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The hedge value of international emissions trading under uncertainty

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ABSTRACT

This paper estimates the value of international emissions trading, focusing on a here-to-fore neglected component; its value as a hedge against uncertainty. Much analysis has been done of the Kyoto Protocol and other potential international greenhouse gas mitigation policies comparing the costs of achieving emission targets with and without trading. These studies often show large cost reductions for all Parties under trading compared to a no trading case. We investigate the welfare gains of including emissions trading in the presence of uncertainty in economic growth rates, using both a partial equilibrium model based on marginal abatement cost curves and a computable general equilibrium model. We find that the hedge value of international trading is small relative to its value in reallocating emissions reductions when the burden sharing scheme does not resemble a least cost allocation. We also find that the effects of pre-existing tax distortions and terms of trade dominate the hedge value of trading. We conclude that the primary value of emissions trading in international agreements is as a burden sharing or wealth transfer mechanism and should be judged accordingly.

1. Introduction

The design and implementation of the Kyoto Protocol includes emissions trading as one of its primary elements (United Nations, 1997). Much analysis has been done on the Protocol and other potential greenhouse gas mitigation policies comparing the costs of achieving greenhouse gas emission targets with and without trading (e.g., Weyant and Hill, 1999; Manne and Richels, 1999; Babiker et al., 2002). These studies often show large cost reductions for all Parties under trading compared to a no trading case. Our contention is that emissions trading has "value" in such studies because the targets assigned to different countries either intentionally or accidentally redistributed the cost burden of reductions among the Parties. In our view, the value estimated in such studies is not the value of emissions trading as a policy instrument per se but is more appropriately thought of as savings from allowing a reallocation from an initial burden sharing agreement to a least cost allocation. This leads to our interest in estimating the additional value of emission trading as a hedge against uncertainty. The "hedge value" results from the fact that countries are uncertain about their future emissions growth. Thus, even if the negotiated targets were such that the expected level of net trade was zero, one might expect that there would be a positive *expected value* of trade because of uncertainty.

The logic for positive expected value when the expected net trade is zero is straightforward; partial equilibrium analysis of emissions trading shows that all parties benefit from trade, whether they are a buyer or a seller. The worst outcome from having the trading option available is that *ex post* has a zero value. Thus, the *ex ante* expected value of trade across uncertain outcomes is necessarily positive. This value of international emissions trading more closely corresponds to the equivalent domestic case for emissions trading, where the regulator has poor information on the relative abatement opportunities among different firms. Trading allows the market to correct an initial misallocation by the regulator of reduction targets among firms. The conventional analyses of the Kyoto Protocol, conducted under certainty, do not capture this value of emissions trading at all.

Our goal is to estimate the hedge value of international emissions trading for greenhouse gas abatement. We develop a stochastic model of emissions growth (and thus abatement cost). We assign Parties a target so that net trade is zero in the case where all parameter values of the abatement model are at their expected value levels. We then simulate the model for hundreds of different parameter sets drawn from probability density functions that drive emissions growth. For each parameter set we simulate the policy with and without emissions trading. Comparing the welfare cost of the trading and no trading case for each parameter set provides an estimate of the value of trade for each realization of the world. The expected value of trade is the mean of this distribution of benefits.

The paper is structured as follows: In Section 2, we describe the model, the data on uncertain parameters, and the policy cases

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we investigate. We use Section 3 to provide a benchmark with the conventional literature on the value of emissions trading, by comparing aggregate costs with and without trading when parameters of the model we use are simulated as if known with certainty. In Section 4, we develop a marginal abatement curve (MAC) model to examine the value of trading under uncertainty in this simple framework. Section 5 then provides a stochastic analysis using a global CGE model where we investigate the value of emissions trading when mitigation policy interacts with existing energy taxes and also affects the terms of trade. Section 6 summarizes the results and discusses the policy relevance of them.

2. Model, data, and policy cases

The emissions prediction and policy analysis (EPPA) model (Paltsev et al., 2005), a computable general equilibrium model of the world economy, is used both to estimate a marginal abatement curve model, and for simulations where we use it directly. EPPA Version 4 is a component of the MIT Integrated Global Systems Model (IGSM), developed to enable detailed studies of the effects of climate policies (Sokolov et al., 2005; Prinn et al., 1999). The main advantage of CGE models are their ability to capture the influence of a sector-specific (e.g., energy, fiscal, or agricultural) policy on other industry sectors, consumption, and also on international trade. EPPA is a recursive-dynamic and multi-regional model covering the entire world economy (Paltsev et al., 2005). It is built on the economic and energy data from the GTAP dataset (Dimaranan and McDougall, 2002; Hertel, 1997). The decisions about production, consumption, investment, and trade are made on the basis of the prices in the period of decision. Savings and total consumption are fixed shares of income. The EPPA model has been used extensively for the study of climate policy (Jacoby et al., 1997; Babiker et al., 2002; Viguier et al., 2003; Paltsev et al., 2003; Reilly et al., 2002; McFarland et al., 2004), climate/multi-gas interactions (Reilly et al., 1999; Hyman et al., 2003; Felzer et al., 2004), and to study uncertainty in emissions and climate projections for climate models (Webster et al., 2002, 2003). Table 1 provides an overview of the basic elements of the model, with greater details in Paltsev et al. (2003, 2004, 2005).

One of the primary drivers of uncertainty in emissions and abatement costs is the uncertainty in economic growth rates (Webster et al., 2002). In EPPA, different rates of economic growth can be simulated by assuming different rates of labor productivity growth. A historical analysis of variability in GDP growth rates between 1960 and 2000 (Webster and Cho, 2006) provides a basis for constructing probability distributions for the labor productivity growth parameters. They fit probability distributions to the historical data for individual countries and aggregate model regions, in annual and 5-year time steps. We used the variability of average annual growth rates over 5-year periods, the time step of the EPPA model. Because projected growth rates differ from average growth rates of the past, for the stochastic simulations, the distributions of GDP growth were normalized for each region such that their median is equal to 1.0. Sample values drawn from these normalized distributions are multiplied times the projected reference labor productivity growth rate between 2005 and 2010. Table 2 shows the assumed reference GDP growth rates in EPPA for all 16 regions for selected years, as annual % rates. Note that after 2000, EPPA solves in 5-year steps, so the annual growth rates are compounded. Table 3 shows the statistics of the distribution of simulated annualized GDP growth, from the assumed uncertainty in labor productivity. As shown, GDP growth rates in Canada and the EUR region composed mostly of the EU-15

Table 1
Countries, regions, and sectors in the EPPA model.

