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Where in the world is it cheapest to cut carbon emissions?*

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Countries with low marginal costs of abating carbon emissions may have high total costs, and vice versa, for a given climate mitigation policy. This may help to explain different countries' policy stances on climate mitigation. We hypothesize that, under a common percentage cut in emissions intensity relative to business as usual (BAU), countries with higher BAU emission intensities have lower marginal abatement costs, but total costs relative to output will be similar across countries, and under a common carbon price, relative total costs are higher in emission-intensive countries. Using the results of the 22nd Energy Modeling Forum (EMF-22), we estimate marginal abatement cost curves for the US, EU, China and India, which we use to estimate marginal and total costs of abatement under a number of policy options currently under international debate. This analysis provides support for our hypotheses, although its reliability is limited by the shortcomings of the EMF-22 models and the degree to which our econometric model can adequately account for the substantial differences among them.

Key words: climate change, carbon emissions, marginal abatement cost, meta-analysis.

1. Introduction

In many countries, including Australia (Grafton and Lambie 2010) and the United States (Bang 2010), the development of climate mitigation policy has been characterized by fierce debate about how the costs of abating greenhouse gas emissions are to be distributed, not only within each country but also internationally. Among the developed countries, Australia and the United States have lagged Europe and Japan in adopting climate mitigation policy. Australia ratified the Kyoto treaty only in 2007 and passed carbon pricing legislation in late 2011, while the U.S.E.P.A. is only in 2011 tentatively beginning to regulate greenhouse gas emissions following a Supreme Court decision (Broder 2010). We show in this paper that rankings of countries and regions by abatement costs differ in a predictable way, depending on

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exactly how both policies and costs are defined. These differences may help explain different national stances towards global climate change policy and perhaps improve mutual understanding in international policy negotiations. We use a simple theoretical model to derive hypotheses about such rankings and then cautiously test these hypotheses using a meta-analysis of a recent international integrated assessment modelling exercise.

Abatement cost can be measured in several ways. First, marginal cost and total cost are different and give rise to quite different rankings. Second, private cost differs from social or economy-wide cost (Paltsev *et al.* 2007). Third, cost can be measured using market exchange rates (MER) or using purchasing power parity (PPP) adjusted exchange rates (Van Vuuren and Alfsen 2006). Our main focus is on the distinction between marginal and total costs, with some consideration of the role of exchange rates. We do not consider the distinction between private and social costs further as this would add considerable complexity to the paper. Also, we only consider carbon dioxide emissions from the combustion of fossil fuels and industrial processes although the general ideas may be more broadly applicable.

It is common sense that there would be relatively more 'low-hanging fruit' (low marginal-cost opportunities) for abating carbon emissions in currently emission-intensive countries like Australia and the United States, than in countries that are less emission intensive as a result of more aggressive energy efficiency and environmental policies. However, more fruit below a given height means a bigger crop–the total abatement cost in response to a common carbon price would then be relatively higher in more emission-intensive countries, because they need a larger relative cut in emissions to reach the same marginal abatement cost. These ideas can be formalized into a range of hypotheses, for example, that more emission-intensive countries have lower marginal costs of abatement for a given percentage cut in emissions or in emissions intensity, both relative to business as usual (BAU). We first illustrate these hypotheses with a simple theoretical model, and then test their empirical relevance, and thus importance for international climate policy.

The empirical analysis uses data from the array of integrated assessment models that participated in the 22nd Energy Modeling Forum (EMF-22, Clarke *et al.* 2009) to estimate private marginal cost curves for abating future carbon dioxide emissions from fossil fuel combustion and industrial processes for the US, EU, China and India (MACCs). We use these estimated curves to rank these regions for five variants of marginal or total cost, under four policy options which have featured in international policy debates: a common global carbon price, and common proportional cuts in emissions intensity, in emissions relative to BAU, or in absolute emissions.

Previous work covers some, but not all of the areas addressed in this paper. Modelling by Paltsev *et al.* (2007) finds that for a common percentage cut in emissions without international trade in emissions permits, there is a roughly inverse relationship between carbon prices and emission intensities in several developed countries. Furthermore, they find that the resultant rankings of countries by carbon price and by percentage consumption losses differ. In this paper, we formalize these observations and test them using the EMF-22 model results. Kuik *et al*. (2009) and Tavoni and Tol (2010) also carry out meta-analyses of private marginal abatement costs and GDP losses, respectively, for a range of integrated assessment models. The latter uses the EMF-22 results. Neither study estimates the MACC nor has a regional breakdown and so cannot be used as a basis for the current study. Kuik *et al*. (2009) focus on explaining why models vary in their predictions of marginal abatement costs. Tavoni and Tol (2010) measure costs as the net present value of global change in GDP and attempt to provide an unbiased estimate of the costs of the more extreme abatement scenarios.

The next section of the paper presents our simple theoretical model, which illustrates the contrast between marginal-cost and total-cost rankings and suggests some hypotheses worth testing. The third and fourth sections describe the EMF-22 data and the econometric methods we use to fit an empirical model to these data. Section 5 then uses the empirical model to rank the US, EU, China and India by various measures of abatement costs in response to a series of policy scenarios, focusing particularly on pledges made following the 2009 UNFCCC conference in Copenhagen. Section 6 concludes.

