are used to reduce labor taxes. The rational for this option is to foster high employment during the carbon transition and hence to substitute energy expenditures by wages. In this article, we provide a quantitative assessment of the macroeconomic effects generated by a fiscal reform based on the carbon tax revenue recycling. To do so, we compare the GDP losses obtained with a use of the revenues to reduce labor taxes (*Labor* scenarios) to those obtained with a fully redistribution of the carbon tax revenue to households (*Hsld* scenarios).

Whatever the time horizon and whatever the timing of emission reductions, the recycling on labor taxes proves to reduce the mitigation costs (Table 2). This is because this measure helps to decrease the energy-to-labor costs ratio in the production process by fostering more intense use of laborers.

The magnitude of this effect is particularly important in the short-term (7% discount rate) where GDP losses obtained with a fiscal reform are reduced in average by 42% with respect to the *Hsld* scenario, while they are reduced in average by 28% with a medium term vision (3% discount rate) and only by 22% under a long term perspective (1% discount rate). This makes sense, because these measures to moderate production costs are particularly important during the first phase of the climate policy, in which energy costs rise and technical change is limited by strong inertias.

	Hsld	***Labor***
T-1	-3.2%	-1.9%
T-2	-2.7%	-1.5%
T-3	-2.1%	-1.2%
T-4	-1.8%	-1.0%

Discount rate 7%

	Hsld	***Labor***
T-1	-6.8%	-5.0%
T-2	-6.5%	-4.7%
T-3	-6.3%	-4.5%
T-4	-6.6%	-4.8%

Discount rate 3%

	Hsld	***Labor***
T-1	-9.6%	-7.53%
T-2	-9.7%	-7.46%
T-3	-10.0%	-7.65%
T-4	-11.1%	-8.62%

Discount rate 1%

Table 2: Global GDP variations between stabilization and reference scenarios (for the different emissions targets, with different assumptions on the discount rate and the recycling modes of the carbon tax revenue)

This phenomenon suggests that a fiscal reform is really efficient on the short term, and that complementary measures are necessary to improve the long term situation.

2. Early action on transport infrastructure: a way to reduce long term costs

The issue of the long term costs' persistence is notably linked to the very specific dynamics of the transportation sector (Jaccard et al. 1997). That is why we finally test a design of climate policy where carbon pricing and the above described fiscal reform are complemented by measures aimed at controlling the long-term dynamics of transport-related emissions. More precisely, we consider:[4]

[4] 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.

(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).

We find that the reduction of mobility needs and the shift towards low-carbon modes allows meeting the same climate objectives with far more moderate GDP losses whatever the temporal perspective adopted and whatever the timing of emission reductions (Table 3). The comparison of the second and third columns of Table 3 shows that these investments have contrasted efficiency according to the time horizon considered. More specifically, they are more (less) efficient in reducing mitigation costs than recycling measures towards labor taxes in the long term (short term), as captured by the 1% (7%) discount rate results.

	Hsld	Hsld + InfraPol	Labor	Labor+ InfraPol
T-1	-3.2%	-2.6%	-1.9%	-1.3%
T-2	-2.7%	-2.1%	-1.5%	-1.0%
T-3	-2.1%	-1.5%	-1.2%	-0.7%
T-4	-1.8%	-1.36%	-1.0%	-0.57%

Table 3.a : Discount rate 7%

	Hsld	Hsld + InfraPol	Labor	Labor+ InfraPol
T-1	-6.8%	-4.7%	-5.0%	-3.0%
T-2	-6.5%	-4.4%	-4.7%	-2.7%
T-3	-6.3%	-4.1%	-4.5%	-2.5%
T-4	-6.6%	-5.82%	-4.8%	-3.71%

Table 3.b : Discount rate 3%

	Hsld	Hsld + InfraPol	Labor	Labor+ InfraPol
T-1	-9.6%	-6.1%	-7.53%	-4.3%
T-2	-9.7%	-6.3%	-7.46%	-4.2%
T-3	-10.0%	-6.4%	-7.65%	-4.4%
T-4	-11.1%	-11.1%	-8.62%	-7.7%

Table 3.c :Discount rate 1%

Table 3 (a,b,c): Global GDP variations between stabilization and reference scenarios (for the different emissions targets, with different assumptions on the discount rate and the recycling modes of the carbon tax revenue)

