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Carbon Abatement Costs: Why the Wide Range of Estimates?

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Abstract

Estimates of marginal abatement costs for reducing carbon emissions in the United States by the major economic-energy models vary by a factor of five, undermining support for mandatory policies to reduce greenhouse gas emissions. We use meta analysis to explain these cost differences, holding policy regimes constant and focusing on the role of baseline emissions projections and structural characteristics of the models. The results indicate that certain assumptions, like freer trade and greater disaggregation of regions and nonenergy goods, lead to lower estimates of marginal abatement costs, while more disaggregated energy goods raise them. Other choices, like myopic optimization by households or the inclusion of an international finance sector, seem less significant. Nor do emissions baseline differences explain much of the cost differences. Our analysis can help indicate which modeling assumptions are most important to understanding the cost discrepancies and developing consistent modeling practices for policy evaluation.

Key Words: climate models, carbon tax

JEL Classification Numbers: Q4, Q25, D58

Contents

Carbon Abatement Costs: Why the Wide Range of Estimates?

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Introduction

Recent reviews of more than a dozen major economic-energy models yield estimates of marginal abatement costs for reducing carbon emissions in the United States that vary by about a factor of five, from $44 up to as high as $227 per metric ton of carbon (Weyant and Hill, 1999; Lasky, 2003). Not surprisingly, this wide range of estimates undermines support for a domestic cap-and-trade system or other mandatory policies to curb carbon emissions.

Recognizing the importance of knowing the price tag on a policy before adopting it, two broad approaches are possible: 1) Develop a policy architecture that tends to reduce the cost uncertainties inherent in controlling carbon emissions, for example, liberal banking of credits (including offsets derived from sinks and/or other types of project-based activities); or a so-called "safety valve" which would mandate the government to sell additional allowances to prevent the price from rising excessively. 2) Attempt to narrow the observed range of estimates by conducting further research on carbon mitigation costs. A particular strain of research, adopted herein, involves developing cross-model comparisons, so-called meta analysis, across a range of economic-energy models to identify methodological or other factors that account for the wide range of cost estimates in the literature.

The cost of the second path—adopted herein—involves new research designed to achieve greater consensus among experts about the appropriate modeling frameworks to be used in estimating carbon mitigation costs. Specifically, we develop a meta analysis

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of major economic-energy models to explain the differences in cost estimates among them.

At the outset, we distinguish the four principal types of factors that explain the differences in estimates of carbon mitigation costs:

- Projections of base case emissions;
- The climate policy regime considered (especially the degree of flexibility allowed in meeting the emissions constraints);
- The structural characteristics of the models, including how the turnover of capital equipment is handled, and how the rate and processes of technological change are incorporated in the analysis; and
- The characterization of the benefits of conventional pollution reductions, especially how and to what extent so-called “ancillary benefits” are included.

The first two of these factors involve assumptions made in individual model simulations. The third represents particular structural elements specific to each economic-energy model. The fourth is a question of whether as well as how benefits are incorporated in the analyses.

The earliest systematic attempt to assess the quantitative importance of these different factors was by Repetto and Austin (1997), hereinafter R/A, in a paper published in the run-up to Kyoto. Widely discussed in policy circles at the time, the R/A paper developed a meta analysis of economic-energy models to try to explain the range of cost estimates available in the (then) existing literature. Overall, differences in policy regimes—such as emissions trading and revenue recycling—emerged as key factors in their analysis, as did the consideration of ancillary benefits. Only limited attention was paid to differences in baselines, or to structural modeling issues—e.g., the representation of substitution possibilities by producers and consumers—or the treatment of technological change in individual models.

Following the Third Conference of the Parties (COP 3) of the United Nations Framework Convention on Climate Change (UNFCCC), which established the initial parameters of the Kyoto Protocol, the Stanford Energy Modeling Forum (EMF) organized a series of comparative analyses of the economic and energy sector impacts of the proposed Protocol. Like the pre-Kyoto studies, these EMF-16 analyses also generated a wide range of cost estimates. Yet, since the models used in EMF-16 were all based on the same relatively well-defined policy regime (i.e., the Kyoto targets), and the simulations restricted to exclude consideration of the ancillary benefits of reduced carbon emissions, the observed variations in cost estimates cannot be attributed to either differences in policy regimes or to the treatment of benefits. Rather, the observed variation in EMF-16 marginal abatement costs is potentially attributable to only two factors: 1) differences in baseline assumptions and 2) different structural characteristics of the individual models. What is not known, however, is the relative importance of baseline versus structural model characteristics and, specifically, which particular structural characteristics are most critical.

The present paper uses the EMF-16 results as inputs, combined with the findings from a number of recent analytical articles on the structural characteristics of the different models, to refine and update the R/A meta analysis. With the expanded information now available we expect to obtain a clearer picture of the importance of baseline differences as well as of individual structural characteristics of the models in explaining the observed variation in carbon abatement costs.

Section II of the paper reviews the R/A analysis, as well as some recent qualitative analyses comparing the structural characteristics of the different models. Section III presents the results of the meta analysis based on the EMF-16 model simulations. Section IV discusses the key findings. Section V offers concluding thoughts.

Background

Three distinct but related issues are relevant to our consideration of the modeling uncertainties: the rationale for conducting a meta analysis of carbon mitigation cost estimates, the original R/A paper, and the key structural characteristics relevant to the individual models.