2. Marginal cost and total cost

In this section, we show how, for a very simple model, countries with higher BAU emissions intensity have lower marginal costs of abatement for a given percentage cut in emissions intensity, but higher total costs for a common carbon price regime. Let country i have a Cobb–Douglas[1] aggregate production function:

$$Y_i = B_i X_i^a E_i^b \tag{1}$$

where E is seen both as energy and as carbon emissions and $1 > b > 0$. In other words, we ignore inter-fuel substitution and carbon sequestration as potential abatement techniques, as well as non-energy-related emissions. X is a composite of non-energy inputs, and B is the total factor productivity index. The parameters of the production function are common across countries. Let q be the exogenous price of energy not including any carbon price. Assume that there is a carbon price p created by a tax or trading scheme, which market forces will equate with the marginal cost of abating carbon. The carbon-inclusive energy price is therefore $q + p$, with $p = 0$ under BAU. In the following, BAU values of variables are indicated by 'bars' and policy-induced

[1] We chose the Cobb–Douglas form as the simplest way of showing how our hypotheses (which are not tied to the Cobb–Douglas case) could be supported theoretically. It would be desirable to derive the hypotheses for other, more general functional forms, but this awaits further research.

levels by 'hats' where these need to be distinguished. Our analysis ignores any international transfers of wealth caused by a country's trading scheme allowance differing from its abated emission level. Efficient energy use in the economy will equate the value of its marginal product (with output Y as numeraire) to its carbon-inclusive energy price:

$$\frac{\partial Y_i}{\partial E_i} = b\frac{Y_i}{E_i} = bB_i X_i^a E_i^{b-1} = q_i + p_i \tag{2}$$

Denoting emissions intensity as $\theta = E/Y$, Equation (2) implies that under a policy price p_i:

$$\hat{\theta}_i = b/(q_i + p_i) \tag{3}$$

while emissions intensity under BAU is determined by the price of energy:

$$\bar{\theta}_i = b/q_i \tag{4}$$

To allow us to compare countries of different income levels and sizes, we can graph marginal abatement cost as a function of emissions intensity (Dasgupta *et al.* 2000):

$$p_i = \frac{b}{\theta_i} - q_i \tag{5}$$

Figure 1 presents these marginal abatement cost curves for two hypothetical countries based on obvious real-world examples. Eurpan is a country with a high energy price and low BAU emissions intensity, while Ameralia has a

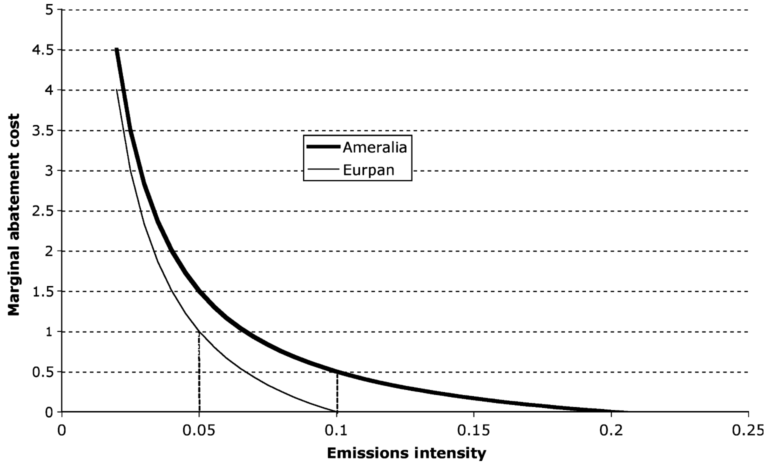

Figure 1 MACCs for countries with different levels of business as usual emissions intensity.

high BAU emissions intensity because of low energy prices. In the figure, $b = 0.1$, and energy prices are 1 in Eurpan and 0.5 in Ameralia. Therefore, Ameralia's BAU emissions intensity is twice Eurpan's. Substituting the solution for q_i from Equation (4) into Equation (5) and manipulating yields:

$$p_i = \frac{b}{\bar{\theta}_i}\left[\left(\frac{\hat{\theta}_i}{\bar{\theta}_i}\right)^{-1} - 1\right] \tag{6}$$

implying that:

Hypothesis 1: For a common proportional decrease in emissions intensity relative to BAU, $1 - (\hat{\theta}/\bar{\theta})$, marginal abatement cost will be higher in the country with a lower BAU emissions intensity, $\bar{\theta}_i$

This can be seen clearly in Figure 1 where halving emissions intensity relative to BAU results in a carbon price of 1 in Eurpan and 0.5 in Ameralia. Solving Equation (2) for the optimal level of energy and substituting into Equation (1) gives:

$$Y_i = \left(B_i X_i^a\right)^{\frac{1}{1-b}} \left(\frac{b}{q_i + p_i}\right)^{\frac{b}{1-b}} = \left(B_i X_i^a\right)^{\frac{1}{1-b}} \theta_i^{\frac{b}{1-b}} \tag{7}$$

with the second equality implied by Equation (3). Therefore, assuming that the level of the composite input is fixed:

$$\frac{\hat{Y}_i}{\bar{Y}_i} = \left(\frac{\hat{\theta}_i}{\bar{\theta}_i}\right)^{\frac{b}{1-b}} \tag{8}$$

implying that:

Hypothesis 2: For a common proportional decrease in emissions intensity relative to BAU, the proportional decline in output is unaffected by the country's BAU emissions intensity.

