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Marginal Abatement Costs of Carbon-Dioxide Emissions: A Meta-Analysis

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Abstract: In this paper we carry out a meta-analysis of recent studies into the costs of greenhouse gas mitigation policies that aim at the long-term stabilization of these gases in the atmosphere. We find the cost estimates of the studies to be sensitive to the level of the stabilization target, the assumed emissions baseline, intertemporal optimisation, the choice of control variable (CO_2 only versus multigas), assumptions on future technological options (backstop and carbon capture and storage), and, to a lesser degree, the scientific "forum" in which the study was developed.

Keywords: greenhouse gas mitigation; meta-analysis, marginal abatement costs.

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Marginal Abatement Costs of Carbon-Dioxide Emissions:
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1. Introduction

In recent years, many research teams have developed computer-based economic models that have computed marginal abatement costs (MAC) of greenhouse gas emissions that are consistent with long-term climate policy targets. These targets are usually expressed in terms of the stabilization at a certain level of concentration of CO_2 or greenhouse gases in the atmosphere or stabilization at a certain level of radiative forcing or global mean temperature. It is possible to interpret these MAC as carbon permit prices in an idealized global emissions trading system that allows the participants maximum “where”, and “when” flexibility, and in some models also “what” flexibility. This means that MAC are equalised across all sources (“where” flexibility), MAC change over time according to some intertemporal optimization rule (“when” flexibility), and that in some models MAC of abating different greenhouse gases are equalised, taking into account their relative warming potentials and different lifetimes (“what” flexibility).

We collected information from 26 different models that were presented in three so-called modelling fora in 2006. A modelling forum is a meeting or a series of meetings of modelling groups that address a common research question, and that use a commonly agreed set of assumptions and a common reporting format. One of the oldest of such fora is the Energy Modeling Forum (EMF) that was established at Stanford University in 1976 to provide a structured forum for discussing important energy and environmental issues. For this study we used the results of the models that participated in EMF-21 that specifically addressed “what” flexibility (trade-offs between different greenhouse gases). We also used results of the models that participated in the Innovation Modeling Comparison Project (IMCP) that specifically addressed the potential impact of induced technical change on long-term abatement and abatement costs and the U.S. Climate Change Science Program (USCCSP) that addressed all these issues.

These different models produce varying estimates of MAC. The analysis presented in this paper examines the sensitivity of MAC estimates to the specifications and assumptions underlying these models. By conducting a meta-analysis of model results we aim to identify consensus in the outcomes and the methodological characteristics that drive differences in results. In addition to providing a statistical synthesis of model outcomes, the meta-regression function can also be used to predict MAC given specific values for explanatory variables included in the regression.

The meta-analysis in this paper uses more up-to-date model results than previous research (Repetto and Austin, 1997; Barker et al., 2002; Fisher and Morgenstern, 2005). This paper uses the same model results as Barker et al. (2006), but many more in addition.

The structure of this paper is as follows. Section 0 introduces the concept of long-term stabilization targets for greenhouse gas emissions in the atmosphere. Section 0 presents the meta-analysis research methodology used in this paper, and section 0 describes the data. Section 0 presents the results of the meta-analysis, while Section **0** concludes.

2. Stabilization Targets

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) is the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*" (UNFCCC, art. 2). There is no consensus yet on the level at which GHG concentrations would need to be stabilised in order to prevent such dangerous anthropogenic interference, although the European Council and Parliament agreed on the objective to limit average global temperature increase to a maximum of 2°C compared to pre-industrial levels (Asselt and Biermann 2007; Tol, 2007). The different studies that we analyse in this paper have examined different stabilization targets, both in terms of metrics and levels. To be able to compare study results we need to standardise the various stabilisation targets to a common metric. The most commonly used metrics are radiative forcing (W.m-2), concentrations of greenhouse gases in the atmosphere expressed in CO_2 equivalents (ppm CO_2-eq), the concentration of the greenhouse gas CO_2 (ppm CO_2), and global mean temperature (ºC). Fisher, Nakicenovic et al. (2007) classified stabilization targets into six different categories (I…VI), and showed how the concordance between the targets in alternative metrics (see Table 1).

