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Long-Term Mitigation Strategies and Marginal Abatement Cost Curves

A Case Study on Brazil

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Abstract

Decision makers facing abatement targets need to decide which abatement measures to implement, and in which order. This paper investigates the ability of marginal abatement cost (MAC) curves to inform this decision, reanalysing a MAC curve developed by the World Bank on Brazil. Misinterpreting MAC curves and focusing on short-term targets (e.g., for 2020) would lead to under-invest in expensive, long-to-implement and large-potential options, such as clean transportation infrastructure. Meeting short-term targets with marginal energy-efficiency improvements would lead to carbon-intensive lock-ins that make longer-term targets (e.g., for 2030 and beyond) impossible or too expensive to reach. Improvements to existing MAC curves are proposed, based on (1) enhanced data collection and reporting; (2) a simple optimization tool that accounts for constraints on implementation speeds; and (3) new graphical representations of MAC curves. Designing climate mitigation policies can be done through a pragmatic combination of two approaches. The synergy approach is based on MAC curves to identify the cheapest mitigation options and maximize co-benefits. The urgency approach considers the long-term objective (e.g., halving emissions by 2050) and works backward to identify actions that need to be implemented early, such as public support to clean infrastructure and zero-carbon technologies.

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Long-Term Mitigation Strategies and Marginal Abatement Cost Curves: A Case Study on Brazil

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Various technical options are available to reduce greenhouse gas (GHG) emissions: fuel switch in the power sector, renewable power, electric vehicles, energy efficiency improvements in combustion engines, waste recycling, forest management, etc. Policy makers have to compare and assess these different options to design a comprehensive mitigation strategy and decide the scheduling of various actions (i.e. decide what measures need to be introduced and when). This is especially true concerning the emission-reduction measures that require government action (e.g., energy-efficiency standards, public investment, public planning).

One tool that has been largely used to assess and compare mitigation actions is the marginal abatement cost (MAC) curve. A MAC curve provides information on abatement costs and abatement potentials for a set of mitigation measures, and ranks them according to their cost, from the least to the most expensive (Fig. 1). The World Bank has collaborated and is collaborating with many countries to build national or local MAC curves (e.g. China, Poland, Mexico, Vietnam).

MAC curves have proven powerful tools to highlight that large amounts of low-cost emission reductions are technically possible. They also show that some emission reductions can pay for themselves thanks to energy efficiency gains, provided implementation barriers can be overcome (Kesicki and Ekins, 2012). This information can help governments decide about the level of ambition of their mitigation strategy, and make informed domestic and international commitments (in the UNFCCC context, for instance). It is also helpful for policy makers searching for synergies and co-benefits between emission reductions and economic development.

In addition to its cost and potential, the speed at which an emission-reduction action may be implemented is a key parameter for decision makers. Indeed, some high-abatement-potential measures, such as switching to renewable power, will

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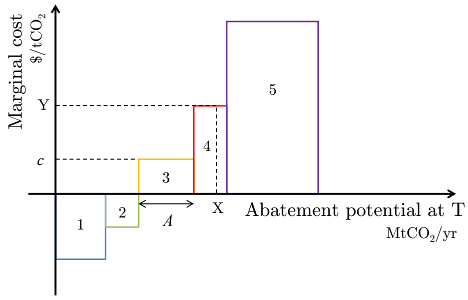


Figure 1: A measure-explicit marginal abatement cost curve. The general appearance of the curve suggests that it is meant to be used as an abatement supply curve, i.e. that the "abatement demand" X should be met by implementing measures 1 to 4, possibly using the carbon price Y.

take decades to implement. This *technical inertia*[1] means that it can be optimal to implement more expensive measures before cheaper ones, if the former have a large potential but are long to implement (Vogt-Schilb and Hallegatte, 2014). Moreover, focusing on short-term targets (e.g., for 2030) without considering longer-term objectives (e.g., for 2050 and beyond) could lead to carbon-intensive lock-ins that would make it very expensive (or even impossible) to achieve the long-term objectives.

MAC curves do not report information on technical inertia, and should not be misinterpreted as supply curves, as they frequently are (e.g. DECC, 2011, fig 17).[2] To avoid this, we proposed in Vogt-Schilb and Hallegatte (2014) to complement MAC curves with information on implementation speeds, and to use a simple optimization tool to derive optimal strategies taking inertia into account.

In this paper, we use a MAC curve built at the World Bank for studying low-carbon development in Brazil in the 2010-2030 period to confirm our theoretical results, and to test our proposed improvements. Lack of data beyond 2030 does not allow us to demonstrate that using the 2010-2030 MAC curve to design a mitigation strategy would lead to suboptimal choices in view of longer-term objectives (2050 and beyond). We can however illustrate this problem by assuming that we want to achieve an objective for 2030, and that we use the MAC curve to design a mitigation strategy for the 2010-2020 period only. Because of inertia, our theoretical results suggest that the resulting strategy would be suboptimal, with insufficient investments in some expensive, long-to-implement and large long-term potential options. And indeed, we find that a strategy for 2010-2020 that disregards the longer-term target under-invests in options such as metro and other transportation infrastructure. Conversely, it over-invests in marginal, cheap but low-potential options, such as heat integration and other improvements in existing refineries.