In Figure 1, the areas under the MACCs for a halving of emissions intensity are equal. The area under the MACCs are given by:

$$\int b\theta_i^{-1} d\theta_i = b \ln \theta_i \tag{9}$$

The definite integral over the interval between $\hat{\theta}_i$ and $\bar{\theta}_i$ is $b \ln(\hat{\theta}_i/\bar{\theta}_i)$, which is proportional to the logarithm of Equation (8) and, therefore, to the percentage change in output. Figure 1 also shows that:

Hypothesis 3: For a common carbon price, countries with a higher BAU emissions intensity suffer a greater percentage fall in output.

This can be seen by substituting Equation (3) into Equation (8):

$$\frac{\hat{Y}_i}{\bar{Y}_i} = \left(\frac{q_i}{q_i + p_i}\right)^{\frac{b}{1-b}} = \left(1 + \frac{p_i}{q_i}\right)^{\frac{b}{b-1}} \tag{10}$$

Therefore, noting that $b/(b-1) < 0$, the lower the pre-existing energy price q_i is, hence the higher BAU emissions intensity $\bar{\theta}_i$ is, and the lower $\hat{Y}_i/\bar{Y}_i$ is, hence the greater is the relative output loss, for a given level of p_i.

Might these three hypotheses, derived here only for a very restrictive Cobb–Douglas model, but stated in a general way, turn out to have more general empirical validity? Our policy analysis in Section 5, using data and econometric methods described in Sections 3 and 4, will find out.

3. Data

Rather than using a single integrated assessment model, we estimate MACCs using a meta-analysis of the results of the global future scenarios simulated by the EMF-22 suite of models (Clarke *et al.* 2009). The EMF program, based at Stanford University, regularly brings together a number of integrated assessment modelling groups to carry out simulations of a common set of scenarios addressing particular energy and climate change issues. Data are available on BAU and policy values of emissions of carbon dioxide and some other greenhouse gases, energy use, population, carbon prices, greenhouse gas concentrations, and (for some participating models) GDP and consumption. Most models provide results for the world as a whole as well as for China, India, EU, USA, non-Russian Annex I countries, the BRICs (Brazil, Russia, India and China) and the rest of the world. Because different modelling groups used different regionalizations and no global carbon price is available, we limit the analysis to four countries/regions: China, EU, India and US.

The EMF-22 models vary in their degree of realism and the degree to which they have been validated against data. Some, such as GTEM, are computable general equilibrium models, while others are much more aggregated and treat more variables as exogenous. We, therefore, caution against placing too much reliance on our quantitative results, which only reflect the average behaviour of an ensemble of models rather than real-world behaviour. On the other hand, using such an ensemble means that our results depend less on the idiosyncracies of any particular model.

The EMF-22 exercise required each model to run ten scenarios based on combinations of three different dimensions of mitigation:

- Three long-term concentration targets: (i) 450 ppmv CO_2-e [or a 2.6 W/m^2 increase in radiative forcing], (ii) 550 ppmv CO_2-e [3.7 W/m^2] and (iii) 650 ppmv CO_2-e [4.5 W/m^2].
- The option to overshoot the concentration target for 2100 in the interim period before eventually reaching the target in 2100. The overshoot option was only considered in the cases of the 450 and 550 ppm targets, which results in there being ten rather than twelve scenarios.
- The time path of international participation in mitigation: full initial participation with a common carbon price across all countries from 2012; or an architecture in which many regions do not engage in climate mitigation until 2030 or beyond. Under this scenario, all Annex I countries with the exception of Russia adopt a common carbon price from 2012, the BRICs enter from 2030 and the rest of the world only from 2050.

Each of these scenarios is characterized by the actual reductions in emissions in each region. However, we also use dummy variables to indicate the partial participation option and the overshoot option and two dummies account for the 450 and 650 ppm scenarios relative to the 550 ppm scenario. Hence, the default scenario in our modelling is the full participation 550 ppm scenario with no overshoot. This is commensurate with the Copenhagen pledges (Jotzo 2010) and is, therefore, the most sensible scenario against which to estimate the marginal costs of action in each country. Other exercises, such as that by Morris *et al.* (2008), also measure marginal abatement cost contingent on other countries also acting.

Ten modelling groups participated in the forum. As some models have more than one variant, a total of fourteen models participated. The MERGE model has no results for India, so we excluded this model. We deal with the differences between models using fixed effects implemented using dummy variables. The sum of the coefficients on these dummy variables is forced to equal zero so that the estimated intercept is the average across the models.

Data are available at each 10-year interval (2020, 2030, etc.). We use dummy variables for each year relative to the base year of 2020. These are designed to account for technological change. Only the ETSAP-TIAM and WITCH models produced policy results for 2010, and so we dropped 2010 from the data set.