When combing these accompanying measures (last column in Table 3), the mitigation costs are sensibly reduced compared to the benchmark case. When we adopt a short term vision (Table 3.a), it appears that the more delayed action is the less costly one with GDP losses amounting less than 1%. In this case, these losses obtained with a fiscal reform and an infrastructure policy deployment are reduced by 69% with respect to the ‘carbon price only’ policy. When medium and long term perspectives are adopted (Table3.b,c.), we find also that a delayed action can be efficient. Indeed, without waiting the last moment to act (T-4), our results show that a postponed mitigation action (T-2 or T-3) is possible and provides less higher GDP losses than in the case of an early action on emissions. Under these two last temporal perspectives too, the gains obtained via the fiscal reform and the infrastructure policy are significant: the costs are reduced by 56 to 60% with respect to the ‘carbon price only’ scenario. This analysis demonstrates that the long-term discounted costs are far less sensitive to the emission trajectory than to the policy mix adopted to reach a climate stabilization objective.

V. Conclusion

This article revisits the role of the time profile of carbon emission reductions in the design of climate policies, when considering that it results from a political decision that may depart from economic optimization. This approach forces to consider the emission objective as an exogenous constraint on the economy and its effects become ambiguous when acknowledging the second-best nature of economic interactions where inertias and imperfect expectations drive economic dynamics away from its optimal trajectory. Indeed, the climate constraint may enhance pre-existing distortions or help to correct sub-optimal choices.

To investigate the effects of alternative emission profiles deciding the pace of the decarbonization process, we conduct a simulation exercice with the CGE energy-economy model Imaclim-R. We demonstrate that the emission profile does not significantly change the time profile and the magnitude of mitigation costs, but rather operates a time shift in their occurrence according to the period where most efforts are conducted.

Two principal sources of high costs are identified. On the one hand, the increase of the energy-to-labor costs ratio consecutive to the introduction of the carbon price in the short-term; on the other hand, transport-related emissions which force a rise of carbon prices in the long-term in all scenarios. We then investigate the effect on these profiles of two complementary policies, an alternative recycling method for carbon revenues towards lower labor taxes and an infrastructure policy aimed at decoupling economic activity from mobility. Both measures taken separately prove to reduce notably mitigation costs by offsetting the short-term energy price increase and limiting the long-term rise of carbon prices, respectively. Taken together, they even prove to combine their effects to offer very important reductions of mitigation costs.

This quantitative assessment leads to the conclusion that the measures accompanying carbon pricing are as an important determinant of mitigation costs as the time profile of emission, and that the sequencing of these options is closely related to the intertemporal tradeoff on emission reduction.

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Appendix: The carbon cycle module and the emission pathways

1. The three-reservoir linear carbon cycle model

The carbon cycle is a three-box model, after Nordhaus and Boyer (2010). The model is a linear three-reservoir model (atmosphere, biosphere + ocean mixed layer, and deep ocean). Each reservoir is assumed to be homogenous (well-mixed in the short run) and is characterised by a residence time inside the box and corresponding mixing rates with the two other reservoirs (longer timescales). Carbon flows between reservoirs depend on constant transfer coefficients. GHGs emissions (CO2 solely) accumulate in the atmosphere and they are slowly removed by biospheric and oceanic sinks.

The stocks of carbon (in the form of CO_2) in the atmosphere, in the biomass and upper ocean, and in the deep ocean are, respectively, *A*, *B*, and *O*. The variable *E* is the CO_2 emissions. The evolution of *A*, *B*, and *O* is given by

$$\frac{dA}{dt} = -\phi_C^{A,B} + E,$$
$$\frac{dB}{dt} = \phi_C^{A,B} - \phi_C^{B,O}, \text{ and}$$
$$\frac{dO}{dt} = \phi_C^{B,O};$$

The fluxes are equal to

$$\phi_C^{A,B} = a_{21}A - a_{12}B, \text{ and}$$
$$\phi_C^{B,O} = a_{23}B - a_{32}O;$$

The initial values of *A*, *B*, and *O*, and the parameters a_{12}, a_{21}, a_{23}, and a_{32} determine the fluxes between reservoirs. The main criticism which may be addressed to this C-cycle model is that the transfer coefficients are constant. In particular, they do not depend on the carbon content of the reservoir (e.g. deforestation hindering biospheric sinks) nor are they influenced by ongoing climatic change (e.g. positive feedbacks between climate change and carbon cycle).