Country or Region	Sectors	Factors
Developed	***Non-Energy***	Capital
United States (USA)	Services (SERV)	Labor
Canada (CAN)	Energy-intensive products (EIT)	Land
Japan (JPN)	Other industries products (OTHR)	Crude oil resources
European Union+[a] (EUR)	Transportation (TRAN)	Natural gas resources
Australia & New Zealand (ANZ)	agriculture (AGRI)	Coal resources
Former Soviet Union[b] (FSU)	***Energy***	Hydro resources
Eastern Europe (EET)	Coal (COAL)	Shale oil resources
Developing	Crude oil (OIL)	Nuclear resources
India (IND)	Refined oil (ROIL)	Wind/solar resources
China (CHN)	Natural gas (GAS)	
Indonesia (IDZ)	Electric: fossil (ELEC)	
Higher Income East Asia[c] (ASI)	Electric: hydro (HYDR)	
Mexico (MEX)	Electric: Nuclear (NUCL)	
Central and South America (LAM)	Electric: solar and wind (SOLW)	
Middle East (MES)	Electric: biomass (BIOM)	
Africa (AFR)	Electric: Natural gas combined cycle (NGCC)	
Rest of World (ROW)	Electric: NGCC with sequestration (GGCAP)	
	Electric: integrated gasification with combined cycle and sequestration (IGCAP)	
	Oil from shale (SYNO)	
	Synthetic gas (SYNG)	
Emissions of climate relevant substances		
Substances	***Sources***	
CO_2, CH4, N2O, HFCs, SF6, PFCs, CFCs, CO, NOx, SOx, VOCs, black carbon (BC), organic carbon (OC), NH3	Combustion of refined oil, coal, gas, biofuels and biomass burning, manure, soils, paddy rice, cement, land fills, and industrial production.	

[a] The European Union (EU-15) plus countries of the European free trade area (Norway, Switzerland, Iceland).
[b] Russia and Ukraine, Latvia, Lithuania and Estonia, Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan.
[c] South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand.
[d] All countries not included elsewhere: Turkey, and mostly Asian countries.

Table 2
Reference GDP growth rates in EPPA (annual %).

	1997	2000	2005	2010	2015	2020	2025	2050	2075	2095
USA	4.2	2.4	3.5	3.4	3.3	3.1	3.1	2.4	1.9	1.8
CAN	4.8	2.9	3.7	3.6	3.3	3.1	3.1	2.4	2.0	1.8
MEX	5.1	2.1	3.4	3.3	3.0	2.8	2.8	2.2	1.8	1.7
JPN	0.9	1.1	3.2	3.3	3.3	3.3	3.4	2.6	2.0	1.8
ANZ	4.2	3.3	3.8	3.7	3.5	3.2	3.3	2.6	2.0	1.8
EUR	3.1	1.8	3.2	3.2	3.1	2.9	2.9	2.5	2.0	1.8
EET	3.3	3.3	3.4	3.4	3.3	3.1	3.2	2.7	2.1	1.9
FSU	3.1	4.5	3.9	4.0	4.0	4.0	3.9	2.4	2.0	1.9
ASI	2.4	3.4	3.4	3.7	3.3	3.1	3.1	2.6	2.0	1.8
CHN	6.5	6.0	4.8	4.6	4.3	4.0	3.9	2.9	2.1	1.8
IND	6.1	5.0	4.3	4.1	3.6	3.2	3.2	2.5	2.0	1.8
IDZ	1.7	2.4	3.6	3.7	3.5	3.6	3.6	2.7	2.0	1.7
AFR	3.0	3.6	4.2	4.0	3.6	3.3	3.1	2.2	2.0	1.9
MES	3.0	3.0	3.8	3.6	3.3	2.9	2.7	2.2	1.9	1.8
LAM	1.1	1.8	3.5	3.7	3.7	3.8	3.9	2.9	2.0	1.8
ROW	3.1	3.5	3.4	3.2	2.9	2.6	2.5	2.4	2.2	2.0

Table 3
Uncertainty in GDP growth rates: projected annual growth rate 2005–2010.

	CAN	JPN	EUR	EET	FSU
Forecast growth rates 2005–2010					
Lower 95%	1.4%	0.9%	1.4%	−7.8%	−6.0%
Median	3.8%	2.8%	2.8%	4.1%	4.0%
Mean	3.8%	3.0%	3.0%	3.5%	3.9%
Upper 95%	6.2%	6.5%	6.4%	11.2%	12.0%

Table 4
Historical correlations in GDP growth rates.

	CAN	EUR	EET	FSU	JPN
CAN	1.00				
EUR	0.66	1.00			
EET	0.68	0.27	1.00		
FSU	0.71	0.64	0.47	1.00	
JPN	0.54	0.76	0.14	0.60	1.00

countries have been less variable than Japan. GDP growth in the transition economies of Eastern Europe (EET), now part of the EU-25, and the Former Soviet Union (FSU) has been most variable. Webster and Cho (2006) also estimated the correlations in growth rates observed historically (Table 4), which we impose in base runs.

In addition to the uncertainty in GDP growth rates, there are many other uncertainties that will affect the costs of abatement, including ease of input substitution in production, the rate of energy efficiency improvements in the economy, and the availability of new alternative fuels and technologies with different emissions characteristics. While GDP growth rates across nations are only weakly correlated, these other technological uncertainties are likely to be strongly correlated if not identical across countries. If an alternative technological option is available, it will be available to all countries. The main advantage in emissions trading in the presence of uncertainty is when the uncertainties are independent or weakly correlated. Therefore, in this study, we focus on the uncertainty in GDP growth.

We simulate three carbon mitigation policy cases to identify the separate effects of the Russian allocation, the effect of differential allocation of allowances among the remaining Parties, and the value of emissions trading as a hedge against uncertainty. In each, we focus on cases in which only CO_2 is constrained, and do not consider other greenhouse gases. The first case, *Kyoto w FSU* approximates idealized implementation of the Kyoto Protocol as it has currently gone into force, with participation by Canada (CAN), the EU (EUR), Japan (JPN), Eastern European Countries (EET), and Russia and the other former Soviet Republics (FSU).[1] The United States (USA) and Australia (ANZ) are not constrained in this policy since they have not ratified the Protocol. The emissions constraints have been modified to account for credits for Article 3.4 carbon sinks negotiated at Bonn and Marrakech (Babiker et al., 2002). The second case, *Kyoto no FSU* excludes the FSU from emissions trading. Many European countries have expressed a desire to meet caps without the Russian "hot air" and realistically Russia may not succeed in setting up a domestic trading system in a timely manner. This may be a more realistic, albeit, still relatively idealized implementation of the Protocol.

The third case, which we refer to as the *Cost-Effective* is constructed by reallocating allowances in the *Kyoto no FSU* case such that there is no incentive to trade when simulating policy under reference assumptions of the model; i.e., the autarkic carbon price is equal across regions. Once uncertainty is introduced, emission growth deviates from the reference, marginal costs of abatement differ, and regions have an incentive to trade. We are not claiming this expected-equal-marginal-cost allocation to be necessarily a goal or a desirable outcome of political negotiations. It is simply designed so that we can separately measure the hedge value of trading.

Each of these policy cases is simulated with and without emissions trading, which we designate with *tr* (trading) and *ntr* (no trading). For the uncertainty analysis, we focus on the cases without the FSU, stochastically simulating them using both the partial equilibrium and general equilibrium model. We then investigate the interactions of climate policy with tax distortions, by developing a case where we remove existing fuel tax distortions. Recent work (Babiker et al., 2004) has shown that trading may not be beneficial to Parties in the presence of tax distortions, a result we find here as well, and this case helps to resolve differences between the partial and general equilibrium results. Finally, we consider cases that test the sensitivity of results to the correlation of growth among countries. While we have an estimate of correlation from Webster and Cho (2006) the statistical significance of it is weak, and with changing international relations (e.g. integration of the EET states into the EU) the historical correlation is likely to be a poor guide in the future.