All modelling groups were required to attempt to carry out model runs representing each of the ten policy scenarios; however, not all models were capable of running the more extreme scenarios. In fact, no model could run the delayed participation with no overshoot 450 ppm scenario. Under the delayed participation scenarios, carbon prices are zero for India and China and no abatement takes place for a period of time. As a result, there are 629 observations available to estimate the models for the USA and the European Union and 590 for China and India. We measure private marginal abatement cost using the carbon price estimated in the models. As not all models include CO_2 emissions from land use and land-use change, and the SGM model does not include any emissions from other greenhouse gases, we measure emissions as fossil fuel and industrial CO_2 emissions.

4. Econometrics

Here, we use EMF-22 model data to estimate emissions relative to BAU as a function of future carbon prices. Although the various EMF-22 models implement a given mitigation policy in different ways, all assume a common carbon price across each of the developed and developing country groups. Abatement within a region reacts to the global cap on emissions mediated through the resulting permit price or carbon tax. Additionally, the degree to which fossil fuel and industrial emissions are abated is an endogenous result that depends on how much other sources of greenhouse gases contribute to mitigation. Therefore, the carbon price is to some degree exogenous, while the relative abatement of fossil and industrial emissions of CO_2 is endogenous.

Figure 2 plots emissions relative to BAU against the logarithm of the carbon price for the USA for all available years, models and scenarios. The charts for the other three regions show similar sigmoid shape curves as does the simple Cobb–Douglas model developed in Section 2. We model emissions relative to BAU as a logistic function of the log of the carbon price:

$$\frac{\hat{E}_{ij}}{\bar{E}_{ij}} = \frac{1}{1 + \exp\left(\alpha_i + \beta_i \ln(p_{ij}) + \sum_u \gamma_{iu} d_{uj} + \sum_v \delta_{iv} t_{vj} + \sum_w \mu_{iw} m_{wj}\right)} + \varepsilon_{ij}, \quad (11)$$

where the index i indicates countries and j observations (combination of year, model and scenario), p is the carbon price (in 2005 US Dollars per tonne of

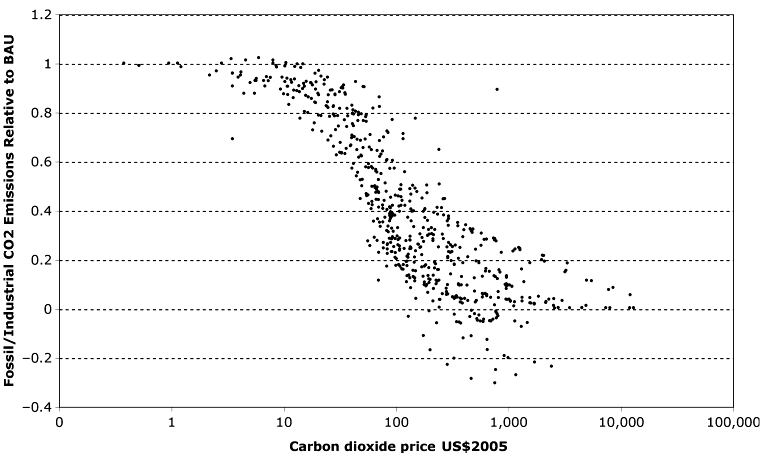

Figure 2 Emissions relative to business as usual and carbon price for USA.

CO_2), the d_u are dummies for the characteristics of the scenarios, the t_v are dummies for the time periods, the m_w are dummies indicating the twelve models and ε is a random error term. The coefficients μ_w sum to zero in each country. This condition is imposed by subtracting the dummy for the WITCH model from the dummies of the other models.

We estimate a separate equation for each country by non-linear least squares with standard errors that are robust to heteroskedasticity and clustering. This is necessary because the model is non-linear and so dummy variables for models do not remove all clustering. We did not use joint estimation of all four equations because there are a different number of available observations for the developing and developed countries, and there are no efficiency gains to joint estimation when all the explanatory variables are common to each country (Greene 1993). Pooling all the data into a single equation is another alternative, but it imposes a common error variance on all countries.

Equation (11) can be converted to a linear model, but we found that the residuals of this model were less normally distributed, and predictions of carbon prices were poorer. For some scenarios and models, emissions are non-positive in some periods. This is because of the extensive use of biomass and carbon sequestration in those models (Clarke *et al.* 2009). The non-linear model (Eqn 11) uses this information, whereas a linearized model with a logarithmic-dependent variable must drop it. Equation (11) forces the model predictions into the range from zero to unity. This could be generalized, but estimates of the generalized model were quite similar.

Shifts in the dummy variables shift the estimated logistic curve left and right without changing its curvature. This is a very useful property because these shifts are orthogonal to the residuals in the $\hat{E}_{it}/\bar{E}_{it}, \ln(p_{it})$ plane and result in good estimates of the time and other effects. To predict carbon prices and hence the MACCs, we invert Equation (11) setting the error term to its expected value:

$$p'_{ij} = \exp\left(-\frac{1}{\beta_i}\left(\alpha_i + \sum_u \gamma_{iu} d_{uj} + \sum_v \delta_{iv} t_{vj} + \sum_w \mu_{iw} m_{wj}\right)\right)\left(\frac{A_{ij}}{\bar{E}_{ij} - A_{ij}}\right)^{\frac{1}{\beta_i}} \quad (12)$$

where the prime indicates the predicted value, and A is abatement $(\bar{E} - \hat{E})$. To compute total cost, C, we integrate Equation (12) with respect to abatement. A reasonable approximation can be obtained by truncating the resulting infinite hypergeometric series at the sixth power.

