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When Starting with the Most Expensive Option Makes Sense

On Marginal Abatement Cost Curves and Optimal Abatement Pathways

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Abstract

This paper investigates the optimal implementation schedule of the measures listed in a Marginal Abatement Cost Curves (MACC). Costs and abating potentials of each measure, provided by a MACC, are completed with a maximum implementation speed. We find that, when coping with a carbon budget, it makes sense to implement some expensive options before exhausting the abating potential of the cheapest options. With abatement targets expressed in terms of emissions at one point in time, e.g. reducing emissions by 20% in 2020 and by 75% in 2050 it can be preferable to start with the most expensive options if their potential is higher and their inertia is great. The best strategy to reach a short-term target depends on whether this target is the ultimate objective or there is a longer-term target. Using just the cheapest options to reach the 2020 target may create a carbon-intensive lock-in and make the 2050 target unreachable. Results suggest that a unique carbon price in all sectors may not be the most efficient approach. Additional sectoral policies, such as the 20% renewable energy target in Europe, may be part of an efficient mitigation policy.

Highlights

- ► MACCs are not abatement supply curves: listed activities may take decades to implement.
- ► Extending MAC curves with inertia changes the optimal order of abatement options.
- ► Reaching short-term targets with cheap options may cause carbon-intensive lock-in.
- ► Using expensive but high-inertia options in the short term may be optimal.
- ► A carbon price could usefully be combined with complementary sector- or technology-specific policies.

Keywords: optimal timing; inertia; sectoral policies; dynamic efficiency

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1. Introduction

To design the best policies to cope with climate change, decision-makers need information about the options for reducing greenhouse gas (GHG) emissions. Such information has been provided to the public in many ways, including through Marginal Abatement Cost (MAC) curves. We call *measure-explicit MACCs* the curves that represent information on abatement costs and potentials for a set of mitigation measures (here, we simply refer to them as *MAC curves* or *MACCs*).[1] These MACCs 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, ranking potential mitigation options from the least to the most expensive (Fig. 1).

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[1] Measures include changing technologies, notably in the transport and power sectors, but also non-technological options such as modal shift in the transportation, waste recycling, reforestation and building retrofitting . The term “MAC curve” refers in the literature to various curves, including continuous curves that do not distinguish explicitly each option as those studied by Klepper and Peterson (2006).

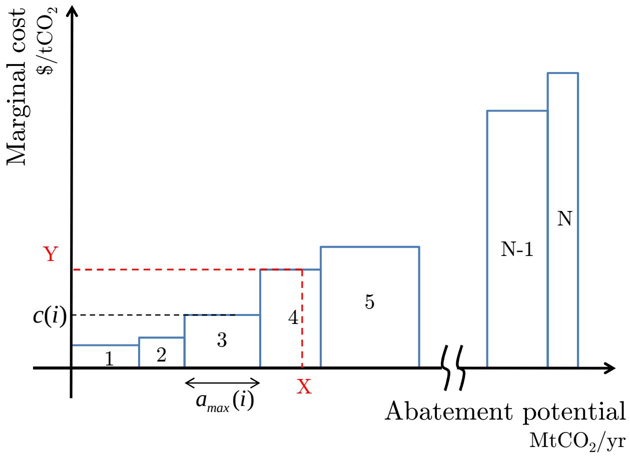

Figure 1: A measure-explicit MAC curve exhibits abatements options $1..N$ characterized by their maximum potential a_{max} and their abatement cost c, ranked from the least to the most expensive. This curves stands for a given date in the future T. We find, maybe counter-intuitively, that the optimal mitigation strategy to reach a short-term target X is not to implement exclusively the measures cheaper than Y.

In this paper, we investigate which options from a MACC should be used to achieve a given abatement target, and in which order these options should be implemented. To do this, we complete the information on costs and potential from a MACC with information on the implementation speed of each measure. This maximum implementation speed makes it possible to distinguish available abatement measures not only using their costs and potentials, but also the time it takes to implement them. For instance, it accounts for the fact that urban planning may be cheaper and may 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). We then use an inter-temporal optimization model to investigate the optimal timing for abatement of GHG emissions (choice across time) along with the optimal dispatch of the reduction burden (choice across abatement measures).