Table 1 Concordance between stabilization targets in alternative metrics

	Additional radiative forcing	CO_2 concentration	CO_2-eq concentration	Temperature
Category	$W.m^{-2}$	Ppm	ppm	ºC
I	2.5 – 3.0	350 – 400	445 – 490	2.1 (1.4–3.1)
II	3.0 – 3.5	400 – 440	490 – 535	
III	3.5 – 4.0	440 – 485	535 – 590	2.9 (1.9–4.4)
IV	4.0 – 5.0	485 – 570	590 – 710	3.6 (2.4–5.5)
V	5.0 – 6.0	570 – 660	710 – 855	4.3 (2.8–6.4)
VI	6.0 – 7.5	660 – 790	855 – 1130	5.5 (3.7–8.3)

Source: Fisher, Nakicenovic et al. (2007).

3. Research Approach: Meta-analysis

Meta-analysis is a statistical technique to combine the results of several studies that address a set of related research hypotheses. Meta-analysis extends beyond a standard literature review by analysing and synthesising the results of multiple studies in a statistical manner. This study is the second meta-analysis of MAC estimates, the first being Fischer and Morgenstern (2005).

In this paper, meta-analysis is used to examine whether modelled estimates of MAC are dependent upon some key modelling assumptions and structural characteristics of the models. To test such dependencies, a meta-regression model is constructed in which the dependent variable (MAC) is a linear function of a set of i explanatory variables (EVi) and a random error (ε):

$$MAC = \sum_i \beta_i EV_i + \varepsilon \qquad 1)$$

When the function is estimated, the estimate b of the coefficient β shows if and how the explanatory variable affects the dependent (MAC) variable. We are particularly interested in the significance (does the variable have a significant effect on MAC?) and sign (if the effect is significant, what is the direction of the effect: will an increase in the explanatory variable increase or reduce the MAC estimate?).

We estimated the meta-regression model by the Ordinary Least Square (OLS) method in the SPSS software package.

4. Description of the Database

The 26 models in our database provided “observations” of MAC for different points in time. We collected 62 observations of MAC for the years 2025 and 2050. We normalized these observations that are expressed in different dimensions and currencies into 2005 Euros per tonne of CO_2 ($€^{2005}/tCO_2$). For normalization, we used consumer price indices (CPI) from the OECD to convert all prices to a common year (2005), market exchange rates from OECD to convert all currencies to a common currency (Euro, €), and molecular weights to convert all physical dimensions to one common physical dimension (CO_2).

Differences between MAC estimates from different studies can be ascribed to differences in the stabilisation targets, assumptions on exogenous developments, and differences in model specification and parameterization. We selected a number of explanatory variables to include in the meta-regression model on the basis of general discussions on MAC in the literature, e.g. IPCC (Fisher, Nakicenovic et al. 2007), and on the basis of an earlier meta-analysis of models that were used to assess the compliance costs of the Kyoto Protocol (Fischer and Morgenstern 2005). The explanatory variables include stabilization target, emissions baseline, various model and policy assumptions, and also the particular forum in which the study was developed. Information on these variables was not available for all MAC estimates. From the 62 observations in our database, 47 (49) observations provided sufficient information to include in the meta-analyses for 2025 (2050). In describing the data below, we therefore make a distinction between the full and restricted data.

The mean MAC value across all 62 observations is € 23.8 per tonne of CO_2 in 2025 and € 63.0 in 2050. (Table 2). The median MAC are lower: € 16.2 in 2025 and € 34.0 in 2050. Table 2 shows that the spread of MAC across observations is quite large: for 2025 the minimum and maximum estimates are € 0.0 and € 199.9 and for 2050 the spread is € 1.4 to € 449.3 per tonne of CO_2. Table 2 also presents the descriptive statistics for the restricted database. The differences between the full database and the restricted database for 2025 are minor. The differences for 2050 are larger, to a large extent because of the exclusion of one study that reported a very high MAC of € 449/t in 2050. The study was excluded from the restricted database because of incomplete information regarding its baseline emissions.

Table 2 Summary statistics of MAC of 26 models (€^{2005}/tCO_2)

	2025		2050	
	Full database	Restricted database	Full database	Restricted database
Mean	23.8	23.8	63.0	55.8
Median	16.2	16.2	34.6	32.2
Maximum	119.9	119.9	449.3	209.4
Minimum	0.0	0.4	1.4	1.4
St.dev.	26.7	27.9	72.5	52.9
N	62	47	62	49

The large differences between mean and median MAC values suggest that the distribution of MAC values in our databases is skewed to the right, perhaps with a “thick” right tail with high values. This is indeed the case, as is shown for the restricted data of the year 2050 in the left panel of Figure 1. Because this skewedness may lead to estimation problems, we have taken natural logs of the MAC values and used ln(MAC) as the dependent variable. The right panel of Figure 1 below shows that the distribution of ln(MAC) tends more towards the normal distribution.

