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Summary

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Keywords: Climate Change Mitigation, Dynamic Efficiency; Inertia, Sectoral Policies

JEL Classification: L98, Q48, Q54, Q58

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Marginal abatement cost curves and the optimal timing of mitigation measures

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Abstract

Decision makers facing abatement targets need to decide which abatement measures to implement, and in which order. Measure-explicit marginal abatement cost curves depict the cost and abating potential of available mitigation options. Using a simple intertemporal optimization model, we demonstrate why this information is not sufficient to design emission reduction strategies. Because the measures required to achieve ambitious emission reductions cannot be implemented overnight, the optimal strategy to reach a short-term target depends on longer-term targets. For instance, the best strategy to achieve European's -20% by 2020 target may be to implement some expensive, high-potential, and long-to-implement options required to meet the -75% by 2050 target. Using just the cheapest abatement options to reach the 2020 target can create a carbon-intensive lock-in and make the 2050 target too expensive to reach. Designing mitigation policies requires information on the speed at which various measures to curb greenhouse gas emissions can be implemented, in addition to the information on the costs and potential of such measures provided by marginal abatement cost curves.

Highlights

► Classification of existing Marginal Abatement Cost Curves (MACC) ► MACCs do not provide separated data on the speed at which measures can be implemented ► Optimal measures to reach a short-term target depend on longer-term targets ► Unique carbon price or aggregated emission-reduction target may be insufficient ► Room for short-term sectoral policies if agents are myopic or governments cannot commit

Keywords: climate change mitigation; dynamic efficiency; inertia; sectoral policies

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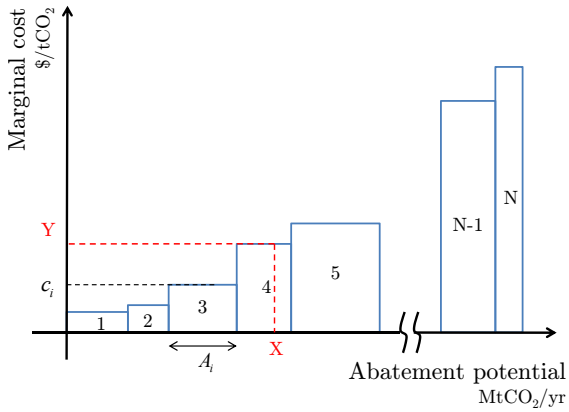


Figure 1: A measure-explicit MAC curve exhibits abatement options $i = 1..N$ characterized by their maximum potential A_i and their abatement cost c_i, ranked from the least to the most expensive. This curves stands for a given date T. We explain why the optimal mitigation strategy to reach a target X at T is not to implement exclusively the measures 1..4 cheaper than Y.

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 in many ways, including through measure-explicit 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. Measures include changing technologies, notably in the transport, housing and power sectors, but also non-technological options such as waste recycling and management of land use and forest. These MACCs are usually constructed for a specific country or region, and for a specific date. They report abatement potentials as a function of the abatement cost, ranking mitigation options from the least to the most expensive (Fig. 1).

Decision makers who face an emission-reduction target need to decide which abatement options to implement, and following which schedule. They can interpret measure-explicit MAC curves as being abatement supply curves. According to this interpretation, the optimal behavior to meet an abatement target (e.g, bringing back GHG emissions at their 1990 level by 2020) is to build a MAC curve for this date, and implement only the cheapest options that allow the target to be met (e.g., DECC, 2011, Fig 17, p. 52).

In this paper, we explain why decision makers need to distinguish available abatement measures using their costs, abating potential, and the time it takes to implement them. Indeed, the high-abating potential options required to meet ambitious emission-reduction targets cannot be implemented overnight. Therefore, the optimal set of measures to reach a short-term target depends on the measures required to meet longer-term targets and on the speed at which these measures can take effect.

We thus propose a new way for reporting information on emission-reduction

options to the general public and decision-makers. Reports could display assessments of the cost of each option, the abating potential or carbon intensity of each option, and the speed at which each option can be implemented – taking into account the required accumulation of human and physical capital. While some MACCs factor in all this information, none provides data on these three dimensions separately.