3. The conventional case: emissions trading under certainty

We simulate a no policy case and three policy cases, with and without international emissions trading using the EPPA model. Resulting carbon prices and consumption changes are reported in Table 5. We show total consumption for each case and the change in consumption between each trading and respective no-trade case. Much of the gain from emissions trading under Case 1, *Kyoto w/FSU*, is the hot air itself. By lowering the aggregate abatement by nearly 230 MtC of carbon, the costs of abatement in participating nations are necessarily lower, and the gains from trade are significant in all regions except EET. Russia also undertakes real abatement of 83 MtC from its reference emissions. The welfare gain from allowing emissions trading when the FSU is included is $5.8B, $77.9B, $12.7B, $0.4B, and $9.1B for CAN, EUR, JPN, EET, and FSU, respectively. Without the FSU, the welfare gain from including emissions trading under

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[1] Russian and Ukraine are part of the Kyoto Parties accepting caps. The other former republics are not part among the capped Parties, but they are not separately identifiable in the EPPA model.

Table 5
Welfare impacts of Kyoto policy under certainty.

	CAN	EUR	JPN	EET	FSU	Total
Welfare (consumption) ($ Billion)						
Reference	641	7654	3372	293	636	12,597
Kyoto w/FSU-ntr	634	7559	3357	293	634	12,476
Kyoto w/FSU-tr	639	7637	3370	293	643	12,582
Kyoto no FSU-ntr	634	7559	3357	293	634	12,476
Kyoto no FSU-tr	635	7575	3361	298	634	12,502
Cost-effective-ntr	637	7581	3362	289	634	12,502
Cost-effective-tr	637	7581	3362	289	634	12,502
Gain from emissions trading (tr-ntr) ($B)						
Kyoto w/FSU	5.8	77.9	12.7	0.4	9.1	106
Kyoto no FSU	1.2	15.8	3.5	5.4	0.0	26
Cost-effective	0.0	0.0	0.0	0.0	0.0	0
Carbon Price ($/ton)						
Kyoto w/FSU-ntr	225	183	199	18	0	
Kyoto w/FSU-tr	25	25	25	25	25	
Kyoto no FSU-ntr	225	183	199	18	0	
Kyoto no FSU-tr	142	142	142	142	0	
Cost-effective-ntr	142	142	142	142	0	
Cost-effective-tr	142	142	142	142	0	

Kyoto is lower for all regions except EET, \$1.2B (CAN), \$15.8B (EUR), \$3.5B (JPN), \$5.4 (EET), and \$0B (FSU).[2] Much of these differences are the savings from lowering the aggregate emissions target. The carbon price in the *Kyoto w/FSU-tr* case is \$25 tC, compared with \$142 tC in the *Kyoto no FSU-tr* case, the difference reflecting the hot air and addition of low cost abatement options in the FSU. We verify that the *Cost-Effective-tr* and *Cost-Effective-ntr* are identical, producing the same carbon price in each region without trading as with, and with no impact on consumption. The autarkic cases show CAN with the highest carbon price at \$225 tC, JPN, and EUR both somewhat below \$200 tC, and the EET with an \$18 tC price. Note that all \$ amounts given as welfare changes or carbon prices are from the model period 2010, representing the five-year Kyoto commitment period. These are dollar amounts in 1997 real U.S. dollars. Because we only examine a single model period, there is no discounting assumed.

4. Emissions trading under uncertainty: partial equilibrium estimates

Fig. 1 offers a simple diagrammatic analysis of the standard partial equilibrium analysis that underlies the expectation that the hedge value of emissions trading should be positive. As shown, Country A has a marginal abatement cost of P_A and Country B has a marginal abatement cost of P_B. When emission trading is introduced, the international carbon price is P_W. At this price, A will buy ΔQ_A permits in order to reduce its abatement level and B will sell ΔQ_B permits and increase its abatement by that amount. The total abatement cost to A falls by a_1+a_2, and the cost of buying permits is a_2, resulting in a net gain of area a_1. The total abatement cost to B increases by b_2, but since revenue from the permit sales is b_1+b_2 there is a net gain of b_1. The worst possible outcome of trading in this situation is no gain when a country's autarkic price is the same as the world price with trading, and the country thus is neither a net buyer or seller.

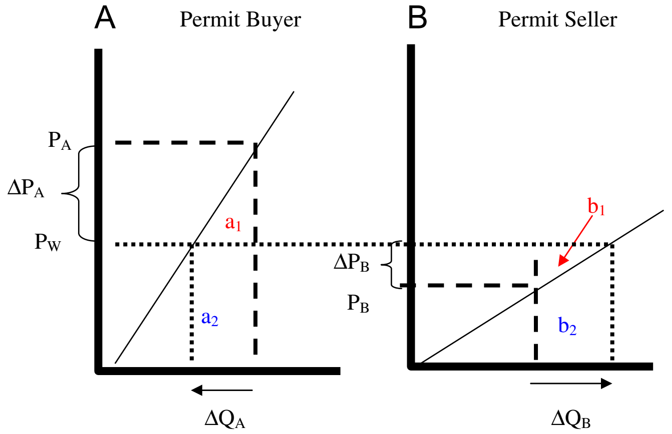

Fig. 1. Graphical description of partial equilibrium gain from emissions trading. Country (A) and (B).

We develop a partial equilibrium model based on marginal abatement curves (MACs), following the approach of Ellerman and Decaux, (1998) and others, to examine the hedge value of emissions trading in this simple case. The MACs are third order polynomial fits of 40 simulations of abatement ranging from 1% to 40% reduction below the reference in 2010 (Fig. 2). To simulate uncertainty in emissions, we sample from the uncertainty in growth rates for all regions based on the historical variability described in Section 2. Latin Hypercube sampling (Iman and Helton, 1988), a stratified sampling method shown to be more efficient than random sampling was used to construct 250 simulations. EPPA is used to project the 250 growth samples under the *Kyoto no FSU* case with and without trading and the *Cost-Effective* case with and without trading. Differences in growth rates result in different reference emissions, which therefore change the amount of abatement required to achieve the fixed target and the cost of that abatement. With shifts in abatement costs of all regions, the number of permits bought/sold will vary correspondingly. The resulting changes in CO_2 for each region as calculated by EPPA between the no-trade and the trading cases are used in conjunction with the MAC curves to calculate the net gain from emissions trading.

