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When Starting with the Most Expensive Option Makes Sense

Use and Misuse of Marginal Abatement Cost Curves

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Abstract

This article investigates the use of expert-based Marginal Abatement Cost Curves (MACC) to design abatement strategies. It shows that introducing inertia, in the form of the "cost in time" of available options, changes significantly the message from MACCs. With an abatement objective in cumulative emissions (e.g., emitting less than 200 $GtCO_2$ in the 2000–2050 period), it makes sense to implement some of the more expensive options before the potential of the cheapest ones has been exhausted. With abatement targets expressed in terms of emissions at one point in time (e.g., reducing emissions by 20 percent in 2020), it can even be preferable to start with the implementation of the most expensive options if their potential is high and their inertia significant. Also, the best strategy to reach a short-term target is different depending on whether this target is the ultimate objective or there is a longer-term target. The best way to achieve Europe's goal of 20 percent reduction in emissions by 2020 is different if this objective is the ultimate objective or if it is only a milestone in a trajectory toward a 75 percent reduction in 2050. The cheapest options may be sufficient to reach the 2020 target but could create a carbon-intensive lock-in and preclude deeper emission reductions by 2050. These results show that in a world without perfect foresight and perfect credibility of the long-term carbon-price signal, a unique carbon price in all sectors is not the most efficient approach. Sectoral objectives, such as Europe's 20 percent renewable energy target in Europe, fuel-economy standards in the auto industry, or changes in urban planning, building norms and infrastructure design are a critical part of an efficient mitigation policy.

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When Starting with the Most Expensive Option Makes Sense: Use and Misuse of Marginal Abatement Cost Curves

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[1]The views expressed in this paper are the sole responsibility of the author. They do not necessarily reflect the views of the World Bank, its executive directors, or the countries they represent.

1 Introduction

To design the best policies to cope with climate change, decision-makers need information about the various options to reduce greenhouse gas (GHG) emissions. Such information has been provided to the public in many different ways, including in the form of Marginal Abatement Cost (MAC) curves. Kesicki (2010) calls *expert-based MAC curves* (here, we simply refer to them as *MAC curves* or *MACCs*) the curves that represent information on abatement costs and potentials for a set of mitigation activities.[2]

MAC curves are usually constructed for a specific country or region, and for a specific time horizon. They report abatement potentials that can be achieved as a function of the abatement cost (Fig. 1). They are constructed following a bottom-up approach: they assess a set of available mitigation options, each taken independently. Where they have been developed, they have proved useful to communicate about abatement options and potentials.

MACCs rank potential mitigation options from the least to the most expensive one. By doing so, they look like "merit-order curves", which are used to describe various production options that are instantly available at a given point in time to satisfy a demand at a given price. In the power generation sector, for instance, merit-order curves are used as supply curves (Fig. 2): crossing them with demand curves actually gives the optimal dispatch (Ongsakul, 1999).

This similarity in the presentation could suggest that MAC curves can be used as conventional supply curves too — this is done for instance in an early attempt by Jackson (1991). If MACCs were conventional supply curves, an abatement activity should be implemented when the carbon price is larger or equal to its marginal abatement cost. In this case, a cost-minimizing strategy would exhaust the cheapest available options, before progressively turning to more expensive options until the committed abatement level is reached.

This paper shows that MACCs are different from merit-order curves because they include activities that could take decades to implement. Because of this inertia (Grubb et al, 1995), the implementation schedule of the various options — and even the choice of mitigation options — suggested by a naive interpretation of MACCs is suboptimal.

The objective of this paper is to investigate the optimal timing of GHG emissions abatement (choice across time) along with the optimal dispatch of the reduction burden (choice across abatement activities). To do so, we introduce inertia — in the form of a *cost in time* of each activity — in a MAC curve and use an inter-temporal optimization model to investigate the "when-flexibility" on the implementation of various abatement options. The cost in time makes it possible to distinguish

[2] In this paper, we call these abatement options "*activities*", following the terminology from Rodrik (2004). Activities include changing technologies, notably in the car and power sectors, but also non-technological options such as modal shift in the transportation, waste recycling, reforestation or building retrofitting sectors. While the terms "MAC curve" can also refer to different curves, as those named *model-derived MAC curves* by Kesicki (2010) and studied for instance by Klepper and Peterson (2006), we focus in this paper on expert-based MAC curves.

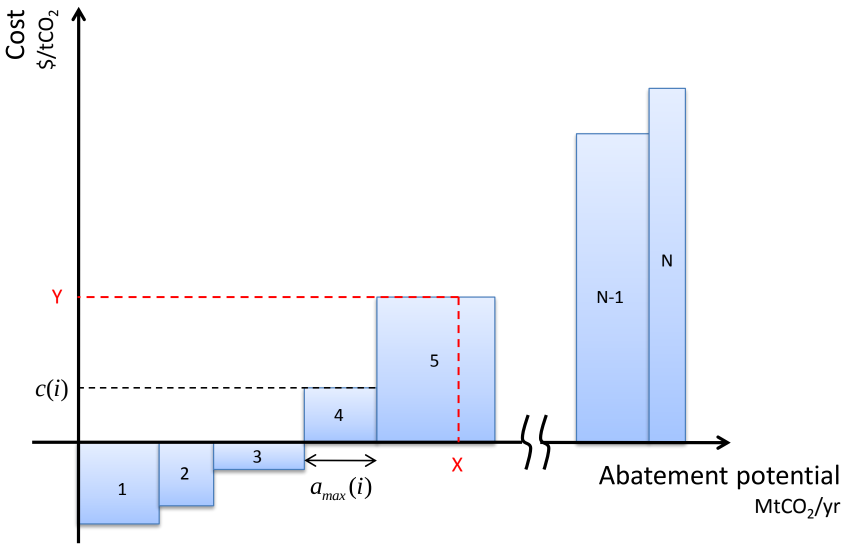


Figure 1: An expert-based MAC curve exhibits abatements options 1..N characterized by their maximum potential a_{max} and their marginal cost c, ranked from the least to the most expensive one. The classical interpretation, challenged in this paper, is that the optimal strategy for achieving abatement X is to implement all the activities cheaper than Y.

available abatement activities not only using their costs and potentials, but also the time it takes to implement them. For instance, it allows taking into account the fact that urban planning may be cheaper and have a higher potential to reduce emissions than technological change in the car industry, but is also much slower and requires much more anticipation to be effective (Gusdorf et al, 2008).