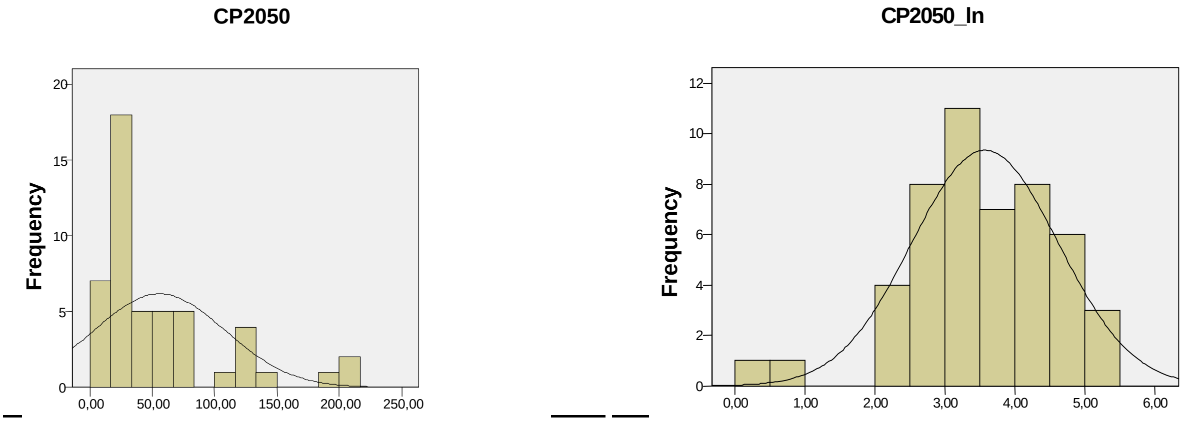

Figure 1 Frequency distribution of MAC (left panel) and ln(MAC) (right panel)

The following description of data will focus on the restricted database that will be used for the actual meta-analysis.

Most of the studies we collected use stabilization targets in categories III and IV (approx. 3.5 to 4.7 W.m-2). These stabilization targets imply a peak of emissions between 2010 and 2030, and between 2020 and 2060, respectively. The change in global emissions in 2050 relative to emissions in 2000 range between – 30 to + 5 percent for category III targets, and + 10 to + 60 percent for category IV targets (Fisher, Nakicenovic et al. 2007). Results of higher stabilization targets (categories V and VI) have been reported, but as Fisher et al (2007) have commented, they are not very ambitious and even overlap with low to medium baseline scenarios – that is, these targets may be reached without explicit climate policy. We have not included these studies in our analysis. Recent scientific evidence suggests that very low stabilization targets may be needed to avoid irreversible and catastrophic damages, and the European Commission recently confirmed its commitment to a long-term stabilization target of 450 ppmv CO_2-eq (= category I stabilization target) (EC 2007). The modelling fora did not, however, include studies that computed marginal CO_2 abatement costs for stabilization targets below 3.5 W.m-2 (categories I and II). In order to increase the range of the stabilization targets included in the data, one study that estimated MAC in accordance with a stabilization target of 350 ppmv CO_2 (450 ppmv CO_2-eq) was added to the database (Van Vuuren et al., 2006).

We converted all stabilization targets to ppmv CO_2 concentration measures. The variable TARGET ranges between 350 and 550 ppmv CO_2. The average stabilization target across all observations in the restricted database is 506 ppmv CO_2.

The studies use different assumptions on economic growth, industry structure and technological developments, resulting in widely differing baseline emissions paths over time. For example, in our restricted database, the increase in baseline CO_2 emissions from energy and cement over the period 2000-2100 ranges between 8 and 380 percent. Fisher et al. (2007) show that the range of baseline emissions for CO_2 and other greenhouse gases in the EMF-21 studies is comparable to the full range of the IPCC SRES scenarios. They report that the median increase in baseline CO_2 emissions in 133 post-SRES studies is 240 percent. The average increase in baseline emissions over the period 2000-2100 across all observations in our database is 174 percent and the median is 179 percent. The baseline in conjunction with the stabilization target determines the emissions reduction effort and thus, we conjecture, the MAC.