We first contribute a classification of existing MAC curves (Section 2). Then, we build a simple model that can compute the optimal timing of GHG emissions reductions (choice across time) along with the optimal dispatch of the reduction burden (choice across abatement measures) from this three dimensions (Section 3). We use it in Section 4 with an objective in terms of cumulative emissions over a long period, a so-called *carbon budget*, reportedly a good proxy for climate change. We show that it make sense to implement the more expensive options before exhausting the whole potential of the cheapest options. We turn in Section 5 to objectives expressed in terms of aggregate abatement at one point in time, closer to the actual practices. In that case, it can be preferable to start implementing the most expensive options before cheap ones, if their potential is large and their inertia is great (Section 5.1). Finally, we explain in Section 5.2 how the optimal short-term strategy depends on the long-term emission objective. This means that MACCs should not be used as supply curves when choosing the optimal strategy to reach short-term emission targets.

2. Overview of existing marginal abatement cost curves

The term "MAC curve" refers in the literature to various curves, constructed in various ways. Here, we distinguish *continuous* MAC curves and *measure-explicit* MAC curves. We then distinguish *full-potential* measure-explicit MACCs and *achievable-potential* measure-explicit MACCs.

2.1. Continuous vs. measure-explicit MAC curves

Continuous MAC curves depict the aggregate shadow cost of an emission target against the stringency of this target. They do not depict particular mitigation measures. The existing literature builds this type of MACCs from Integrated Assessment Models (IAM). It has for instance emphasized that the cost of reducing GHG emissions inside an economy depends on external factors such as energy prices or climate policies decided abroad (Klepper and Peterson, 2006; Kuik et al., 2009; Morris et al., 2011).

In this paper we take the perspective of a decision maker who faces an exogenous abatement target and needs to decide which emission-reduction options to implement, and in which order. Continuous MACCs are out of the scope of this paper. We focus on measure-explicit MAC curves that represent information on abatement costs and potentials for a set of mitigation measures (Fig. 1).

Measure-explicit MACCs have recently reached a wide public, when McKinsey and Company published an assessment of the cost and potentials in the United States (Enkvist et al., 2007) and at the global scale (McKinsey, 2009). These curves are increasingly used to inform policymakers: among others, McKinsey currently lists 15 MAC curves in its website, the World Bank has assessed reduction potentials in many countries in the form of MACCs (ESMAP, 2012), and Sweeney and Weyant (2008) have proposed such a MACC for California.

Their usage goes beyond climate mitigation: for instance, similar depictions have been used to describe available options to reduce energy consumption (e.g., Jackson, 1991), waste production (Beaumont and Tinch, 2004) and water consumption (McKinsey, 2009).

Recent research has identified – and proposed solutions for – methodological issues when *building* measure-explicit MAC curves (Kesicki and Ekins, 2012); this has allowed to enhance the reporting of abatement costs and potentials. A first issue relates to uncertainty when assessing future costs – it can be addressed by presenting ranges of costs and potentials instead of best-guest estimates (IPCC, 2007, SPM6 p.11). A second issue is that MACCs do not depict 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), even if they are built taking these interactions into account (Kesicki, 2012b). Kesicki and Ekins (2012) identify other shortcomings, like the fact that MACCs frequently assess project or technological costs only, excluding institutional barriers, transaction costs and non-monetary costs.

In contrast, we focus in this paper on how to *use* MAC curves, that is on how they can help to design optimal emission-reduction strategies.

2.2. Full potential vs. achievable potential measure-explicit MAC curves

While similar in appearance, two types of measure-explicit MAC curves should be distinguished, depending on their implicit definition of the abating potential of a measure.

The *full-potential* approach gives an information on how much GHG could be saved if the measure was used at his technical maximum. It is calculated against a reference or baseline technology, taking into account the carbon intensity and imperfect substitutability of different technologies. For instance, this approach takes into account that an Electric Vehicle (EV) does not emit any GHG (e.g. saves 140 gCO_2/km compared to the average new vehicle sold in Europe in 2010) but that all passenger vehicles cannot be replaced by EVs due to limited driving range. This approach does not take into account any dynamic aspect.