The partial equilibrium estimates of the gains from emissions trading are calculated for these four regions (Table 6). The gain from trade under the *Cost-Effective* case is a measure of the hedge value of emissions trading, which under this case we find to have mean values of \$0.1B (CAN), \$0.3B (EUR), \$0.4B (JPN), and \$1.5B (EET). The 95% probability ranges are \$0–\$0.4B (CAN), \$0–\$1.3B (EUR), \$0–\$1.3B (JPN), and \$0–\$7B (EET). In contrast, the *Kyoto no FSU* case has mean gains from trade of \$1B, \$0.7B, \$4.6B, and \$0.7B for EUR, JPN, EET, and CAN, respectively. As expected no region is ever worse off with trading. The hedge value of trading is a small component of the total value of trading in this case; at the mean value it is about one-third for the EUR and EET, half for JPN, and about 15% for CAN. The hedge value that we derive from the MAC model reflects the uncertainty distribution. The more uncertain the emissions, the greater the hedge value of trading. The range is fairly wide because there are some cases in the sample where some regions have very high growth while others have low, and thus trading is particularly valuable. However, these results suggest that they are redistribution goals implicit in the Kyoto Protocol that give greater value to trading than uncertainty in growth of emissions. This is true even in comparison with the

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[2] EPPA is based on the GTAP-E data base, and all regional economies are denominate in US \$ at base year (1997) exchange rates, and all commodities, including emissions permits, are traded at these exchange rates. Aggregate benefits are summed across regions in US dollar as denominated in the model. A further issue, not explored here, is the aggregation of welfare measures across regions using exchange rates. In principle, a real purchasing power index, such as the purchasing power parity (PPP) index should be used to make such cross country comparisons. We abstract from that issue here but these PPP differentials represent another violation of the perfectly competitive and idealized market conditions of this simple case, part of which we take up in the next section.

Kyoto no FSU case. *Kyoto w/FSU* has even stronger implicit redistribution goals.

The value of trading estimated with the partial equilibrium (PE) model is smaller than the value of trading simulated with the CGE model under certainty. In those we found the gains from trade to be \$1.2B for CAN (\$0.1B PE), \$15.8B for EUR (\$0.3B PE), \$3.5B for JPN (\$0.4B PE), and \$5.4B for EET (\$1.5B PE), and those did not include a hedge value since the calculation was under certainty. The MAC costs, derived from integrating under marginal abatement curves, and the welfare cost computed from the CGE model would not be expected to be identical because the CGE results include feedback effects. As shown elsewhere, pre-existing tax distortions can lead to a large difference between the direct cost, the area under a MAC, and the estimated welfare cost (Paltsev, et al., 2004). We investigate this difference further in Section 5.

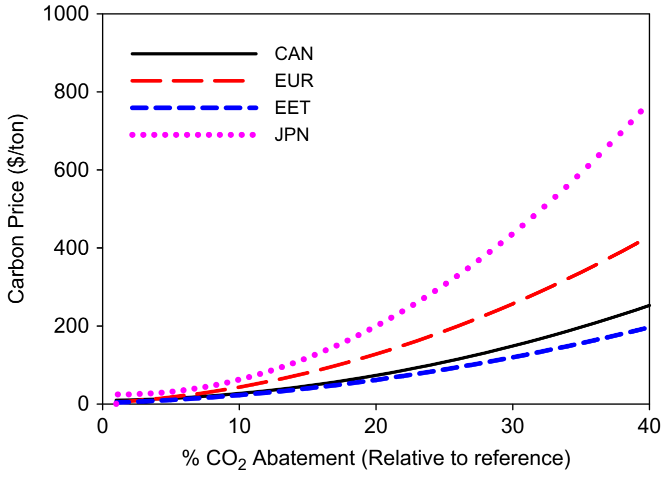

Fig. 2. Marginal abatement cost curves derived from EPPA model.

Table 6
Uncertainty estimates of gains from trading: partial equilibrium results (\$ Billion 1997 US)

	CAN	EUR	JPN	EET
Kyoto no FSU				
Lower 95%	0.05	0.01	0.00	0.73
mean	0.67	0.96	0.74	4.65
Upper 95%	1.53	2.89	3.28	10.43
Cost-effective				
Lower 95%	0.00	0.00	0.00	0.01
mean	0.11	0.34	0.38	1.53
Upper 95%	0.41	1.33	1.34	7.02

Not surprisingly, the pattern of who buys and who sells emissions permits differs significantly between these two policies (Fig. 3). Under *Kyoto w/o FSU*, the probability of being a permit seller for CAN , EUR, JPN, and EET are, respectively, 2%, 5%, 18%, and 99%. The fact that the EET is a permit seller in nearly all cases and JPN, EUR, and CAN are buyers in nearly all cases reflects the burden redistribution aspects of the Kyoto Protocol that favored the EET. Under the *Cost-Effective* case, the probability of being a net permit seller for CAN, EUR, JPN, and EET are, respectively, 35%, 59%, 60%, 42%, much closer to even odds of being either a buyer or a seller. This reflects the allocation design where reference growth rates in all regions will result in no trading.

5. Emissions trading under uncertainty: general equilibrium estimates

The partial equilibrium analysis provided a numerical test of the simple case made for emissions trading—that it reduces the cost for both buyers and sellers of permits. As already noted, the CGE estimates of trading gains in the certain case were much larger than the mean from the partial equilibrium analysis. Previous studies have shown in simulations under reference conditions (i.e., certainty) that the economy-wide implications of trading can differ from that for individual firms, which would be the direct buyers and sellers due to the presence of tax distortions and terms of trade effects (Babiker, et al., 2004; Paltsev et al., 2004).

We turn now to results of stochastically simulating the CGE model to investigate emissions trading where these distortions and other feedbacks exist. We again use Latin Hypercube sampling from the distributions on GDP growth provided in Section 2. We translate these into changes in the growth of labor productivity such that we reproduce the historical variability in GDP in the forward forecasts. As noted in Section 2, we normalize the historical distributions around the reference forecasts of the EPPA model. We again focus on the *Kyoto no FSU* and *Cost-Effective* cases. In addition, we include a case with the cost-effective allocation where we remove all fuel taxes, which we label *Cost-Effective-n.f.t.*

Table 7 provides the key results. Here, we see that the median gains from trade in *Kyoto no FSU* are much closer to the estimate

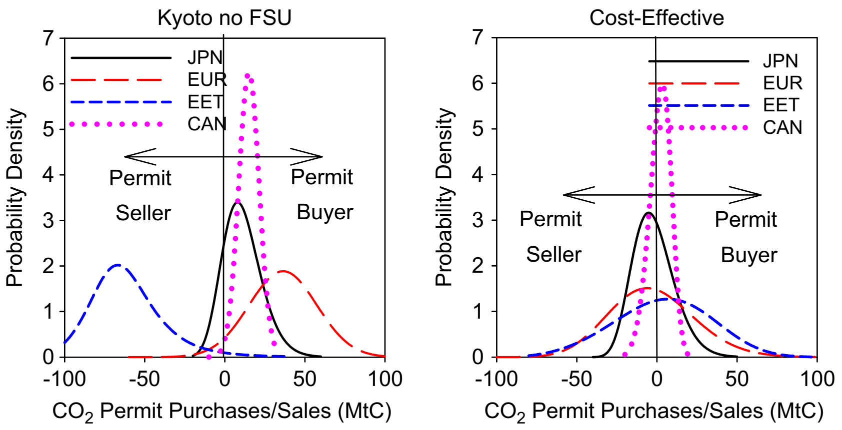

Fig. 3. Buyers and sellers of permits: partial equilibrium results.

Table 7
Uncertainty estimates of effects of trading: general equilibrium results.