Table 1 presents the econometric estimates of Equation (11) for each of the four countries. The models fit well and have quite a lot of similarity across the countries. The effect of the carbon price is a little larger in the Indian model than in the models for the three other countries. All the time effects are positive and increase monotonically over time (with the minor exception of the change in India between 2090 and 2100). As we see from Equation (12), this has the effect of reducing the marginal abatement cost

Table 1 Regression results

	China	India	EU	USA
Constant	−3.964 (−6.264)	−4.696 (−6.091)	−4.713 (−5.228)	−4.356 (−5.440)
Price	0.765 (4.988)	0.992 (4.998)	0.760 (3.936)	0.766 (4.520)
2030	0.269 (3.449)	0.370 (5.462)	0.468 (4.157)	0.378 (3.360)
2040	0.587 (3.354)	0.590 (4.775)	0.879 (4.892)	0.723 (4.282)
2050	0.955 (4.467)	0.827 (4.269)	1.161 (5.314)	1.091 (6.192)
2060	1.235 (5.061)	1.105 (5.234)	1.376 (5.404)	1.399 (7.200)
2070	1.432 (5.208)	1.283 (5.629)	1.579 (5.647)	1.607 (7.756)
2080	1.693 (5.673)	1.520 (6.036)	1.830 (5.785)	1.906 (8.655)
2090	1.812 (5.863)	1.580 (5.266)	1.920 (5.316)	2.092 (8.850)
2100	1.906 (6.342)	1.517 (3.703)	1.959 (4.450)	2.185 (8.208)
Overshoot	−0.130 (−1.422)	−0.178 (−1.767)	0.157 (2.796)	0.113 (1.545)
Delayed	−0.162 (−2.713)	−0.134 (−2.248)	−0.071 (−1.493)	−0.095 (−2.093)
450 ppm	0.572 (3.136)	0.655 (3.205)	0.611 (2.797)	0.555 (4.138)
650 ppm	−0.383 (−4.018)	−0.284 (−2.640)	−0.383 (−3.267)	−0.449 (−4.400)
Model dummies				
ETSAP-TIAM	−0.467 (−11.154)	0.301 (4.941)	0.339 (5.018)	0.200 (4.628)
FUND	0.521 (5.670)	0.557 (6.013)	−0.539 (−2.580)	0.047 (0.430)
GTEM	0.330 (8.581)	0.521 (8.999)	−0.259 (−11.707)	0.267 (6.298)
IMAGE	−0.219 (−3.251)	−0.089 (−1.153)	0.237 (2.284)	−0.035 (−0.566)
IMAGE-BC	0.007 (0.056)	−0.560 (−3.450)	0.413 (2.977)	0.114 (1.046)
MESSAGE	−0.424 (−7.000)	−0.227 (−3.748)	0.376 (3.438)	−0.010 (−0.168)
MESSAGE No BECS	−0.467 (−6.815)	−0.738 (−8.878)	−0.098 (−1.236)	−0.379 (−7.557)
MINICAM Base	0.656 (5.625)	0.712 (5.287)	0.767 (4.497)	0.357 (3.372)
MINICAM Lo Tech	0.043 (0.600)	−0.531 (−4.434)	−0.183 −(1.516)	−0.624 (−4.645)
POLES	0.156 (5.144)	0.320 (6.936)	−0.271 (−5.283)	−0.031 (−1.261)
SGM	0.580 (8.795)	0.475 (7.376)	−0.924 (−5.944)	−0.212 (−3.807)
WITCH	−0.716 (−4.664)	−0.744 (−4.504)	0.144 (1.323)	0.307 (7.295)
Adjusted R-squared	0.916	0.892	0.893	0.909

t-statistics are in parentheses.

over time. The reduction in cost over time is very substantial. In China and the EU, costs in 2100 are around 8% of costs in 2020, *ceteris paribus*, in the US 6% and in India 22%. The cost reduction between 2020 and 2030 ranges from 46% in the EU (6.0% p.a.) to 30% (3.4% p.a.) in China.

The overshoot scenarios are associated with higher carbon prices in China and India and lower carbon prices in the US and EU, while the delayed participation scenarios result in higher carbon prices in all countries. The 450 ppm scenario has lower carbon prices in all countries and the 650 ppm scenario higher ones, *ceteris paribus*. Most models do not have a consistent pattern of either higher or lower carbon prices across countries. For example, FUND finds lower carbon prices in China and India than do other models but higher prices in the European Union. Only the MINICAM Base model finds lower carbon prices than other models in all regions.

5. Policy analysis

We now use the econometrically estimated model (Eqn 11) to derive the MACC (Eqn 12) for each country. Then we use the integral of the MACC to derive the total costs of abatement under several policy options. These exercises throw light on the validity of the hypotheses suggested by the simple theory in Section 2.