[1] Using the wording by Grubb et al. (1995), Ha-Duong et al. (1997); Lecocq et al. (1998) and Vogt-Schilb et al. (2012).

[2] Such interpretation would lead to "*implement the cheapest measure first, preferring measures with a lower total saving potential but more cost-effective than those with a higher GHG saving potential in absolute terms*" (Wächter, 2013).

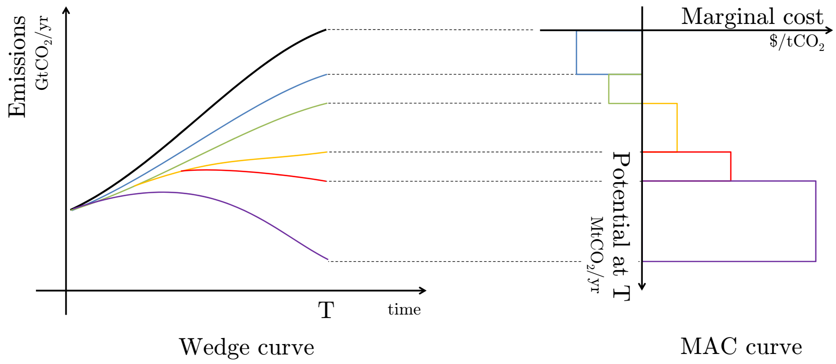


Figure 2: By displaying "flipped" achievable-potential MAC curves nearby the corresponding emission reduction scenarios (wedge curves), confusion on how to interpret MAC curves may be avoided.

This work confirms two limits of current MAC curves.

First, MAC curves do not report a very important piece of information, namely the implementation speed of each measure and option. We show however that with marginal modifications, MAC curves could mitigate this problem and better inform decision makers on optimal mitigation strategies. To do so, MAC curves can easily be completed with information on the speed at which a measure produces abatement results. We propose in Appendix B some guidance for the experts in charge of collecting the information to build a MAC curve, to make sure constraints on implementation speed are collected and reported together with data on costs and potentials. Also, existing and future MAC curves could be presented together with the corresponding emission reduction scenarios or *wedge curves* (Pacala and Socolow, 2004; Davis et al., 2013), making the dynamic component on the mitigation scenarios more explicit (Fig. 2).

Second, MAC curves are designed for a relatively short term horizon (e.g., 2030), while mitigation objectives go way beyond this horizon. Many countries have longer-term objectives (e.g., the EU has a 2050 objective); and most importantly, tackling climate change and other environmental threats will require to reduce emissions to near-zero levels by the end of the century (Matthews and Caldeira, 2008; Steinacher et al., 2013). There is no easy way around this problem. We suggest to combine a synergy approach based on MAC curves (to identify mitigation options that provide co-benefits in terms of development, economic growth, job creation, local environmental quality, or poverty alleviation) with an urgency approach, based on defining long-term objectives and working backward to identify which early measures are needed to get there on time.

The rest of the paper is structured as follows. In section 1, we review different types of MAC curves. While the construction of MAC curves sometimes requires to investigate the diffusion speed of emission-reduction options, MAC curves do not report separately the long-term abatement potential and the diffusion speed. In section 2, we reanalyze the data from the Brazilian MAC curve and confirm our theoretical results. We also propose a simple optimization model that can be used with this information to compute the least-cost emission-reduction schedule. In section 3, we conclude and formulate recommendations on the gathering and reporting of data to inform the policy debate on emission-reduction options.

1. Existing MAC curves

Measure-explicit MAC curves have been developed since the early 1990s (Rubin et al., 1992), and have recently reached a wide public, when McKinsey and Company published assessments of the cost of abatement potentials in the United States (Enkvist et al., 2007) and at the global scale (McKinsey, 2007). This type of curve is increasingly used to inform policy makers. For instance, McKinsey currently lists MAC curves for 15 different countries or regions on its website. The World Bank also uses MAC curves routinely (ESMAP, 2012), and has recently developed the MACTool to help build such MAC curves (see below). Similar depictions have been used by other institutions (e.g., Climate Works Australia, 2010; NERA and Bloomberg, 2011; CE Delft, 2012) and to analyze other topics such as waste reduction, energy savings and water savings (see Kesicki and Ekins, 2012; Vogt-Schilb and Hallegatte, 2014).

Depending on their implicit definition of the abating potential of a measure, two types of measure-explicit MAC curves should be distinguished.[3]

1.1. Full potential MAC curves

The full-potential approach gives information on how much GHG could be saved if the measure was used at its technical maximum. It is calculated against a reference or baseline technology, as for instance those used in the present (Wächter, 2013), taking into account the carbon intensity and imperfect substitutability of different technologies. For instance, this approach assesses what fraction of passenger vehicles can be replaced by electric vehicles (EV), accounting for limited driving range and exiting mobility practices. Given emissions from baseline vehicles (e.g 140g/km today in Europe) and emissions from EVs (e.g. none), one can compute an amount of emissions avoidable using electric vehicles.

Rubin et al. (1992) use 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 used for base load and intermediate load operation in 1989 (Table 3, footnote j). In this example, the authors assumed that nuclear power is suited for baseload and intermediate load operation, but not for providing peak power.

