What to Expect from an International System of Tradable Permits for Carbon Emissions

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ABSTRACT

We use an econometrically-estimated multi-region, multi-sector general equilibrium model of the world economy to examine the effects of using a system of internationally-tradable emissions permits to control world carbon dioxide emissions. We focus, in particular, on the effects of the system on flows of trade and international capital. Our results show that international trade and capital flows significantly alter projections of the domestic effects of emissions mitigation policy, compared with analyses that ignore international capital flows, and that under some systems of international permit trading the United States is likely to become a significant permit *seller*, the opposite of the conventional wisdom.

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The views expressed in this paper are those of the authors and should not be interpreted as reflecting the views of the organizations with which they are affiliated.

1 Introduction

One of the leading proposals for controlling global climate change is an international system of tradable permits for carbon dioxide emissions. In fact, the Kyoto Protocol to the United Nations Framework Convention on Climate Change, signed in Kyoto in December 1997, includes provisions for setting up just such a system among industrial ("Annex I") countries. The theoretical attraction of permit trading is that it is efficient: it guarantees that emissions reductions will be obtained at minimum cost. As a political matter, especially in the United States, an equally important virtue of a permit system is that it does not involve new taxes.

Despite the enthusiasm for international permit trading, little empirical work has been done on estimating the effects of such a policy. In this paper we attempt to fill that gap by using a multi-region, multi-sector intertemporal general equilibrium model of the world economy called "G-Cubed".[1] We examine and compare three potential policies: (1) unilateral stabilization of U.S. carbon emissions at 1990 levels, (2) stabilization of OECD emissions at 1990 levels on a country by country basis without international permit trading, and (3) joint stabilization of OECD emissions with full international permit trading. We focus particularly on the effects of the policies on output, exchange rates and international flows of goods and capital. In addition, by comparing the second and third simulations we are able to calculate the gains from allowing international permit trading.[2]

[1] G-Cubed stands for "Global General Equilibrium Growth".

[2] We examine trading within the OECD rather than within the broader "Annex I" group which includes Eastern Europe and the states of the former Soviet Union. The reason is that we want to measure the efficiency gains from trading and in order to do that we need the overall level of abatement to be the same with or without trading. That would not be the

2 Model Structure

At the most abstract level G-Cubed consists of a set of eight general equilibrium models, each corresponding to a geographic region, linked by international flows of goods and assets. We assume the regions each consist of a representative household, a government sector, a financial sector, twelve industries, and a sector producing capital goods. The regions and sectors are listed in Table 1. Although the regions are similar in structure (that is, they consist of similar agents solving similar problems), they differ in endowments, behavioral parameters and government policy variables.[3] In the remainder of this section we present the key features of the regional models.[4] To keep the notation from becoming cumbersome, we will generally not subscript variables by country. The complete model, however, consists of eight regional modules linked by trade and asset flows.

2.1 Producer Behavior

Within a region, each producing sector is represented by a single firm which chooses it inputs and its level of investment in order to maximize its stock market value subject to a multiple-input production function and a vector of prices it takes to be exogenous. We assume that output can be represented by a constant elasticity of substitution (CES) function of inputs of

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case if we examined Annex I trading because the former Soviet Union is currently about 300 million metric tons below its 1990 emissions. If we included it in the trading regime, moving from independent stabilization to trading would essentially just relax the emissions constraint by 300 million metric tons.

[3] This is enough to allow the regions to be quite different from one another. For example, even though all of the regions consist of the twelve industries in Table 2 we do not impose any requirement that the output of a particular industry in one country be identical to that of another country. The industries are themselves aggregates of smaller sectors and the aggregation weights can be very different across countries: the output of the durable goods sector in Japan will not be identical to that of the United States. The fact that these goods are not identical is reflected in the assumption (discussed further below) that foreign and domestic goods are generally imperfect substitutes.

[4] A more complete description of the model is contained in McKibbin and Wilcoxen (forthcoming).

capital, labor, energy and materials. Energy and materials, in turn, are CES aggregates of inputs of intermediate goods: energy is composed of the first five goods in Table 1 and materials is composed of the remaining seven.

We used a nested system of CES equations rather than a more flexible functional form because data limitations make even the CES model a challenge to estimate. In principle we need price and quantity data for 14 inputs (twelve goods plus capital and labor) in each of 96 industries (12 industries in 8 regions). Moreover, data on intermediate inputs (which is published in the form of input-output tables) is not collected annually in any major country and is collected infrequently, if at all, in developing countries. For many of our regions we had access to only a single input-output table. There is simply too little data for a more flexible specification to be feasible.

In fact, the scarcity of input-output data requires us to restrict the model further by imposing the assumption that the substitution elasticities for each industry be identical across countries (although they may differ across industries). In other words, we assume that each industry has the same energy, materials and KLEM substitution elasticities no matter where it is located. This is consistent with the econometric evidence of Kim and Lau in a number of papers (see for example Kim and Lau, 1994).

Although the substitution elasticities are identical across countries, the overall production models are not identical because we obtain the CES input weights from the latest available input-output data for each country or region.[5] Thus, the durable goods sectors in the United States and

[5] Input-output tables were not available for the regions in the model larger than individual countries. The input weights for those regions were based on data for the United States.

Japan, for example, have identical substitution elasticities but different sets of input weights. The consequence of this is that the cost shares of inputs to a given industry are based on data for the country in which the industry operates, but the industry's response to price changes is identical across countries.