Confirming previous results from Lecocq et al (1998) and Jaccard and Rivers (2007), introducing inertia changes the order in which various options should be implemented, and — under some conditions — can make it optimal to start with the introduction of the most expensive options. Moreover, with inertia, a uniform carbon price across sectors cannot trigger the optimal dispatch of activities, unless its long-term evolution is perfectly credible and economic actors have perfect foresight. In a realistic setting — one with inertia, public-policy long-term credibility issues, and imperfect foresight — it can make sense to use sector-specific complementary policies such as Europe's 20% renewable energy target in Europe or fuel economy standards in the auto industry (An et al, 2007).

The article starts with a review of the literature on two parallel research questions: the MAC curves methodology and limits (Section 2.1) and the timing of mitigation strategies (Section 2.2). Section 3 then presents a model that computes the least-cost abatement strategy to reach a climate objective, taking into account technological ceilings, costs and inertia. In Section 4, this model is used to design an optimal abatement strategy to reach an objective expressed in terms of cumulative emissions (for instance emitting less than 200 $GtCO_2$ over the 2000-2050 period). We show that, because of the interplay of inertia and discounting, this optimal abatement strategy will not

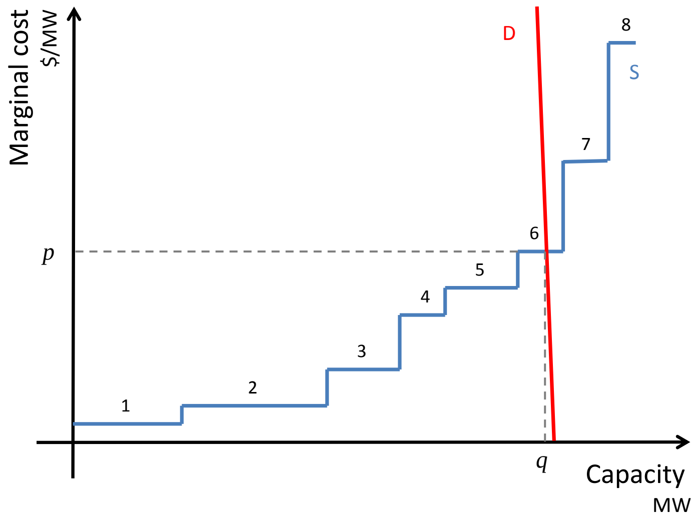


Figure 2: Merit order in the power generation sector. The graph exhibits a supply curve (S) made by aggregating 8 available power plants and a demand curve (D). Each power plant is characterized by available capacities (in MW) and a marginal cost (in \$/MW). The optimal response to the demand is to call power plants 1 to 6 and to let 7 and 8 idle.

necessarily exhaust all cheap abatement options before starting to implement more expensive ones. In Section 5, we examine optimal strategies to achieve emission targets at one point in time (e.g., Europe's goal of reducing emissions by 20% by 2020). In this case, we demonstrate it can make sense to start with the most expensive options rather than with the cheapest. We also show why MAC curves should not be used as supply curves to find the optimal "activity mix" to achieve a particular abatement at a given time horizon. Instead, this mix strongly depends on longer-run objectives, so that the optimal activity mix to reach a given target in 2020 is strongly dependent on the objective for later years (e.g. 2050). Our conclusion (Section 6) discusses how to translate a general climate objective (whether expressed in cumulative emissions, carbon budget or concentration) into sectoral objectives in terms of emissions at one point in time, and shows that MAC curves could be usefully extended to account for additional information on inertia.

2 Literature review

2.1 Expert-based MAC curves usage and their limitations

Expert-based MAC curves are built in a bottom-up, engineering, approach. They investigate available technical options to mitigate GHG emissions, and present them in terms of their abatement potential and marginal cost. Kesicki (2010) proposes a definition of expert-based MAC curves and a review of their use in the literature. They differ from model-based MACC curves (Klepper and Peterson, 2006) which are outside of the scope of this paper and therefore not discussed here.

McKinsey and Company have built expert-based MAC curves assessing potentials in the USA in 2030 (McKinsey and Company, 2007) and Ireland in 2030 (Motherway and Walker, 2009). The World Bank has assessed Poland's and Mexico's reduction potentials in 2030 in the form of MACCs (Poswiata and Bogdan, 2009; Johnson et al, 2009). And Sweeney and Weyant (2008) have proposed a MAC curve for California in 2020. MAC curves are designed to provide synthetic and easily usable information to policymakers. Their use has however been criticized. For instance, Ekins et al (2011) mention that:

- MAC curves generally neglect non-climate benefits such as air pollution reduction or increase in energy security. They also neglect co-costs, like negative distributional impacts.
- They do not account for synergies between abatement activities (e.g., MACCs do not report that promoting electric vehicles and green electricity together would allow to save more GHG than the sum of the two isolated abatement activities).
- They also neglect possible rebound effects (Greening et al, 2000) and the need for behavioral or institutional changes.
- They assess project or technological costs only, excluding institutional barriers and transaction costs. This is the classical explanation for why MAC curves often report negative-costs abatement options — so-called no-regret options (Bréchet and Jouvet, 2009).

These weaknesses are due to the fact that MAC curves are developed in a bottom-up framework. However, this approach has advantages compared with integrated assessments, which often appear as "black-boxes", and has proved useful for communication and debate.