Context for the Meta Analysis

Consider the situation where only two models exist to analyze the costs of mitigating a particular environmental problem (A and B). Imagine that Model A was developed by a top-level university team (with National Science Foundation funding), subject to extensive peer review, and employed state-of-the-art analytical techniques. In contrast, Model B was developed by a third tier consulting firm with support from commercial interests. It was not based on the latest techniques and had not been peer reviewed. Not surprisingly, the cost estimates generated by the two models differed dramatically, in the expected direction. In this case the issue of model choice is simple: any independent analyst would ignore Model B and, instead, rely exclusively on Model A, presumably conducting some form of sensitivity analysis to develop uncertainty bounds associated with this single model.

Now consider the case of carbon, where more than a dozen type A models are available for estimating mitigation costs. The fact that so many independent, relatively sophisticated economic-energy models are used to estimate carbon mitigation costs reflects both the state of the art as well as the importance attached by modelers (and funders) to this issue. The wide range of estimates reflects the divergent views of modelers on a broad set of analytic issues.

One approach to addressing the diverse set of model results is to harmonize assumed policy regimes and other relevant assumptions and then explore, via a mixture of quantitative and qualitative analysis, the methodological issues that drive the broad model differences. In general terms, this is the approach adopted in EMF-16. For their analysis, the EMF-16 organizers assembled more than a dozen major (type A) models and developed a comparative analysis of the economic and energy sectors impacts of the Kyoto Protocol. The principal outputs of the EMF analysis were a set of marginal abatement cost curves for each model, based on a standardized policy regime (the Kyoto Protocol), plus a series of explanations offered to rationalize the observed differences among the models.[1] A related but distinct approach—the one adopted by R/A—is to define a number of specific variables that reflect the different factors presumed to explain model differences and then develop a meta analysis to assess the quantitative importance of these variables. If, in fact, only a handful of easily understandable factors are important to determining the results, then by estimating their influence on the cost estimates, the meta analysis can help inform judgments about these factors. This, in turn, could help build support for particular modeling approaches and thus narrow the range of uncertainty associated with carbon abatement costs. Notwithstanding the obvious statistical limitations of any meta analysis based on a small number of underlying studies—including the present one—we believe this technique can bring certain insights that could help to clear the fog created by the wide range of cost estimates available in the literature.

The First Meta Analysis: Repetto and Austin

The data underlying the R/A analysis is drawn from 162 pre-Kyoto model runs from 16 different energy-economic models published in the period 1983–1997.[2] The covered time period differs by model, but all fall between 2000–2050. R/A adopted a nonlinear formulation and regressed the percentage change in gross domestic product (GDP) costs on 11 independent variables:[3] **GDP** (percentage change in GDP relative to the baseline projections for the terminal year of the simulation); **CO_2** (percentage reduction in CO_2 emissions relative to the baseline projections for the terminal year of the

[1] EMF-16 also developed a set of priorities for future research.

[2] The individual models are: BKV (Boyd, Krutilla and Viscusi (1995)); CRTM (Rutherford (1992)); DGEM (Jorgenson and Wilcoxen (1992)); DRI (Data Resources Inc. (1994); Edmonds-Reilly-Barns (Edmonds and Reilly (1983, 1985); EPPA (Yang, et. al. (1996)); Fossil2 (AES (1990); G-Cubed (McKibben and Wilcoxen (1992)); Global 2100 (Manne and Richels (1990)); Goulder (Goulder (1995)); GREEN (Burniaux et al. (1991)); IIAM (Charles River (1997)); LINK (Kaufmann et al. (1992)); Markal-Macro (Hamilton et al. (1992)); MERGE2 (Manne and Richels (1995)); SGM (Edmonds et al. (1993)).

[3] The following form was used for the regression:

$$\text{GDP} = \alpha_0 + \alpha_1 \text{CO}_2 + \alpha_2 (\text{CO}_2)^2 + \sum_{i=1}^{8} \beta_i \cdot X_i \cdot (\text{CO}_2) + \beta_9 \cdot X_9 \cdot (\text{CO}_2)^2 .$$

simulation); **MACRO** (1 if a macro model, 0 if a CGE model); **NCBACK** (1 if there is a constant cost noncarbon backstop technology, 0 otherwise); **RECYCLING** (1 if revenues from the policy instrument are used to reduce existing distorting taxes, 0 otherwise); **CLIMATE** (1 if averted climate change damages are modeled, 0 otherwise); **NONCLIMATE** (1 if averted air pollution damages are modeled, 0 otherwise); **JI** (1 if joint implementation or global emissions trading is modeled, 0 otherwise); **PRODUCTION** (1 if the model allows for product substitutions, 0 otherwise); **FUELS** (the number of primary fuel types recognized for possible inter-fuel substitution); **YEARS** (the number of years available to meet the abatement target).

At first glance the R/A results appear to be quite solid (Table 1): they have a relatively large sample, achieve a good fit (R^2), and find a large number of variables that appear significant, and with the expected sign. [4] Yet, careful review suggests a number of concerns about the individual economic-energy models chosen for the meta analysis, the variable definitions, and the econometric methods used.