Recent studies have emphasized the cost savings potential of a multigas policy towards the stabilization of greenhouse gas concentrations and radiative forcing. The EMF-21 forum was for example specifically organised to assess this potential. On the basis of the EMF-21 studies, it can be concluded that a multigas policy ("what" flexibility) can potentially reduce marginal abatement costs substantially in comparison to a "CO_2 only" policy. Weyant et al. (2006) report that the EMF-21 studies find on average that MAC of a multigas policy in 2025 are 48 percent lower than a CO_2 only policy for the same long-term stabilization target. The reduction in MAC ranges from 15 to over 70 percent in individual models. In our database, we constructed the dummy variable MULTIGAS, which takes a value of 1 if the study examined a multigas policy, and 0 otherwise. Of the 49 observations in our database, 22 are for multigas.

Another "hot" issue in climate economics research is the impact of "induced" technical change on abatement costs. The IMCP forum specifically addressed this issue. The central idea of induced technical change is that the direction and magnitude of technical change in abatement technologies is dependent upon the overall greenhouse gas reduction policy and the subsequent carbon price. Hence, dynamic economic models should not take technical progress over time as given, but should explicitly model the interactions between policy and technical change. The models in the IMPC forum generally found that induced technical change would lower MAC in comparison to a calculation without this feature.[1] An interesting result of induced technical change is that it can create "path dependency" in the sense that the transformation to a carbon-free energy system can become irreversible if the carbon-free technologies become the least-cost option because of (induced) technical progress. If this occurs, the carbon price can begin to decline. Some studies project such a turning point towards the end of this century. The dummy variable ITC has a value of 1 if the model included a specification of induced technical change, and 0 otherwise. 17 observations are for ITC.

In a meta-analysis of economic models that examined the economic consequences of the Kyoto Protocol, Fisher and Morgenstern (2005) found evidence that a model's level of aggregation of regions and sectors had an impact on its estimate of MAC. Statistical significance was found for the number of regions and the number of energy sources in a model. For both variables the relationship with MAC was positive. The authors suggested that greater disaggregation might result in a more realistic representation of rigidities in, for example, international energy markets. We constructed the variables REGIONS and ENERGIES, where REGIONS indicates the number of regions in a model, and ENERGIES the number of primary energy sources. In our database REGIONS varies between 1 and 77; ENERGIES varies between 1 and 9.

From the 1970s there has been a fierce debate on the relative advantages and disadvantages of so-called "top-down" and "bottom-up" approaches in modelling energy-economy interactions. Traditionally, bottom-up models are rich in technical detail, but poor in modelling micro-economic behaviour and macro-economic feedbacks, while the opposite is true for traditional top-down models. The "top-down/bottom-up" controversies have naturally propagated into the area of climate change economics. However, since the mid-1990s a productive dialogue has started between the proponents of the two approaches (Hourcade, Jaccard et al. 2006). Observers have noticed some convergence to a middle ground that they have labelled "hybrid modelling" (Hourcade, Jaccard et al. 2006). Nevertheless, there are still differences between the approaches that might affect the assessment of abatement costs. The dummy variable CGE takes a value of 1 when the model is CGE ("top-down") and 0 otherwise. 33 observations were derived from a CGE model.

A different issue concerns the treatment of intertemporal dynamics within the models. Some models assume the existence of long-lived decision-makers that optimize the timing of

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[1] Note that Smulders and de Nooij (2003) argue that this result is likely in partial models of the knowledge market as used in the IMCP, but unlikely in a complete model of innovation and diffusion.

consumption, investments and abatement over the entire planning period (intertemporal optimization), while other models optimize only period for period (recursive dynamic). It might be that different dynamics lead to different emissions profiles over time, thereby affecting MAC in any particular year. For further reference we notice, however, that the more stringent the stabilization targets, the less flexibility there is for alternative emissions pathways (Fisher, Nakicenovic et al. 2007). The dummy variable IDO takes the value 1 when the model solves by intertemporal dynamic optimization (IDO), and 0 otherwise. 23 observations are from models that used IDO as the solution concept.