In this paper, the main criticism we address to the MAC curves is not related to the way they are built, but rather to the interpretation made of them. As we will show, one major issue with the MAC curves is that they do not take into account inter-temporal dynamics and inertia, which play a key role in determining the optimal timing of abatement options.

2.2 The timing of mitigation strategies

The optimal timing of greenhouse gases abatement to limit climate change is widely discussed in the literature. In many cases, these discussions are developed with models that represent the economy as one single aggregated sector. For instance, the topic has emerged from arguments in favor of postponing emission reductions, proposed by Nordhaus (1992), Hammitt et al (1992) and Wigley et al (1996). Those arguments include the risk of sunk investments if climate change reveals less threatening than expected, and the role of discounting. Others have studied the effect of technical change (Goulder and Mathai, 2000; Manne and Richels, 2004; Sue Wing, 2006), the risk of early impact of climate change and the interplay between uncertainty in the carbon and climate cycles and irreversible investments (Ha-Duong et al, 1997; Ambrosi et al, 2003). A more complete literature review can be found in Kverndokk and Rosendahl (2007).

A different approach investigate the link between when- and how-flexibility using models with multiple sectors. Lecocq et al (1998), Gilotte (2004) and Jaccard and Rivers (2007) focus on the role that long-lived capital plays in the design of mitigation policies. They argue that the differences in inertia across different economic sectors matter, and that the design of optimal abatement strategies cannot therefore be investigated using aggregated models. Lecocq et al (1998) conclude that in absence of perfect foresight, classical policy instruments (such as a carbon price) might not be enough to decarbonize economies at low costs, and they call for specific policies directed toward green infrastructure and long-lived capital. Jaccard and Rivers (2007) find that early action is preferable in long-lived capital sectors, even if marginal costs are higher there.

A third branch of the literature studies the interplay between technology and environmental policies (Jaffe et al, 2005). They often focus on the effect of the learning by doing (LBD) when there are several available technologies and imperfect foresight (Kverndokk and Rosendahl, 2007; del Rio Gonzalez, 2008). In this framework, carbon prices cannot trigger investments in the most promising solutions if initial costs are too high; targeted policies are therefore needed to encourage early action and initiate costs reductions.

Our contribution is threefold: first, we to develop a new — independent from LBD — argument for early action in some expensive activities, based on the interplay of inertia and high abatement potentials; second we show that factoring in inertia is not only necessary for sectors like infrastructure and urbanism, but that information on the implementation inertia of all abatement activities is critical to design optimal strategies; third, we show that MAC curves can easily be extended to account for this additional information.

3 Model description

Our model is called MACinert (Marginal abatement cost curves and inertia). It is consistent with the MAC curves framework (see Section 2.1), i.e. abatements are achieved by applying changes to a fixed baseline. We do not incorporate more realistic but complex dynamics, such as capital accumulation, learning-by-doing, sectoral interactions, or crowding-out effect on investment. Instead, a social planner controls GHG abatements from an emission baseline, by spending time and money in abatement activities, characterized by a MAC curve and a "cost in time" — the latter takes inertia into account.

We then use this model to carry out simple numerical experiments. Parameters corresponds roughly to the European Union situation, but these simulations have an illustrative purpose only. They demonstrate what MACCs can and cannot do, and provide insight on how to use them.

3.1 GHG emissions

There are N abatement options, indexed by i. The model is run on a period that goes from 2000 to 2050 with a time step, Δt, of one year. At each time step t, emissions are computed from the baseline emissions $E_{base}(t)$ and the abatement achieved with each activity i.

$$E(t) = E_{base}(t) - \sum_{i=1}^{N} a(i,t) \tag{1}$$

We assume constant baseline emissions, that is $E_{base}(t) = 5$ $GtCO_2/yr$.

The cumulative emissions $M(t)$ are then computed as the sum of emissions:

$$M(t) = E(t) \cdot \Delta t + M(t-1) \tag{2}$$

$$M(0) = 0 \tag{3}$$

3.2 Potentials, costs, and inertia

Abatements efforts in each sector are subject to two restrictions. First, each activity i has a technical ceiling, i.e. a maximum abating potential $a_{max}(i)$, expressed in avoided annual emissions, i.e. in $MtCO_2/yr$. This potential is commonly represented by the rectangles width in MAC curves (see Fig. 1). For instance, switching to more efficient thermal engines for personal vehicles could save a fraction of GHG emissions associated with private mobility, but not more.

$$a(i,t) \leq a_{max}(i) \tag{4}$$

In the MAC curve, each activity i is qualified with a constant marginal cost of abatement $c(i)$ (see Fig. 1). Here, we assume that marginal abatement costs are independent of cumulative abatements and of time. In particular, we do not model technical change and learning-by-doing. Therefore, abatements $a(i,t)$ achieved thanks to activity i at time t have a cost $I(i,t)$ which reads:

$$I(i,t) = a(i,t) \cdot c(i) \tag{5}$$

The innovation here is the introduction of inertia in the MACCs. Inertia is defined by a "*cost in time*": a given amount of abatement requires to spend a positive amount of time for its implementation. This cost could be expressed in years per $MtCO_2$, and is assumed independent of the financial cost of the option. In other words, there is a maximum amount of supplementary abatement that is achievable with each activity during a given time interval, which is expressed in $MtCO_2$ per year.[3]

Let $\alpha(i)$, in $MtCO_2/yr^2$, be the maximal incremental amount of GHG emissions abatement achievable with activity i over a year. Note that $\alpha(i)$ is the algebraic inverse of the "cost in time". For

[3]This modeling differs from the *time-to-build à la* Kydland and Prescott (1982). Time-to-build would reflect the idea that there is an incompressible lag between investment decisions and actual abatements. With time-to-build, an arbitrary large amount of abatements would require as much time to be implemented as a small abatement (if achieved through the same activity). With our cost in time, in contrast, the time expenditures are proportional to the amount of abatement, in the same way as financial expenditures.

the sake of simplicity, we assume $\alpha(i)$ is constant and does not depend on the previously achieved abatements nor current time step t. In other terms, there is no learning-by-doing leading to a reduction in the cost in time of an activity.