The main value of full potential MAC curves is descriptive: they highlight to which extent some key measures could reduce emissions in the long-run. As they do not integrate any consideration on speed, they are not fully operational.

1.2. Achievable potential MAC curves

Achievable-potential MAC curves have a prospective dimension, as they are built for a date in the future. This approach fully acknowledges that large-scale diffusion of new technologies can take up to decades (Grübler and Messner, 1998; Grübler et al., 1999; Wilson et al., 2013). In this context, the abating potential

[3]This classification was first proposed by Vogt-Schilb and Hallegatte (2014)

of a technology is an assessment of the abatement that could be achieved with such a technology if it was implemented at a given speed, starting at a given date (McKinsey, 2009, p. 46). 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, hence limited emission reductions from EVs by 2020 or 2030. The potential achievable by a given date is therefore lower or equal than the full potential discussed above.

One weakness of the achievable potential is that it makes the slow diffusion process indistinguishable from the full potential. The reader of a MAC curve does not know if a small potential for abatement from residential building retrofit means that residential buildings are already almost entirely retrofitted in the region (the full potential is low), or that only a small fraction of buildings may be retrofitted during the period (the diffusion is slow).

A key advantage of the achievable-potential approach is that it requires investigating reasonable assumptions regarding the possible implementation speed of a measure (e.g. 1% of the dwellings can be retrofitted each year). This information is key for a policy maker scheduling emission-reduction investments. Unfortunately, assessed diffusion speeds are not displayed in the resulting MAC curve, and are seldom discussed in the accompanying reports.

The MAC curve we reanalyze in this paper is an achievable-potential MAC curve. In each economic sector, emission reduction scenarios have been assessed taking into account implementation barriers (de Gouvello, 2010).

1.3. MAC curves at the World Bank: MACTool

The World Bank develops and promotes a piece of software called MACTool, which can produce achievable-potential MAC curves. One aim of the MACtool is to provide policy makers with a common framework to analyze available mitigation measures. MACTool may become a reference, notably on what is the relevant information that a decision maker requires to take action regarding mitigation plans.

MACTool takes as inputs the key socio-technical parameters of a set of large mitigation measures, and macroeconomic variables. For instance, technology options to produce electricity are characterized by required capital and operation expenditures, as well as their lifetime, energy efficiency and type of fuel used. Physical constants as the carbon intensity of each fuel are factored in. The user must also specify at least one scenario on the future macroeconomic variables of interest, such as the price of fossil fuels and the future demand for electricity. Finally, the user must provide scenarios of future penetration of (low-carbon) technologies, in both a baseline and at least one emission-reduction scenario.

As outputs, MACTool computes the amount of GHG saved by each measure in the long run (in $MtCO_2$), and the cost of doing so (in $\$/tCO_2$). This information is illustrated with two figures: an achievable potential MAC curve, and an abatement wedge curve.

The tool itself does not provide information on what is achievable, this information comes directly from the input scenarios. Input scenarios therefore need to be built taking into account the constraints on technology diffusion and implementation speed. For instance, these scenarios may come from models that factor such constraints in, or be built by sector experts who guesstimate possible penetration scenarios (see also Kesicki and Ekins, 2012).

MACTool also reports the investment needed in different emission reduction scenarios. While the abatement costs are computed using the social discount rate entered by the user, MACTool can also compute the carbon price signal that would be required to trigger investments from the private sector, taking into account the opportunity cost of capital for private actors (that is higher than the social discount rate, especially in developing countries).

2. Proof of concept: Re-analyzing the case of Brazil by 2030

In a theoretical framework, we found that focusing on short-term targets and disregarding constraints on implementation speed would lead to suboptimal strategies, and could lead to carbon-intensive lock-ins that make the longer-term target impossible or too expensive to reach (Vogt-Schilb and Hallegatte, 2014). We developed a simple optimization model to factor implementation speed in the analysis and avoid this problem.

Here, we perform a proof of concept for these ideas, reanalyzing the data used at the World Bank to create a MAC curve for Brazil with MACTool (de Gouvello, 2010). We confirm using this data the findings of the theoretical paper, and we test the optimization model using proxies and indirect methods to reconstruct data on implementation speed constraints.

2.1. Objective

We take the point of view of a social planner who chooses in 2010 an emission-reduction schedule to comply with a future emission target for 2030. We use two simulations. In the first one, an emission-reduction target is set for year 2030 and an optimal emission strategy is created taking into account implementation speed constraints. Then, the abatement obtained in 2020 in this optimal strategy is used as a target for 2020, and the MAC curve is used to design a mitigation strategy between 2010 and 2020, disregarding the constraint in terms of implementation speed. We then investigate differences of the optimal emission reductions up to 2020 in the two simulations, to confirm on this case the findings of the theoretical paper: using a MAC curve without taking into account implementation speed and long-term objectives would lead to insufficient short-term investments in options with high potential and slow implementation speed.

2.2. Methods and data

We use a spreadsheet program based on the model proposed by Vogt-Schilb and Hallegatte (2014). The program provides the least-cost emission-reduction schedule that complies with the abatement target. As inputs, it requires a list of measures, characterized by a marginal abatement cost, a maximum diffusion speed, and a maximum abatement potential (see Appendix A).