In effect we are assuming that all regions share production methods that differ in first-order properties but have identical second-order characteristics. This is intermediate between one extreme of assuming that the regions share common technologies and the other extreme of allowing the technologies to differ across regions in arbitrary ways. The regions also differ in their endowments of primary factors, their government policies, and patterns of final demands, so although they some common parameters they are not simple replicas of one another.

To estimate the elasticities we constructed time-series data on prices, industry inputs, outputs and value-added for the country for which we were able to obtain the longest series of input-output tables: the United States. The following is a sketch of the approach we followed; complete details are contained in McKibbin and Wilcoxen (1995).

We began with the benchmark input-output transactions tables produced by the Bureau of Economic Analysis (BEA) for years 1958, 1963, 1967, 1972, 1977 and 1982.[6] The conventions used by the BEA have changed over time, so the raw tables are not completely comparable. We transformed the tables to make them consistent and aggregated them to twelve sectors. We then shifted consumer durables out of final consumption and into fixed investment.[7] We also increased

[6] A benchmark table also exists for 1947 but it has inadequate final demand detail for our purposes. Subsequent to our estimation work a 1987 table has become available.

[7] The National Income and Product Accounts (and the benchmark input-output tables as well) treat purchases of consumer durables as consumption rather than investment.

the capital services element of final consumption to account for imputed service flows from durables and owner-occupied housing. Finally, we used a data set constructed by Dale Jorgenson and his colleagues to decompose the value added rows of the tables,[8] and a data set produced by the Office of Employment Projections at the Bureau of Labor Statistics to provide product prices.

Table 2 presents estimates of the substitution elasticities for each industry; standard errors are shown in parentheses.[9] A number of the estimates had the wrong sign or could not be estimated (the estimation procedure failed to converge). In such cases we examined the data and imposed elasticities that seemed appropriate; these values are shown in the table without standard errors.[10] For most of the imposed parameters, the data suggest complementarities among inputs, which is incompatible with the CES specification. If more data were available, it would be worthwhile to use a more flexible functional form.

Maximizing the firm's short run profit subject to its capital stock and the production functions above gives the firm's factor demand equations. At this point we add two further levels of detail: we assume that domestic and imported inputs of a given commodity are imperfect substitutes, and that imported products from different countries are imperfect substitutes for each other. As noted earlier, given the model's level of aggregation these are more a simple acknowledgment of reality than an assumption.[11] Thus, the final decision the firm must make is

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[8] This data set is the work of several people over many years. In addition to Dale Jorgenson, some of the contributors were Lau Christiansen, Barbara Fraumeni, Mun Sing Ho and Dae Keun Park. The original source of data is the Fourteen Components of Income Tape produced by the Bureau of Economic Analysis. See Ho (1989) for more information.

[9] The parameters were estimated using systems of factor demand equations derived from the KLEM portion of the production function and the dual versions of the energy and materials tiers.

[10] For this study we also imposed lower KLEM substitution elasticities on a few of the energy industries where it seemed that the estimated elasticities might overstate the true ability of the industry to shift factors of production.

[11] This approach is based on the work of Armington (1969).

the fraction of each of its inputs to buy from each region in the model (including the firm's home country). Due to data constraints we represent this decision using a Cobb-Douglas function.[12] Moreover, we assume that all agents in the economy have identical preferences over foreign and domestic varieties of each particular commodity.[13] We parameterize this decision using trade shares based on aggregations of the United Nations international trade data for 1987.[14] The result is a system of demand equations for domestic output and imports from each other region.

In addition to buying inputs and producing output, each sector must also choose its level of investment. We assume that capital is specific to each sector, it depreciates geometrically at rate δ, and that firms choose their investment paths in order to maximize their market value. Following the cost of adjustment models of Lucas (1967), Treadway (1969) and Uzawa (1969) we assume that the investment process is subject to rising marginal costs of installation. To formalize this we adopt Uzawa's approach by assuming that in order to install J units of capital the firm must buy a larger quantity, I, that depends on its rate of investment (J/K) as follows:

$$I = \left(1 + \frac{\phi}{2}\frac{J}{K}\right)J \tag{1}$$

where ϕ is a non-negative parameter and the factor of two is included purely for algebraic convenience. The difference between J and I may be interpreted many ways; we will view it as installation services provided by the capital vendor.

Setting up and solving the firm's investment problem yields the following expression for

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[12] This assumption is far from ideal and we intend to relax it in future work.

[13] Anything else would require time-series data on imports of products from each country of origin to each industry, which is not only unavailable but difficult to imagine collecting.

[14] Specifically, we aggregate up from data at the 4-digit level of the Standard International Trade Classification.

investment in terms of parameters, the current capital stock, and marginal q (the ratio of the marginal value of a unit of capital to its purchase price):

(2) $$I = \frac{1}{2\phi}\left(q^2 - 1\right)K$$

In this expression τ_2 is the corporate tax rate and τ_4 is rate of the investment tax credit. Following Hayashi (1979), we extend (2) and write I as a function not only of q, but also of the firm's current profit π:

(3) $$I = \alpha_2 \frac{1}{2\phi}\left(q^2 - 1\right)K + \left(1 - \alpha_2\right)\frac{\pi}{\left(1 - \tau_4\right)P^I}$$

This improves the empirical behavior of the specification and is consistent with the existence of firms that are unable to borrow and therefore invest purely out of retained earnings. The parameter a_2 was taken to be 0.3 based on a range of empirical estimates reported by McKibbin and Sachs (1991).