	$ Billion 1997 U.S.				Percent change			
	CAN	EUR	JPN	EET	CAN	EUR	JPN	EET
Kyoto no FSU								
Lower 95%	0.3	−2.0	−1.7	0.1	0.05	−0.03	−0.06	0.03
Median	1.3	12.7	2.3	4.3	0.20	0.17	0.07	1.47
Mean	1.3	13.7	3.6	4.8	0.20	0.18	0.10	1.88
Upper 95%	2.5	37.0	16.3	13.1	0.36	0.43	0.41	5.63
Cost-effective								
Lower 95%	−0.1	−14.9	−3.9	−0.1	−0.02	−0.20	−0.12	−0.02
Median	0.1	−2.1	−0.7	0.6	0.01	−0.03	−0.02	0.17
Mean	0.1	−0.5	0.2	1.2	0.02	−0.01	0.00	0.50
Upper 95%	0.6	20.2	10.0	6.0	0.09	0.26	0.25	3.36
Cost-effective-n.f.t								
Lower 95%	−0.6	−4.4	−0.3	−0.6	−0.08	−0.06	−0.01	−0.17
Median	−0.1	0.6	0.1	0.0	−0.02	0.01	0.00	0.00
Mean	0.0	0.6	0.2	0.4	0.00	0.01	0.01	0.20
Upper 95%	1.0	6.0	1.2	3.9	0.18	0.08	0.04	1.52

under certainty than with the partial equilibrium results. Because of non-linearities, skewness of the distributions, and the imposed correlation structure we would not expect the median or mean from this stochastic simulation of the CGE to be exactly the same as when simulated under certainty with reference growth assumptions. The 95% range for the gain from trading in *Kyoto no FSU* is comparable to the range under the partial equilibrium calculation for CAN ($0.3 to $2.5B) and EET ($0.1 to $13.1B), but is significantly wider for EUR (−$2.0B to $37.0B) and JPN (−$1.7B to $16.3B). More striking is the fact that in the *Kyoto no FSU* case, we see that in some cases EUR and JPN lose from emissions trading.

In the *Cost-Effective* case, the likelihood of losses from emission trading occurs more frequently, and can occur in any of the regions. In the *Cost-Effective-n.f.t* case, some of this tendency for emissions trading to cause welfare losses for regions is reduced. The median effect of trade for EUR changes from a loss of $2.1B to a gain of $0.6B, and for JPN from a loss of $0.7B to a gain of $0.1B. Similarly, the absence of fuel taxes results in 95% lower bounds for EUR (−$14.9B to −$4.4B) and JPN (−$3.9 to −$0.3B) that are

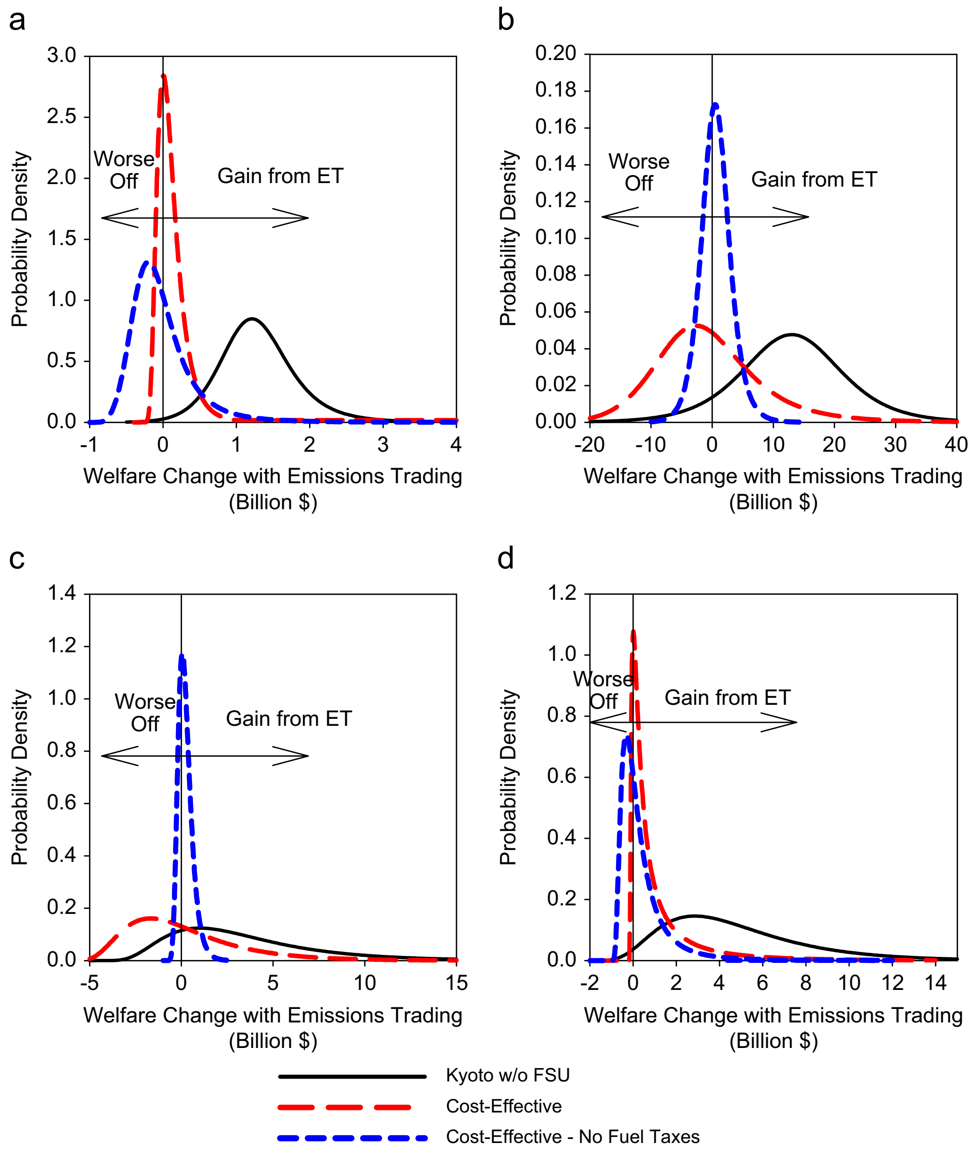

Fig. 4. Probability distributions of welfare impacts of emissions trading under uncertainty (general equilibrium estimate). (a) CAN, (b) EUR, (c) JPN and (d) EET.

smaller losses from trade. Fuel taxes are particular high in EUR and JPN, and a main benefit of emissions trading is to avoid those circumstances where EUR or JPN grow rapidly relative to other regions, forcing a high autarkic carbon price that greatly exacerbates the tax interactions effect. Fitted probability density functions for welfare impacts in the four participating regions are shown in Fig. 4.