Note that the abatement potential may evolve through time. For instance, if available technology limits intermittent wind power to 20% of the electricity production and electricity production is expected to grow over time, then the abating potential of wind power grows over time. On the other hand, if natural resources provide only few opportunities to build dams, the abating potential of hydro power is fixed, regardless of total electricity demand growth.

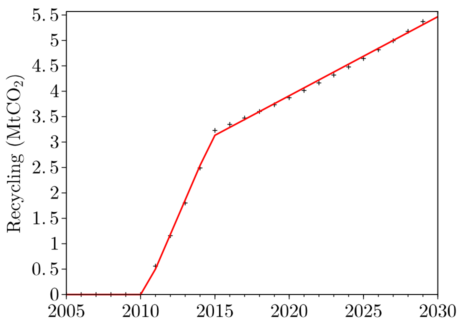


Figure 3: In the data from MACTool, many emission reduction scenarios (+) may be approximated by a piecewise-linear function (red curve). The slope of the first piece provides the diffusion speed for that measure. The second part is interpreted as the maximum potential, that grows over time.

We use the model with data collected at the World Bank to build a MAC curve (using MACTool) during a case study on Brazil (de Gouvello, 2010). The MAC curve provides a list of emission-reduction measures, their marginal abatement cost, and the potential achievable by 2030. While the list of measures and their cost can be used directly in our spreadsheet program (see the first two columns of Tab. 1), our program requires the full-abatement potential and diffusion speed.

Since this data was not collected when the MAC curve was prepared, we have to reconstruct it with indirect methods, using the emission-reduction scenarios that were provided to MACTool. For each measure, the shape of the emission-reduction scenarios can be classified in one out of three cases.

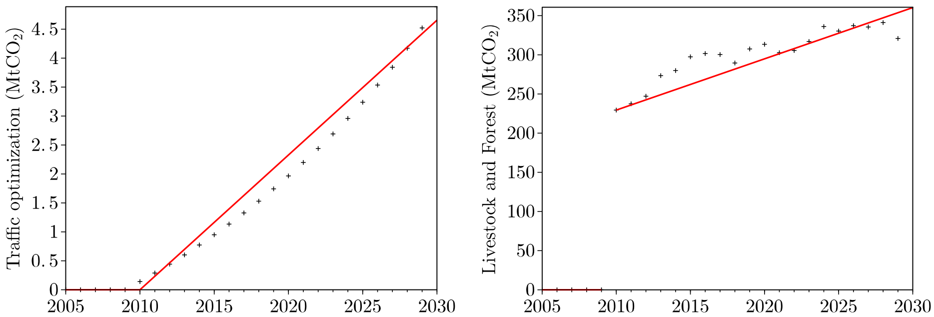
In the first case, emission-reduction scenarios may be approximated by a two-phases piecewise-linear function as in figure 3. In this case, the diffusion speed is given by the slope of the first piece, and the second phase is interpreted as the growth in full potential. About half the measures fall in this category.

Other emission-reduction scenarios may be approximated by a single linear diffusion (Fig. 4a). In this case, the full potential is not binding before 2030. We calibrate the diffusion speed from the slope of the penetration pathway, and denote the lack of data on the full potential with a dot ($\cdot$) in the two last columns of Tab. 1.

In some cases the emission-reduction scenario lacks the first phase; abatement immediately "jumps" to a growing full-potential (Fig. 4b). We denoted them with a dot in the diffusion speed column in Tab. 1. There is usually a handful of such cases in MAC curves exercises. One example from the Brazilian study is solid residues management. In the emission-reduction scenario, solid residues management is able to reduce emissions by more than 40 $MtCO_2$ in one year, and then grow at less than 1 $MtCO_2$/yr. From the perspective of the user of a MAC curve, it may be unclear whether this should be considered as a shortcoming in the data (if the investigation could not identify the constraints that limit the diffusion of solid residues management), or a realistic emission-reduction scenario (if solid residues management can actually save lots of GHG

Measure	MAC $\$/tCO_2$	Diffusion speed $ktCO_2$	Potential in 2010 $MtCO_2$	Potential growth $ktCO_2$
Combustion optimization	-28.4	955	3.3	218
Heat recovery	-59.6	168	0.6	37
Steam recovery	-62.4	339	1.1	77
Furnace heat recovery	-12.8	1780	8.6	743
New processes	25.8	1200	4.5	265
Other Energy Efficiency	-7.5	162	0.6	35
Thermal Solar	-34.8	228	0.8	50
Recycling	-23.6	679	2.3	155
Natural gas	0	397	1.3	90
Biomass	4.3	716	·	·
Reforestation	·	·	26.9	1002
Wind	64	138	1.2	0
Comb. Heat Power	-43.2	1517	5.7	241
Solar heat	83.9	18	·	·
Air conditioning	419.1	·	0	0
Residential Lightning	-91.9	·	0.1	0
Cooler	5.2	79	·	·
Motor	-5.8	13	·	·
Industrial Lightning	-36.2	3	·	·
Commercial lightning	-27.3	9	·	·
GTL	0.6	1021	·	·
New Refineries	16.4	352	·	·
Refineries Heat Integration	10.9	510	3.1	37
Refineries Fouling Mitigation	45.8	59	0.5	0
Refineries Advanced Control	79.1	59	0.5	0
Ethanol	1.8	1444	·	·
Rail and Waterways	23.3	494	·	·
Bullet train	376.3	45	0.9	0
Rapid transit bus	42	·	0	0
Metro	95.7	1007	·	·
Traffic optimization	0.2	232	·	·
Bike Lanes	2.6	120	·	·
Solid residues	2.1	·	40.4	732
Resid. wastewater	7.8	513	·	·
Indust. Wastewater	80.4	·	8	333
Restauration	·	5899	·	·
Livestock and Forest	0.7	·	229.4	6542
Tilage	-0.2	2578	17.6	185

