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Marginal abatement costs of greenhouse gas emissions: A meta-analysis

Onno Kuik [a,*], Luke Brander [a], Richard S.J. Tol [b,a,c,d]

[a] Institute for Environmental Studies, VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
[b] Economic and Social Research Institute, Whitaker Square Sir John Rogerson's Quay, Dublin, Ireland
[c] Department of Spatial Economics, VU University Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands
[d] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

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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 stabilisation of these gases in the atmosphere. We find the cost estimates of the studies to be sensitive to the stringency of the stabilisation target, the assumed emissions baseline, the way in which the time profile of emissions is determined in the model, the choice of control variable (CO_2 only versus multigas), the number of regions and energy sources in the model and, to a lesser degree, the scientific "forum" in which the study was developed. We find that marginal abatement costs of the stringent long-term targets that are currently considered by the European Commission are still very uncertain but might exceed the costs that have been suggested by recent policy assessments.

1. Introduction

Climate change continues to be high on the political agenda, and politicians sometimes seem to be engaged in a bidding war about who dares to propose the most ambitious target. Although in the public debate much emphasis is placed on the potential damage costs of unchecked climate change, a policy to mitigate climate change by reducing the emissions of greenhouse gases also bears costs. The study of abatement costs can be confusing to the uninitiated because many studies have produced a wide range of estimates and these estimates are dependent on a number of key assumptions that are not always well documented. Therefore, this paper seeks to clarify the assessment of marginal cost of greenhouse gas emission reduction by means of a meta-analysis of recent estimates.

In recent years, many research teams have developed computer-based economic models that have computed marginal abatement costs (MAC) of greenhouse gas (GHG) emissions that are consistent with long-term climate policy targets, in terms of maximum concentrations or temperature increases. It is possible to interpret these MAC as carbon permit prices in an idealised global emissions trading system that allows the participants maximum "where" flexibility, and in some models also "what" and "when" flexibility. This means that MAC are equalised across all sources ("where" flexibility), and that in some models MAC change over time according to some intertemporal optimisation rule ("when" flexibility), and 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 (i.e., trade-offs between different greenhouse gases) (Weyant et al., 2006). We also used results of the models that participated in the Innovation Modeling Comparison Project (IMCP) that specifically addressed the potential impact of the induced technical change on long-term abatement and abatement costs (Edenhofer et al., 2006), and the US Climate Change Science Program (USCCSP) that addressed all these issues (Clarke et al., 2006).

The different assessment models produce varying estimates of MAC. The first aim of the analysis presented in this paper examines the sensitivity of MAC estimates to the specifications and assumptions underlying these models. Among other factors, we examine the influence on MAC of stabilisation targets, baseline emissions, the inclusion of other GHGs in addition to CO_2 in the emissions target, and induced technological change.

* Corresponding author. Tel.: +31 23 5989513; fax: +31 23 5989553.
E-mail address: onno.kuik@ivm.vu.nl (O. Kuik).

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By conducting a meta-analysis of model results we aim to identify the key factors that drive the 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. Thus, the second aim of this paper is to predict MAC (or MAC ranges) for alternative stabilisation targets for greenhouse gas concentrations.

A number of existing studies provide syntheses of MAC estimates and analyse the influence of modelling assumptions. The meta-analysis in this paper uses more up-to-date model results than previous research (Barker et al., 2002; Fischer and Morgenstern, 2005; Repetto and Austin, 1997). This paper uses the same model results as Barker et al. (2006b), but many more in addition. Where useful, we compare our results with those of earlier studies.

The structure of this paper is as follows. Section 2 introduces the concept of long-term stabilisation targets for greenhouse gas emissions in the atmosphere. Section 3 presents the meta-analysis research methodology used in this paper. Section 4 describes the data. Section 5 presents the results of the meta-analysis, while Section 6 concludes.

2. Stabilisation 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 global 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 (EC, 2007). The different studies that we analyse in this paper have examined different stabilisation 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 ($W\,m^{-2}$), the concentration of the greenhouse gas CO_2 (ppm CO_2), concentrations of greenhouse gases in the atmosphere expressed in CO_2 equivalents (ppm CO_2-eq), and global mean temperature (°C). IPCC (2007) classified stabilisation targets into six different categories (I–VI), and showed the concordance between the targets in alternative metrics (see Table 1).

Table 1
Concordance between stabilisation targets in alternative metrics.

Category	Additional radiative forcing ($W\,m^{-2}$)	CO_2 concentration (ppm)	CO_2-eq concentration (ppm)	Global mean temperature increase (°C)
I	2.5–3.0	350–400	445–490	2.0–2.4
II	3.0–3.5	400–440	490–535	2.4–2.8
III	3.5–4.0	440–485	535–590	2.8–3.2
IV	4.0–5.0	485–570	590–710	3.2–4.0
V	5.0–6.0	570–660	710–855	4.0–4.9
VI	6.0–7.5	660–790	855–1130	4.9–6.1

Source: (IPCC, 2007, Table SPM.5).

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 (Nelson and Kennedy, 2008; Stanley, 2001).

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 assumed to be a linear function of a set of explanatory variables and a random error. 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 et al., 2007), and on the basis of earlier meta-analyses (Barker et al., 2002, 2006b; Fischer and Morgenstern, 2005). The explanatory variables include stabilisation target, emissions baseline, various model and policy assumptions, and also the particular forum in which the study was developed.

Nelson and Kennedy (2008) identified four major problems in this kind of meta-regression. These are selection bias, heterogeneity in data and methods, heteroskedasticity and non-independence of multiple observations from primary studies. Selection bias occurs if not all members of the target population (in our case: the population of cost-of-GHG-stabilisation-studies) have an equal chance of being selected in the sample. While some potential sources of selection bias are difficult to control (e.g., publication bias), we did our best to minimise bias by selecting as many studies from different lineage as possible. As a result, we ended up with a heterogeneous set of studies. We limited the heterogeneity, however, by selecting only those studies that focussed on long-term stabilisation targets (and not on some (intermediate) emissions target).[1] Methodological heterogeneity was addressed by the use of methodological dummy variables in the regression. Heteroskedasticity, or the non-constancy of the variance of the error term of the regression, and non-independence across observations in the sample are addressed in Section 5 below.

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 normalised these observations that are expressed in different dimensions and currencies into 2005 Euros per tonne of CO_2 ($€^{2005}/tCO_2$-eq). For normalisation, 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-eq). Appendix I provides a tabulated overview of all studies in the database. Complete information on the explanatory variables was available for 47 observations for 2025 and 49 observations for 2050 (Table 2).

[1] We also followed the suggestion of Nelson and Kennedy to analyse more homogeneous subsamples from the heterogeneous sample. This did not lead to additional insights, however. We will return to this issue in Section 5.