The likelihood that trading results in a welfare loss is shown in Table 8. The probability that emissions trading results in a welfare loss is lowest under the *Kyoto no FSU* case (0%, 6%, 18%, and 1% for CAN, EUR, JPN, and EET, respectively) and highest under the *Cost-Effective* case 30%, 59%, 60%, and 11% for CAN, EUR, JPN, and EET, respectively), with probabilities between these extremes in the *Cost-Effective-n.f.t* case. This suggests that a substantial number of the cases of welfare losses in the general equilibrium context are the result of the tax effects. Under conditions of perfect competition, well-known theoretical results demonstrate that free trade would lead to an increase in welfare to all parties. We see the possibility of welfare losses from emissions trading even with the elimination of energy taxes. These stem from the presence of other tax distortions and a specification of foreign and domestic goods as imperfect substitutes, which differ from the theoretical assumptions needed to show free trade as necessarily welfare improving. A further implication of the assumption of imperfect substitutes among goods of each region is that the price of utility in each region, which we use as the numeraire, diverges. Hence a simple sum of the regional welfare changes is not a measure of aggregate welfare. That is, welfare is well-defined for each region's representative agent but the formulation does not have a world welfare function that provides a basis to sum welfare among regions.

Paltsev et al. (2004) and Babiker et al. (2004) also identify terms of trade effects as potentially important. Because the terms-of-trade change endogenously in the model, we are not able to simply eliminate them as we did with fuel taxes. We thus examine changes in terms of trade by relating these to losses and gains from emissions trading. Fig. 5 shows the probability distribution of the change in the terms of trade when trading is allowed. Under the Kyoto without FSU policy, the permit buyers (EUR, JPN, CAN) experience a decrease in the terms of trade of up to a half a percent, and the permit seller (EET) experiences an improvement in the terms of trade. Under the cost-effective case, regions are roughly equally likely to experience a gain or loss in their terms of trade. The size of this effect is relatively small, less than a percent for EUR, JPN, and CAN and up to two or three percent for EET.

Table 8
Probability that trading reduces welfare: general equilibrium results.

	CAN	EUR	JPN	EET
Kyoto no FSU	0%	6%	18%	1%
Cost-effective	30%	59%	60%	11%
Cost-effective-n.f.t.	62%	38%	27%	50%

We plot the change in welfare measured as the change in consumption against the change in terms of trade in Fig. 6 for each region for the *Cost-Effective-n.f.t* case. This case eliminates other sources of disparity (i.e., fuel tax interactions) and thus comes closest to isolating the terms of trade as a cause of the welfare change. EUR and CAN show a strong positive relationship: losses (gains) in terms-of-trade are strongly associated with losses (gains) in consumption. The relationship is very tight suggesting that the terms-of-trade effect strongly dominates any direct benefits of emissions trading. The results for EET and JPN show a more complex relationship. With large shocks in either direction (i.e., large terms of trade effects), there is a tendency for consumption gains. Climate policy interactions with the terms of trade effect are complex, affecting multiple export and import markets, and dependent on the specific trading relationships and trading partners. Whether the terms of trade effect will dominate the direct cost effect of carbon policy will also depend on how important trade is in a region's economy. Each of the realizations of the future represented in the 250 parameter sets is a unique combination of differential growth rates among the regions.

It is perhaps surprising that the "indirect" terms-of-trade effect can dominate the "direct" effect of emissions trading. A primary reason for this is likely a feedback effect on the domestic economy from terms of trade changes caused by emissions trading among other regions. Consider the case where, for example, EET's autarkic price is exactly at the world trading price. In this circumstance, the direct benefit from trade is necessarily zero because net trade would be zero. However, suppose other regions have an incentive to trade, then opening emissions trading would thus affect the international prices of goods, including those for EET's exports and imports even though there was no direct effect of emissions trading on EET's economy. As this example is constructed, the terms of trade change are the only economic change affecting the EET. Any welfare change thus will be completely determined by the change in the terms of trade. The allocation in the *Cost-Effective-n.f.t.* case is set so that countries will often have only small incentives to trade. Only in those cases where the region's autarkic price is far from the world

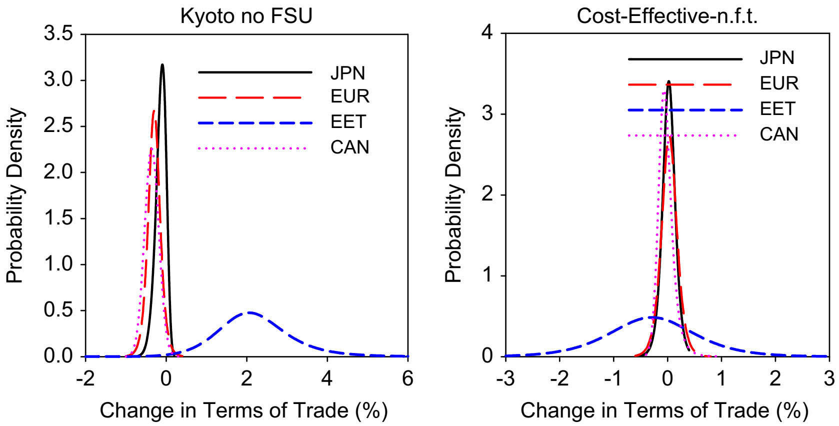

Fig. 5. Impacts of emissions trading on terms of trade relative: terms of trade in the trading case compared with the no trading case.