The additional forcing caused by CO_2 and non-CO_2 gases is given by

$$F_A = F_{2X} \frac{\log\left(\frac{A}{A_{PI}}\right)}{\log 2} + F_{non-CO_2},$$

where A_{PI} is the pre-industrial CO_2 concentration (280 ppm), F_{2x} is the additional radiative forcing for a doubling of the CO_2 concentration (3.71 $W.m^{-2}$), and F_{non-CO_2} is the additional radiative forcing of non-CO_2 gases.

2. Building a family of alternative emissions pathways corresponding to the same radiative forcing target in 2100

a. The choice of the target

The target chosen corresponds to the radiative forcing in 2100 from the pathway developed by IMAGE model in Energy Modeling Forum 24 study as an intermediate scenario between the Representative Concentration Pathway 3 Peak&Decline (RCP-3PD) and the RCP 4.5 from RCP database[5].

b. Calibration of the carbon cycle model

Nordhaus original calibration has been adapted to reproduce data until 2010 and results from IMAGE model for a given trajectory of CO2 emissions (see below), giving the following results (for a yearly time step): a12= 0.02793, a21=0.03427, a23=0.007863, a32=0.0003552, with the initial conditions: A2010=830 GtC (i.e. 391ppm), B2010=845 GtC and O2010=19254 GtC.

Figure A1, panel B, compares the trajectory of total radiative forcing calculated with the three-box carbon cycle model and the IMAGE model forced with the emissions trajectory used for calibration. This emissions trajectory, from Energy Modeling Forum 24 study, is between

[5] http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about#

those of RCP 3PD and RCP 4.5 from RCP database. Panels A and C compares the three-box carbon cycle model and IMAGE model results for the RCP 3PD and the RCP 4.5 emissions trajectories, respectively. The differences are linked to elements modifying transfer coefficients, such as reforestation or deforestation for instance, not accounted for in the three-box model with constant transfer coefficients.

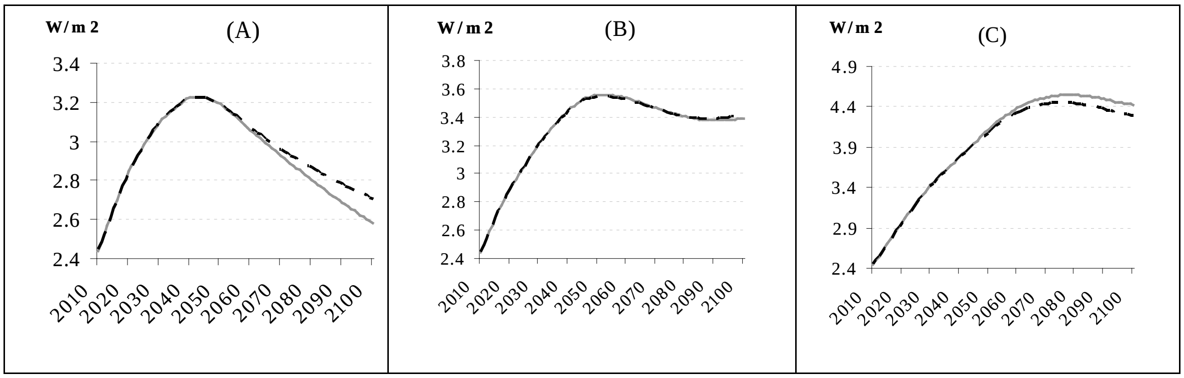


Figure A1. Trajectories of total radiative forcing calculated with the three-box carbon cycle model (dashed black lines) and IMAGE model (solid grey line) for three given emissions trajectories: (A) the RCP 3-PD emissions trajectory, (B) the emissions trajectory used for calibration, from EMF24 study, between those of RCP 3-PD and RCP 4.5, and (C) the RCP 4.5 emissions trajectory.

c. Building a family of emission trajectories leading to the same radiative forcing in 2100

For a defined level of radiative forcing in 2100 (RF_{2100}), we build a family of global CO_2 emission pathways (from energy only[6]) over 2010-2100 that differ by the date of the peak of emissions (T_{peak}) but all lead to this same radiative forcing RF_{2100} in 2100[7].

We use as exogenous parameters the trajectories (i) of CO_2 emissions from industrial processes and from land-use change, and (ii) of radiative forcing from non-CO_2 gases (see Figure 1 and Figure 2).

[6] Trajectories of CO2 emissions from industrial processes and from land-use change are taken as exogenous parameters, equal to the pathways from the scenario developed by IMAGE model in Energy Modeling Forum 24 study that is between those of RCP 3PD and RCP 4.5.