In addition to the twelve industries discussed above, the model also includes a special sector that produces capital goods. This sector supplies the new investment goods demanded by other industries. Like other industries, the investment sector demands labor and capital services as well as intermediate inputs. We represent its behavior using a nested CES production function with the same structure as that used for the other sectors, and we estimate the parameters using price and quantity data for the final demand column for investment. As before, we use U.S. data to estimate the substitution elasticities and country or region data to determine the γ parameters.

2.2 Households

Households consume goods and services in every period and also demand labor and capital services. Household capital services consist of the service flows of consumer durables plus residential housing. Households receive income by providing labor services to firms and the government, and from holding financial assets. In addition, they receive imputed income from ownership of durables and housing, and they also may receive transfers from their region's government.

Within each region we assume household behavior can be modeled by a representative agent with an intertemporal utility function of the form:

$$U_t = \int_t^{\infty} (\ln C(s) + \ln G(s))\, e^{-\theta(s-t)}\, ds \tag{4}$$

where $C(s)$ is the household's aggregate consumption of goods at time s, $G(s)$ is government consumption, which we take to be a measure of public goods supply, and θ is the rate of time preference and is equal to 2.5 percent.[15] The household maximizes its utility subject to the constraint that the present value of consumption be equal to human wealth plus initial financial assets. Human wealth, H, is the present value of the future stream of after-tax labor income and transfer payments received by households. Financial wealth, F, is the sum of real money balances, real government bonds in the hands of the public (Ricardian neutrality does not hold in this model because some consumers are liquidity-constrained; more on this below), net holdings of claims against foreign residents and the value of capital in each sector. Under this specification, the desired value of each period's consumption is equal to the product of the time preference rate and household wealth:

[15] This specification imposes the restriction that household decisions on the allocations of expenditure among different goods at different points in time be separable. Also, since utility is additive in the logs of private and government

$$P^C C = \theta (F + H) \tag{5}$$

There has, however, been considerable debate about whether the actual behavior of aggregate consumption is consistent with the permanent income model.[16] Based on the evidence cited in Campbell and Mankiw (1990), we assume that only a fraction β of all consumers choose their consumption to satisfy (5) and that the remainder consume based entirely on current after-tax income. This could be interpreted in various ways, including the presence of liquidity-constrained households or households with myopic expectations. For the purposes of this paper we will not adopt any particular explanation and will simply take β to be an exogenous constant.[17]

This produces the final consumption function shown below:

$$P^C C = \beta\theta(F_t + H_t) + (1-\beta)\gamma INC \tag{6}$$

where γ is the marginal propensity to consume for the households consuming out of current income. Following McKibbin and Sachs (1991) we take β to be 0.3 in all regions.[18]

Within each period, the household allocates expenditure among goods and services in order to maximize *C*(*s*), its intratemporal utility index. In this version of the model we assume that *C*(*s*) may be represented by a nested CES function. At the top tier, consumption is composed of inputs of capital services, labor, energy and materials. Energy and materials, in turn, are CES

consumption, changes in government consumption will have no effect on private consumption decisions.

16 Some of the key papers in this debate are Hall (1978), Flavin (1981), Hayashi (1982), and Campbell and Mankiw (1990).

17 One side effect of this specification is that it will prevent us from using equivalent variation or other welfare measures derived from the expenditure function. Since the behavior of some of the households is implicitly inconsistent with (8), either because the households are at corner solutions or for some other reason, aggregate behavior is inconsistent with the expenditure function derived from our utility function.

18 Our value is somewhat lower than Campbell and Mankiw's estimate of 0.5.

aggregates of inputs of individual goods.[19] The elasticities of substitution at the energy and materials tiers were estimated to be 0.8 and 1.0, respectively. In this version of the model the top tier elasticity has been imposed to be unity.

Finally, the supply of household capital services is determined by consumers themselves who invest in household capital. We assume households choose the level of investment to maximize the present value of future service flows (taken to be proportional to the household capital stock), and that investment in household capital is subject to adjustment costs. In other words, the household investment decision is symmetrical with that of the firms.

2.3 Labor Market Equilibrium

We assume that labor is perfectly mobile among sectors within each region but is immobile between regions. Thus, within each region wages will be equal across sectors. The nominal wage is assumed to adjust slowly according to an overlapping contracts model where nominal wages are set based on current and expected inflation and on labor demand relative to labor supply. In the long run labor supply is given by the exogenous rate of population growth, but in the short run the hours worked can fluctuate depending on the demand for labor. For a given nominal wage, the demand for labor will determine short-run unemployment.

Relative to other general equilibrium models, this specification is unusual in allowing for involuntary unemployment. We adopted this approach because we are particularly interested in the transition dynamics of the world economy. The alternative of assuming that all economies are always at full employment, which might be fine for a long-run model, is clearly inappropriate

[19] This specification has the undesirable effect of imposing unitary income and price elasticities. There is abundant

during the first few years after a shock.

2.4 Government

We take each region's real government spending on goods and services to be exogenous and assume that it is allocated among final goods, services and labor in fixed proportions, which we set to 1987 values for each region. Total government spending includes purchases of goods and services plus interest payments on government debt, investment tax credits and transfers to households. Government revenue comes from sales, corporate, and personal income taxes, and by issuing government debt. In addition, there can be taxes on externalities such as carbon dioxide emissions.