This α, by introducing inertia in the modeling framework, also introduces path dependency: achievable abatements at time $t+1$ directly depend on already achieved abatements at time t.

$$a(i,t) \leq a(i,t-1) + \alpha(i) \cdot \Delta t \tag{6}$$

These costs in time may come from several factors, such as (i) availability of skilled workers, (ii) availability of productive capacities, (iii) emissions being embedded in capital, and (iv) incompressible institutional requirements. Points (i) and (ii) could be overcome by training workers or redirecting unemployed workers and unused capital; but training and redirecting are activities *per se* and cannot be done overnight either. The third point is related to capital vintages and turnover: if one sees emissions as embedded in capital (Davis et al, 2010; Guivarch and Hallegatte, 2011), decarbonization cannot be faster than capital turnover, except by wasting valuable productive capital through early scrappage (see Section 2.2). In the case of urban planning, transforming a city cannot be done in less than decades, and an aggressive action can lead to strongly negative distributional impacts within a city (Gusdorf et al, 2008). The issue of institutional or organizational delays is well documented (World Bank, 2010). Reducing them is an activity *per se*, and takes time. We thus see the maximal amount α as an exogenous constraint — independent of the cost — that the social planner must take into account when searching for optimal abatement strategies.

3.3 Social planner objectives

The objective of the social planner is to achieve a climate-related target while minimizing abatement costs. The social planner minimizes C, the total present cost of abatements, discounted at rate ρ over the period:

$$C = \sum_{t=0}^{T} \sum_{i=1}^{N} \frac{I(i,t)}{(1+\rho)^t} \tag{7}$$

Theoretically, the social planner could control GHG emissions in order to equalize the marginal costs of mitigation and adaptation, in a cost-benefit approach as in Nordhaus (1992). Because of uncertainty surrounding both climate response to a change in GHG emissions and adaptation costs, and because decision-making is done at national scale (and not at the global scale as would be required for a global public goods issue like climate change), it is common to adopt a cost-effectiveness approach (Ambrosi et al, 2003).

In our model, this can be done by constraining cumulative emissions M to remain below a given objective M_{obj}.

$$M(t) \leq M_{obj} \tag{8}$$

Cumulative emissions can be used as proxies for climate change (Matthews et al, 2009; Meinshausen et al, 2009; Allen et al, 2009); in practice, however, governments and other public agencies can hardly implement them. In contrast, they may provide emission objectives for given points in time. To do so, they mostly rely on emissions targets.[4] For instance, the European Commission has the objective of cutting its emissions by 20 % of 1990 levels by 2020. Other countries have different objectives, such as the UK objective of cutting emissions by 75 % by 2050.

In our model, this type of objectives can be implemented by defining a set of "milestones" indexed by m, and constraining emissions at each milestone:

$$E(t_m) = E_m^{obj} \tag{9}$$

3.4 Numerical values

For illustrative purpose, we assumed a MAC containing only two contrasted activities ($N = 2$), labeled "*cheap*" and "*deep*". *Cheap* has a lower abatement cost than *deep*, but the latter has a greater abatement potential (see Tab. 1 and Fig. 3). *Cheap* could represent for instance the activity of switching energy sources in the buildings, and *deep* could stand for retrofitting those buildings. In the auto industry, *cheap* could stand for energy efficiency gains in the internal combustion engines and *deep* for switching to other energy sources, such as electricity or biofuels.

The cost in time is arbitrarily assumed to be equal to 50 $MtCO_2/yr^2$ in both activities. As shown by the ratios a_{max}/α, this means that *deep* presents more inertia than *cheap*, because implementing the full potential of *deep* takes 60 years, while it takes only 30 years for *cheap*.

	Abatement cost	Abatement potential	Maximal increment
	c ($/($tCO_2$))	a_{max} ($MtCO_2/yr$)	α ($MtCO_2/yr^2$)
Cheap	30	1 500	50
Deep	60	3 500	50

Table 1: Numerical assumptions

These values are not meant to represent accurately concrete sectors of the economy. We use them to carry out illustrative experiments, which help draw more general conclusions. We solve this simple model using a linear programing algorithm provided by GAMS (Brook et al, 1988). The source code is available upon request. The main results are presented in the next two sections.

[4] In the auto industry, it is common to adopt intensity objectives, expressed in gCO_2/km (An et al, 2007). In the framework of a MAC curve, nonetheless, intensity targets can be treated as emission targets. The MACCs are built assuming a given baseline; in particular, they assume that the aggregate driven distance is given (Sweeney and Weyant, 2008). The multiplication of this distance by the intensity objectives provides an emission target.

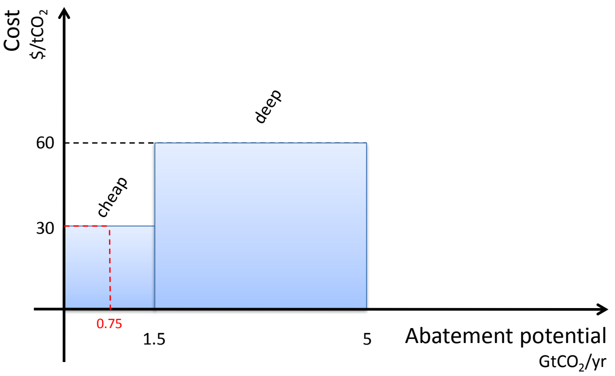


Figure 3: The MAC curve used in our experiments. According to the supply-curve interpretation, an abatement of annual emission by 750 $MtCO_2$/yr should be achieved through the implementation of *cheap* only.