Among others, Rubin et al. (1992) used this approach. For instance, they assess the potential of nuclear power (in the US) as the quantity of GHG that would be saved if nuclear replaced *all* the fossil fuel capacity that was used for base load and intermediate load operation in 1989, and find 1 500 $MtCO_2$/yr. (Table 3, footnote j). More recently, Wächter (2013) built a MAC curve for Austria based on the same approach, using 2008 data.

We call the other approach the *achievable-potential* approach. It seems to have been popularized by McKinsey. Achievable-potential measure-explicit MAC curves have a prospective dimension, as they are built for a date in the future. This approach takes into account that large-scale diffusion of new technologies can take up to decades (Grübler et al., 1999). In this context, the abating potential of a technology assesses the abatement that could be achieved with such a technology if it was implemented at a given speed (McKinsey, 2009, Exhibit 1). For instance, this approach takes into account that even ambitious fiscal incentives in favor of electric vehicles would induce a limited increase of EV sales, resulting in a limited share of EVs by 2020 or 2030. The achievable-potential by a given date mixes the information on the full potential and the

slow diffusion process, and is therefore lower than the full potential described above.

A MACC built this way is the one by Sweeney and Weyant (2008): they find for instance that solar photovoltaic power can only save 0.8 $MtCO_2$/yr in California by 2020. They also distinguish the abating potential of industrial combined heat and power achievable thanks to price incentives and the potential that can be reached after an "aggressive growth" (Table 11 page 50). As IAMs account for slow technological diffusion (Wilson et al., 2013), they can be used to produce achievable-potential measure-explicit MACCs. One example is the MACC built by Kesicki (2012a) for the UK transport sector by 2030.

In the following we show the value of combining the two approaches, i.e. how the full-potential and the implementation speed, reported separately, can be used to decide which options to implement, and in which order, to comply with exogenous emission targets. We propose a methodology to do so, based on three information pieces per measure – its cost, full potential, and implementation speed – and a simple intertemporal optimization model.

3. Model

A social planner controls GHG abatements from an emission baseline, by spending money and time on a set of options described by their cost, full abatement potential, and implementation speed. We do not incorporate more realistic but complex dynamics, such as sectoral interactions or crowding-out effects on investment.

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 3 months. At each time step t, emissions are computed from the baseline emissions E_t^{ref} and the abatement $a_{i,t}$ achieved with each measure i at time t.

$$e_t = E_t^{ref} - \sum_{i=1}^{N} a_{i,t} \tag{1}$$

We assume constant baseline emissions, that is $E_t^{ref} = 5\,GtCO_2$/yr. The cumulative emissions M_t are then computed as the sum of emissions:

$$M_t = e_t \cdot \Delta t + M_{t-\Delta t} \tag{2}$$

3.2. Potentials, costs and inertia

Each measure is described by three figures. First, each measure i has a maximum abating potential A_i, expressed in avoided annual emissions, in $MtCO_2$/yr. For instance, switching to more efficient thermal engines for passenger vehicles may not save more than a fraction of GHG emissions associated with private mobility. In *full-potential measure-explicit* MACCs, this potential is represented by the width of the rectangles (see Fig. 1).

$$a_{i,t} \leq A_i \tag{3}$$

Second, 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:

$$I_{i,t} = a_{i,t} \cdot c_i \tag{4}$$

Third, a given amount of abatement requires a non-negative amount of time for its implementation. This is modeled as a constant maximum speed v_i, (in $MtCO_2/yr/yr$), assumed to be independent of the financial cost of the measure[2]: achievable abatements at time t directly depend on already achieved abatements at time $t - \Delta t$.

$$a_{i,t} \leq a_{i,t-\Delta t} + v_i \cdot \Delta t \tag{5}$$

These growth constraints may come from any bottleneck such as (i) availability of skilled workers, (ii) availability of productive capacities, (iii) incompressible institutional requirements, (iv) emissions being embedded in long-lived capital, or (v) requirement for knowledge accumulation before technologies spread.