The rest of the paper is organized as follows. Section 2 proposes a review of the literature on the MACCs methodology and limits. In Section 3, we present our model. Then, we use it in Section 4 with an objective in terms of cumulative emissions over a long period, a so-called *carbon budget*, which is reportedly a good proxy for climate change. We find that it makes sense to implement the more expensive options before exhausting the whole potential of the cheapest options. Also, it may be optimal to use expensive options even when cheap ones are sufficient to reach the abatement target, in order to delay action and save present value. We then turn to objectives expressed in terms of aggregate abatement at one point in time, closer to the actual practices. In that case, we find that it can be preferable to start by implementing the most expensive options, if their potential is large and their inertia is great (Section 5.1). An other counterintuitive result is that MACCs should not be used as supply curves when choosing the optimal strategy to achieve short-term emission targets, as the optimal short-term strategy actually depends on the long-term emission objective (Section 5.2). We conclude in section 6.

2. Literature on measure-explicit MAC curves

Since the firsts proposals by Jackson (1991), Rubin et al. (1992) and Stoft (1995), measure-explicit MACCs have been used to characterize available options to mitigate GHG emissions (or to save energy) in terms of their abatement potential (respectively energy saving potential) and abatement cost. More recently, McKinsey and Company have published measure-explicit MACCs assessing potentials in 2030 at the global scale (McKinsey and Company, 2009). The World Bank has assessed reduction potentials of many countries in the form of MACCs (e.g., Johnson et al. (2009)). Also, Sweeney and Weyant (2008) have proposed a MACC for California in 2020.[2]

Recent research has identified — and proposed solutions for — methodological issues when building measure-explicit MAC curves; this has allowed to enhance the reporting of abatement costs and potentials. A first issue relates to uncertainty when assessing future costs. It is commonly addressed by presenting ranges of costs and potentials instead of just two figures (IPCC, 2007, SPM6 p.11). A second issue comes from the interaction between different measures (e.g, promoting electric vehicles and green electricity together would allow to save more GHG than the sum of the two isolated abatement measures). This can be tackled by using integrated models to build the MACCs (Kesicki, 2012b). Also, future abatement costs at a given date (e.g. 2030) will depend on previous efforts to reduce GHG emissions, and on expectations about the future price of carbon. Kesicki (2012a) studies this question by testing different abatement pathways, along with differences in social and private discount rates. Other issues are more difficult to address, like the fact that MACCs neglect non-climate benefits — such as air pollution reduction or increase in energy security —, or that they assess project or technological costs only, excluding institutional barriers, transaction costs and non-monetary costs (Kesicki and Ekins, 2012).

Our contribution is an investigation of how the information presented in a MACC could be used to decide which options to use — and in which order — to achieve a given abatement target. To do so, we characterize each option by their inertia, in addition to their cost and abating potential.[3]

3. Model description

A social planner controls GHG abatements from an emission baseline, by spending money on a set of options described by their cost and abatement potential. We do not incorporate more realistic but complex dynamics, such as sectoral interactions, crowding-out effect on investment, or learning-by-doing (del Rio Gonzalez, 2008; Kalkuhl et al., 2012). Instead, we only extend the MACC with information on how long it takes to implement each of the measures.

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 0.25 years. At each time step t, emissions are computed from the baseline emissions $E_{base}(t)$ and the abatement $a(i,t)$ achieved with each measure i at time t.

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

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:

$$M(0) = 0 \tag{2}$$

$$M(t) = E(t) \cdot \Delta t + M(t - \Delta t) \tag{3}$$

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[2] For a more comprehensive review of existing MACCs, see Kesicki (2012a).

[3] Note that time considerations are already included in the *building process* of the MACCs, and play an important role in assessing both the potential and the cost of each options (Kesicki, 2012a). However, the resulting MACC does not report any information on inertia, making it difficult to build optimal strategies from MACCs only. One conclusion will be that this information on time could be displayed along with information on costs and potentials nearby the MACCs to allow a debate on optimal implementation schedules of the presented mitigation options *using* these extended MACCs.