The difference between revenues and total spending gives the budget deficit, which is endogenous. Deficits are financed by sales of government bonds. We assume that agents will not hold bonds unless they expect the bonds to be serviced, and accordingly impose a transversality condition on the accumulation of public debt in each region that has the effect of causing the stock of debt at each point in time to be equal to the present value of all future budget surpluses from that time forward. This condition alone, however, is insufficient to determine the time path of future surpluses: the government could pay off the debt by briefly raising taxes a lot; it could permanently raise taxes a small amount; or it could use some other policy. We assume that the government levies a lump sum tax in each period equal to the value of interest payments on the outstanding debt. In effect, therefore, any increase in government debt is financed by consols, and future taxes are raised enough to accommodate the increased interest costs. Thus, any increase in

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empirical evidence against this assumption and we intend to generalize it in future work.

the debt will be matched by an equal present value increase in future budget surpluses. Other fiscal closure rules are possible such as always returning to the original ratio of government debt to GDP. These closures have interesting implications but are beyond the scope of this paper.

Finally, because we our wage equation depends on the rate of expected inflation, we need to include money supply and demand in the model. The supply of money is determined by the balance sheet of the central bank and is exogenous. We assume that money demand arises from the need to carry out transactions and takes the following form:

$$M = PY\, i^{\varepsilon} \tag{7}$$

where M is money, P is the price level, Y is aggregate output, I is the interest rate and ε is the interest elasticity of money demand. Following McKibbin and Sachs (1991) we take ε to be -0.6.

2.5 International Trade and Asset Flows

The eight regions in the model are linked by flows of goods and assets. Each region may import each of the 12 goods from potentially all of the other seven regions. In terms of the way international trade data is often expressed, our model endogenously generates a set of twelve 8x8 bilateral trade matrices, one for each good. The values in these matrices are determined by the import demands generated within each region.

Trade imbalances are financed by flows of assets between countries. We assume that asset markets are perfectly integrated and that financial capital is freely mobile.[20] Under this

[20] The mobility of international capital is a subject of considerable debate; see Gordon and Bovenberg (1994) or Feldstein and Horioka (1980). Also, this assumption should not be confused with our treatment of *physical* capital, which we assume to be specific to sectors and regions and hence completely immobile. The consequence of assuming mobile financial capital and immobile physical capital is that there can be windfall gains and losses to owners of physical capital. For example, if a shock adversely affects profits in a particular industry, the physical capital stock in that sector

assumption, expected returns on loans denominated in the currencies of the various regions must be equalized period to period according to a set of interest arbitrage relations of the following form:

(8) $$i_k + \mu_k = i_j + \mu_j + \frac{\dot{E}_k^j}{E_k^j}$$

where i_k and i_j are the interest rates in countries k and j, μ_k and μ_j are exogenous risk premiums demanded by investors (possibly zero), and E_k^j is the exchange rate between the two currencies. The risk premiums are calculated in the course of generating the model's baseline and are generally held constant in simulations. Finally, we also assume that OPEC chooses its foreign lending in order to maintain a desired ratio of income to wealth subject to a fixed exchange rate with the U.S. dollar.

2.6 Constructing the Base Case

To solve the model, we first normalize all quantity variables by the economy's endowment of effective labor units. This means that in the steady state all real variables are constant in these units although the actual levels of the variables will be growing at the underlying rate of growth of population plus productivity. Next, we must make base-case assumptions about the future path of the model's exogenous variables in each region. In all regions we assume that the long run real interest rate is 5 percent, tax rates are held at their 1990 levels and that fiscal spending is allocated according to 1990 shares. Population growth rates vary across regions as shown in Table 3.

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will initially be unaffected. Its value, however, will immediately drop by enough to bring the rate of return in that sector back to into equilibrium with that in the rest of the economy.

A crucial group of exogenous variables are productivity growth rates by sector and country. The baseline assumption in G-Cubed is that the pattern of technical change at the sector level is similar to the historical record for the United States (where data is available). In regions other than the United States, however, the sector-level rates of technical change are scaled up or down in order to match the region's observed rate of aggregate productivity growth. This approach attempts to capture the fact that the rate of technical change varies considerably across industries while reconciling it with regional differences in overall growth. This is clearly a rough approximation; if appropriate data were available it would be better to estimate productivity growth for each sector in each region.

Given these assumptions, we solve for the model's perfect-foresight equilibrium growth path over the period 1990-2050. This a formidable task: the endogenous variables in *each* of the sixty periods number over 6,000 and include, among other things: the equilibrium prices and quantities of each good in each region, intermediate demands for each commodity by each industry in each region, asset prices by region and sector, regional interest rates, bilateral exchange rates, incomes, investment rates and capital stocks by industry and region, international flows of goods and assets, labor demanded in each industry in each region, wage rates, current and capital account balances, final demands by consumers in all regions, and government deficits.[21] At the solution, the all budget constraints for all agents are satisfied, including both intratemporal and intertemporal constraints.

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[21] Since the model is solved for a perfect-foresight equilibrium over a 60 year period, the numerical complexity of the problem is on the order of 60 times what the single-period set of variables would suggest. We use software developed by McKibbin (1992) for solving large models with rational expectations on a personal computer.