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 and International Finance Corporation, 2013). Reducing them is also a measure *per se*, and takes time. The fourth 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 premature replacement (Lecocq et al., 1998; Lecuyer and Vogt-Schilb, 2013). Concerning (v), Mansfield (1998), and Agarwal and Bayus (2002) have found that research and development is typically carried out from several years to few decades before new technologies experience market uptake.

As noted in section 2.2, MAC curves built for a date in the future T frequently provide an achievable potential, not a full potential. In our framework, the achievable potential $\tilde{A}_i$ is linked to the full potential A_i and the implementation speed v_i :

$$\tilde{A}_i = \min\left(v_i \cdot T, A_i\right) \tag{6}$$

We can also define the implementation time as A_i/v_i, the ratio of the abatement potentials over the maximum speed.

3.3. Social planner objectives

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

$$C = \sum_{t=T_0}^{T} \sum_{i=1}^{N} \frac{I_{i,t}}{(1+r)^{t \cdot \Delta t}} \tag{7}$$

[2] Note that abatement is expressed in $MtCO_2/yr$.

			Cheap	Deep
Marginal Abatement Cost	c	$/tCO$_2$	30	60
Full potential	A	GtCO$_2$/yr	1.5	3.5
Speed	v	MtCO$_2$/yr^2	60	50

Table 1: Numerical assumptions

Theoretically, a benevolent social planner can 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_t to remain below a given carbon budget M_{obj}.

$$M_t \leq M_{obj} \tag{8}$$

Cumulative emissions can be used as proxies for climate change (Allen et al., 2009; 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.[3] In our model, these objectives can be implemented by defining a set of milestones indexed by m, and by constraining emissions at each milestone:

$$e_{t_m} \leq E_m^{obj} \tag{9}$$

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 (Fig. 6). *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 hydrogen.

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. They lead to values for v of respectively 50 MtCO$_2$/yr^2 and 60 MtCO$_2$/yr^2. We use $r = 5\%$/yr as the discount rate. 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

[3] 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, 2009, p. 37).

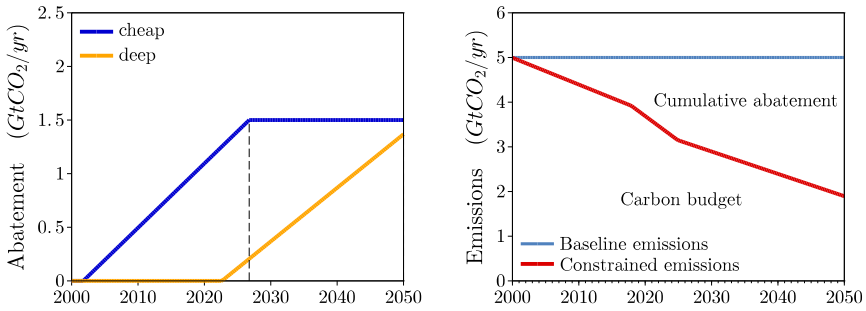


Figure 2: Left: Optimal abatement strategy to limit cumulative emissions below 175 $GtCO_2$ between 2000 and 2050. Inertia and discounting mean that *deep* has to enter before the potential of *cheap* has been exhausted. Right: curves represent emissions in the baseline and in the constrained simulation; in-between areas represent the cumulative abatement and the carbon budget in the constrained simulation.

page. Results may be verified using the spreadsheet model provided on the corresponding author's web page.

4. Optimal schedule under a cumulative 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 (Eq. 8). We 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 2 shows the optimal strategy for maintaining cumulative emission below 175 $GtCO_2$ over the 2000-2050 period.[4] This value is used for illustrative purpose, and will allow us to make some comparisons with subsequent simulations (in Section 5).

The abatement paths (figure 2, left panel) have triangular or trapezoidal shapes; this shows that one of the inertia (Eq. 5) or maximum potential (Eq. 3) constraint is always binding. The cumulative abatement corresponds to the area between baseline emissions and emissions in the constrained run (figure 2, 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. 3) confirms that for any objective it is never preferable to implement the expensive *deep*

[4] 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.