In some models, MAC are bound by some "backstop technology".[2] A backstop technology with respect to energy-related CO_2 emissions is a (hypothetical) technology that can produce any amount of CO_2-free energy at constant (high) cost. Marginal CO_2 abatement costs in a model with a backstop technology can never rise above a level for which the backstop technology would be the least-cost option. Some recent models have included the technology "carbon capture and storage" (CCS) as a sort of quasi-backstop technology. It is not a real backstop technology because the economic model still endogenously determines the price of CCS, but it nevertheless puts some quasi-cap on MAC.

We have constructed the dummy variable CCS that has value 1 if the model includes CCS or some undefined backstop technology, and 0 otherwise. Among the 49 observations, 26 have explicitly considered CCS or a backstop technology.

Finally, we have constructed dummy variables for the different modelling fora. The dummy variables IMCP and USCCSP have been introduced to check whether there are significant, but otherwise unexplained differences between the three modelling fora. This is all the more interesting as the IMCP models have been accused of making overly optimistic assumptions on technological progress and the costs of emissions abatement (Tol 2006).

The dummy variables IMCP and USCCSP have values 1 if the observation was presented in this forum, and 0 otherwise (some models participated in multiple fora). The forum EMF-21 does not have a dummy; the results of this forum are included in the constant of the regression in the following section. Among the 49 observations, 14 are from IMCP and 6 from USCCSP.

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[2] In other models, the upper bound on the MAC is implicit and may be rather complex.

5. Results

We present the results of two meta-regression models in Table 3. The first model (model 1) includes all variables that were described above. The second model (model 2) was derived by stepwise regression and only includes variables that are at least significant at the 10% level. Results of models 1 and 2 are presented for the years 2025 and 2050.

Model 1 explains more than 50 percent of the variance in the projected MAC across the studies, and it explains the MAC for 2025 a little better than those for 2050. The unexplained share of the variance is due to unobserved differences in, e.g., model structure and parameterization. The sign and significance of the independent variables are as follows.

The stabilization target and the baseline emissions have a significant effect on MAC, as we would expect. The signs of the coefficients are also as expected: an increase in the stabilization target reduces MAC, and an increase in baseline emissions increases MAC.

A multigas policy, offering "what" flexibility in climate policy, reduces MAC in 2025. This result is as expected, as we argued above. While the coefficient of multigas is still negative in 2050, it is no longer significant. Overall, the difference between single gas and multigas models appears smaller than might be expected. As argued in Tol (2006), the option to mitigate other greenhouse gases than carbon dioxide increases flexibility and so reduces costs. However, the only way to stabilize climate change is to reduce carbon dioxide emissions to zero. Therefore, the other greenhouse gas emissions have a substantial effect on costs only in the medium term. Furthermore, differences between models in the treatment of non-CO_2 greenhouse gases are large, and some models have many such gases while other models have few. The distance between baseline emissions and target emissions depends on the gases included in the analysis. Therefore, the multigas results are noisier than the single gas results, and this also explains the lack of significance in 2050.

The dummy variable indicating the assumption of induced technical change is significant for 2025, but not for 2050. What is remarkable, however, is that the 2025 coefficient seems to have an unexpected sign. The assumption of ITC seems to increase MAC rather than reduce it. This is not completely contrary to the conclusions of the IMCP forum, that emphasized the large differences among models regarding assumptions on, for example, existing market distortions, long-term investment behaviour and the nature of the technological options considered

(Edenhofer, Lessmann et al. 2006). In general we might conclude that the inclusion of ITC in IAMs is still, to a large extent, in an experimental phase.

Contrary to the results of Fisher and Morgenstern (2005) we do not find significant effects for aggregation characteristics across our models. There is no significant difference between MAC from models with a high level of detail in terms of primary energy sources and regions and those with low levels of detail.

Table 3 Results of meta-analysis

	MAC2025				MAC2050			
	Model 1		Model 2		Model 1		Model 2	
	b	t	b	T	b	t	b	t
CONSTANT	10.623	5.218 ***	8.922	6.523 ***	10.594	5.480 ***	8.217	7.355 ***
TARGET	–.016	–4.565 ***	–.015	– 5.487 ***	–.013	–3.902 ***	–.010	–4.204 ***
BASELINE	.667	3.524 ***	.677	4.202 ***	.267	1.487	.308	2.124 **
MULTIGAS	–.643	–1.787 *			–.499	–1.459		
ITC	.586	1.908 *	.607	2.115 **	–.021	–.073		
REGIONS	.000	.030			.006	.593		
ENERGIES	–.061	–.869			–.017	–.247		
CGE	–.444	–.977			–.009	–.022		
IDO	–.791	–2.229 **	–.790	–2.930 **	–.822	–2.441 **	–.852	–3.433 ***
CCS	–.511	–1.302	–.636	–2.153 **	–.250	–.670		
IMCP	–.727	–1.338			–.764	–1.481		
USCCSP	.415	.785			.146	.290		
R2	.650		.602		.536		.477	
R2 (adjusted)	.533		.551		.381		.439	