5.1. Marginal abatement cost

The MACCs for each country in MER terms and in terms of abatement relative to BAU are shown logarithmically in Figure 3 for 2020 and Figure 4 for 2050. In 2020, China has the lowest marginal abatement cost and the EU the highest for a small cut in emissions. India has the second highest marginal cost for small cuts, but for cuts greater than about 20% its marginal cost is lowest. The ranking of the other three countries does not change with the degree of

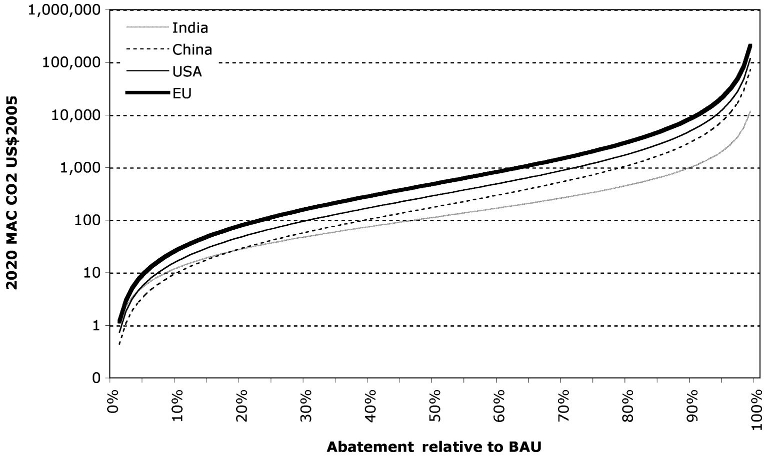

Figure 3 Marginal abatement cost curves 2020.

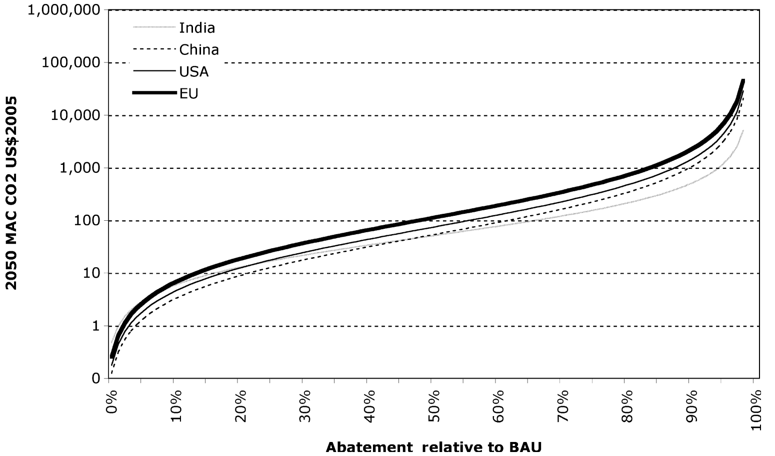

Figure 4 Marginal Abatement cost curves 2050.

abatement. There is some relationship between these prices and the BAU emission intensities shown in Table 2. In MER terms, China has the highest emissions intensity in 2020 and the European Union the lowest, while in PPP terms, USA is highest and India is lowest. However, India has a higher marginal abatement cost for small cuts in emissions than does the US despite having higher emissions intensity so that there is not a perfectly inverse relationship between marginal abatement cost and emissions intensity (Hypothesis 1) unless we focus on a cut in emissions of around 10% relative to BAU.

Carbon prices typical of those discussed in the media and policy debates and as seen in the European emissions trading market of $20 or so per tonne of CO_2 (Treasury 2008; CBO 2010) are seen in the developed countries only for cuts of 10% or less in emissions. Prices already reach $100 a tonne in Europe for a 23% emissions cut relative to BAU by 2020, in the US for a 31% cut and in China for a 40% cut. Emissions are cut by 47% in India before the marginal cost reaches $100. It is clear that a common global carbon tax policy or free trading of emissions credits will result in much larger percentage cuts in emissions in the developing economies than in the developed economies.

In 2050, India has the highest marginal cost for a small cut in emissions and again the lowest for large cuts. Otherwise, the ranking remains the same, but, of course, marginal costs have fallen across the board. A $100 marginal cost is reached for 66% abatement relative to BAU in India, 62% in China, 56% in the US and 48% in the EU. The MACCs are more closely bunched together than in 2020 because of slower technical progress in India. Clearly, to reach the reductions in emissions in the developed economies required by typical policy scenarios, such as those in the EMF-22 exercise (Clarke *et al.* 2009) or the Garnaut or Australian Treasury Reviews (Garnaut 2008; Treasury 2008), will require prices higher than $100 per tonne of CO2 in 2050 and probably nearer $1000 per tonne. Again, excluding India, there is an inverse relationship between emissions intensity and marginal abatement costs (Hypothesis 1). India has the highest emissions intensity in 2050 under BAU, but also the highest marginal abatement cost for small cuts in emissions.

Table 2 BAU emissions intensity

	MER		PPP adjusted	
Country/Region	2020	2050	2020	2050
China	1.33	0.61	0.39	0.18
European Union	0.29	0.20	0.33	0.23
India	1.16	0.66	0.28	0.16
USA	0.40	0.25	0.40	0.25

BAU, business as usual; MER, market exchange rates; PPP, purchasing power parity.
MER emission intensities are the average of BAU scenarios of the 12 EMF-22 models and are measured in kg of CO_2 per 2005 US$ of GDP. PPP adjusted rates multiply these values by the appropriate 2007 PPP exchange rate relative to the MER from the Penn World Table (Heston *et al.* 2009). European Union PPP exchange rates computed by summing GDP measured in PPP prices in each country to obtain the total PPP GDP and dividing by total market GDP in the region.