[4] R/A report standard errors as an indication of fit, but they do not attempt to claim statistical significance, due to methodological limitations. Note that since the dependent variable is defined as the percentage change in GDP, a negative number, the regression coefficients reflect cost *decreases.*

Table 1: Repetto and Austin Regression Results

Independent Variables	Coefficient (t-value)
CO_2	-0.02319 (2.556)
$(CO_2)^2$	-0.00079 (7.182)
MACRO	-0.05548 (3.977)
NCBACK	0.00051 (10.2)
RECYCLING	0.04427 (6.79)
CLIMATE	0.00943 (2.363)
NON-CLIMATE	0.03823 (4.914)
JI	0.02337 (7.147)
PRODUCTION	0.00378 (1.036)
FUELS	0.00018 (0.155)
YEARS	0.00005 (0.833)

R-squared=0.83

First, R/A relied on a fairly heterogeneous group of models, including short-term macro forecasting models (e.g., DRI, LINK), linear programming models (e.g., Markal-Macro), and highly stylized CGE models (e.g., Goulder).[5] In contrast, EMF-16 was able to draw on a more homogeneous set of models, mostly of the CGE variety.[6]

Second, there are concerns about the econometric methods used by R/A. In effect, they incorrectly treat multiple observations from the same economic-energy model as if they were independent observations.[7] We believe it is more plausible to assume that observations from the same model are related to one another; some models will tend to generate systematically higher marginal abatement cost estimates than others, while other models will generate systematically lower estimates than others. The preferred approach is to "cluster" the observations from the same models via a "robust variance estimator."[8] Failure to use such an estimator leads to downwardly biased standard errors. Interestingly, even with the biased estimates of standard errors reported by R/A, only a single variable addressing

[5] R/A define an independent variable (MACRO) to distinguish the two short-term models in their data set from the others.

[6] Only one of the EMF models (Oxford) is considered a pure macro model.

[7] R/A report that as many as 24 of the observations came from a single model (Jorgenson and Wilcoxen) and as few as three observations came from another model (Markal-Macro). The average was slightly more than 10 observations per model.

[8] See Huber (1967) and Rogers (1993) for both the analysis of the problem and the rationale for the robust variance estimator.

structural model characteristics, NCBACK (which allows for noncarbon backstop fuels) appears to be statistically significant.[9] Neither of the other variables used to address structural issues (PRODUCTION and FUELS) is reported as significant. Thus, R/A are only able to identify a single significant variable to reflect the complex structural characteristics of the models analyzed.

The principal variables that appear to have significant explanatory power in the R/A analysis involve the policy regime (JI, RECYCLING) and the inclusion of benefits (CLIMATE, NONCLIMATE). While these results support the notion that differences in policy regimes and the incorporation of ancillary benefit measures are important determinants of carbon mitigation costs, they do not address the structural differences among the models, certainly not those relevant in the EMF-16 results.

Unlike the model runs used in EMF-16—which were all calibrated to the year 1990—the suite of models used in the R/A analysis cover different time periods. The variables YEARS and GDP partially adjust for these differences, but not entirely so, since they cannot account for technological change occurring over time. YEARS is not statistically significant, even without incorporating a robust variance estimator.

Notwithstanding these concerns, it is fair to say that the R/A paper represents a novel and quite clever approach to assessing the variability of model results. Arguably, their empirical work was hampered by the limited number of model simulations then available to serve as inputs for their meta analysis, as well as by certain methodological limitations. More recently, the rich set of simulation results produced by EMF-16, combined with the greater availability of information to document the individual models, creates opportunities for updating the R/A approach, with a particular focus on baselines and model structural characteristics as potential determinants of differences in marginal abatement costs.

[9] MACRO is also reported as statistically significant. However, as noted, this is merely capturing the presence of two macro models in the group (DRI and LINK).

Structural Characteristics of the Models

The period immediately following COP 3 in Kyoto may go down in history as the golden age of economy-energy modeling. The modeling community was extremely active in analyzing the various features specified in the Protocol and, particularly, in conducting sensitivity analyses on key parameter assumptions. The EMF-16 results—which incorporated many of the new modeling innovations developed during this period—were published in a special issue of the *Energy Journal* (1999). Equally impressive was the work by experts not associated with particular models, but nonetheless knowledgeable about a range of models. Ghersi and Toman (1999), hereinafter G/T, examined the detailed structural characteristics of a number of economic-energy models and developed an analytic framework for comparing them. Specifically, they expanded the R/A list of structural elements to 13 such elements in four separate areas: equity, technical change, carbon trade, and international linkages. Overall, their analysis covered more than a dozen different models (see Appendix for their full results).

Selecting from the important modeling differences identified by G/T for the 11 models used in our analysis, we have created a set of variables representing eight of the relevant factors.[10] These variables include whether households are modeled as infinitely lived; whether a noncarbon backstop technology exists; whether the model has endogenous technical change; the number of energy goods and the number of nonenergy goods in the model; the degree of geographic disaggregation; the substitutability of goods in international trade; and whether an international financial sector is modeled, an indicator of capital mobility. In addition, two other variables are included: a measure of the baseline differences among the models, and whether the model is of the macro or

[10] Only nine of the EMF-16 models had sufficient modeling descriptions and price data for all four regions. Two more EMF models (CETA and Oxford) are added for the U.S. regressions. Oxford is also used for the EU and Japan analyses.

CGE variety.[11] Since our focus is on domestic mitigation costs, we are able to abstract from some of the modeling differences identified by G/T, notably those related to carbon trade regimes.[12] Finally, we note that our dependent variable differs from R/A in that we focus on marginal as opposed to total abatement cost.

To obtain a consistent set of cost estimates across a range of abatement levels for the individual models, we rely on a parameterization of the EMF-16 results developed by Ghersi (2001). Specifically, Ghersi adopted a simple $a\,x^n$ functional form to reconstruct the abatement cost curves developed by Weyant and Hill (1999), both with and without international emissions trading (among Annex B nations).[13] For each region and model, we use the Ghersi estimates to calculate the costs of reaching three alternative reduction targets (without permit trade): Kyoto, Kyoto + 5% (i.e., a less stringent abatement target), and Kyoto + 10% (i.e., an even less stringent target).