* significant at 10% level
** significant at 5% level
*** significant at 1% level

There are also no significant differences between CGE and other models. The absence of a significant difference might be interpreted as a confirmation of the suggestion of Hourcade, Jaccard et al. (2006) suggestion of a convergence of the modelling approaches – or at least the results.

Intertemporal dynamic optimisation is significant and has the expected sign. Flexibility in choosing the optimal reduction path (“when” flexibility) seems to matter a great deal.

The difference between models that include backstop technologies and CCS is significant for 2025 (for Model 2), but not for 2050. The sign of the coefficients is negative, suggesting that backstop technologies and CCS reduce MAC in comparison to models that do not include these options. The signs seem to make sense, and are contrary to the results of Fisher and Morgenstern (2005).

Compared to the EMF-21 modelling forum, the models in the IMCP forum tend to report lower MAC, and the models in USCCSP tend to report higher values. The coefficients, however, are not significant. The lower values for MAC in IMCP are not due to their inclusion of ITC. In the first place, the data include IMCP both results computed with and without ITC. Furthermore, in the regression model ITC is already accounted for in a separate variable.

In sum, the meta-analysis suggests that differences between MAC across studies can to some extent be explained by differences in target and baseline, intertemporal optimization, the inclusion of non-CO_2 gases, and the inclusion of CCS or a backstop technology. Other technical features of models, such as type (CGE or not), ITC, and aggregation issues, have random effects on MAC. There is some influence of the Modelling Forum on the MAC results: the more "experimental" models of the IMCP forum tend to report lower values than the more mature and standard models that participated in the USCCSP forum. This gives some support to the critique of Tol (2006) on IMCP. The EMF-21 forum takes a middle position.

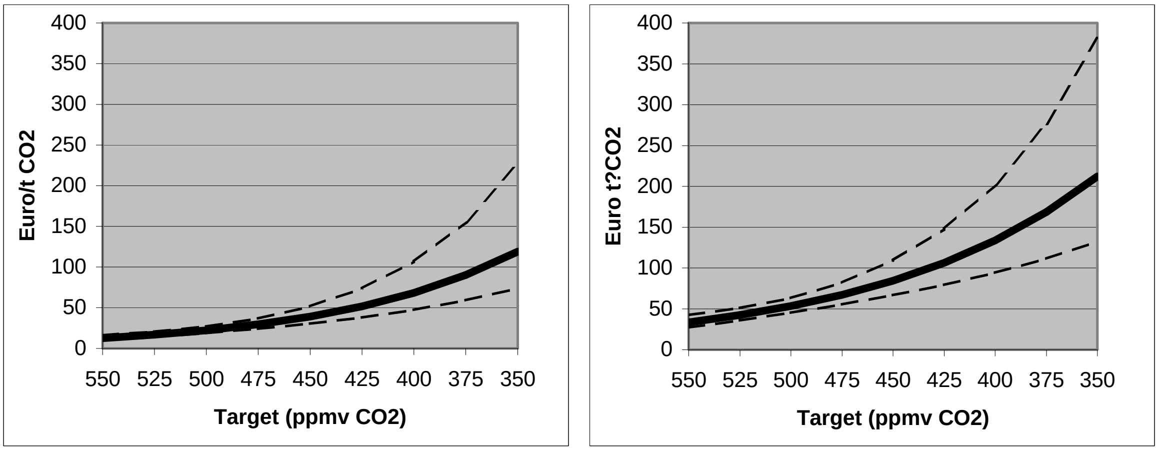
The estimated meta-regression functions can be used to predict MAC given specific values for the significant explanatory variables. We have tried to examine the association between MAC and TARGET based on the estimated meta-models (model 2). A problem in using these models for prediction is that the dependent variable is a logarithmic transformation of MAC and not MAC itself. We therefore use the following formula to recover the MAC value in original dimension from the estimated function.

$$MAC = EXP\left(\ln(MAC) + \frac{1}{2}\sigma^2 \right) \tag{2}$$

where σ^2 is the variance of the error term of the regression. The half-variance term is included in the exponent of Eq. (2) because the logarithmic transformation is a non-linear transformation (Verbeek 2004).