	Cost c \$/tCO$_2$	Abatement potential a_{max} MtCO$_2$/yr	Growth constraint α MtCO$_2$/yr^2	Implementation time a_{max}/α yr
Cheap	30	1 500	60	25
Deep	60	3 500	50	70

Table 1: Numerical assumptions

3.2. Potentials, costs and inertia

Abatements efforts in each sector are subject to two restrictions. First, each measure i has a maximum abating potential $a_{max}(i)$, expressed in avoided annual emissions, in MtCO$_2$/yr. For instance, switching to more efficient thermal engines for passenger vehicles may save a fraction of GHG emissions associated with private mobility, but not more. In MACCs, this potential is commonly represented by the width of the rectangles (see Fig. 1).

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

In the MACC, each measure i is qualified with a constant abatement cost $c(i)$ — the heights in Fig. 1. Here, we also assume that abatement costs are independent of cumulative abatements and time. Abatement $a(i,t)$ achieved thanks to measure i at time t has a cost $I(i,t)$ which reads:

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

So far, the model could be calibrated with data from a MACC. We add an explicit representation of economic inertia, in the form of a measure-specific constraint on implementation pace. A given amount of abatement requires a non-negative amount of time for its implementation. This is modeled as a maximum speed $\alpha(i)$, (in MtCO$_2$/yr per year), assumed to be independent of the financial cost of the option[4]: achievable abatements at time t directly depend on already achieved abatements at time $t - \Delta t$.

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

For simplicity, we assume that $\alpha(i)$ is constant and does not depend on the previously achieved abatements nor current time step t.

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 abatement would require as much time to be implemented as a small abatement (if achieved through the same measure). In our framework, in contrast, the required time lag is proportional to the amount of abatement.

These “costs in time” may come from any bottleneck, such as (i) availability of skilled workers, (ii) availability of productive capacities, (iii) incompressible institutional requirements, or other factors such as (iv) emissions embedded in long-lived capital. Issues (i) and (ii) could be overcome by training workers or redirecting unemployed workers and unused capital; but training and redirecting are measures *per se* and cannot be done overnight either. The issue of institutional or organizational delays is well documented (World Bank, 2010). Reducing them is also a measure *per se*, and takes time. The last point is related to capital vintages and turnover: if one sees emissions as embedded in capital (Davis et al., 2010), decarbonization cannot be faster than capital turnover, except by wasting valuable productive capital through premature replacement (Lecocq et al., 1998).

The value of α for a given measure can be assessed from available data. For instance, if cars are typically scrapped 12 years after they are manufactured, switching from conventional cars to plug-in hybrids would

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[4] Note that abatement is expressed in MtCO$_2$/yr.

take at least 12 years. Taking into account slow technological diffusion (Guivarch and Hallegatte, 2011) — sales are not likely to switch overnight from 100% conventional cars to 100% plug-in hybrid cars —, it can take as long as 30 years (IEA, 2009a). This full implementation time T_f is linked to the abatement potentials a_{max} and the maximum speed α:

$$T_f(i) = \frac{a_{max}(i)}{\alpha(i)} \tag{7}$$

3.3. *Social planner objectives*

The objective 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:

$$C = \sum_{t=0}^{T} \sum_{i=1}^{N} \frac{I(i,t)}{(1+\rho)^{t \cdot \Delta t}} \tag{8}$$

Theoretically, the social planner could control GHG emissions in order to equalize the marginal costs of mitigation and adaptation in a cost-benefit approach. Because of uncertainty surrounding both climate response to a change in GHG emissions and adaptation costs, and because decisions are made at national instead of global scale, 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 carbon budget M_{obj}.

$$M(t) \leq M_{obj} \tag{9}$$

Cumulative emissions over a long period can be used as proxies for climate change (Matthews et al., 2009). In practice, however, governments and other public agencies frequently provide objectives for given points in time. For instance, the EU has the objective of cutting its emissions by 20 % of 1990 levels by 2020.[5]

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

$$E(t_m) \leq E_m^{obj} \tag{10}$$

3.4. *Numerical values*

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

In the absence of reliable data, we assume that it takes 70 years to implement the whole potential of *deep*, while *cheap* only requires 25 years. Applying Eq. 7 gives values for α of respectively 50 $MtCO_2/yr^2$ and 60 $MtCO_2/yr^2$. We also use a discount rate $\rho = 5\%/yr$. These values are not meant to represent accurately concrete sectors of the economy, even though they do not differ much from the two sectors modeled by Lecocq et al. (1998). 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 also uses Scilab (Scilab Consortium, 2011). Code and data are available on the corresponding author's web page.