The complete set of variables used are described in the following table:

[11] Baseline differences are taken from Ghersi (2001) who, in turn, derived them from EMF-16 data.

[12] These differences were held constant for the calculations used to determine the domestic marginal abatement cost curves.

[13] Figures 8 and 10 of Weyant and Hill (1999) are integrated to obtain for each model and zone the two points *(abatement, marginal price)* necessary for calibration. Those two points are specifically chosen as the *No Trading* and *Annex 1 Trading* results to match the EMF results exactly. With (x_1, p_1) and (x_2, p_2) the *No Trading* and *Annex 1 Trading* data, $\{ p_1 = \alpha x_1^{\ n},\ p_2 = \alpha x_2^{\ n} \}$ yields $n = \ln(p_1 / p_2) / \ln(x_1 / x_2)$ and $a = x_1^{\ n} / p_1$.

Table 2: Definition of Independent Variables

BASELINE	% abatement from baseline necessary to achieve Kyoto target
REGIONS	Number of countries/regions in model
ENERGY	Number of energy goods in model
NONENERGY	Number of nonenergy sectors in model
HOUSEHOLDS	1 if households infinitely lived, 0 otherwise
BACKSTOP	1 if noncarbon backstop available, 0 otherwise
TECHNOLOGY	1 if model incorporates endogenous technological change; 0 if exogenous change
TRADE	1 if perfect substitutes, 0 if Armington or other specifications[14]
FINANCE	1 if capital mobile internationally, 0 if no international financial sector
MACRO	1 if macroeconometric model, 0 if CGE or otherwise

Table A.1 in the Appendix displays the values assigned to the individual models for baselines as well as for the identified structural characteristics. Separate baseline estimates are reported for each of the four regions analyzed by EMF-16 (U.S., EU, CANZ, Japan).[15] We define a set of dummy variables with the following extensions: _5% to denote the emissions target of 5% over Kyoto; _10% to denote a target of 10% over Kyoto; _EU for the European Union; _JAPAN for Japan; and _CANZ for the group of Canada, Australia, and New Zealand.

[14] These characterizations apply to the bulk of the internationally traded goods. Some goods, like electricity or distributed gas, may not be traded across regions. Other goods, like oil, may still be modeled as perfect substitutes in models with Armington assumptions for final goods and other inputs.

[15] Baselines are defined as the percent reduction in emissions needed to meet the Kyoto target.

BASELINE was chosen as an independent variable, as in R/A, since the necessary amount of abatement needed to reach a fixed target is expected to increase costs. Next, we include a class of variables indicative of the degree of economic disaggregation in the models: REGIONS, ENERGY, and NONENERGY. We would expect that greater opportunities for substitution and reoptimization among countries, consumption goods, and energy inputs would tend to lower costs. On the other hand, greater detail about market rigidities or supply constraints, particularly in electricity, natural gas, or other fuels distribution, could tend to raise marginal abatement costs. Two variables related to the modeling of technology were chosen: BACKSTOP and TECHNOLOGY. The availability of a noncarbon backstop should, all else equal, lower predicted costs if the option comes into play. Endogenous technological change, since it is optimized rather than autonomous, should also allow for lower costs. [16] The structural variable HOUSEHOLDS is included, since the horizon of the consumer problem might be important; in theory, dynamic optimization should improve overall efficiency compared to myopic optimization. The MACRO variable is intended to test—a la R/A—whether the macroeconometric modeling method produces consistently different results than CGE or aggregated cost models.[17]

Although we evaluate domestic marginal abatement costs, these estimates were derived from a set of (mostly) general equilibrium models that include international linkages.[18] Thus, we include two variables representing international linkages—TRADE and FINANCE—though REGIONS could also be related to this group. Greater substitutability of goods in international trade and the inclusion of an international finance sector should allow for better global resource allocation, although specific countries might experience losses in terms of trade, investment flows, and asset values (including permit assets). In the EMF policy experiment, the domestic marginal

[16] In practice, however, only the ABARE-GTEM model includes endogenous technical change, so in our regressions this variable effectively functions as a dummy for this relatively high-cost model.

[17] In practice, as with endogenous technology, only one model (Oxford) falls in this category.

[18] Klepper and Peterson (2003) discuss why domestic marginal abatement cost curves are not independent of the level of abatement in the rest of the world. World energy prices are an important link, and the strength of the cost dependence is influenced by factors like trade elasticities and trade structures.

abatement cost estimates also reflect an equilibrium in which all the Annex I countries are abating carbon emissions; marginal abatement costs in the EU might be quite different in an international system in which a large emitter like the United States does not abate.

Meta Analysis Results

As a first stage of the analysis, we examine the importance of differences in baselines among the models as determinants of differences in marginal abatement costs as estimated by EMF-16. Second, we consider the importance of the structural characteristics identified by G/T in explaining the observed range of cost estimates.

Baseline Issues

To address the issue of how baseline differences can effect the resulting cost estimates, we simply regress the natural logarithm of marginal abatement costs (MAC) on the baseline emissions (BASELINE, defined as the percentage reduction from baseline emissions required to meet the Kyoto target), for different emission reduction levels. The percent of the variation in MAC explained by this basic equation—calculated as the R^2—is shown in Table 3 for each of the four regions considered by EMF-16.