Figure 2 shows the association between MAC and TARGET for the full range of TARGET values in our database (350-550 ppmv). Figure 2 also shows the 95% prediction interval around the central prediction. The prediction interval quickly increases if we leave the range 450-550 ppmv where the bulk of our observations are. According the Figure 2, MAC for a stringent long-term target of 350 ppmv CO_2, which is more or less consistent with the EU's 2°C target (see Table 1), could be between € 74 and € 227 in 2025 and between € 132 and € 381 in 2050.

Figure 2 MAC as a function of Target (Left 2025; Right 2050)



As explained in the Introduction, our MAC estimate can be viewed as the carbon permit price in an idealized global emissions trading system. We can compare this "ideal global" MAC with two recent policy estimates at country and EU levels. The first relates to the United Kingdom's (UK) target of achieving a 60% reduction in greenhouse gas emissions by 2050[3], and the second to the recently announced policy targets of the EU (EC 2007; Elzen, Lucas et al. 2007).[4] Table 4 presents estimated MAC for the UK and EU targets in 2020 and 2050 (2050 for the UK only). Table 4 shows that estimated MAC (across the target range 550-350 ppmv) span the full range of the national estimates for both years.

Table 4 National and regional MAC (€^{2005}/tCO$_2$)

	2020	2050	source
UK	15 – 60	142 – 193	(Watkiss 2005)
EU27	23 – 93		(Elzen, Lucas et al. 2007)
MAC*	13 – 119**	34 – 212	This paper

* MAC across the target range 550-350 ppmv CO$_2$.
** These values refer to 2025.

6. Conclusions and Discussion

We have analysed information on MAC from 62 recent studies that assessed the economic impacts of meeting long-term stabilization targets of greenhouse gases in the atmosphere. All the studies computed a least-cost trajectory of global abatement efforts to meet such a target. The MAC assessed by these studies were shown to depend on the level of the stabilization target, the

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[3] The Energy White Paper "Our Energy Future – Creating a Low Carbon Economy" (2003).

[4] In January 2007, the European Commission proposed that the EU should (in the context of international negotiations) pursue the objective of a reduction of 30 percent in greenhouse gas emissions by 2020 (compared to 1990). Without international cooperation the EU should unilaterally commit to a reduction target of 20 percent in 2020 (EC, 2007).

assumed emissions baseline, intertemporal optimisation, the choice of control variable (CO_2 only versus multigas), assumptions on future technological options (backstop and CCS), and, to a lesser degree, on the scientific "forum" in which the study was developed.

The estimated MAC can be considered as "idealized global MAC": they assume a perfectly rational, efficient and global policy that would equate MAC across a ll sources of emissions at each point in time and would also result in an optimal trajectory of MAC over time. In less "ideal" settings, the MAC may well be substantially higher. We compared our "ideal global MAC" with MAC that were assessed in the context of real policy proposals in the UK and the EU and found that the policy-specific estimates and our central estimates are of the same order of magnitude. We also found, however, that the uncertainty of the estimates increases quickly if we move in the direction of more stringent targets.

1.1 Annex I Database of GHG stabilization studies

No.	Model	Platform
1	AIM	EMF-21, IMCP
2	AMIGA	EMF-21
3	GTEM	EMF-21
4	GEMINI	EMF-21
5	PACE	EMF-21
6	EDGE	EMF-21
7	EPPA	EMF-21
8	IPAC	EMF-21
9	SGM	EMF-21
10	WIAGEM	EMF-21
11	COMBAT	EMF-21
12	FUND	EMF-21
13	GRAPE	EMF-21
14	MERGE	EMF-21, USCCSP
15	IMAGE	EMF-21
16	MESSAGE	EMF-21, IMCP
17	MiniCAM	EMF-21, USCCSP
18	POLES	EMF-21
19	DEMETER-ICCS	IMCP
20	DNE21+	IMCP
21	E3MG	IMCP
22	ENTICE-BR	IMCP
23	FEEM-RICE	IMCP
24	GET-LFL	IMCP
25	IMACLIM-R	IMCP
26	IGSM	USCCSP

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