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[5] It is also common to adopt intensity objectives, as the efficiency standards in the auto industry. Our model may be used with existing intensity MACCs (IEA, 2009b, p. 37).

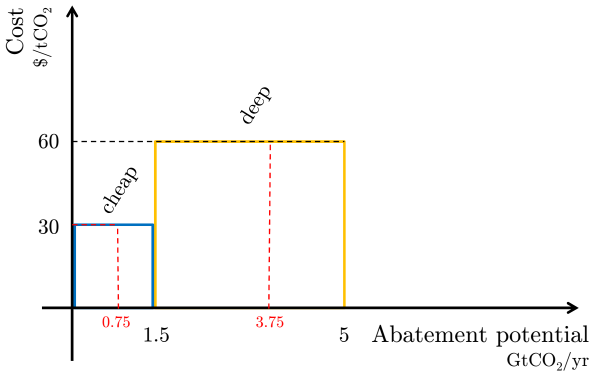

Figure 2: The MACC used in our experiments. We find that the long-term target of 3.75 $GtCO_2$/yr should not be achieved by implementing first *cheap* and then *deep*. We also find that a short-term abatement target of 750 $MtCO_2$/yr should not be achieved implementing just *cheap*.

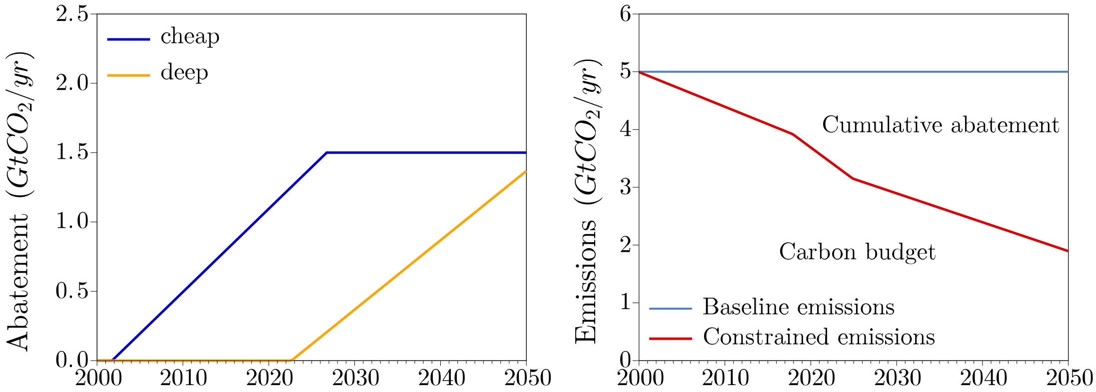

Figure 3: Left: Optimal abatement strategy to limit cumulative emissions below 175 $GtCO_2$ between 2000 and 2050. Because of inertia and discounting, *deep* has to enter before the potential of *cheap* has been exhausted. Right: curves represent emissions in the baseline and in the constrained simulation; in-between areas represent the cumulative abatement and the carbon budget in the constrained simulation.

4. Optimal implementation schedule to cope with a carbon budget

In this section, we investigate the optimal abatement pathway when using a carbon budget, i.e. with full flexibility on when to reduce emissions. This is implemented in our model by excluding Eq. 10, and including Eq. 9. We then test a range of carbon budgets (M_{obj}), and assess the consequence on the optimal reduction pathway.

4.1. Using expensive options before exhausting the potential of cheap ones

Figure 3 shows the optimal strategy for maintaining cumulative emission below 175 $GtCO_2$ over the 2000-2050 period.[6] This value is used for illustrative purpose, and will allow us to make some comparisons with subsequent simulations (in Section 5).