The results suggest considerable variation in the relative importance of BASELINE across regions and abatement levels. For example, if the goal is to reduce U.S. CO_2 emissions to a level that is 10 percent above Kyoto target emissions, baseline differences among the models only explain about 2.5 percent of the observed differences in marginal abatement costs among the models. At the full Kyoto abatement levels, baseline differences explain 8 percent of the variation. In the case of CANZ, this effect is more extreme, with baseline differences explaining 24 percent of the marginal cost differences at Kyoto target levels, but only 1.2 percent at Kyoto plus 10 percent. For the other regions, a different story emerges: In the case of Japan, the baseline differences among the models explain more than a quarter of the observed variation in costs in the case of Kyoto plus 10 percent. Unlike the U.S. case, baseline differences in Japan and the EU seem to be more important at higher abatement levels than at lower levels.

Table 3: Effects of Baseline Differences on Marginal Abatement Costs

	Kyoto Target Emissions			
	US	EU	CANZ	JAPAN
	8.0	1.6	24	7.9
	Kyoto Plus 5% Emissions			
Percent variation in LnMCs explained by baseline differences among models*	US	EU	CANZ	JAPAN
	5.1	3.8	16.4	15.0
	Kyoto Plus 10% Emissions			
	US	EU	CANZ	JAPAN
	2.5	11.9	1.2	26.8

*Note: This estimate is the R-squared obtained by regressing LnMC on Baseline

Stepwise Regression Results

Our analysis uses a stepwise regression that proceeds to exclude variables without significant explanatory power. To cope with the problem of calculating standard errors when observations are drawn from the same source, we "cluster" the observations from the same models using a "robust variance estimator" available as a "CLUSTER" command in STATA. We perform five regressions, one for each region, and one overall regression with regional dummies. The results are reported in Table 5.

Due to limited degrees of freedom, we did not include interaction terms between variables. However, we note that these effects may be present. For example, the assumptions about substitutability in international trade may have greater impacts if there is more geographic or economic disaggregation.

BASELINE

All else equal, models with relatively high baseline emissions should predict higher costs of reaching fixed targets, since more abatement would be required. Our meta analysis indicates that this relationship holds in the overall regression, but it was not a significant predictor in the individual regional regressions. This may be explained by the fact that baseline emissions are not actually an exogenous assumption. Rather, like marginal abatement costs, they are predicted outputs of the model, so it is likely that the relationships would be more complex. For example, if marginal abatement costs are low because energy technologies are more easily substituted in production and consumption activities, then, in the absence of a zero carbon price, use might shift more to higher carbon content inputs than in other models, leading to higher baseline emissions.

REGIONS

The extent of geographic disaggregation in the models is associated with a slight negative effect on marginal abatement costs. This effect was significant for all but the Japan regression. Greater disaggregation may indicate greater opportunities for trade and specialization, and perhaps within-region emissions optimization. Such opportunities could also be associated with emissions "leakage" to countries without emissions caps, but we do not have sufficient information to fully gauge this effect.

HOUSEHOLDS

The treatment of household behavior is an important issue in model development. Whether households are infinitely lived is a question of whether the optimization is myopic, in which case consumers base choices only on current prices. Alternatively, in forward-looking models, consumers optimize over time. One would expect costs to be lower when consumers are dynamically optimizing. While the relationship is indeed negative for the U.S. and CANZ, it is actually positive for the EU, although it is not significant in the overall regression or for Japan.

BACKSTOP

All else equal, the availability of a noncarbon backstop technology should make meeting more stringent abatement targets easier, as long as the carbon price is sufficient to bring the backstop online. Of course, all else is not equal in these models, and the incorporation of the backstop technology may be associated with different specifications of other technologies. Unfortunately, we lack detailed information on these points. However, we find that the inclusion of a noncarbon backstop is associated with lower marginal abatement costs overall, particularly for the EU, but it is not a significant factor for the U.S. or Japan and is even associated with higher costs for CANZ. This result is consistent with that of R/A, who found that GDP declines more when the reference scenario implies more abatement is necessary to meet the emissions targets.

TECHNOLOGY

The technology variable is intended to reflect the presence of endogenous technical change. Theory indicates that induced technological change should reduce the costs of compliance, since productivity investments are optimized across sectors with respect to carbon prices. In practice, however, the *relative* rate of technological change also depends on competing assumptions about the exogenous rate of progress. Since only one model of this set includes endogenous technical change, in our regressions this variable effectively functions as a dummy for the ABARE-GTEM. The coefficient is always positive and significant, since this model consistently predicts some of the highest marginal abatement costs of all the models.

NONENERGY

The disaggregation of nonenergy goods provides a richer representation of the economic sectors that use energy inputs. We postulate that with more substitution possibilities in the demand for energy—i.e., not just in production but also in consumption of the range of final products—abatement targets might be more easily achieved. Our meta analysis indicates that modeling more nonenergy goods is related to lower marginal abatement costs across all models and within the overall regression.

ENERGY

A richer modeling of energy sectors could allow for more substitution options. Alternatively, it could also allow for better modeling of the rigidities inherent in many of these markets, such as distribution constraints for natural gas or electricity, capacity constraints, and the like. The regression results suggest that greater disaggregation of energy goods is associated with higher marginal abatement costs, though the effect seems smaller than that for nonenergy goods.