Table 1: Calibrated speed, cost and potential. A dot (·) denotes lack of reliable data



(a) No potential **(b)** No speed

Figure 4: For some abatement measures, the data needed to calibrate our model cannot be derived from the emission-reduction scenarios provided in MACTool. In some cases (a), the long term potential is not binding, because it cannot be reached before 2030. In some other cases (b), the diffusion speed was not investigated (or maybe the measure can reach its full potential in less than one year).

in a short time lapse).[4] To avoid this situation in the future, we recommend that the terms of reference for the experts in charge of collecting data on emission reductions options should explicitly ask to report possible diffusion speeds (Appendix B).

Finally, some emission-reduction measures (reforestation, air conditioning and rapid bus transit) were included in the list while lacking either a marginal abatement cost or an emission scenario. These measures, as well as those for which the diffusion speed could not be estimated, are discarded for the rest of the analysis.

The remaining options allow to reduce Brazilian emissions by 223 $MtCO_2$ in 2030 (compared with 812 $MtCO_2$ in the original MAC curve).

2.3. Optimal strategy with a 2030 objective

In a first simulation, we run our spreadsheet model to design the optimal strategy to achieve 223 $MtCO_2$ of emission reductions by 2030 (Tab. 2).

The optimal emission-reduction strategy has the following characteristics. All negative-cost measures are introduced at full speed from year 2010, independently of the emission-reduction target. This simply reflects that these measures are desirable *per se*, as they bring more benefits than costs even in the absence of any carbon pricing or climate change impacts. For the positive-cost measures, the least-cost strategy is to implement them as late as possible, to

[4] Livestock and forest management is a particular example. In the emission-reduction scenarios, this measures allows to save 229 $MtCO_2$, that is almost one third of the total abatement potential by 2030, as soon as 2010. Since Brazil has already managed to reduce drastically its emissions from deforestation (-80% between 2004 and 2009), the study considered that this mitigation option is already enforced. Sustaining such effort over a long period will require disseminating new technologies in the livestock sector to ensure that productivity gains are enough to free-up pasture land at a rhythm that allows to accommodate the growth of the livestock-agriculture sector without deforesting, as recommended in the Brazil Low-carbon study (de Gouvello, 2010). Such dissemination will face a similar inertia issue; however, this is a slightly different discussion.

Figure 5: Bias from short-term (2020) time horizon compared with optimal long-term (2030) strategy. On the positive side, measures are used excessively in the 2020 strategy, compared to what they should be used to reach the 2030 target; on the negative side, measures are used insufficiently. Only the 5 larger absolute differences are shown.

benefit from the discount rate. This means that under an emission-reduction target in one point in time, such as -30% by 2030, the two-phase penetration pictured in Fig. 3 is not optimal for positive-cost measures. A better solution is to delay the implementation such that the maximum potential is reached just in time, when the target needs to be achieved.[5]

2.4. Strategy with a 2020 objective

The optimal emission reduction pathway to achieve 223 $MtCO_2$ in 2030 leads to 127 $MtCO_2$ of emission reductions in 2020. To investigate how focusing on short-term targets may lead to suboptimal outcomes, we run a second simulation with the only constraint of reducing emissions by 127 $MtCO_2$ in 2020, and we investigate the "optimal" solution provided by our model in this case (Tab. 3).

In line with Vogt-Schilb and Hallegatte (2014), the least-cost strategy for 2010-2020 uses different emission-reduction options, depending on whether the strategy aims at a short-term target (127 $MtCO_2$ in 2020) or at a longer-term one (223 $MtCO_2$ in 2030). The simulation that ends in 2020 uses notably less investment in metro and other clean transportation infrastructure, and more heat integration and other marginal improvements in existing refineries (Fig. 5). All the measures that are underused in this scenario are characterized by a huge abatement potential, which cannot be exhausted before 2030. In the long-term target scenario, those are implemented as fast as possible. In the short-term target scenario for 2020, they are replaced by cheaper and faster to implement measures (see also Fig. 6).

The short-term target masks the longer-term target, such that long-to-implement options required in the long term are not promoted soon enough.