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[6] Cumulative emissions in the baseline amount to 5 Gt/yr during 51 years, with a total of 255 Gt. The carbon budget thus amounts to 69% of cumulative emisions.

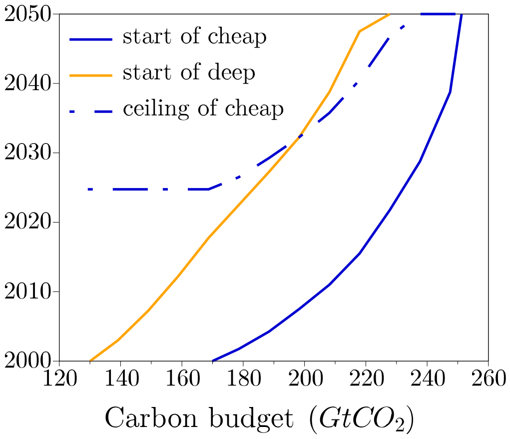

Figure 4: Entry date and ceiling date of each abatement measure as a function of the carbon budget. "Start of deep/cheap" is the date when the respective measure begins to be implemented; the ceiling date is the date when the abating potential is exhausted.

The abatement paths (figure 3, left panel) have triangular or trapezoidal shapes; this shows that one of the inertia (Eq. 6) or maximum potential (Eq. 4) constraint is always binding. The cumulative abatement corresponds to the area between baseline emissions and emissions in the constrained run (figure 3, right panel). In this case, the intuitive ranking of abatement measures is respected: the social planner starts by implementing *cheap* before *deep*. However, she does not use the whole potential of *cheap* before starting using *deep*. *Deep* enters in 2023 while *cheap* does not reach its full potential before 2027. A more stringent objective would force *deep* to start even earlier (see below).

The optimal implementation strategy does not follow a merit order in which the whole potential of the cheapest solutions is used before more expensive solutions are introduced.

A more systematic analysis using a range of carbon budgets (Fig. 4) confirms that for any objective it is never preferable to implement the expensive *deep* before *cheap*. It also shows that if the objective is stringent enough (about 195 $GtCO_2$), *deep* has to begin before the whole potential of *cheap* has been exploited — the implementation is not sequential. And if the carbon budget is even more stringent (about 130 $GtCO_2$), *deep* is forced to start in 2000, at the same time as *cheap*.

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

Let us analyze a case in which the carbon budget is not very stringent, e.g. 210 $GtCO_2$. This translates into cumulative abatements of 45 $GtCO_2$ over the period.[7] *Cheap* has a cumulative abatement potential of more than 55 $GtCO_2$.[8] It is then possible to achieve the abatement objective by implementing only *cheap*. An intuitive strategy could be to focus on *cheap* and to not implement *deep*. Our simulation 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 later and reach the objective in spite of the delayed action.

In our simulations (Fig. 4), the optimal strategy to meet a (lax) 210 $GtCO_2$ carbon budget is to implement *deep* from year 2040, which makes it possible not to implement *cheap* before 2011 (for a strategy starting in 2000). The additional cost of using *deep* is more than compensated by the delay on implementing *cheap*. In

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

[8] Its annual abatement potential is 1.5 Gt/yr and takes 25 years to implement in full (see Tab. 1); adding the cumulated potential during the take-off phase (25 yr × 1.5 Gt/yr)/2 and the potential when annual abatements have reached their maximum value 25 yr×1.5 Gt/yr gives a total of 56.25 Gt.

other words, the optimal strategy uses an expensive measure even when a cheaper measure appears sufficient to fulfill the objective.

Policymakers and the public should be informed of abatement potentials and costs, and MAC curves provide this information. But they also need to be informed on the duration of the implementation process of these measures. MACC providers could enhance their reporting with this information.

5. Optimal abatement pathways with emission targets

Commitments in terms of carbon budget are difficult to enforce: there is an incentive for decision-makers to delay investments and efforts beyond their mandate. Alternative policies include the definition of emission targets at one or several points in time. Short-term targets can be enforced with tradable emissions permits, such as the EU ETS system. In the next two sections, we assume that commitments are made in terms of abatement levels at different points in time.