[7] Trajectories of radiative forcing from other gases than CO_2 are taken as exogenous parameters.

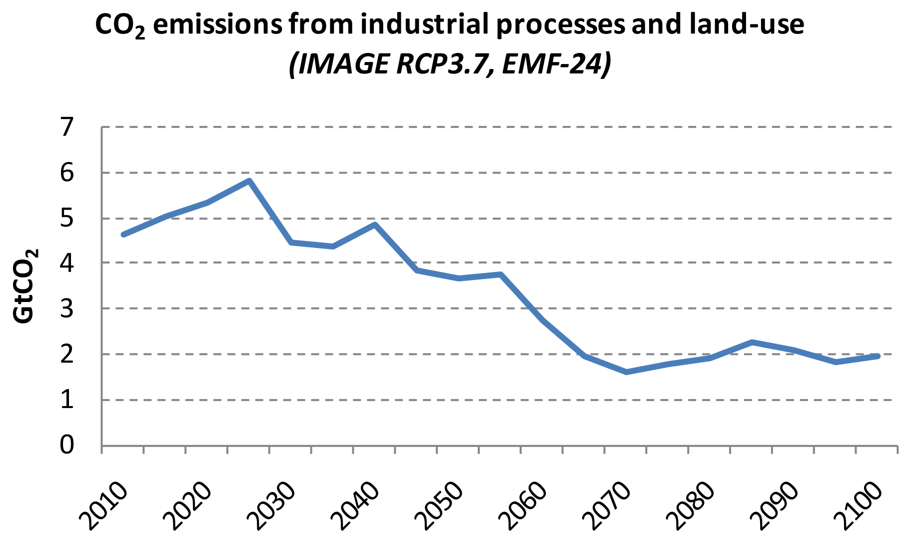


Figure 1; Trajectory CO_2 emissions from industrial processes and land-use from IMAGE RCP3.7 from EMF-24 study.

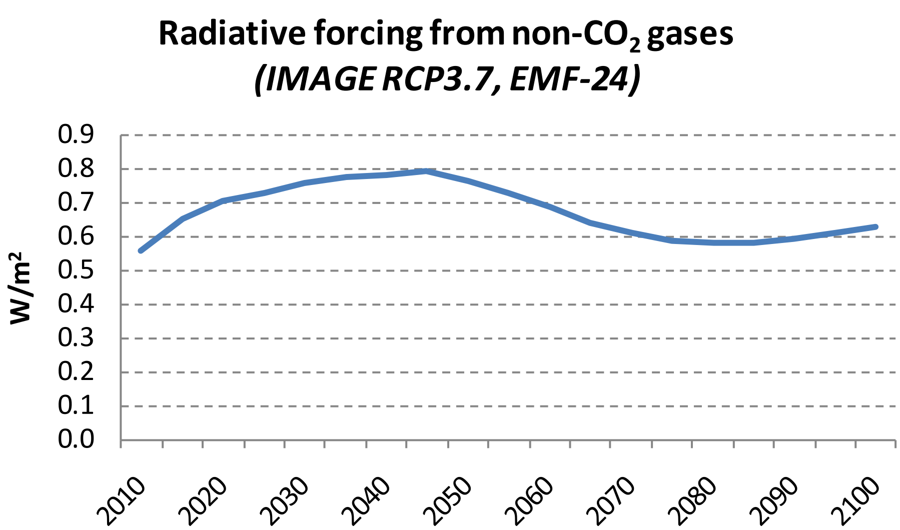


Figure 2: Trajectory of radiative forcing from non-CO_2 gases from IMAGE RCP3.7 from EMF-24 study.

Each trajectory complies with the following constraints: (1) it starts from current global emissions in 2010; (2) the rate of emissions growth the first year is equal to the mean annual growth rate over 2005-2010; (3) the peak year T_{peak} represents a date when emissions derivative is equal to zero; (4) in 2100 global emissions are stabilized at level E_{2100} such that the radiative forcing in 2100 due to the emission trajectory is equal to RF_{2100}; (5) the point in E_{2100} is attained with a derivative equal to zero.