[5] If the climate mitigation target is expressed in terms of a carbon budget (i.e. if it limits cumulative emissions instead of emissions at one point in time), then the two-phase penetration target may be optimal (Vogt-Schilb and Hallegatte, 2014).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	**2020**
Combustion optimization	0.96	1.91	2.87	3.82	4.19	4.41	4.63	4.84	5.06	5.28	**5.50**
Heat recovery	0.17	0.34	0.51	0.67	0.78	0.82	0.86	0.90	0.93	0.97	**1.01**
Steam recovery	0.34	0.68	1.02	1.36	1.49	1.56	1.64	1.72	1.80	1.87	**1.95**
Furnace heat recovery	1.78	3.56	5.34	7.12	8.90	10.69	12.47	13.84	14.58	15.32	**16.07**
New processes	-	-	-	-	-	-	-	-	-	-	**-**
Other Energy Efficiency	0.16	0.33	0.49	0.65	0.75	0.79	0.83	0.86	0.90	0.93	**0.97**
Thermal Solar	0.23	0.46	0.68	0.91	1.06	1.11	1.16	1.21	1.26	1.31	**1.36**
Recycling	0.68	1.36	2.04	2.72	2.98	3.13	3.29	3.44	3.60	3.76	**3.91**
Natural gas	0.40	0.79	1.19	1.59	1.74	1.83	1.92	2.01	2.10	2.20	**2.29**
Biomass	0.72	1.43	2.15	2.87	3.58	4.30	5.02	5.73	6.45	7.17	**7.89**
Wind	-	-	-	-	-	-	-	-	-	-	**-**
Comb. Heat Power	1.52	3.04	4.55	6.07	6.68	6.92	7.16	7.40	7.64	7.88	**8.13**
Solar heat	0.02	0.04	0.06	0.07	0.09	0.11	0.13	0.15	0.17	0.18	**0.20**
Cooler	0.08	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.71	0.79	**0.87**
Motor	0.01	0.03	0.04	0.05	0.07	0.08	0.09	0.11	0.12	0.13	**0.15**
Industrial Lightning	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	**0.04**
Commercial lightning	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.08	0.09	**0.10**
GTL	1.02	2.04	3.06	4.09	5.11	6.13	7.15	8.17	9.19	10.21	**11.24**
New Refineries	0.35	0.70	1.06	1.41	1.76	2.11	2.47	2.82	3.17	3.52	**3.87**
Refineries Heat Integration	-	-	-	-	-	-	-	-	-	-	**-**
Refineries Fouling Mitigation	-	-	-	-	-	-	-	-	-	-	**-**
Refineries Advanced Control	-	-	-	-	-	-	-	-	-	-	**-**
Ethanol	1.44	2.89	4.33	5.78	7.22	8.67	10.11	11.56	13.00	14.44	**15.89**
Rail and Waterways	0.49	0.99	1.48	1.98	2.47	2.97	3.46	3.96	4.45	4.95	**5.44**
Bullet train	0.01	0.06	0.10	0.15	0.19	0.24	0.28	0.33	0.38	0.42	**0.47**
Metro	1.01	2.02	3.02	4.03	5.04	6.05	7.05	8.06	9.07	10.08	**11.09**
Traffic optimization	0.23	0.47	0.70	0.93	1.16	1.40	1.63	1.86	2.10	2.33	**2.56**
Bike Lanes	0.12	0.24	0.36	0.48	0.60	0.72	0.84	0.97	1.09	1.21	**1.33**
Resid. wastewater	0.51	1.03	1.54	2.05	2.57	3.08	3.59	4.11	4.62	5.13	**5.65**
Tilage	2.58	5.16	7.74	10.31	12.89	15.47	18.05	18.91	19.09	19.28	**19.46**

Table 2: Otpimal strategy to reach the 2020 target when the 2030 target is taken into account

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	**2020**
Combustion optimization	0.96	1.91	2.87	3.82	4.19	4.41	4.63	4.84	5.06	5.28	**5.50**
Heat recovery	0.17	0.34	0.51	0.67	0.78	0.82	0.86	0.90	0.93	0.97	**1.01**
Steam recovery	0.34	0.68	1.02	1.36	1.49	1.56	1.64	1.72	1.80	1.87	**1.95**
Furnace heat recovery	1.78	3.56	5.34	7.12	8.90	10.69	12.47	13.84	14.58	15.32	**16.07**
New processes	-	-	-	-	-	1.16	2.36	3.56	4.77	5.97	**7.17**
Other Energy Efficiency	0.16	0.33	0.49	0.65	0.75	0.79	0.83	0.86	0.90	0.93	**0.97**
Thermal Solar	0.23	0.46	0.68	0.91	1.06	1.11	1.16	1.21	1.26	1.31	**1.36**
Recycling	0.68	1.36	2.04	2.72	2.98	3.13	3.29	3.44	3.60	3.76	**3.91**
Natural gas	0.40	0.79	1.19	1.59	1.74	1.83	1.92	2.01	2.10	2.20	**2.29**
Biomass	0.72	1.43	2.15	2.87	3.58	4.30	5.02	5.73	6.45	7.17	**7.89**
Wind	-	-	-	-	-	-	-	-	0.14	0.28	**0.41**
Comb. Heat Power	1.52	3.04	4.55	6.07	6.68	6.92	7.16	7.40	7.64	7.88	**8.13**
Solar heat	-	-	-	-	-	-	-	-	-	0.02	**0.04**
Cooler	0.08	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.71	0.79	**0.87**
Motor	0.01	0.03	0.04	0.05	0.07	0.08	0.09	0.11	0.12	0.13	**0.15**
Industrial Lightning	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	**0.04**
Commercial lightning	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.08	0.09	**0.10**
GTL	1.02	2.04	3.06	4.09	5.11	6.13	7.15	8.17	9.19	10.21	**11.24**
New Refineries	-	0.35	0.70	1.06	1.41	1.76	2.11	2.47	2.82	3.17	**3.52**
Refineries Heat Integration	-	-	-	-	0.51	1.02	1.53	2.04	2.55	3.06	**3.57**
Refineries Fouling Mitigation	-	-	-	-	-	-	-	0.06	0.12	0.18	**0.24**
Refineries Advanced Control	-	-	-	-	-	-	-	-	0.03	0.09	**0.15**
Ethanol	1.44	2.89	4.33	5.78	7.22	8.67	10.11	11.56	13.00	14.44	**15.89**
Rail and Waterways	-	-	-	0.49	0.99	1.48	1.98	2.47	2.97	3.46	**3.96**
Bullet train	-	-	-	-	-	-	-	-	-	-	**-**
Metro	-	-	-	-	-	-	-	-	-	1.01	**2.02**
Traffic optimization	0.23	0.47	0.70	0.93	1.16	1.40	1.63	1.86	2.10	2.33	**2.56**
Bike Lanes	0.12	0.24	0.36	0.48	0.60	0.72	0.84	0.97	1.09	1.21	**1.33**
Resid. wastewater	0.51	1.03	1.54	2.05	2.57	3.08	3.59	4.11	4.62	5.13	**5.65**
Tilage	2.58	5.16	7.74	10.31	12.89	15.47	18.05	18.91	19.09	19.28	**19.46**