Cumulative-emissions constraint (Eq. 9) is thus excluded from the model, we include the emission constraint with a single milestone ($m \in \{1\}$, $t_1 = 2050$) and we test various emission objectives (E_1^{obj} in Eq. 10). In absence of inertia — i.e. an infinite α in Eq. 6 — the optimal response to an emission objective would be to remain on the baseline emissions pathway from 2001 to 2049, and to implement abatement options in 2050 only.[9] We find that with inertia — i.e., with a finite α in Eq. 6 — the shape of the optimal mitigation strategy depends on the stringency of the emission target.

5.1. Implementing expensive options before cheap ones

Figure 5 shows the optimal abatement pathway for achieving an ambitious reduction of 75% of emissions in 2050. In this case, the optimal strategy is to start by implementing the most expensive option before the cheapest (i.e., *deep* before *cheap*).

Indeed, the emission objective translates into abatements by 3.75 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 60 MtCO$_2$/yr^2, it has to enter in 2026. Then 2.25 GtCO$_2$/yr remain to be abated with *deep* by 2050. To do so, *deep* has to enter as soon as 2006, 20 years before *cheap*.

The 75% reduction in emissions leads to cumulative emissions of 175 GtCO$_2$, and is thus comparable to the simulation proposed in Section 4.1.[10] Compared to the carbon budget simulation (CB), this simulation with emission targets (ET) leads to start *cheap* later and *deep* sooner. Short-term abatements are lower — in 2020, they amount to 750 MtCO$_2$/yr in ET, against 1.3 GtCO$_2$/yr in CB — but long-term abatements are higher.

The loss of when-flexibility eventually raises the present cost of abatements, from 390 G$ in the CB case to 630 G$ in the ET simulation for the same final cumulative emissions.[11] This illustrates the fact that, compared to emission objectives, carbon budgets with full when-flexibility allow the social planner to reach the same climate target at lower cost.

A more systematic analysis is presented in Fig. 6. It gives the optimal entry dates of both measures (*cheap* and *deep*), as a function of the 2050 emission target. It shows that below a threshold emission target, the optimal strategy starts to implement the expensive, inert and high abating potential measure before the cheap one. In our example, this happens when the emission target is lower than 2.25 GtCO$_2$/yr — i.e. when the abatement objective is higher than 2.75 GtCO$_2$/yr.

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[9] One could say that this would be done by starting with the cheapest measure and continuing with the more expensive one until the emission objective is achieved. In this context, however, the terms “starting” and “continuing” would not have a chronological meaning, as the abatement measures would both be implemented 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*.

[10] Since cumulative emissions are good proxies for climate change, both simulations would lead to comparable climate change impacts.

[11] In other words, 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 aggregate emission target in 2050.

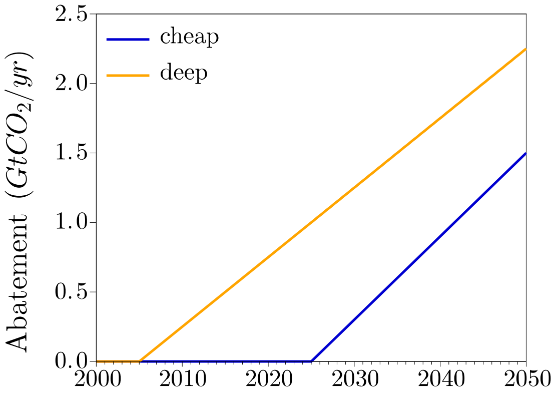


Figure 5: Optimal abatement pathways to achieve ambitious abatements (3.75 $GtCO_2$/yr) in 2050. The expensive option with large abatement potential is implemented before the cheaper option.