FINANCE

The inclusion of an international finance sector and mobile capital should allow for a more efficient allocation of capital worldwide, although the impact on individual countries would vary. A costly climate policy would be associated with lower rates of return, and investment would tend to flow to non-Annex I countries or, possibly, to Annex I counties with less burdensome carbon abatement requirements. Thus, carbon policies, whether with permit trade or not, still operate in an international equilibrium and can have significant impacts on financial flows.

In terms of predicting marginal abatement costs, however, we find that capital mobility does not have a significant effect overall. It is associated with higher marginal costs in the U.S. and CANZ and lower marginal costs in the EU. This could reflect the direction of investment flows to or from these regions, but we do not have sufficiently detailed information to support such a hypothesis. For example, a relatively lower rate of return in the EU could lower investment, in turn lowering demand for energy and driving down carbon prices.

TRADE

Greater substitutability of goods in international trade should also allow for carbon policies to have a greater impact on international resource allocations and prices. In part, lower energy demand in Annex I countries is more likely to drive down worldwide energy prices and increase import demand for energy-intensive goods from non-Annex I nations. Although this activity would constitute carbon "leakage," it is likely to lower marginal abatement costs by allowing Annex I countries to specialize more in low-carbon goods rather than use costly methods to produce energy-intensive goods with less carbon. The meta analysis indicates that models with traded goods as perfect substitutes tend to produce lower marginal abatement costs than those using Armington assumptions with imperfect substitution between foreign and domestic goods.

MACRO

The Oxford model is the only fully macroeconometric model among the EMF-16 suite of models. Simple inspection of the marginal abatement curves shows that it predicts some of the highest marginal abatement costs. Further, in their meta analysis, R/A showed that macro models tend to yield higher (total) abatement costs than CGE models. However, in our meta analysis, the MACRO variable was rejected in all the stepwise regressions as having insignificant explanatory power compared to the other structural variables, so we do not include it in the table of results.

Table 4: Results of Meta Analysis

Dependent Variable: Natural Log of Marginal Abatement Cost for Meeting Kyoto Commitment

Independent variable name	All regions	US	EU	CANZ	Japan
BASELINE	0.37 (2.76)	*	*	*	*
REGIONS	-0.07 (-10.47)	-0.02 (1.90)	-0.20 (97.09)	-0.05 (4.71)	*
HOUSEHOLDS	*	-0.20 (2.56)	0.20 (24.64)	-0.69 (7.31)	*
BACKSTOP	-0.93 (-8.44)	*	-2.84 (144.84)	0.28 (2.41)	*
TECHNOLOGY	3.74 (23.95)	2.85 (18.30)	5.15 (189.67)	2.16 (11.22)	2.73 (7.12)
NONENERGY	-0.40 (-14.09)	-0.29 (14.84)	-0.56 (160.23)	-0.16 (5.73)	-0.27 (5.33)
ENERGY	0.15 (12.96)	0.09 (7.27)	0.23 (109.97)	0.01 (1.82)	0.11 (3.32)
FINANCE	*	0.53 (5.95)	-0.90 (59.07)	0.44 (4.24)	*
TRADE	-1.96 (-10.38)	-0.71 (5.24)	-3.94 (110.54)	*	-1.04 (2.45)
Kyoto + 5% reduction	-0.36 (-16.51)	-0.36 (8.00)	-0.39 (9.49)	-0.31 (6.16)	-0.39 (9.16)
Kyoto + 10% reduction	-0.81 (-17.18)	-0.79 (8.16)	-0.88 (9.02)	-0.71 (5.32)	-0.87 (8.64)
Dummy_EU	0.57 (4.09)				
Dummy_CANZ	0.18 (2.50)				
Dummy_Japan	0.77 (8.47)				
Constant	6.02	5.55	10.87	6.15	6.08
No. of observations	120	33	30	27	30
R-squared	0.9018	0.9579	0.9814	0.9401	0.8924
MSE	0.24379	0.15978	0.12277	0.18173	0.28593

* dropped by stepwise regression
Note: ‘t’ statistics shown in parentheses

Conclusion

Policymakers weighing the cost and benefits of reducing greenhouse gas emissions need to understand why the estimated costs of complying with the Kyoto Protocol vary so widely. Differences in assumptions about how compliance policies would be implemented are one source of variation, and have been a previous focus of attention. However, even holding these policy scenarios constant, the major energy models still produce a wide range of estimates. Thus, we have focused on the role of baseline emissions and modeling frameworks as sources of differences in the estimates of carbon mitigation costs.

Our meta analysis indicates that, broadly speaking, certain modeling choices can have important effects on the estimated costs of reducing greenhouse gas emissions. Not surprisingly, assumptions of freer trade and more perfect substitution of goods across countries tend to lower cost estimates. Similarly, greater disaggregation in terms of regions and nonenergy goods in the economic system leads to lower marginal abatement costs. At the same time, greater disaggregation in energy goods tends to raise estimated costs. This may be because the former allows for richer opportunities to shift production and consumption to less energy intensive products, while the latter allows for a richer presentation of energy market rigidities. However, the question of why these choices matter can only be answered with much greater detail about the models.

Somewhat surprisingly, we find that baseline differences among the models explain only a small amount of the differences in marginal abatement costs. While baseline differences have slightly larger effects in the case of Japan, and to some extent in CANZ, the overall effects are quite modest. However, since the baseline scenarios are generated by the models—i.e., they are not truly exogenous—their relationship to the cost estimates is likely to be a complex function of the underlying model frameworks and parameters.