3 The Effects of Tradable Emissions Permits

We now explore the effects of international trading in carbon permits by considering three scenarios. As a benchmark for comparison, we begin by examining the effects of unilateral stabilization by the United States. In this scenario, the U.S. government holds annual auctions of carbon emissions permits in each of the years from 2010 to 2020.[22] The permits are required for the use of primary fossil fuels (coal and crude oil and gas) and the quantity is set equal to U.S. emissions in 1990. Revenues from the permit sales are returned to households via a deficit-neutral lump sum rebate.[23] The policy is announced in 2000 so that agents have a decade to anticipate the policy and adapt to it.

In the second scenario, all countries in the OECD follow similar policies. Each country auctions permits equal to its 1990 emissions and returns the revenue to its citizens as a lump sum rebate. The permits can be traded within countries but not from one country to another.[24] This simulation allows us to measure the heterogeneity of the OECD regions. Differences in baseline emissions growth and initial fossil fuel prices mean that the regions face substantially different costs of achieving stabilization. This will be reflected in the pattern of permit prices (which will indicate the cost of stabilization at the margin) and GDP losses across regions.

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[22] Beyond 2020 the supply of permits is allowed to increase at such a rate as to leave the real permit price at its 2020 value.

[23] The rebate is chosen to leave the deficit unchanged. It is not necessarily equal to the revenue raised by permit sales because other changes in the economy may raise or lower tax revenue. This formulation is not equivalent to free distribution of permits ("grandfathering") – that would be represented in a similar fashion in the model but would involve a 100% lump-sum recycling, with no revenues retained to maintain deficits at baseline levels.

[24] Even though there is no trading *between* regions, trading is implicitly allowed between the countries *within* a region. In particular, the "Other OECD" region lumps together the European Union, Canada and New Zealand, so trading is implicitly allowed between these countries.

The third scenario is identical to the second except that we allow international trading in emissions permits among OECD countries. The effect of allowing trading will be that arbitrage will cause the price of a permit to be equal throughout the OECD. This will ensure that marginal costs of carbon abatement will be equal across countries and that OECD stabilization will be achieved at minimum cost. Countries with relatively low abatement costs will sell permits and abate more than in the previous scenario; countries with high costs will buy permits and do less abatement. Comparing scenarios 2 and 3 will allow us to estimate of the gains to be had from international permit trading.

3.1 Unilateral Emissions Stabilization by the United States

Key results for the unilateral U.S. policy are shown in Table 4. In order to achieve stabilization, emissions would need to drop by 24 percent relative to the baseline in 2010 and 35 percent in 2020.[25] The resulting price of carbon emissions permits would be $51 per tonne in 2010 rising to $59 per tonne in 2020.[26] Most of the drop in emissions comes about through a decline in coal consumption as total energy use drops and the fuel mix shifts toward natural gas, the least carbon-intensive fuel. This is reflected in the industry-level results shown in Table 5: the after-tax price of coal rises by more than 100 percent and coal output declines by nearly 40 percent in 2010 and by more than 50 percent in 2020. The crude oil and gas sector is also strongly affected: output declines by 12 to 26 percent over the period.

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[25] Some of the emissions eliminated within the United States – roughly 10% in 2010 – are offset by increases in emissions elsewhere. Initially, over half of this "leakage" is due to the fact that other countries buy and burn the oil that the U.S. stops importing. This effect diminishes over time: by 2020 about two-thirds of the leakage is due to higher energy demand resulting from greater economic activity.

[26] Throughout the paper carbon will be measured in metric tons (tonnes) and prices will be in 1995 U.S. dollars.

Outside the energy industries prices and output are affected very little. The only noteworthy result is that investment rises by about one percent during the period before the policy is implemented (2001-2009). This stems from the fact that the demand for services increases slightly when households and firms substitute away from energy. As a result, investment by the service industry increases as well. The increase in investment is financed by an inflow of foreign capital, which causes the exchange rate to appreciate by about 1.6 percent during that time. The exchange rate appreciation hurts exports, primarily of durable goods.

The international effects of the policy vary across regions. Most OECD countries experience mild decreases in GDP on the order of -0.1 percent, mild exchange rate depreciations, and increases in their net investment positions. The exception is Australia, which benefits from taking up the slack in U.S. coal exports. China and the former Soviet Union are almost completely unaffected. Other developing countries receive minor capital inflows after 2010, experience slight exchange rate appreciation and slightly higher GDP, but also have lower production and exports of durable goods due to the change in exchange rates.

3.2 OECD Emissions Stabilization Without Permit Trading

OECD stabilization without trading produces the results shown in Table 6. The effects of the policy differ substantially across the regions: in 2010, permit prices range from a low of $60 in the United States to a high of $213 in the "Other OECD" region. (To avoid ambiguity we will refer to the "Other OECD" region as "Europe" in the remainder of the text).[27] The effect on

[27] This is a misnomer since the "Other OECD" region also includes Canada and New Zealand. We adopt it, however, in order to avoid ambiguity in certain comparisons. For example, "Permit prices in the US are lower than in the rest of the OECD" compares the US to Japan, Australia and the "Other OECD" region as a group but could easily be confused

GDP follows a similar pattern: U.S. GDP is essentially unchanged from its baseline value while GDP in Japan and Europe falls by 1.5 and 1.7 percent, respectively. These results show that both marginal and average costs of abating carbon emissions differ substantially across countries. The differences among regions stem in part from differences in the fuel mix: stabilization is cheapest in coal-intensive countries like the United States and Australia; in Japan and Europe, stabilization requires larger cuts in oil and gas consumption.