4 Optimal timing with cumulative-emissions objectives

In this section, we investigate the optimal abatement pathway when using a constraint in terms of cumulative emission, i.e. with full when-flexibility on how to reduce emissions. Cumulative emissions can be seen as good proxies for climate change (Matthews et al, 2009; Meinshausen et al, 2009; Allen et al, 2009). This is implemented in our model by excluding Eq. 9, and using Eq. 8. We then test several values of the objective (M_{obj}), and assess the consequence on the optimal reduction pathway.

4.1 Using expensive options before the potential of cheap ones is exhausted

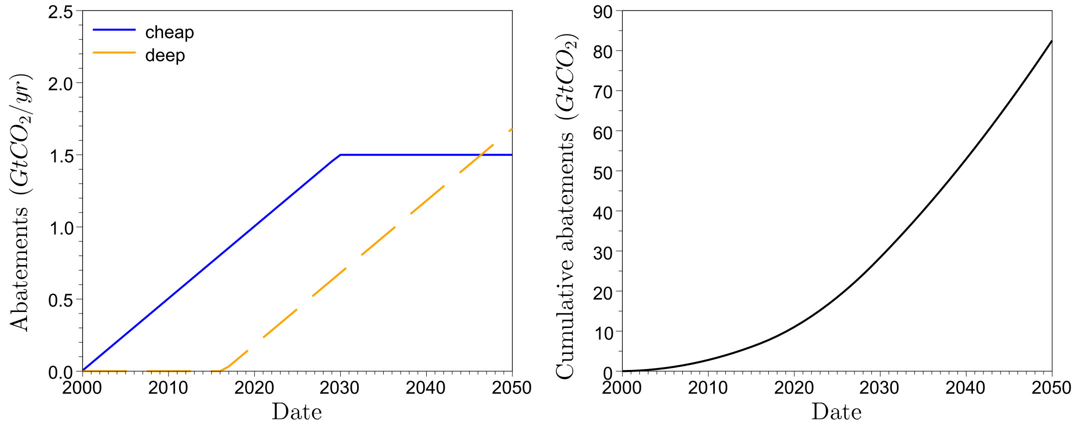


Figure 4: Optimal abatement strategy to limit cumulative emissions below 175 $GtCO_2$. Because of inertia and discounting, the *deep* option enters before the potential of *cheap* has been exhausted.

Figure 4 shows the optimal strategy for maintaining cumulative emission below 175 $GtCO_2$.[5]

[5]Cumulative emissions in the baseline amount to 5 Gt/yr during 51 years, with a total of 255 Gt.

This particular value is used for illustrative purpose, and will allow us to make some comparisons with subsequent simulations with emissions targets (see Section 5).

The abatement paths have triangular or trapezoidal shapes; this shows that one of the inertia (Eq. 6) or ceiling (Eq. 4) constraint is always binding. In this case, the intuitive ranking of abatement activities is respected: the social planner starts implementing *cheap* before *deep*. But the social planner does not use the full potential of *cheap* before starting using *deep*, which enters in 2017 while *cheap* does not reach its ceiling before 2030. Moreover, a more stringent objective would force *deep* to start even earlier (see below).

The optimal implementation strategy does not strictly follow an hypothetical merit-order in which all the potential of the cheapest solutions is used before more expensive solutions are introduced. This example illustrates why the MAC curves should not be interpreted as abatements supply curves.

A more systematic analysis using different cumulative emission objectives (Fig. 5) confirms that — for any objective — it is never preferable to implement the expensive *deep* before *cheap*. But it shows that if the objective is stringent enough (about 210 $GtCO_2$), *deep* has to begin before all the potential of *cheap* has been exploited; the implementation is not sequential. If it is even more stringent (about 135 $GtCO_2$), *deep* is forced to start in 2000, at the same time as *cheap*.

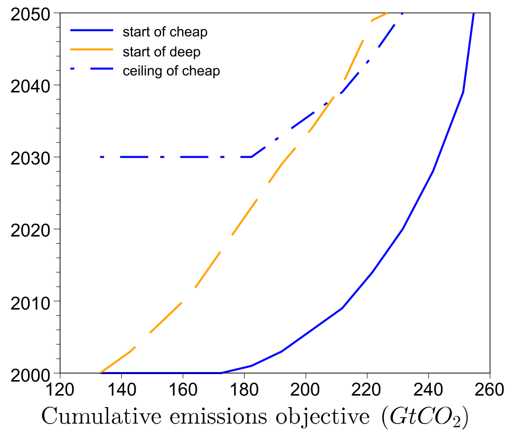


Figure 5: Entry date et ceiling date of each abatement activity as a function of the cumulative emission objective. The entry date is the date when an activity begins to be implemented; the ceiling date is the date when the full potential of an activity is achieved.

4.2 Expensive options may be useful even when cheaper ones appear sufficient

Let us first analyze a case in which the climate objective is not very restrictive, say 210 $GtCO_2$. This translates into cumulative abatements of 45 $GtCO_2$ over the period.[6] *Cheap* has a cumulative abate-

[6]Cumulative emissions in the baseline amount to 5 Gt/yr during 51 years, with a total of 255 Gt.

ment potential of 54 $GtCO_2$.[7] It is then possible to achieve the abatement objective by implementing *cheap* only, without implementing *deep*. A naive strategy could then focus on implementing *cheap* and not implementing *deep*, because *cheap* has the lowest marginal cost. But our simulations show that this is not the optimal strategy, because there is a trade-off between (i) implementing only the cheapest solutions, but starting early to give them enough time to reach the objective; (ii) delaying abatements in order to save present value (thanks to the discounting), but undertaking both *cheap* and *deep* to be more aggressive and reach the objective in spite of the delayed action.