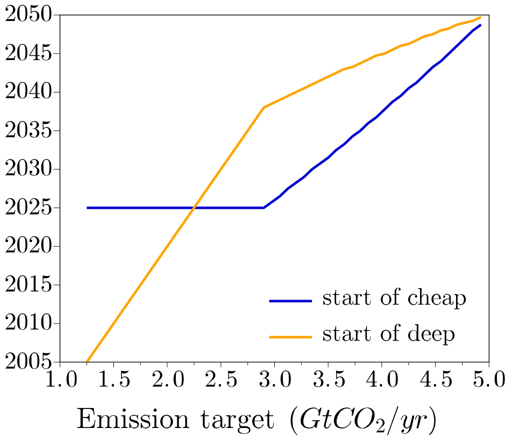
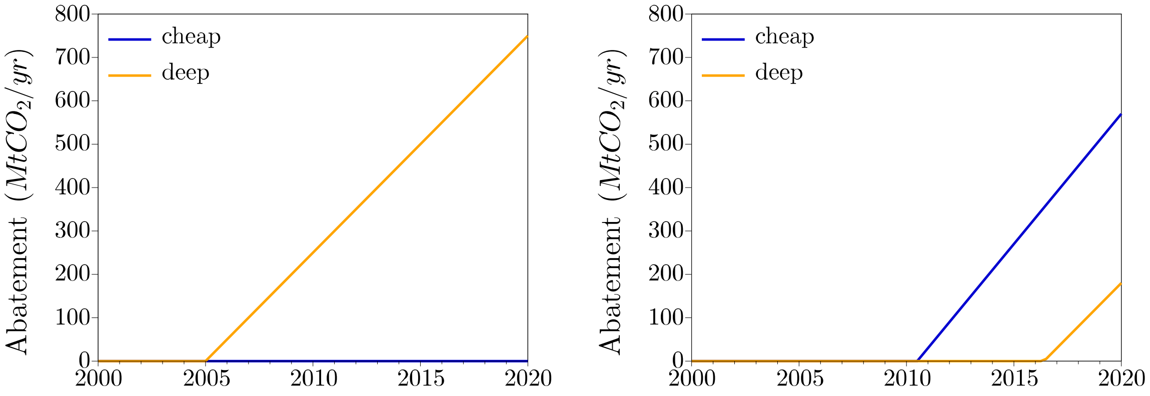


Figure 6: Entry date of each measure as a function of emission objective for 2050. For ambitious emission targets (below 2.25 $GtCO_2$/yr), the expensive option with large abatement potential is implemented before the cheaper option.



a. Short-term and Long-term objs. *b.* Short-term Only

Figure 7: Comparison of optimal abatement strategies to reach the same target for 2020, taking into account or disregarding the longer-term 2050 objective (respectively S&L and SO). With an ambitious long-term target, the short-term strategy is based on the more expensive option with higher abatement potential, not on the cheapest option.

The fact that, with emission targets, expensive options may have to be implemented before cheap ones illustrates that, in presence of inertia, marginal abatement costs should not necessarily be equal across sectors (Vogt-Schilb et al., 2012). It also poses a practical problem. Considering the difficulty 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. 5 shows that this measure should be implemented as early as 2005 to reach the stringent objective (emissions of 750 MtCO$_2$/yr in 2050) at the lowest possible cost. But this high carbon price would also trigger the implementation of *cheap* (because its abatement cost, 30 \$/tCO$_2$, is lower than the signal) in 2005, i.e. too soon, leading to a suboptimal abatement pathway.

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

Actual policies include shorter-term emission objectives, such as the EU target to abate emissions 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 they are only a milestone toward a more ambitious climate target in the long run, as the -75% by 2050 objective in Europe.

In this section, we find that it is dangerous to use only information on costs and abating potential to decide which measures to implement in order to achieve the intermediate target, because it can make the long term target impossible to reach.

We compare two simulations. The first simulation, labeled SO (Short-term Only), has a short-term constraint for 2020, but no long-term constraint:

$$E_1^{obj} = E(2020) = 4.25 \text{ GtCO}_2/\text{yr} \tag{11}$$

The second simulation, S&L (Short-term and Long-term objectives), has the same short-term target for 2020, and a longer-term constraint: a reduction by 75% of GHG emissions in 2050. In this simulation, there are thus two emission milestones (see Eq. 10):

$$E_2^{obj} = E(2050) = 1.25 \text{ GtCO}_2/\text{yr} \tag{12}$$

$$E_1^{obj} = E(2020) = 4.25 \text{ GtCO}_2/\text{yr} \tag{13}$$

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. We find that long-term objectives impact strongly the short-term strategy.