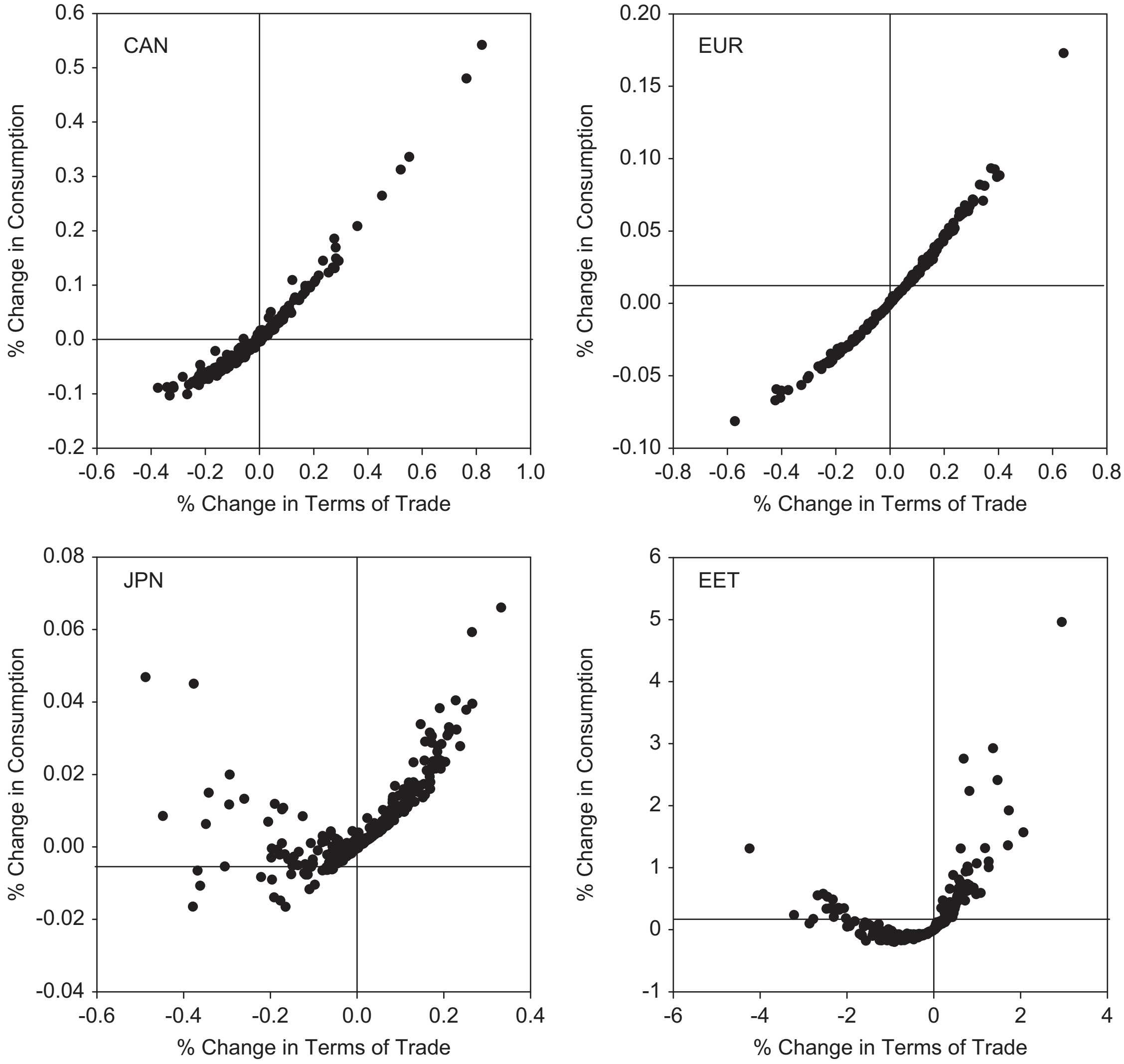

Fig. 6. Relationship between change in terms of trade and change in welfare from allowing emissions trading (cost-effective-n.f.t.).

price, will there be a big “direct” welfare gain from trading. And, only in these circumstances is it likely that the direct gains from trading can dominate the indirect terms-of-trade effect. The EET and JPN, regions where the relationship between the terms of trade change and the consumption loss is more complex, are also those regions where simulated growth is more variable as discussed in Section 2 and shown in Table 3.

It is useful to compare the general equilibrium results under uncertainty to those from the partial equilibrium analysis. For example, for EUR, the change in total abatement costs under partial equilibrium for trading in the *Cost-Effective* policy had a mean and 95% lower and upper bounds, respectively, of \$0.3, \$0, and \$1.3 billion. The general equilibrium welfare impact has a mean of close to zero with or without tax distortions, and 95% ranges of −\$15 to \$20 billion with existing fuel taxes and from −\$4 to \$6 billion when we remove fuel taxes. The results for the other regions are comparable, and the uncertainty in the impact of emissions trading is much larger in the general equilibrium context. Distortions and terms of trade effects can either overwhelm gains from trade to result in net losses or amplify these gains to appear much larger. In fact, the median hedge value of trade is negative in the *Cost-Effective* case for EUR and JPN and is nearly zero for all regions in the *Cost-Effective-n.f.t* case, indicating that half or more of the cases emissions trading is welfare worsening.

The results presented so far are based on imposing correlations among growth as observed over the period 1960–2000. The statistical significance of these correlations were relatively weak, and there are reasons to believe that these correlations may not apply in the future. We thus compare the results with historical correlations to the same policies simulated with growth rates sampled assuming no correlation (probabilistically independent) and with a very strong correlation of 0.90. These correlations are imposed pairwise between every pairing of the four regions where the policy constraints are imposed. We show in Table 9 the results only for the *Cost-Effective-n.f.t* case, as the effects of correlation are similar across policies. The effect of different correlations on the mean welfare change is negligible, and the effect on the extremes of the distribution is that weaker correlation causes more uncertainty in welfare change (longer tails). The effect of correlation on other variables is similar to that of welfare. Thus, our overall conclusion is that even with extreme assumptions about correlation, the main results of our study are little affected.

6. Conclusions

In this study we have estimated what we refer to as the hedge value of international emissions trading as a greenhouse gas

Table 9
Sensitivity of general equilibrium results to correlation of GDP growth among regions (*cost-effective-n.f.t.*)

	CAN	EUR	JPN	EET
Lower 95%				
Uncorrelated	−0.10	−0.07	−0.01	−0.21
Historical	−0.08	−0.06	−0.01	−0.17
Corr=0.9	−0.06	−0.02	0.00	−0.42
Mean				
Uncorrelated	0.02	0.01	0.02	0.27
Historical	0.00	0.01	0.01	0.20
Corr=0.9	0.00	0.01	0.00	−0.07
Upper 95%				
Uncorrelated	0.35	0.12	0.09	2.37
Historical	0.18	0.08	0.04	1.52
Corr=0.9	0.24	0.07	0.02	0.19

mitigation policy instrument. In our definition, this is the value of trade as a cushion against uncertainty in emissions growth. Previous estimates of the value of trade have estimated its value under certainty, in the context of the Kyoto emissions targets. Much of this value resulted from Russian "hot air" that effectively lowered the aggregate emissions target by, in our reference case, 230 MtC. Trading under certainty with the FSU included results in the largest gains from emissions trading, but the majority of this is due to the fact that it increases the allowances available to all parties by the hot air amount. Removing the FSU reduces the gains from trade to all remaining regions, except EET, which becomes the net permit seller. We find the hedge value of emissions trading under uncertainty to be small in comparison. From the partial equilibrium analysis, the mean gains from trading ranged from $0.1 to $1.5 billion. When we estimated the hedge value by stochastically simulating a general equilibrium model, we found strong interactions of the climate policy with pre-existing fuel taxes and terms of trade effects. These interactions meant that emissions trading could often be welfare worsening for any region, and thus the hedge value (the mean value in our stochastic simulation) for all regions was even smaller and sometimes a net loss than in the partial equilibrium analysis. With the current levels of fuel taxes left in place, there were significant probabilities that emissions trading would induce a net welfare loss to any region. With fuel taxes removed, the likelihood of a net welfare loss in any region was smaller but remains substantial due to the terms of trade effects. The distortion and terms of trade effect also greatly increase the variance of the value of emissions trading.

The value of international emissions trading and its components identified in this paper (hedge value, burden redistribution, tax interaction, and terms of trade effects) obviously strongly depend on specific circumstances of the trading participants. The hedge value depends on the uncertainty in emissions forecasts, conditions specific to individual regions. We used historical variability in growth rates to estimate likely future variability for these regions. The burden redistribution value of trade obviously depends on the initial allowance allocation. Fuel taxes vary among countries, and terms of trade effects depend on particular exports and imports and the geographic patterns of trade. We also emphasize that we would expect much different results for the value of emissions trading in a domestic context, where trading is among individual firms or entities, rather than among countries as we have simulated here. Our suspicion is that the hedge value in the domestic trading context may be much larger because of the scope for large and unexpected changes in emissions for individual entities. Thus, the lessons from domestic trading systems may not necessarily transfer to international trading systems or vice-versa.