Table 3: Otpimal strategy to reach the 2020 target if the 2030 target is disregarded

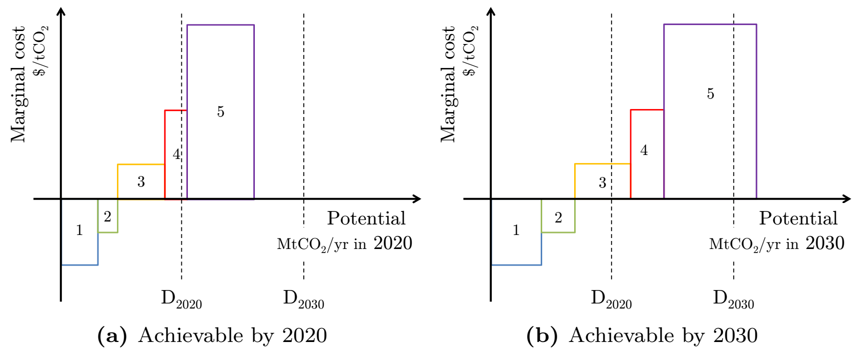


Figure 6: In this example, the 2020 MAC curve (a) suggests that the 2020 target (D_{2020}) should be met with options 1–4, disregarding option 5 before 2020. But then only a fraction of option 5 could be implemented between 2020 and 2030. The 2030 MAC curve (b) however shows that options 1–5 should be implemented by 2030 to meet the D_{2030} target. For option 5 to deliver all the abatement listed by 2030, it should be implemented before 2020. A MAC curve built for longer-term horizons (e.g. 2050) would show that even more options should be deployed early.

In this example, reaching the 2030 target requires to implement 95 additional $MtCO_2$ between 2020 and 2030. However, a 2020-2030 strategy would be able to save 84 $MtCO_2$ additionally at best, since not enough time would be left to deploy time intensive solutions. This new low-carbon scenario would therefore be short 11 $MtCO_2$ or 12% in 2030 compared to the first one. In other words, the 2030 target becomes impossible to achieve after 2020, as the limited diffusion speed prevents high-abatement-potential options to achieve their optimal 2030 level in 10 years.

3. Conclusion

This paper confirms with a case study on Brazil the theoretical findings from Vogt-Schilb and Hallegatte (2014). Using a MAC curve to design a mitigation strategy for the 2010-2020 period without accounting for a longer-term goal for 2030 would lead to insufficient investments in options with low implementation speed and large abatement potential. In this example, we find that omitting the 2030 target would lead to less investment in clean transportation infrastructure, and more investment in marginal improvements of existing refineries by 2020. This would even lead to a lock-in in carbon-intensive patterns, making it impossible for a subsequent 2020-2030 strategy to reach the 2030 target, as better transportation infrastructure is critical to reduce emissions on the long term.

These results suggest that using a 2030 MAC curve to plan a mitigation strategy that has a long-term objective (for 2050 and beyond) will lead to similar issues, namely the under-investment in some of the most important mitigation options and the creation of a carbon lock-in.

We propose a few solutions to this problem.

First, MAC curves can be displayed differently to avoid their misinterpretation as abatement supply curves. It is indeed possible to display achievable MAC curves together with the corresponding emission-reduction scenarios, also known as *wedge curves* (Fig. 2). This graphical interpretation makes it explicit that MAC curves are built from emission scenarios, and in particular that it takes time to achieve the *achievable potential*.

Second, the example studied here shows that the abatement potential and the abatement cost are not sufficient information to schedule emission reduction. The implementation speed is instrumental to investigating emission-reduction strategies, and should explicitly be investigated when building a MAC curve (Appendix B).