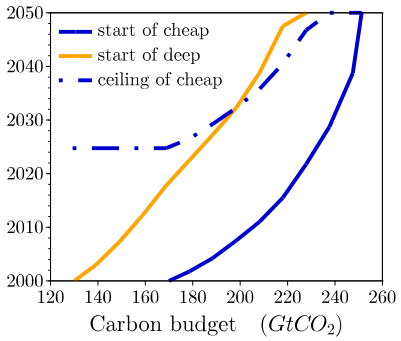


Figure 3: Entry date and ceiling date of each abatement measure as a function of the carbon budget. Lower carbon budgets, on the left, correspond to tighter climate objectives and require more abatement. *Start of deep/cheap* is the date when the respective measure begins to be implemented; the *ceiling date* is the date when the abating potential is exhausted.

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.[5] *Cheap* has a cumulative abatement potential of more than 55 $GtCO_2$.[6] 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 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 later and reach the objective in spite of the delayed action.

In our simulations (Fig. 3), 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 other words, the optimal strategy uses an expensive measure even when a cheaper measure is sufficient to reach the objective.

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

[6] Its annual abatement potential is 1.5 Gt/yr and takes 25 years to implement in full (see Fig. 6); 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.

5. Optimal abatement pathways with annual 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. In the next two sections, we assume that commitments are made in terms of abatement levels at different points in time.

The cumulative-emissions constraint (Eq. 8) is thus excluded from the model, and we include the emission constraint with a single milestone ($m \in \{1\}$, $t_1 = 2050$). We test various emission objectives (E_1^{obj} in Eq. 9). In absence of inertia — i.e. with an infinite v — the optimal response to an emission objective would be to remain on the baseline emissions pathway from 2001 to 2049, and wait 2050 to implement abatement. We find that with inertia — i.e., with a finite v in Eq. 5 — the shape of the optimal mitigation strategy depends on the stringency of the emission target.

5.1. Implementing expensive options before cheap ones

Figure 4 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* starts 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.[7] Compared to the carbon-budget simulation, this emission-targets simulation leads to start *cheap* later and *deep* sooner. Short-term abatements are lower — in 2020, they amount to 750 $MtCO_2/yr$ under an emission target, against 1.3 $GtCO_2/yr$ under a carbon budget — but long-term abatements are higher.

The loss of when-flexibility eventually raises the present cost of abatements, from 390 G$ to 630 G$ when the carbon budget is replaced by an emission target.[8] Compared to emission objectives, carbon budgets are more flexible and allow the social planner to reach the same climate target at lower cost.

A more systematic analysis is presented in Fig. 5. 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

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

[8] 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.

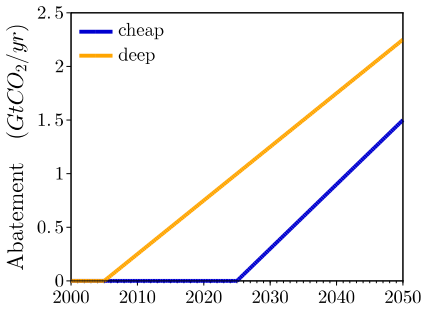


Figure 4: Optimal abatement pathways to achieve ambitious abatements (3.75 $GtCO_2$/yr) in 2050. The expensive option with large abatement potential is implemented before the cheaper option.

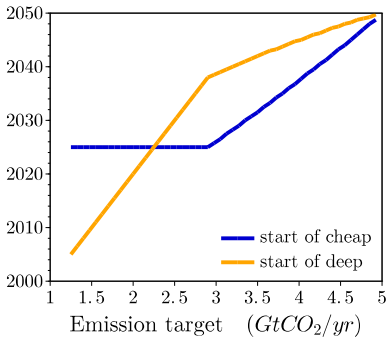
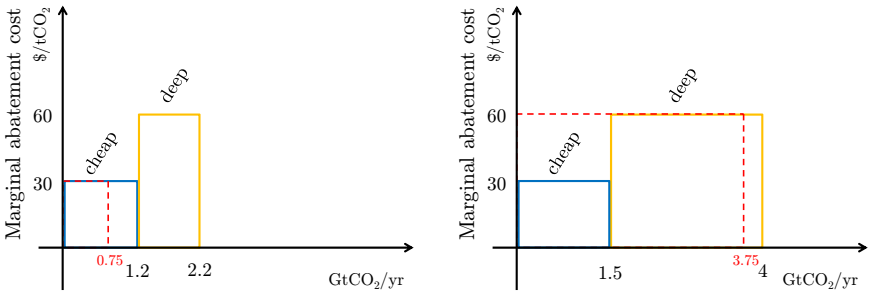