Comparing this simulation with the previous one shows that the United States is significantly better off under the OECD policy than it is when it stabilizes on its own. In 2010, U.S. GDP remains at its baseline value while under the unilateral policy it would have fallen by 0.6 percent. In 2020, U.S. GDP is actually above its baseline value by 0.1 percent; under the unilateral policy it would have fallen by 0.5 percent. The reason for this lies in the fact that the United States has substantially lower marginal costs of abating carbon emissions. This causes rates of return in the U.S. to fall less than in other OECD countries, which induces investors to shift their portfolios toward U.S. assets, leading to an increase in U.S. investment. The effect is particularly apparent in the years immediately before the policy takes effect: U.S. investment is 7.4 percent above baseline in 2005. In addition, the U.S. also benefits from lower world oil prices as OECD oil demand falls. The boost in investment and lower oil prices both tend to raise energy demand and cause permit prices to rise relative to the unilateral stabilization scenario – from $51 to $60 in 2010 and from $59 to $67 in 2020. Although U.S. GDP rises slightly relative to the baseline, it would be wrong to conclude that the policy was actually good for the United States.

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with a comparison between the US and the "Other OECD" region alone. When the latter comparison is intended we will phrase it as "Permit prices in the US are lower than in Europe".

Much of the additional resources are owned by foreigners and the results for GNP are generally less positive or actually negative.

Examining the effect of the policy on different regions, Japan and especially Europe – which face the greatest costs of stabilizing emissions – have large capital outflows, accumulating to roughly a trillion 1995 dollars by 2020. Most of this goes to the United States, although some capital flows to Australia, which has comparatively low costs of abatement, and some to developing countries, which are not controlling emissions at all. Capital flows to developing countries are limited by adjustment costs, however: it is expensive for a region with a relatively small capital stock to absorb a large flow of new capital.

Capital flows cause the U.S., Australian and developing country exchange rates to appreciate and the Japanese and European currencies to depreciate. These changes lead directly to changes in export patterns. Japanese and European exports of durable goods increase by about 13% and 18%, respectively, over baseline; U.S. exports of durables fall by 15% to 18% and exports from developing countries fall by 25% to 35%.[28] At the same time, capital flows cause Japanese and European GNP to fall by less than GDP.

Overall, the effect of stabilization on countries with high abatement costs (Japan and Europe) is to reduce GDP, cause an outflow of capital, depreciate the exchange rate and stimulate exports. The effect on low cost countries is the opposite: capital inflows tend to raise GDP, appreciate the exchange rate and diminish exports. Australia is somewhat of an exception: capital inflows benefit it slightly but the economy is substantially hurt by the impact of Japanese carbon

[28] Even though capital inflows to developing countries raise overall economic activity, the durables sector declines slightly because exports are adversely affected by exchange rate appreciation. This effect limits the "leakage" of

controls on Australian coal exports. Finally, oil exports from OPEC countries decline about 10 percent and world oil prices decline by about 10 percent as well.

3.3 OECD Emissions Stabilization With Permit Trading

Results for this scenario are shown in Table 7. In contrast to independent stabilization, international permit trading leads to a uniform permit price throughout the OECD that rises from about $91 per tonne in 2010 to $108 per tonne in 2020. Because it has the lowest abatement costs, the United States reduces emissions further than in the previous scenario in order to sell permits on the world market. U.S. carbon emissions decline by over 40%, significantly more than the 25% reduction needed to return U.S. emissions to their 1990 levels. Annual permit sales exceed 300 million tonnes ($30 billion) in 2010 and reach nearly 600 million tonnes ($64 billion) in 2020. Cumulative payments to the U.S. over the 2010-2020 period are on the order of $500 billion. The largest purchaser by far is Europe.

Because energy prices are substantially higher in the U.S. than in the previous case, GDP during the 2010-2020 period is significantly lower (excluding permit revenue). Exchange rate changes are similar in sign but generally larger in magnitude. The Japanese and European currencies, in particular, depreciate somewhat more. This depreciation, combined with lower energy costs in those countries, causes exports from Japan and Europe to expand more than in the previous simulation. In fact, the Japanese and European trade surpluses grow by amounts roughly comparable to what each country spends on emissions permits. This leaves the pattern

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emissions arising from redirection of trade away from emissions-controlling regions to developing countries.

and magnitude of net international capital flows similar to those from the previous scenario. In effect, these countries pay for their emissions permits with exports of durables.

The overall gains from emissions trading total about $50 billion in 2010 and between $80 and $90 billion in 2020. These gains reduce OECD GDP losses from about $270 billion (1.1% of the total) to about $220 billion (0.9%) in 2010; and from about $340 billion (1.1%) to $250 billion (0.8%) in 2020. Trading thus reduces overall OECD losses by 20% to 25%. The gains from trading are unevenly distributed: in 2010, Europe gains about $50 billion in GDP from trading; Australia and Japan together gain about $10 billion; and the U.S. loses about $10 billion.[29] By 2020, the U.S. gains about $10 billion from trading; Japan and Australia together experience gains of about $15 billion, and Europe gains about $60 billion.