Figure 7 compares the optimal abatement strategies from 2000 to 2020 in the two cases. With both the 2020 and the 2050 objectives (simulation S&L, panel *a.*), the social planner starts by 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 social planner starts abating later (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 abatement in $MtCO_2$ is the same.

If the 2050 target is not taken into account before 2020, it may then appear extremely costly or even impossible to achieve. In this illustrative example, the 75% reduction in emissions becomes indeed impossible to achieve in 2050 in this case.[12]

Despite short-term aggregate emissions being abated to the same level in SO as in S&L by 2020, the Short-term Only (SO) strategy produces a lock-in in a carbon intensive pathway that cannot be reversed in the second period. In other words, the optimal strategy to reach the 2020 target is different (it uses more expensive options) if the 2050 objective is included in the optimization. With an ambitious long-term objective, the short-term target needs to be achieved implementing the options with the largest potentials and the greatest inertia, not with the cheapest solutions.

6. Conclusion

This paper investigates the use of measure-explicit MAC curves to design optimal abatement strategies taking inertia into account. Inertia is modeled as a maximum amount of abatement that can be achieved over a given period of time with a given measure from a MACC. This maximum implementation speed complements the cost and abating potential already provided by existing MACCs. It has a large influence on the optimal schedule of the various abatement measures.

In particular, optimal abatement strategies may (i) implement expensive options before the whole potential of cheaper measures has been exploited; (ii) use expensive options even when cheap ones appear sufficient to meet the climate target; or (iii) start to implement expensive options before cheap ones. If the climate objective is stringent and their inertia is large enough, the optimal strategy would be to start implementing at the same time a set of measures covering a wide range of abatement costs.

These results confirm the need to account for specific inertia when designing climate policies. Transforming climate objectives into emissions pathways cannot be done with aggregate 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; Vogt-Schilb et al., 2012).

This has some implication for current mitigation policies. In the European Union, there is currently a debate on whether aggregate GHG emissions should be abated by 20% or 30% in the short-term (i.e. 2020). This question on when to abate GHG emissions cannot be separated from the question on how these abatements have to be done (i.e., in which sector and with which measures). Economic actors might otherwise focus on cheap and fast-to-implement solutions to reach the short-term target, neglecting high-potential but high-inertia options which may be required to meet an ambitious objective in 2050. For this reason, the optimal approach to achieve a given abatement target at one point in time may not be to set a carbon price and introduce all the abatement options that show an abatement cost below this carbon price. It may be preferable to use additional policies, targeted at high-potential but long-to-implement options, such as urban planing or deployment of low-carbon technologies.

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[12] *Cheap* has entered in 2006. It would reach its full potential (1.5 Gt/yr) in 2030. If *deep* enters in 2021, it would also reach abatements of 1.5 Gt/yr in 2050, 30 years after (30 yr × 50 $MtCO_2$/yr). The total would be abatements of 3 Gt/yr in 2050, when the target is 3.75 Gt/yr.

There is of course a balance to maintain (Azar and Sandén, 2011): 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 (this is for instance the case of existing fuel economy standards in the auto industry). Because of information asymmetry and the risk of rent-seeking behavior, micro-managing mitigation by defining over-targeted objectives can be counter-productive (Laffont, 1999). Also, objectives need to be updated when new information is available (Rodrik, 2008); for instance if one measure turns out to be more expensive, or turns out to save less GHG, than expected. Finally, if these sectoral policies overlap, they may come with additional costs that should be analyzed carefully (Braathen, 2007; Böhringer and Rosendahl, 2010; Fischer and Preonas, 2010) and taken into account.

Our results are still theoretical, based on illustrative examples. We propose that MAC providers enhance their reporting to the decision-makers and the public, supplying also an assessment of the implementation speed of each option. With this information, the simple model proposed in this paper could be used to assess the optimal implementation schedule of the various existing abating options. Short-term sectoral or technological targets (e.g for 2020 or 2030) could then be derived from these pathways. This process would provide figures to debate new or existing sectoral policies, such as the objective of 20% of renewable energies in 2020, the fuel economy standards in the auto industry, or proposed changes in land-use planning, building norms and infrastructure design.

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