Figure 5: Entry date of each measure as a function of emission objective for 2050. For ambitious emission targets (below 2.25 $GtCO_2$/yr), the expensive option with large abatement potential is implemented before the cheaper option.

lower than 2.25 $GtCO_2$/yr — i.e. when the abatement objective is higher than 2.75 $GtCO_2$/yr.

The fact that, with emission targets, expensive options may have to be implemented before cheap ones illustrates the finding by Vogt-Schilb et al. (2013): in presence of inertia, the equimarginal principle does not mean that efforts to reduce emissions should be equal to the carbon price at each point in time.

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 may not rely on long-term prices. If actors consider only the current carbon price, then a carbon price of 60 $\$/tCO_2$ would be necessary in 2006 to trigger the entry of *deep* (Fig. 4). 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 2006, i.e. too soon, leading to a suboptimal abatement pathway.



(a) Abatement potential by 2020 **(b)** Abatement potential by 2050

			Cheap	Deep
Time Horizon	t_1	yr	20	
Achievable potential	$\tilde{A}$	$GtCO_2/yr$	1.2	1.0
Time Horizon	t_2	yr	50	
Achievable potential	$\tilde{A}$	$GtCO_2/yr$	1.5	2.5

Figure 6: MACCs derived from our numerical values, using the achievable-potential approach. We explain why the 2020 target should not be reached by implementing only *cheap*.

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. They are milestones 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 achievable potential to decide which measures to implement in order to achieve an intermediate target (Fig 6), 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:

$$E_1^{obj} = E(2020) = 4.25\,GtCO_2/yr \tag{10}$$

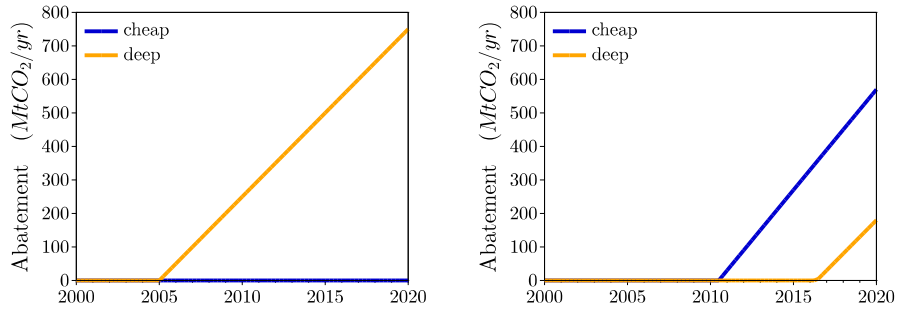
The second simulation, S&L (Short-term and Long-term objectives), has the same short-term target for 2020, and a longer-term constraint: a reduction by 75% of GHG emissions in 2050. In this simulation, there are thus two emission milestones (see Eq. 9):

$$E_1^{obj} = E(2020) = 4.25\,GtCO_2/yr \tag{11}$$

$$E_2^{obj} = E(2050) = 1.25\,GtCO_2/yr \tag{12}$$

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. 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,



(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.

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 was 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.[9]

Despite short-term aggregate emissions being reduced to the same level in SO and 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 it's a milestone to a 2050 target than if it is the ultimate target. 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.

In the previous subsection, we concluded that a unique price instrument may not be the best approach to trigger the right investments in emission-reduction measures, provided that actors may not rely on long-term signals. The same warning applies to aggregate emission targets.