To respect these constraints, the functional forms chosen are a polynomial of order 2 over 2010-T_{peak} and a polynomial of order 3 over T_{peak}-2100. Given these functional forms, there exists a single global emissions trajectory that peaks at year T_{peak} and leads to the radiative forcing RF_{2100} in 2100. Figure 3 gives examples of such emissions trajectories. The three-reservoir linear carbon cycle model presented above is used to determine the level E_{2100} corresponding to each peak date T_{peak}. Note that the definition of the emissions trajectories does not impose whether there is an overshoot in terms of radiative forcing over the 2010-2100 horizon or not (i.e. whether the radiative forcing over 2010-2100 is always lower than the level RF_{2100} – no overshoot – or there is a date between 2010 and 2100 when radiative forcing is above the RF_{2100} level – overshoot). As we will see, the chosen resulting trajectories all exhibit an overshoot.

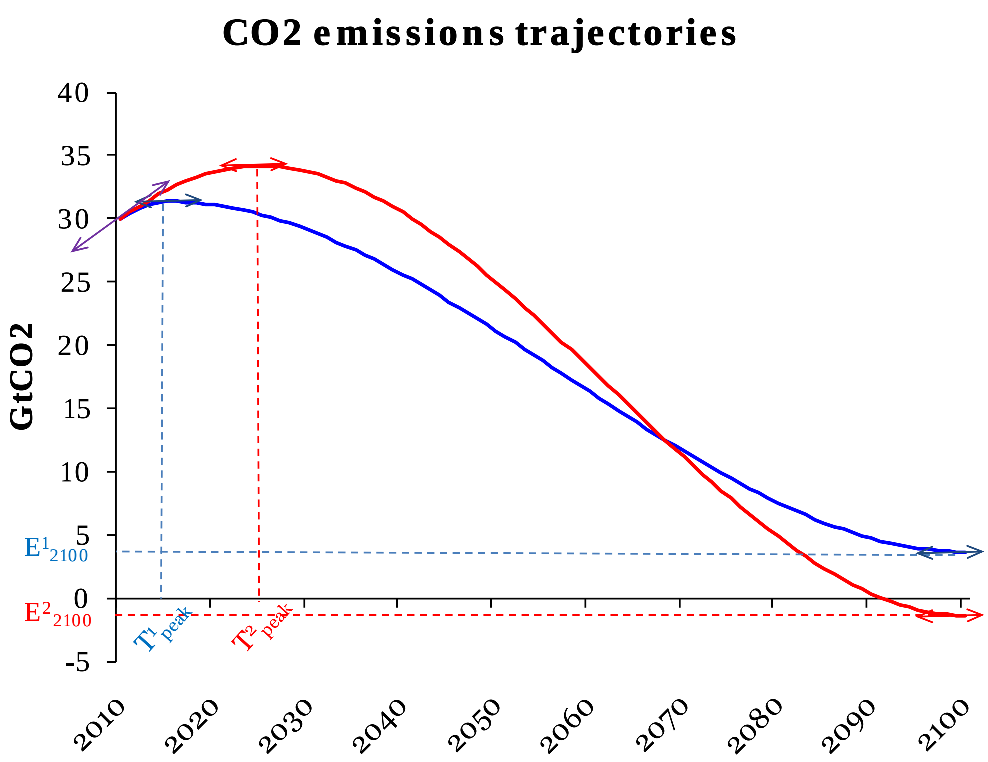
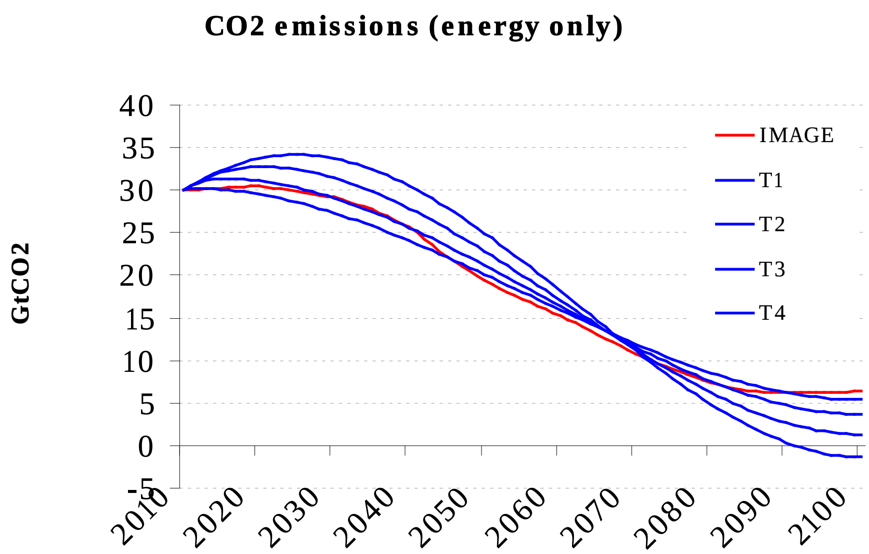
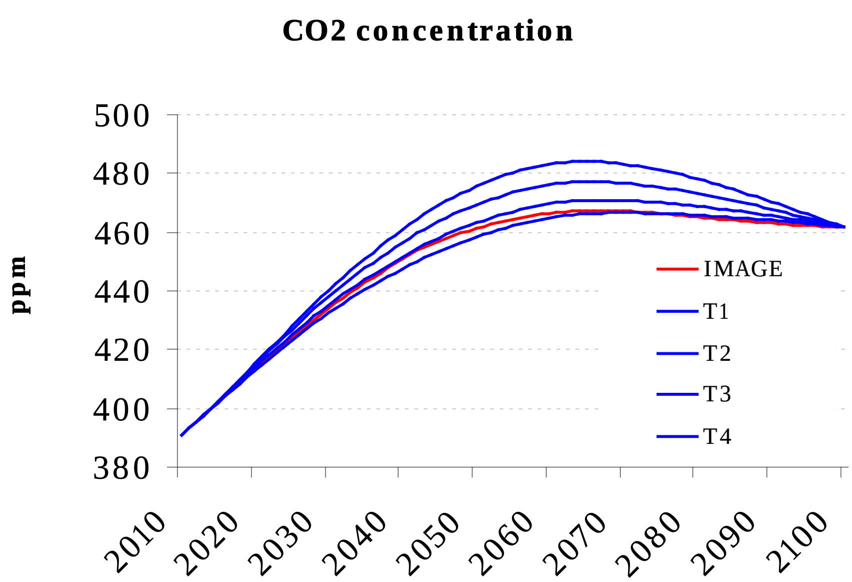