In our simulations (Fig. 5), the optimal strategy to reach the (lax) 210 $GtCO_2$ objective calls *deep* from year 2038, which makes it possible not to call *cheap* before 2009 (for a strategy starting in 2000). The additional cost of using *deep* is more than compensated by the delay in the implementation of *cheap* (again, thanks to the discounting). In other words, the optimal strategy uses an expensive activity even when a cheaper activity appears sufficient to attain the objective, in order to take advantage of the discounting. Again, this result challenges the interpretation of MAC curves as abatement supply curves providing a merit-order ranking. Furthermore, it rules out one of the most common interpretation of the MACCs, namely that only the cheapest options should be implemented in order to reach a given amount of abatements (see Fig. 1).

These experiments illustrate the importance of taking into account the interplay of discounting with differentiated inertias when designing a mitigation strategy. Interpreting a MAC curve as a merit-order curve could lead to postpone expensive abatements after the cheap options are exhausted, which would lead to suboptimal mitigation pathways. With discounting and inertia, it makes sense to implement expensive abatement activities in parallel to cheap ones, to be more aggressive and be able to postpone action. Of course, this conclusion does not take into account policy and behavior inertia, and the incentive for policy-makers to delay action beyond their term of office, which justify the use of emission targets (at one point in time) instead of cumulative-emission objectives.

Policymakers should be informed of abatement potentials and costs, and MAC curves provide this information. But policymakers also need to be informed on the duration of the implementation process of these activities. MAC curves would be more operational if they had a third dimension, namely our “cost in time” for each abatement option.

5 Optimal abatement pathways with emission targets in 2050

Commitments in terms of cumulative emissions are difficult to introduce and enforce. Indeed, with cumulative emissions, there is an incentive for decision-makers to delay investments and efforts beyond their mandate. Alternatives policies include the definition of emission targets at one or several points in time. They can be enforced with tradable emissions permits, as the ETS system in Europe.

[7]Its annual abatement potential is 1.5 Gt/yr and takes 30 years to implement in full (see Tab. 1); adding the cumulated potential during the take off phase (30 yr $\times$ 1.5 Gt/yr)/2 and the potential when annual abatements have reached their ceiling 21 yr$\times$1.5 Gt/yr gives a total of 54 Gt.

When these abatement commitments are well designed, the gain in realism and enforceability could compensate for the loss of when-flexibility. In the next two sections, we assume that commitments are made in terms of abatement levels, at different points in time.

We thus exclude the cumulative-emissions constraint (Eq. 8) from our model, and make use of the emission constraint with $m \in \{1\}$, $t_1 = 2050$ and varying E_1^{obj} (Eq. 9). In absence of inertia — i.e., with an infinite α in Eq. 6 — the optimal response to an emission objective would be to remain in the baseline emissions pathway from 2001 to 2049, and to implement abatement options in 2050 only.[8] With inertia — i.e., with a finite α in Eq. 6 — the optimal mitigation strategy depends on the emission target.

5.1 Implementing expensive options before cheap ones

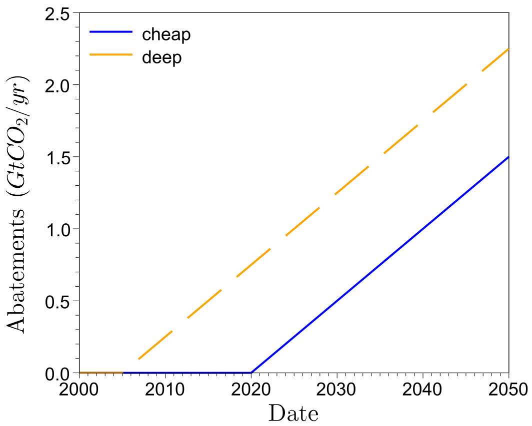


Figure 6: Optimal abatement pathways to achieve, in 2050, ambitious abatements (3.25 $GtCO_2/yr$). The expensive option with large abatement potential is implemented before the cheaper option.

Figure 6 shows the optimal abatement pathway for achieving an ambitious reduction in emissions in 2050, namely a reduction by 75%. It leads to a cumulative emissions of about 175 $GtCO_2$, which makes this simulation comparable with the one proposed in Section 4.1.

In this case, the optimal strategy implements the expensive *deep* before implementing *cheap*. Indeed, the emission objective translates into abatements by 4.75 $GtCO_2/yr$ in 2050, which cannot be achieved by implementing *cheap* alone. The cheapest way to achieve this objective in 2050 is to use *cheap* to abate as much GHG emissions as possible, i.e. 1.5 $GtCO_2/yr$. Because *cheap* cannot penetrate faster than 50 $MtCO_2/yr^2$, it has to enter in 2021. Then 3.25 $GtCO_2/yr$ remain to be abated by *deep* in 2050. To do so, *deep* has to enter as soon as 2006, 15 years before *cheap*.

[8] One could say that this would be done by "starting" with the cheapest activity and "continuing" with the more expensive one until the emission objective is achieved. But in this context, the terms "starting" and "continuing" would not have a chronological meaning, as the abatement activities would both be implemented instantly in 2050. Instead, those words would denote the fact that the social planner, while designing the optimal strategy, would first consider to implement *cheap* and then to implement *deep*.

This examples highlights the fact than when establishing a merit-order to design an optimal abatement strategy, time may play a more important role than cost.

The fourfold reduction in emissions leads to cumulative emissions of 175 $GtCO_2$, and is thus comparable to the simulation proposed in Section 4.1. Compared to the cumulative-emission-constrained simulation (CC), this emission-constrained simulation (EC) leads to start *cheap* later and *deep* sooner. Short-term abatements are lower — for instance, they amount to 750 $MtCO_2$/yr in 2020 in EC, against 1.2 $GtCO_2$/yr in CC — but long-term abatements are higher. The loss of when-flexibility eventually raises the present cost of abatements, which amounts to 390 G$ in the CC case and to 630G$ in the EC simulation for the same final atmospheric concentration.[9] This illustrates the fact that cumulative emission objectives, with full when-flexibility, allow the social planner to find lower-cost pathways to reach equivalent climate targets than emission objectives.