Our results can help indicate which parts of the black box of modeling seem most important to open and examine to understand these discrepancies. First of all, elasticities of substitution among goods for consumers and factors of production for producers are likely to differ significantly across models and have important impacts, as they determine the opportunities for shifting demand and production inputs in response to a carbon price increase. Substitutability is important not only within countries, but also across countries, as terms of trade effects can impact compliance costs. Other areas of interest are the assumptions about rigidities in energy markets.[19] Models can also differ in their assumed constraints on the distribution of natural gas or electricity, transportation costs, market power, and regulation.

The rate and mechanisms of technological progress have been a major focus of theorists in the area of climate policy and should have important effects on the long-run costs of reducing carbon intensity. Since only one model in our group incorporated endogenous technical change, it is not yet possible to draw conclusions about the effect of endogeneity. But even among those with autonomous increases in energy efficiency, there may be significant variation in the rates assumed and whether progress occurs in the form of increases in factor productivity, changes in production methods, or improvements in the availability and cost of a backstop technology. Further, in considering the impact of modeling technology adoption via use of a constant cost noncarbon backstop, it is important to understand not only whether such an approach is employed, but at what price the model adopts the new technology.

The value of this kind of meta analysis is to identify in a systematic way which aspects of energy-economic models are the key drivers of abatement costs. With these results, we can help target analytical efforts toward refining our understanding of these driving forces. Such efforts could include future EMF-style exercises that not only hold policy scenarios constant, but also use more uniform modeling assumptions to further investigate the sources of variation and the interplay among framework assumptions. Another direction could be to refine some of the factors identified in G/T. Even if we reduce modeling uncertainties, inherent uncertainties over the real-world parameters will remain. But knowing which variables and mechanisms drive the costs in the models can

[19] Lasky (2003) notes a wide range of carbon price sensitivities among economic-energy models, and attempts some rough adjustments.

help us target empirical research toward reducing the most important uncertainties. Ultimately, improving consensus among modelers and lowering variation in cost estimates, that is, establishing a clearer price tag, is likely to spur development of binding greenhouse gas abatement policies.

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Appendix

Table 5: Baselines and Structural Characteristics of Various Models

Model	% Reduction from Baseline to Kyoto Target				Households Infinitely Lived	Backstop Technology	Endogenous Technical Change	Goods Perfect Substitutes in Trade	Nonenergy Goods	Energy Goods	Geographic Disagg.	Int'l Financial Sector
	US	EU	CANZ	Japan								
ABARE-GTEM	27.5	25.2	28.5	21.8	0	0	1	0	11	5	18	1
AIM	24.7	17.8	22.7	21.8	0	0	0	0	4	7	21	1
G-Cubed	29.5	32.8	37.5	20.6	0	0	0	0	7	5	8	1
MERGE3	28.1	22.4	14.3	34.4	1	1	0	1	2	18	9	0
MIT/EPPA	29.3	27.4	33.7	28.3	0	1	0	0	3	7	12	0
MS-MRT	30.2	18.1	24.5	24.3	1	1	0	0	2	4	10	1
RICE	22.7	21.3	28.4	26.9	1	1	0	0	1	0	13	0
SGM	31.6	30.1	30.6	29.6	0	0	0	1	2	11	12	0
Worldscan	26.7	25.6	39.6	24.8	1	0	0	0	7	4	13	1
CETA	28.5	NA	NA	NA	1	1	0	1	1	12	2	0
Oxford	29.6	21.9	NA	24.3	1	0	0	0	1	6	22	1

Table 6: Marginal Abatement Cost Estimates of Different Models

	MAC in $1990							
	US		EU		CANZ		JAPAN	
Model	Kyoto	+10%	Kyoto	+10%	Kyoto	+10%	Kyoto	+10%
ABARE-GTEM	322.02	177.13	666.94	309.64	423.88	238.49	652.00	250.14
AIM	151.98	77.50	196.97	64.68	148.05	75.15	234.06	114.56
G-Cubed	76.06	46.22	228.11	136.21	158.05	105.11	122.02	31.07
MERGE3	264.01	130.28	218.06	108.29	250.01	66.08	503.08	304.12
MIT-EPPA	191.99	56.28	276.02	106.70	248.00	87.45	502.97	251.76
MS-MRT	235.97	119.81	179.01	68.67	212.93	100.42	404.01	125.16
RICE	132.91	60.79	162.03	69.05	145.93	76.31	251.08	119.33
SGM	187.98	63.61	409.95	149.75	200.06	99.28	357.93	171.24
Worldscan	45.94	24.34	87.93	48.74	46.93	36.99	124.95	67.60
CETA	167.98	98.32	NA	NA	NA	NA	NA	NA
Oxford	410.98	117.13	966.01	251.72	NA	NA	1076.04	339.55

Table 7: Summary of Models (Toman and Ghersi, 1999)

		Goulder Goulder (1995)	**MIT-EPPA(version 1.6)** Yang et al. (1996) Jacoby et al. (1999)	**MARKAL-MACRO** Hamilton et al. (1992)
Equity issues	regions	1 (U.S.)	12 (global)	1 (U.S.)
	sectors	13 (6 energy-related)	10 (7 energy-related)	
	households	1 infinitely-lived representative household	1 myopic representative household	infinitely-lived single agent economy
	other	n.a.	n.a.	bottom-up energy module
Technical change	in energy	carbon liquid backstop, available 2010	*carbon liquid backstop, available 2000 *carbon-free electric backstop, av. 2000 *global constant AEEI in all nonenergy sectors *global constant efficiency improvement for oil and gas supplies	AEEI differing in energy demands
	other	n.a.	n.a.	n.a.
International Linkage	trade	*Armington specification for all goods except oil and gas Heckscher-Ohlin *zero balance constraint every period	*Armington specification for all goods except oil and gas Heckscher-Ohlin *zero balance constraint after 4 periods	n.a.
	finance	n.a.	n.a.	n.a.