Short-term targets are *a priori* relevant, because there is visibility over the

[9] *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 $\times$ 50 $MtCO_2$/yr). The total would be abatements of 3 Gt/yr in 2050, when the target is 3.75 Gt/yr.

short term on technology availability, macroeconomics trends and institutional frameworks. For instance, they can be enforced with tradable emissions permits, such as the EU ETS system. However, if decision makers omit the longer-term target when deciding which measures can be implemented to reach the short-term target, they will focus on the cheapest available options (Fig. 6a and 7b).

It is therefore a good practice to announce long-term objectives along with short-term binding policies. An example are the existing carbon-intensity or fuel-efficiency standards for new passenger vehicles (ICCT, 2013): governments have enacted short-term standards (e.g. 130 g/km in 2015 in Europe), and also enacted or proposed longer-term ones (95 g/km in 2020 in Europe).

This result also sheds a new light on sector-specific mitigation targets, such as energy-efficiency standards in the automobile sector or the 20% renewable power in the European Union. This kind of sectoral short-term targets in favor of expensive but high-potential technologies may be a way to ensure that aggregate targets (the 20% reductions of greenhouse gas emissions) are not reached using only the cheapest options.

6. Conclusion

This paper investigates the design of optimal abatement strategies using information on the cost, the abating potential and the implementation speed of a set of available measures.

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 some expensive options before cheaper ones. If the climate objective is stringent and inertia is large, the optimal strategy would be to start implementing at the same time a set of measures covering a wide range of abatement costs.

Our results have policy and methodological implications.

In the European Union, there was 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 should not 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 required to meet an ambitious objective in 2050 (see also Rose et al., 1999; Sandén and Azar, 2005; Narain and Veld, 2008).

The optimal approach to achieve an emission target is not to set a growing carbon price and to implement sequentially the abatement options that show an abatement cost below this carbon price. Decision makers need assessments of the speed at which various measures to curb greenhouse gas emissions can be implemented, and they should be informed of long-term objectives in advance. Further research could investigate how policies targeted at high-potential but long-to-implement options, such as urban planing or deployment of low-carbon technologies, may complement a carbon price in the absence of perfect foresight or long-term policy credibility.

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 may be the case, for instance, 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 sectoral policies overlap, they may come with additional costs (Braathen, 2007; Böhringer and Rosendahl, 2010) or benefits (Fischer and Preonas, 2010; Lecuyer and Quirion, 2013) that should be analyzed carefully and taken into account.

Our results are based on illustrative examples. The main conclusion is methodological: we reinforce the need to account for sector-specific inertia when designing climate policies. To date, the literature has focused on cross-sector differences on knowledge spillovers (e.g. Manne and Richels, 2004; Rosendahl, 2004). While some numerical studies (Lecocq et al., 1998; Schwoon and Tol, 2006; Jaccard and Rivers, 2007) and integrated assessment models (Wilson et al., 2013) factor this type of differentiated inertias, the optimal timing and cost of emission reduction taking into account differentiated inertias is the object of only few theoretical contributions (e.g, Vogt-Schilb et al., 2012).

Measure-explicit marginal abatement cost curves have proved extremely effective in communicating some results from the economics of climate mitigation to decision makers and the general public. For instance, by reporting the cost and potential of a list of mitigation measures, MACCs illustrate in a simple way why energy-efficiency is a key option: it can save significant amounts of GHG at a low or negative cost. Existing MAC curves, however, do not explain why more expensive options, such as carbon capture and storage or renewable power, should receive significant attention today. Our answer is that these options can abate large amounts of GHG in the future, and that they need time to be implemented (Grübler et al., 1999). The reporting currently carried out by MAC curves could be enhanced by supplying assessments of the cost, potential, and implementation speed of each option.

With this information, the optimal implementation schedule of the various existing abating options could be assessed in a simple, transparent and accessible process, for instance using linear models like the one proposed in this paper. Such a model certainly is less sophisticated than state-of-the-art integrated assessment models, but can prove nonetheless useful for researchers from other fields, decision makers, and the general public. This process would also provide figures to debate new or existing sectoral policies, such as the objective of 20% of renewable energies in Europe by 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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