We put particular focus on estimating the hedge value of emissions trading, a value that has here-to-fore not been estimated for international greenhouse gas trading. We would argue that the hedge value is most closely related to the pure value of trading as a policy instrument where economic efficiency is the sole objective of policy design, and distributional effects of the policy are ignored as economists would often like to do. Given the importance of the implications of distributional goals implicit in the Kyoto allocations for the value of trading, at least in the Kyoto Protocol as we have simulated it, it seems clear that this aspect of a negotiated agreement needs to be a central consideration of economic analysis. From that perspective, the appeal of emissions trading is that it allows equity/burden sharing considerations while allowing the trading system to then re-establish a cost-effective solution—at least from a partial equilibrium perspective that does not include general equilibrium effects where trading can be welfare worsening.

Interestingly, our results suggest that if the redistribution of the burden is large, then we might expect trading to be welfare improving, even if not optimal in the sense that further consideration of tax effects and terms of trade effects could further improve the outcome. However, if trading is among countries where each has an allocation that is likely to be close to the trading result (little burden redistribution), then there is a good chance that trade can be net welfare worsening. Once recognizing that the primary use of international emissions trading is a burden sharing or wealth transfer device, concerns for the sustainability or self-reinforcing nature of the agreement may lead one to question whether an emissions trading system is the best method for achieving the redistribution goal.

While countries do what they do for many stated and unstated reasons, the US withdrawal from the Kyoto Protocol likely reflected an unwillingness to go through with the burden sharing agreement in the Protocol that would have involved considerable gain for Russia, to be borne by the US. Europe maintains that it will not use Russian hot air. Whether that position will hold through the end of the Kyoto commitment period is yet to be seen, but again this appears to be an unwillingness to follow through on the burden redistribution agreement in the original deal. The large redistribution implicit in the Kyoto Protocol as originally negotiated is just the situation where trading would have been highly beneficial. From the evidence to date on international implementation of climate policy, it is not clear that agreements with large redistribution goals are sustainable. In the end, the value of emissions trading as a policy instrument for international agreements should be judged on its ability to actually accomplish burden sharing goals (while achieving cost effectiveness), as compared with alternative policy approaches.

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References

Babiker, M.H., Jacoby, H.D., Reilly, J.M., Reiner, D.M., 2002. The evolution of a climate regime: Kyoto to Marrakech. Environmental Science and Policy 5 (3), 195–206.

Babiker, M., Reilly, J., Viguier, L., 2004. Is emissions trading always beneficial. Energy Journal 25 (2), 33–56.

Dimaranan, B., McDougall, R., 2002. Global Trade, Assistance, and Production: the GTAP 5 Data Base. Center for Global Trade Analysis. Purdue University, West Lafayette, Indiana.

Ellerman, A.D. & A. Decaux (1998). Analysis of post-Kyoto CO_2 emissions trading using marginal abatement curves. MIT Joint Program Report #40, Cambridge, MA. See http://web.mit.edu/globalchange/www/reports.html#pubs.

Felzer, B., Kicklighter, D.W., Melillo, J.M., Wang, C., Zhuang, Q., Prinn, R., 2004. Ozone effects on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. Tellus B 56 (3), 230–248.

Hertel, T., 1997. In: Global Trade Analysis: Modeling and Applications. Cambridge University Press, Cambridge, UK.

Hyman, R.C., Reilly, J.M., Babiker, M.H., De Masin, A., Jacoby, H.D., 2003. Modeling non-CO_2 greenhouse gas abatement. Environmental Modeling and Assessment 8 (3), 175–186.

Iman, R.L., Helton, J.C., 1988. An investigation of uncertainty and sensitivity analysis techniques for computer models. Risk Analysis 8 (1), 71–90.

Jacoby, H., Eckaus, R., Ellermann, A.D., Prinn, R., Reiner, D., Yang, Z., 1997. CO_2 emissions limits: economic adjustments and the distribution of burdens. Energy Journal 18, 31–58.

Manne, A., Richels, R., 1999. The Kyoto protocol: a cost-effective strategy for meeting environmental objectives? The costs of the Kyoto protocol: a multi-model evaluation.. The Energy Journal, 1–23 (Special Issue).

McFarland, J.R., Reilly, J.M., Herzog, H.J., 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26 (4), 685–707.

Paltsev, Sergey, John M. Reilly, Henry D. Jacoby, Richard S. Eckaus, James McFarland, Marcus Sarofim, Malcolm Asadoorian, Mustafa Babiker(2005), The MIT emissions prediction and policy analysis (EPPA) model: Version 4, MIT joint program on the science and policy of global change. Report 125. See http://web.mit.edu/globalchange/www/reports.html#pubs.

Paltsev, S., H.D. Jacoby, J. Reilly, L. Viguier & M. Babiker (2004). Modeling the transport sector: the role of existing fuel taxes in climate policy. MIT joint program on the science and policy of global change. Report 117.

Paltsev, S., J.M. Reilly, H.D. Jacoby, A.D. Ellerman & K.H. Tay (2003). Emissions trading to reduce greenhouse gas emissions in the united states: the mccain-lieberman proposal. MIT joint program on the science and policy of global change. Report 97.

Prinn, R., Jacoby, H., Sokolov, A., Wang, C., Xiao, X., Yang, Z., Eckaus, R., Stone, P., Ellerman, D., Melillo, J., Fitzmaurice, J., Kicklighter, D., Holian, G., Liu, Y., 1999. Integrated global system model for climate policy assessment: feedbacks and sensitivity studies. Climatic Change 41, 469–546.

Reilly, J., Mayer, M., Harnisch, J., 2002. The Kyoto protocol and non-CO_2 greenhouse gases and carbon sinks. Environmental Modeling and Assessment 7 (4), 217–229.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A., Wang, C., 1999. Multi-gas assessment of the Kyoto protocol. Nature 401, 549–555.

Sokolov, A.P., C.A. Schlosser, S. Dutkiewicz, S. Paltsev, D.W. Kicklighter, H.D. Jacoby, R.G. Prinn, C.E. Forest, J. Reilly, C. Wang, B. Felzer, M.C. Sarofim, J. Scott, P.H. Stone, J.M. Melillo & J. Cohen,July 2005: The MIT integrated global system model (IGSM) Version 2: model description and baseline evaluation, MIT joint program on the science and policy of global change. Report 124, Cambridge, MA, July.

United Nations (1997). Kyoto Protocol to the United Nations Framework Convention on Climate Change. FCCC/CP/1997/L.7/Add.1. Bonn.

Viguier, L., Babiker, M., Reilly, J., 2003. The costs of the Kyoto Protocol in the European Union. Energy Policy 31 (5), 459–481.

Webster, M.D., Babiker, M., Mayer, M., Reilly, J.M., Harnisch, J., Sarofim, M.C., Wang, C., 2002. Uncertainty in emissions projections for climate models. Atmospheric Environment 36 (22), 3659–3670.

Webster, M.D., Cho, C.-H., 2006. Analysis of variability and correlation in long-term economic growth rates. Energy Economics 28 (5–6), 653–666.

Webster, M.D., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P., Wang, C., 2003. Uncertainty analysis of climate change and policy response. Climatic Change 61 (3), 295–320.

Weyant, J.P. and J. Hill (1999). Introduction and overview, The costs of the Kyoto Protocol: a multi-model evaluation. The Energy Journal (Special Issue): vii-xliv.