5.2. Policy simulations

To test our hypotheses further, we use our estimated MACCs to rank the four countries using marginal and total cost in MER and PPP terms (using exchange rates for 2007 from the Penn World Table) for four policies:

Policy 1: A common global carbon dioxide price of $50 per tonne in 2020.
Policy 2: A common 30% reduction in emissions intensity by 2020 relative to 2010. This is 2/3 of the high end of China's Copenhagen pledge for emissions intensity in 2020 relative to 2005 and is similar to the implied pledges of several other countries (Jotzo 2010). We assume that GDP remains at the BAU level under this policy. Therefore, it is only an approximation of a common reduction in emissions intensity.
Policy 3. A common 25% reduction in emissions relative to BAU by 2020. This is the average of the US, EU and Chinese Copenhagen pledges according to Jotzo (2010).
Policy 4. A common 15% reduction in absolute emissions by 2020 relative to 2010. This is roughly 2/3 of the mid-point of the European Union's Copenhagen pledge when measured relative to 2005 instead of 1990 (Jotzo 2010).

To evaluate each goal, we compute the average emissions and GDP under BAU in 2010 and 2020 across the twelve EMF models we use. Total costs are measured on both per capita and relative to GDP bases.

Table 3 presents the changes in emissions relative to BAU under the four policies. Absolute emissions reductions (Policy 4) result in the smallest reduction relative to BAU in the European Union and the greatest in China because of the relative economic growth rates of the four countries. Emissions growth under BAU is very low in China and India in the EMF-22 scenarios compared to that assumed in Stern and Jotzo (2010) and Jotzo (2010). This difference depends partly on a different understanding of BAU and partly on a lower forecast economic growth rate. The EMF-22 BAU scenarios assume a rapid rate of decarbonization compared to recent trends. Also, in contrast to Stern and Jotzo (2010) and Jotzo (2010), the 30% reduction in emissions intensity (Policy 2) results in little change in emissions intensity in China

Table 3 Percentage change in emissions relative to BAU 2010–2020

	Policy			
Country/Region	1. $50 Carbon dioxide price	2. 30% Reduction in emissions intensity	3. 25% reduction relative to BAU	4. 15% Absolute reduction in emissions
China	−27.45	−1.73	−25.00	−37.90
European Union	−14.92	−19.03	−25.00	−18.61
India	−30.67	−22.14	−25.00	−29.38
USA	−20.44	−18.75	−25.00	−21.33

BAU, business as usual.
BAU is the average of the 12 EMF-22 models.

relative to BAU, but similar reductions of around 20% relative to BAU in the other three countries. Under the $50 carbon price policy (Policy 1), the largest and smallest cuts in emissions occur, respectively, in the country with the lowest marginal cost for a 30% cut in emissions (India) and the country with the highest marginal costs throughout the MACC (the EU).

Tables 4–7 present marginal and total costs for each country under each policy, where total cost relative to GDP refers to private abatement costs alone. Actual changes in GDP could differ radically from these values. We derive the total costs by integrating Equation (12) with respect to abatement while setting all dummy variables to zero.

The reduction in emissions intensity relative to 2010 (Policy 2) imposes the lowest total costs on the developing countries (Table 5) whether measured in per capita terms in either MER or PPP terms or as a percentage of GDP.

Table 4 Marginal cost and total cost for policy 1: $50 carbon dioxide price in 2020

		China	EU	India	USA
MER	MC	$50.00	$50.00	$50.00	$50.00
	TC per capita	$32.32	$26.68	$11.73	$70.49
PPP exchange rates	MC	$171.76	$42.70	$203.05	$50.00
	TC per capita	$111.03	$22.79	$47.65	$70.49
TC/GDP_{BAU}		0.69%	0.09%	0.78%	0.16%

BAU, business as usual; MER, market exchange rates; PPP, purchasing power parity.

Table 5 Marginal cost and total cost for policy 2: 30% cut in emissions intensity from 2010 to 2020

		China	EU	India	USA
MER	MC	$0.91	$73.48	$15.26	$43.46
	TC per capita	$0.04	$49.00	$1.53	$58.96
PPP exchange rates	MC	$3.11	$62.76	$61.99	$43.46
	TC per capita	$0.14	$41.85	$6.21	$58.96
TC/GDP_{BAU}		0.00%	0.16%	0.10%	0.13%

BAU, business as usual; MER, market exchange rates; PPP, purchasing power parity.

Table 6 Marginal cost and total cost for policy 3: 25% cut in emissions in 2020 relative to BAU

		China	EU	India	USA
MER	MC	$42.38	$116.39	$37.58	$70.23
	TC per capita	$25.31	$98.63	$7.40	$128.81
PPP exchange rates	MC	$145.59	$99.41	$152.62	$70.23
	TC per capita	$86.95	$84.24	$30.07	$128.81
TC/GDP_{BAU}		0.54%	0.32%	0.49%	0.27%

BAU, business as usual; MER, market exchange rates; PPP, purchasing power parity.