		RICE-99 Nordhaus et al. (1999a,b)	FUND (version 1.6) Tol (1999)	GRAPE Kurosawa et al. (1999)
Equity issues	regions	13 (global)		
	sectors households	infinitely-lived single agent economy	non-overlapping generations single agent economy	infinitely-lived single agent economy
	other	n.a.	n.a.	bottom-up energy module
Technical change	in energy	*carbon-free energy backstop (high price) *region-specific A Carbon El in the aggregated sectors	*global AEEI in the aggregated sector *global A Carbon EI in the aggregated sector	*AEEI in the aggregated sector *oil substitutes in transports av. 2010 *nuclear substitute available 2050
	other	Region-specific exogenous growth in total facto productivity in the aggregated sector	n.a.	n.a.
International linkage	trade	n.a., except single output in compensation of permits	n.a.	*in single output *in energy products in the bottom-up energy module
	finance	n.a.	n.a.	n.a.

		WORLDSCAN Bollen et al. (1999) http://www.cpb.nl/nl/pub/bijzonder_20	AIM Kainuma et al. (1999) http://www-cger.nies.go.jp/ipcc/aim	MS-MRT Bernstein et al. (1999)
Equity issues	regions	13 (global)	21 (global)	10 (global)
	sectors	11 (4 energy-related)	11 (7 energy-related)	6 (4 energy-related)
	households	overlapping generations	1 myopic representative household	1 infinitely-lived representative households
	other	*high and low-skilled labor *region-specific uniformal (low-productivity) sectors	n.a.	n.a.
Technical change	in energy	n.a.	*global constant AEEI *global constant A Carbon EI	*carbon-free backstop (high price) *AEEI
	other	region- and sector-specific exogenous growth in factors productivity rate	n.a.	region- and sector-specific growth in total factor productivity, endogenous but to equate returns on capital
International linkage	trade	Armington specification for all goods turning to Heckscher-Ohlin in the long-run	*all foreign goods perfectly substitutable *Armington specification for domestic and aggregated foreign goods	*Armington specification for all goods except oil Heckscher-Ohlin and electricity nontradable *trade balanced over total time horizon *study of terms-of-trade variations *evolution of output in energy-intensive sector provide assessment of trade impacts
	finance	imperfect global investment market	perfect global investment market	*zeroed on the balanced growth path *perfect mobility of capital

		MERGE Manne et al. (1995, 1999) http://www.standford.edu/group/MERGE/	SGM MacCracken et al. (1999) Edmonds (1995)	G-CUBED McKibbin et al. (1995, 1999)
Equity issues	regions	5 (global), 9 (global) in MERGE 3.0	12 (global)	8 (global)
	sectors	infinitely-lived single agent economy	13 (11 energy-related)	12 (5 energy-related)
	households		1 myopic representative household	1 hybrid representative household
	other	9 electric, 9 nonelectric energy supplies in energy module	n.a.	n.a.
Technical change	in energy	*2 carbon-free electric backstops, av. 2010 (low cost) and 2020 (high cost) *carbon liquid backstop (high price) *global constant AEEI in the aggregated sector	sector-specific exogenous growth in total productivity rate for energy sectors	*global constant AEEI *region-specific exogenous growth in total productivity rate for energy sectors
	other	n.a.	sector-specific exogenous growth in total productivity rate	region-specific exogenous growth in total productivity rate
International linkage	trade	*oil, gas, coal and the single output, plus energy-intensive goods (EIG) in MERGE 3.0 are perfectly substitutable *carbon permits are perfectly substitutable *zero balance constraint every period *international transport priced *S/D ratio of domestic EIG provide assessment of trade impacts	*all goods perfectly substitutable except distributed gas nontradable *possibility of fixed quantities or prices *zero balance constraint after a few periods	Armington specification for all goods, with sensitivity analysis on the elasticities
	finance	n.a.	n.a.	global investment market, perfect in OECD, constrained elsewhere

		ABARE-GTEM Tulpule et al. (1999) http://www.abare.gov.au/pdf/gtem.doc	OXFORD Cooper et al. (1999)	CETA Peck and Teisberg (1992, 1999)
Equity issues	regions	18 (global)	22 (mostly OECD), key macro variables for 50 more	2 (global)
	sectors	16 (5 energy-related)		
	households	1 myopic representative households	infinitely-lived single agent economy	infinitely-lived single agent economy
	other	saving decisions (forward-looking) are disaggregated in age groups	6 energy supplies, 4 energy demands in energy module for 8 regions	7 electric, 5 nonelectric energy supplies in energy module
Technical change	in energy	endogenous	n.a.	*nonelectric and electric carbon-free backstops (high prices) *global constant AEEI in the aggregated sector
	other	endogenous	region-specific growth in total factor productivity, exogenous trend corrected by energy prices ("crowding-out wise")	n.a.
International linkage	trade	*Armington specification for all goods *international transport priced	Armington specification for the single output	Carbon permits, the nonenergy good, oil and gas, and synthetic fuel are perfectly substitutable
	finance	imperfect global investment market	perfect global investment market	n.a.