A more systematic analysis is presented in Fig. 7. It gives the optimal entry dates of both activities (*cheap* and *deep*), as a function of the 2050 emission target. It shows that when the emission target is lower than 2 $GtCO_2$/yr (i.e. when the abatement objective is higher than 3 $GtCO_2$/yr), the optimal strategy starts to implement the expensive activity before the cheap one.

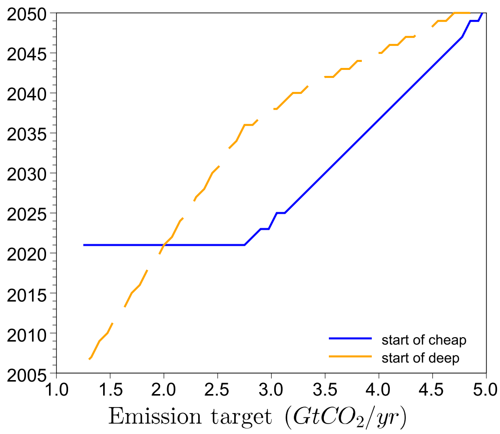


Figure 7: Entry date of each activity as a function of emission objective for 2050. For ambitious emission targets (below 2 $GtCO_2$/yr), the expensive option with large abatement potential is implemented before the cheaper option.

The fact that, with emission targets, expensive options may have to be implemented before cheap ones is problematic. Considering the difficulty for the government in creating a credible long-term signal for the price of carbon — and in government ability to commit in general (Kydland and Prescott, 1977; Dixit and Lambertini, 2003)—, economic actors cannot rely on long-term prices. If actors consider only the current carbon price, then a carbon price of 60 \$/(tCO_2) would be necessary to trigger the entry of *deep* (see Tab.1). Fig. 6 shows that this activity should be implemented as early as 2005 to reach the stringent objective (emissions of 750 $MtCO_2$/yr in 2050) at the lowest

[9]Note that 390 G$ is the lowest possible cost to reach the carbon budget constraint, while 630G$ is the lowest cost for reaching the same carbon budget through one aggregated emission target in 2050.

possible cost. But this high carbon price would also trigger the implementation of *cheap* (because its marginal cost, 30 $/(tCO_2)$, is lower than the signal) in 2005, i.e. too soon, leading to a suboptimal abatement pathway. In this case, achieving the optimal pathway through differentiated carbon prices across sectors makes sense.[10]

This finding is even stronger when taking into account a shorter-term target, such as the EU target to abate by 20 or 30% in 2020. Short-term targets are *a priori* relevant because there is visibility over the short term on technology availability, macroeconomics trends and institutional frameworks. But focusing on aggregated short-term objectives has also its drawbacks, as the next section will show.

5.2 The influence of long-term objectives on short-term strategies

Here, we compare two simulations with the same short-term aggregated target, but different long-term targets. The first simulation, labeled SO (Short-term Only), has a short-term constraint for 2020, but no long-term constraint:

$$E(2020) = 4.25\ \mathrm{GtCO_2/yr} \tag{10}$$

The second simulation, labeled SL (Short-term and Long-term objectives), provides the optimal abatement strategy to reach the same short-term target for 2020, but with an additional long-term constraint, namely a fourfold reduction in GHG emissions in 2050.[11] In this simulation, there are thus two emission milestones (see Eq. 9) with the following emissions objectives:

$$E(2050) = 1.25\ \mathrm{GtCO_2/yr} \tag{11}$$

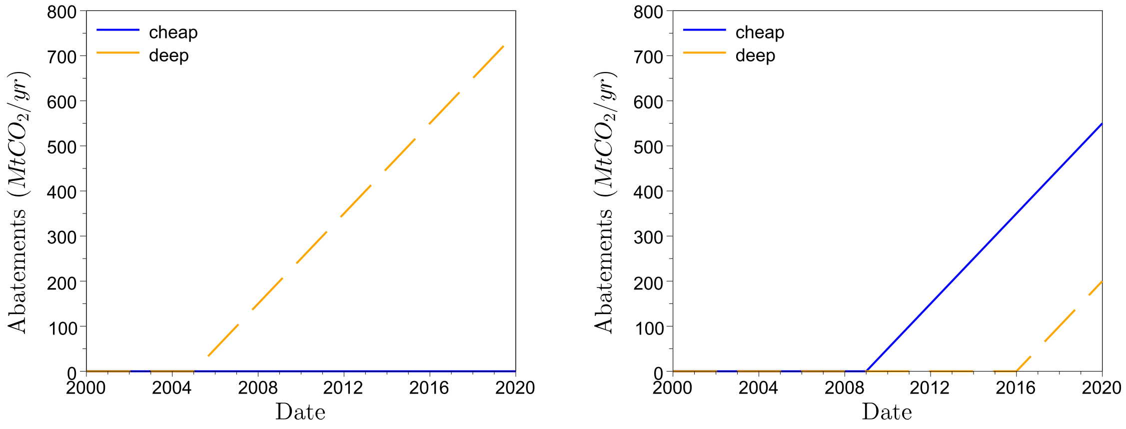
$$E(2020) = 4.25\ \mathrm{GtCO_2/yr} \tag{12}$$

Our objective is to assess the difference — over the short-term — between a strategy aiming at a short-term target and a strategy aiming at both short-term and long-term targets. Our purpose here is to explore the impact of long-term emission objectives on the short-term strategy.