Table 7 Marginal cost and total cost for policy 4: 15% cut in absolute emissions from 2010 to 2020

		China	EU	India	USA
MER	MC	\$93.46	\$70.87	\$77.22	\$53.64
	TC per capita	\$77.60	\$46.32	\$22.55	\$91.47
PPP exchange rates	MC	\$321.06	\$60.53	\$313.60	\$53.64
	TC per capita	\$266.56	\$39.56	\$91.58	\$91.47
TC/GDP_{BAU}		1.66%	0.15%	1.49%	0.18%

BAU, business as usual; MER, market exchange rates; PPP, purchasing power parity.

Their total costs are lower than those of the developed countries by all three measures. It is, therefore, unsurprising that China and India's Copenhagen pledges are in terms of emissions intensity. This result is because of the more rapid improvement in emissions intensity under BAU in the two developing economies than in the two developed economies.

A cut in absolute emissions (Table 7, Policy 4) imposes high per capita costs in PPP terms and high losses relative to GDP for the developing countries relative to the developed countries. The European Union suffers the smallest costs. It is not surprising, perhaps, that the EU pledge is posed in terms of an absolute cut in emissions. A reduction in emissions relative to BAU (Table 6, Policy 3) results in losses in GDP terms that are not dissimilar across countries but a bit higher in the developing countries. A common global carbon price (Table 4, Policy 1) results in large losses relative to GDP in the developing countries and low total costs in the EU relative to the US.

Next, we look in more detail at the differences in marginal and total cost under the policy options and the different ranking of countries depending on which criterion is selected. Hypothesis 3 states that under the common carbon price policy, total costs relative to output would be higher in emission-intensive countries. Table 4 shows such a relationship for China, the US and the European Union. India shows higher percentage costs than China, but the expected relationship holds between the two developing economies as a whole and the US and EU. Total per capita costs in MER terms are lowest in India, however, because income per capita is lowest there.

The reduction in emissions intensity in Table 5 is relative to a benchmark year and not relative to BAU and, therefore, does not match the situation in Hypothesis 2. Percentage losses are greatest in the European Union, but total costs per capita are higher in the US because of its higher income per capita. The higher percentage losses in the EU are because it is already the least emission-intensive region, so its improvement in emissions intensity under BAU is lowest.

The common percentage cut in emissions relative to BAU (Table 6) is more relevant to Hypothesis 2, especially as GDP losses are relatively small for this level of emissions cut. As predicted, the percentage losses are somewhat similar across countries. The percentage losses are somewhat higher in China and India, which are the more emission-intensive countries in MER terms.

The common cut in absolute emissions (Table 7) results in higher marginal costs in the developing countries because, due to rapid economic growth, emissions grow faster there under BAU than they do in the developed economies. Percentage costs are much higher in the developing countries than in the developed economies.

More generally, we see that in Table 6, low marginal costs are associated with higher percentage total costs, while under the various policies in Tables 5 and 7, high marginal costs are associated with high percentage total costs. Also, while China always has a lower MACC than the developed economies, under a variety of plausible policies, it suffers higher percentage total costs. The one constant here is thus that the ranking of countries depends on what definitions of cost and policy are chosen.

6. Conclusions

In this paper, we estimated future carbon marginal abatement cost curves for China, India, the European Union and the United States using the results of the 22nd EMF exercise. We used these models to see how outcomes vary across countries in terms of marginal and total costs of abatement under a variety of policies and using market and PPP adjusted exchange rates. These empirical results broadly, but by no means exactly, confirm three hypotheses about marginal and total abatement costs suggested by a simple Cobb–Douglas theoretical model.

The constructed curves for China, EU and USA are similar, but marginal costs at MER are lowest in China and highest in the EU. Marginal cost in India is relatively high for small cuts in emissions and relatively low for larger cuts. We note that the reliability of the quantitative analysis is limited by the shortcomings of the EMF-22 models and the degree to which our econometric model can adequately account for the substantial differences among them. Our policy analysis shows that emissions intensity targets favour the developing economies, while absolute cuts in emissions and common carbon prices result in the lowest total costs in the European Union.

We have shown that whether a country is a relatively 'low-cost' or 'high-cost' place for carbon abatement depends on whether we measure costs using marginal cost of abatement, total per capita cost or total abatement cost as a proportion of output, and also on whether we use market or PPP exchange rates. Generally, the empirical results do support the theory-based hypothesis that emissions intensity is inversely related to marginal cost of abatement (Hypothesis 1).

Hypothesis 3, that under a common carbon price, total costs as a proportion of output will be higher in more emission-intensive countries, also finds support. Hypothesis 2, that under a common percentage reduction in emissions intensity relative to BAU, percentage output losses would be equal across countries, is also somewhat supported by the data.

We suggest that these differences in costs between countries under the different policy scenarios might help to explain why particular governments favour particular policy options, as revealed, for example, by the different types of abatement pledges made by key countries after the UNFCCC Copenhagen conference. Clearly, an analysis of international climate negotiations and policy options needs to consider both the marginal cost of abatement and the total costs of meeting any policy. In particular, countries with low marginal costs may well face high total costs of cutting emissions.

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