4 Conclusion

The theoretical appeal of an international permits program is strongest if participating countries have very different marginal costs of abating carbon emissions – in that situation, the potential gains from trade are largest. Our results show that within the OECD, abatement costs are indeed quite heterogeneous: the marginal cost of stabilizing emissions in Japan and Europe is nearly four times that of stabilizing emissions in the United States. Because of these differences, under a trading regime the U.S. emerges as a large seller of emissions permits and ends up doing far more abatement than if it had stabilized its emissions unilaterally. The shift of abatement to the

[29] The small U.S. GDP loss from trading in 2010 is due business cycle effects stemming from our assumption that wages adjust slowly: the sharp increase in U.S. energy prices under the trading scenario temporarily reduces labor demand relative to the no-trading case.

United States provides total gains to the OECD as a group of $50 billion to $90 billion a year. International trading, in other words, provides significant gains in efficiency.

Because the United States (and to a lesser extent, Australia) can reduce carbon emissions at relatively low cost, under any OECD stabilization policy – with or without trading – it will benefit from a significant inflows of international financial capital. This will cause the dollar to appreciate which will reduce exports of durable goods. Japan and Europe, as high cost countries, will see capital outflows, exchange rate depreciation, and increased exports of durables. Total flows of capital will be substantial, accumulating to about one trillion dollars over the period between 2000 and 2020.

Finally, it is important to note that OECD trading has only a modest effect on the costs of stabilizing emissions, and that it causes the United States to do more abatement than it would otherwise. Although this is efficient, it is the opposite of what many U.S. supporters of international permit trading seem to expect. Much of the political support for trading seems to be founded on the hope that it would allow the U.S. to do substantially *less* abatement. Our results show that in order for U.S. abatement to fall under a trading regime (that is, for the U.S. to be come an importer of permits), permits would have to be available at a price below $60 per tonne and in sufficiently large quantity (substantially more than 300 million tonnes) as to be able to supply the demands of Europe and Japan as well as the United States. This will only be possible if China, Brazil and other developing countries join the trading program *and* they are given very large allotments of permits.

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Table 1: Regions and Sectors in G-Cubed

Regions	Sectors
1. United States 2. Japan 3. Australia 4. Other OECD countries 5. China 6. Former Soviet Union 7. Oil exporting developing countries 8. Other developing countries	1. Electric utilities 2. Gas utilities 3. Petroleum refining 4. Coal mining 5. Crude oil and gas extraction 6. Other mining 7. Agriculture 8. Forestry and wood products 9. Durable goods 10. Nondurables 11. Transportation 12. Services

Table 2: Production Elasticities

Sector	Energy	Materials	Output	
			Estimated	Imposed
Electricity	0.200	1.000	0.763 (0.076)	0.200
Natural Gas	0.933 (0.347)	0.200	0.810 (0.039)	0.200
Petroleum Refining	0.200	0.200	0.543 (0.039)	0.200
Coal Mining	0.159 (0.121)	0.529 (0.018)	1.703 (0.038)	0.493
Crude Oil & Gas	0.137 (0.034)	0.200	0.493 (0.031)	
Other Mining	1.147 (0.136)	2.765 (0.028)	1.001 (0.315)	
Agriculture	0.628 (0.051)	1.732 (0.105)	1.283 (0.047)	
Forestry & Wood	0.938 (0.138)	0.176 (0.000)	0.935 (0.080)	
Durables	0.804 (0.058)	0.200	0.410 (0.019)	
Nondurables	1.000	0.057 (0.000)	1.004 (0.012)	
Transportation	0.200	0.200	0.537 (0.070)	
Services	0.321 (0.045)	3.006 (0.073)	0.256 (0.027)	

Table 3: Population Growth Rates

Region	Population Growth Rate
United States	0.5
Japan	0.0
Australia	0.8
Other OECD	0.7
China	1.5
Former Soviet Union	0.5
Other developing countries	1.0

Table 4: Aggregate Effects of Unilateral U.S. Stabilization

	2001	2005	2010	2020
Permit price	--	--	$51	$59
Carbon emissions	0.0%	0.1%	-24%	-35%
Coal consumption	0.0%	0.1%	-39%	-53%
Oil consumption	0.0%	0.3%	-7%	-11%
Gas consumption	0.0%	0.3%	-2%	-3%
GDP	0.0%	0.1%	-0.6%	-0.5%
Consumption	0.1%	0.3%	-0.7%	0.2%
Investment	1.0%	0.9%	-0.9%	-1.0%
Exchange rate	1.7%	1.6%	0.7%	3.2%
Exports	-1.8%	-1.9%	-0.9%	-3.5%
Imports	0.0%	0.0%	-0.9%	-1.0%
Net foreign assets (Bil.)	$0	-$39	-$117	$28
GNP	0.0%	0.0%	-0.6%	-0.5%