Third, our simulations show that aggregated short-term abatement targets may be misleading. They should be completed with credible long-term aggregated targets, or short-term sector- or even technology-specific targets (see also Sandén and Azar, 2005; Narain and Veld, 2008; del Rio Gonzalez, 2008; Bosetti et al., 2009; Vogt-Schilb and Hallegatte, 2014).

Finally, the long-term cost, abatement potential and diffusion speed of emission reduction measures is subject to large uncertainties (e.g., regarding the potential for cost reduction due to learning by doing). In the design of a mitigation strategy, we thus recommend to combine a synergy approach with an urgency approach based on a long-term view, as suggested in World Bank (2012, p 153).

The synergy approach identifies the cheapest mitigation options, and those that provide co-benefits in terms of development, economic growth, job creation, local environmental quality, or poverty alleviation. The urgency approach considers the long-term objective (e.g., halving emissions by 2050, or being carbon neutral in 2100) and works backward to identify actions that need to be implemented early to make it possible to reach that goal. Various policies can then be implemented, for instance combining a carbon price to capture low-cost abatement opportunity (e.g., through a carbon tax) with regulations or direct investment to trigger actions where anticipation is critical (e.g., with urban land-use plans, infrastructure, and the development of zero-carbon technologies for the power and transportation sectors).

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Appendix A. Model

We extend the model proposed by Vogt-Schilb and Hallegatte (2014).

The quantity of emission reductions done with measure i at time t is denoted $a_{i,t}$. The abatement potential of measure i is denoted $A_{i,t}$, imposing the following constraint:[6]

$$\forall(i,t),\ a_{i,t} \leq A_{i,t} \tag{A.1}$$

The second constraint on emission reduction is that they cannot grow faster than the diffusion speed v_i, such that:

$$a_{i,t+1} \leq a_{i,t} + v_i \tag{A.2}$$

The abatement target, set for a date in the future T (e.g. 2020 or 2030), is denoted $a^\star_T$. It sets the following constraint:

$$\sum_i a_{i,T} \geq a^\star_T \tag{A.3}$$

[6] In the model proposed by Vogt-Schilb and Hallegatte (2014), abatement potentials do not evolve over time. This is the only difference.

Taking the discount rate r as given, the model computes the least-cost emission reduction schedule, where the cost of measure i is c_i:

$$\min_{a_{i,t}} \sum_{i,t} e^{-rt} c_i \, a_{i,t} \tag{A.4}$$

An Excel implementation of this model is available online.

Appendix B. Information collection guidance

The following proposes guidance on how data on emission reduction measures could be collected to take into account the findings of this paper. The objective is to collect data that can be used to build MAC curves as usual, and also to inform a prescriptive model. Asking specifically to disclosure assumptions on speed (3c) should help identify bottlenecks preventing some measures to be implemented. Also, collecting this data does not require more work that what is currently done to build MAC curves; clarifying the difference between implementation speed and full technical potential may actually facilitate the data-gathering process.

Of course, this sketch should be adapted to local conditions; for instance, it should account for existing plans and projections when defining emission baseline and abatement potentials.

1. Inventory of existing GHG emissions
   (a) Provide the list of GHG emissions at a given date in the recent past. Chose the most recent date for which data is available .
   (b) Provide a breakdown of these emissions by sector, e.g. power generation, industry, residential sector, transportation, agriculture. Use subsectors, as provided by ISI.
   (c) Provide information of the output of such sectors.
      i. Use physical measures of output when possible, e.g:
         A. In the transportation sector, use passenger-kilometre and ton-kilometer.
         B. In the power sector, use MWh.
         C. In the residential sector, use number of inhabitants at given comfort.
      ii. Express these emissions in CO_2 equivalent using accepted conversion factors.
2. Prospective
   (a) Provide projections of future GHG emissions reported in I. using the same breakdown.
3. List available emission-reduction measures
   (a) Full technological potentials
      i. Provide emission-intensity of each activity.
      ii. Provide maximum penetration rate with today's technology: e.g. hydro power limited by river availability, electric vehicles limited by range. If relevant provide maximum penetration rate given political and societal constraints (e.g. nuclear unacceptable).
   (b) Costs
      i. Report Capex and Opex separately

    A. Report input-efficiency (e.g. fuel-efficiency and fuel type)
    B. Report input prices (report taxes separatedly)
  ii. Report domestic and foreign expenses separately.
  iii. Report costs used to pay domestic salaries separately (e.g. a photovoltaic power module must be imported but the installation is paid to a local worker; avoided gasoline use from electric vehicles means less oil imports, but also less tax revenue)

(c) Speed at which new technologies may enter the market. This piece of data assesses the speed at which each option can be implemented – taking into account the required accumulation of human and physical capital.
  i. Report typical capital lifetimes for considered technologies and related technologies in the sector — e.g. cars typically live 12 years.
  ii. Report past penetration rates for similar technologies in the sector — e.g. diesel sales took 30 years to go from 0 to 50% in the past.
  iii. Report current bottlenecks (institutional barriers, available resources) — e.g. available workforce can retrofit 100 000 dwellings per year.