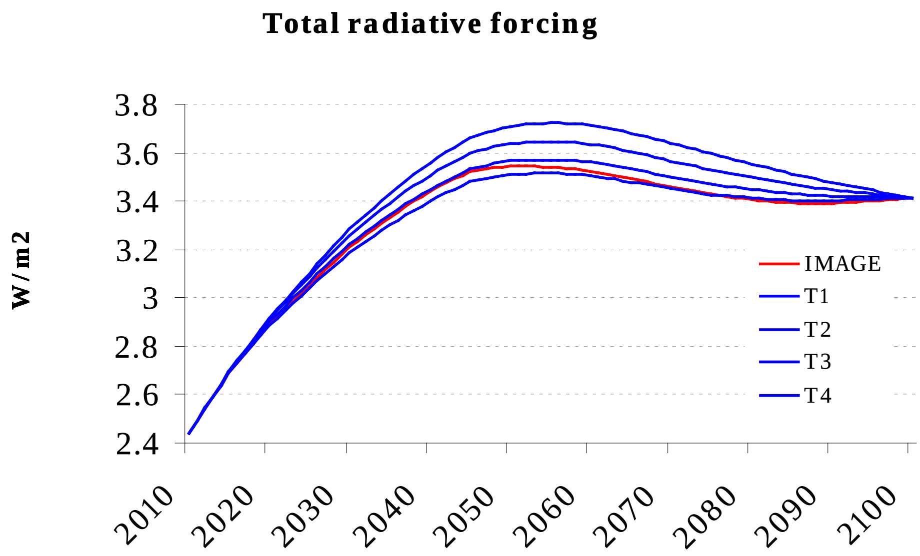
Figure 3: Example of alternative CO2 emissions pathways.

d. Resulting emissions trajectories

The resulting families of alternative CO2 emissions trajectories are given in XX. XX shows the corresponding carbon budgets over 2000-2049 and 2000-2100. XX and XX give the associated trajectories of total CO2 concentration and of total radiative forcing respectively.
The carbon budgets can be compared with results from Meinshausen et al. (2009). The comparison indicates that the trajectories correspond to about 30% to 40% chances not to exceed 2°C warming (median values, with a range of [15%-65%]).







	Carbon budget from energy, processes and land-use ($GtCO_2$)	
	2000-2049	2000-2100
IMAGE	1565	2099
T1	1528	2092
T2	1586	2120
T3	1657	2157
T4	1726	2196