Table 5: Industry Effects of Unilateral U.S. Stabilization

	2005		2010		2020	
	Price	Qty	*Price*	Qty	*Price*	Qty
Energy Industries						
Electric utilities	*-0.0%*	0.2%	*3.2%*	-3.0%	*6.7%*	-5.0%
Gas utilities	*-0.1%*	0.2%	*3.4%*	-1.9%	*6.4%*	-3.6%
Petroleum refining	*-0.2%*	0.1%	*6.5%*	-7.4%	*10.9%*	-13.1%
Coal mining	*0.1%*	0.0%	*111.2%*	-38.8%	*157.4%*	-52.5%
Oil and gas extraction	*-0.0%*	0.0%	*17.2%*	-12.0%	*25.3%*	-25.6%
Other Sectors						
Other mining	*-0.2%*	0.0%	*0.9%*	-1.2%	*0.4%*	-1.7%
Agriculture	*-0.0%*	0.1%	*0.4%*	-1.0%	*-0.2%*	-0.3%
Forestry and wood	*-0.3%*	0.0%	*0.3%*	-0.6%	*-0.6%*	-0.4%
Durable goods	*-0.6%*	-0.2%	*0.2%*	-0.7%	*-1.0%*	-0.8%
Nondurables	*-0.2%*	0.1%	*0.5%*	-1.3%	*-0.2%*	-0.6%
Transportation	*-0.1%*	0.2%	*0.2%*	-1.0%	*-0.3%*	-0.5%
Services	*-0.0%*	0.2%	*-0.4%*	-0.3%	*-0.6%*	0.4%

Table 6: OECD Stabilization Without Permit Trading

	United States	Japan	Australia	Other OECD
2005				
Permit price	--	--	--	--
Carbon emissions	1.4%	-3.3%	1.6%	-2.3%
Coal consumption	1.0%	-0.6%	1.1%	-0.7%
Oil consumption	3.1%	-5.9%	3.7%	-4.1%
Gas consumption	2.2%	-2.3%	0.9%	-2.0%
GDP	0.5%	-0.4%	5.6%	-0.4%
Investment	7.4%	-5.0%	5.5%	-6.1%
Exchange rate	13.7%	-23.4%	17.9%	-26.0%
Net foreign assets (Bil.)	-$306	-$65	-$35	$267
GNP	0.3%	0.0%	-0.3%	-0.3%
2010				
Permit price	$60	$205	$105	$213
Carbon emissions	-25%	-21%	-37%	-30%
Coal consumption	-46%	-24%	-55%	-57%
Oil consumption	-4%	-15%	-3%	-15%
Gas consumption	1%	-6%	-2%	-6%
GDP	0.0%	-1.5%	-0.4%	-1.7%
Investment	6.2%	-6.2%	-6.8%	-9.4%
Exchange rate	11.8%	-23.7%	27.9%	-24.4%
Net foreign assets (Bil.)	-$842	$54	-$101	$662
GNP	-0.4%	-0.8%	-5.3%	-1.6%
2020				
Permit price	$67	$237	$128	$264
Carbon emissions	-37%	-31%	-53%	-44%
Coal consumption	-60%	-31%	-75%	-78%
Oil consumption	-9%	-24%	-12%	-24%
Gas consumption	-1%	-8%	-7%	-10%
GDP	0.1%	-1.4%	-1.7%	-1.9%
Investment	5.4%	-6.4%	-2.1%	-9.2%
Exchange rate	14.3%	-23.1%	11.9%	-24.4%
Net foreign assets (Bil.)	-$838	$92	-$249	$965
GNP	-0.2%	-0.3%	-6.1%	-1.8%

Table 7: OECD Stabilization With Permit Trading

	United States	Japan	Australia	Other OECD
2005				
Permit price	--	--	--	--
Annual permit sales (Bil.)	--	--	--	--
Carbon emissions	1.2%	-3.3%	1.6%	-2.5%
Coal consumption	0.9%	-0.6%	1.1%	-0.8%
Oil consumption	2.9%	-6.0%	3.5%	-4.6%
Gas consumption	2.3%	-2.3%	0.9%	-2.3%
GDP	0.5%	-0.3%	0.9%	-0.4%
Investment	7.5%	-5.1%	5.6%	-6.7%
Exchange rate	13.5%	-24.2%	17.8%	-29.0%
Net foreign assets (Bil.)	-$312	-$68	-$34	$292
GNP	0.3%	0.1%	-0.4%	-0.4%
2010				
Permit price	$91	$91	$91	$91
Annual permit sales (Bil.)	$30	-$4	-$1	-$25
Carbon emissions	-41%	-11%	-32%	-14%
Coal consumption	-70%	-11%	-48%	-25%
Oil consumption	-9%	-11%	-2%	-9%
Gas consumption	-1%	-4%	-2%	-4%
GDP	-0.4%	-1.3%	-0.1%	-1.1%
Investment	4.8%	-4.5%	-6.0%	-7.2%
Exchange rate	10.9%	-25.2%	27.6%	-28.5%
Net foreign assets (Bil.)	-$864	$52	-$100	$750
GNP	-0.8%	-0.7%	-3.2%	-0.9%
2020				
Permit price	$108	$108	$108	$108
Annual permit sales (Bil.)	$64	-$8	-$2	-$55
Carbon emissions	-62%	-16%	-44%	-19%
Coal consumption	-96%	-15%	-62%	-33%
Oil consumption	-18%	-15%	-10%	-12%
Gas consumption	-3%	-6%	-6%	-6%
GDP	-0.3%	-1.0%	-1.3%	-1.1%
Investment	4.1%	-5.1%	-1.3%	-7.3%
Exchange rate	15.8%	-24.4%	11.7%	-28.3%
Net foreign assets (Bil.)	-$830	$82	-$240	$1052
GNP	-0.7%	0.1%	-5.6%	-1.1%