Figure 8 compares the optimal abatement strategies from 2000 to 2020 in the two cases. With both the 2020 and the 2050 objective (simulation SL, panel *a.*), the social planner starts implementing *deep* in 2006, and does not implement *cheap* before 2020 (as in Section 5.1). In contrast, when the 2050 milestone is disregarded (simulation SO, panel *b.*), the climate objective seems easier to

[10] More technically, this reminds us that in a dynamic framework, the equimarginal principle does not necessarily translate in equal instantaneous carbon prices across economic sectors (Gilotte, 2004; Kverndokk and Rosendahl, 2007), as it does in a static framework (del Rio Gonzalez, 2008). Our model does return equal marginal values of investment in both activities at each time step; but these marginal values cannot be interpreted directly as a static carbon shadow price at those time steps, because they arise from an intertemporal optimization and encompass information on inertia.

[11] In this case, with perfect credibility of the 2050 target, the 2020 milestone does not add anything, since a simulation with only the 2050 target already leads to emissions of 4.25 $\mathrm{GtCO_2/yr}$ in 2020 (this simulation is thus identical to the simulation presented in Fig. 6, panel *b.*).



a. Taking into account both 2020 and 2050 objective

b. Taking into account 2020 objective only

Figure 8: Comparison of optimal abatement strategies to reach the same target for 2020, taking into account or disregarding the longer-term 2050 objective. With an ambitious long-term target, the short-term strategy is based on the more expensive option with higher potential, not on the cheapest option.

achieve. As a result, the social planner starts abating latter (in 2010 vs 2006) and uses cheaper and lower-potential options, namely *cheap* and *deep* instead of *deep* only. The discounted expenditures in abatement measures amounts to 28 G$, against 112 G$ when the 2050 objective is taken into account: the optimal short-term financial effort is much higher if the long-term target is taken into account (even though the abatment in $MtCO_2$ is the same).

If the 2050 target is not taken into account in the 2000-2020 period, then the 2050 target may appear in 2020 extremely costly, or even impossible, to achieve. In this illustrative example, the fourfold reduction in emissions becomes indeed impossible to achieve in 2050 if the long-term objective is not taken into account from the beginning, in 2000.

In other words, despite aggregate emissions being abated at the same pace in SO as in SL, the SO pathway produces a lock-in in a carbon intensive pathway that cannot be reversed in the second period from 2020 to 2050. In plain language, the optimal strategy to reach the 2020 target is different (and more expensive) if the 2050 objective is included in the optimization. With an ambitious long-term objective, the short-term target needs to be achieved through the implementation of the options with the largest potentials and the largest inertia, not with the cheapest solutions, as the MAC curve could suggest (see Fig 3).

6 Conclusion

This article investigates the use of expert-based MACCs to design abatement strategies. It shows that introducing inertia, in the form of a maximum amount of abatement that can be achieved over a given period of time, changes significantly the message from MACCs. This "cost in time", which complements the financial cost, has a large influence on the rank order of various strategies. In particular, the dynamic aspect makes MACCs radically different from merit-order curves: at one point in time, the best approach is not to set an instantaneous carbon price and introduce all the abatement options with a marginal cost below it.

With an objective in terms of *cumulative* emissions over a long period of time — a good proxy for climate change —, it is preferable to start by implementing the cheapest strategies, but it makes sense to implement the more expensive ones at the same time, or at least before all the potential of the cheapest options has been exhausted. Reaching ambitious objectives requires the implementation of abatement options that are slow to act, such as urban planning. This means that the implementation date is also defined by the time constraint, not only by the cost of options.

We also tested objectives expressed in terms of aggregated abatements at one point in time, closer to the actual practices, e.g., the -75% in 2050 of the United Kingdom. In that case, the order can even be reversed, it can be preferable to start with the implementation of the most expensive options, if their potential is higher and their inertia is large. This optimal schedule cannot be enforced with a carbon price in a world without perfect foresight and perfect credibility of the long-term carbon price signal.

Moreover, we show that short-term emission target can dangerously mask longer-term targets. In the European Union, the best way of reducing emissions by 20% by 2020 is different, depending on whether this is the ultimate objective or only one milestone in a trajectory toward a 75% reduction in 2050. With an ambitious long-term objective, the short term target needs to be achieved through the implementation of the options with the largest potentials and the largest inertia, not with the cheapest solutions.

These results confirm the need to account for inertia in various economic sectors in the design of climate policies. Transforming climate objectives into emissions pathways cannot be done with aggregated models if perfect foresight and long-term policy credibility are not assumed. Without these assumptions, emissions pathway need to be multi-sectoral, distinguishing in particular heterogeneous capital turnovers (Lecocq et al, 1998; Jaccard and Rivers, 2007), and promising activities subject to learning by doing (del Rio Gonzalez, 2008). Policymakers could for instance use the information provided by MAC curves and additional information on inertia and learning-by-doing potential to identify a decarbonization path in each sector (or activity). In that case, emissions target can be made credible and enforceable, and mimic the abatement pathways obtained in models with more appropriate targets that allow for when-flexibility.

There is a balance to maintain, however: emission objectives (or sectoral policies) should be targeted enough to distinguish differences in inertia, but broad enough to let economic agents select the best options and technologies to reach them. Because of information asymmetry and the risk from rent-seeking behavior, micro-managing mitigation by defining too targeted objectives can be counter-productive (Laffont, 1999). Also, objectives need to be updated when new information is available; for instance if one activity turns out to be less promising than expected. In a nutshell, the definition of mitigation policies should take into account recent propositions on industrial policy (Rodrik, 2008).

In the European Union, the current mitigation objective has been set for 2020 only. It could therefore lead to economic actors to focus on cheap and rapid solutions, and to neglect high-potential but high-inertia options which will however be required to meet an ambitious objective in 2050. One solution could be to count on the 2020 target (and the corresponding carbon price created by the EU ETS system) to take care of the fast-to-implement solutions, and to add policies targeting other solutions with high inertia and potential. Examples are the existing objective of 20% of renewable energies in 2020, the fuel economy standards in the auto industry, and proposed changes in land-use planning, building norms and infrastructure design. None of those policies would necessarily imply equal carbon prices across sectors at one point in time.

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