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VALUING TRADEABLE CO_2 PERMITS FOR OECD COUNTRIES

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Abstract

We estimate a structural model of OECD countries in which GDP and CO_2 emissions are endogenous. We use the estimated model to simulate the price of tradeable CO_2 permits and the efficiency gains from trade. Our estimated prices are high, relative to previous estimates, and the efficiency gains are substantial. We also find, contrary to previous literature, that higher income is associated with reduced emissions.

Key words: tradeable permits, greenhouse gasses, carbon reductions, environmental Kuznets curve.

JEL Classification Numbers: F17; Q28; Q43.

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1 Introduction

We estimate a system of simultaneous equations in which national income and CO_2 emissions are endogenously determined by country-specific characteristics, including levels of capital, labor and technology. These estimates shed light on two issues: the likely effects of allowing trade in emissions permits, and the relation between income and pollution.

Our principal objective is to estimate the effects of allowing trade in CO_2 emissions permits, in a world where aggregate emissions are fixed by an international agreement. We view pollution and GDP as joint outputs of a production function that depends on capital, labor and technology, variables which we treat as exogenous. We estimate a national revenue function by regressing GDP on capital, labor, technology and emissions. This function represents the efficiency frontier between income and emissions, for given levels of the exogenous variables. A country's environmental policies and economic structure, which we proxy using per capita energy consumption, determine the equilibrium level of GDP and of emissions (the equilibrium point on this frontier).

We use the estimated model to simulate prices and efficiency gains under tradeable emissions permits. We suppose that countries enter into an international agreement which allocates CO_2 emissions permits, and that this agreement supersedes the mechanism that would otherwise determine the country's emissions (the point on its efficiency frontier). The joint production function (which depends on technology and factor endowments) has not been altered by the agreement. Thus, we can use the estimated revenue function to determine the effect on GDP of a change in emissions. This function implies a demand for emissions permits, which we use to calculate the price of permits when trade is permitted. We compare our simulated price of permits to previous estimates, which were obtained using estimates of the marginal cost of reducing emissions. We also simulate the efficiency gains resulting from trade in permits.

This paper also contributes to the literature on the "environmental Kuznets curve". That literature estimates the relation between income (GDP) and the level of various pollutants. Previous papers treat GDP as exogenous, even though emissions may be one determinant of GDP. A systems approach takes into account the endogeneity of GDP in the equation that determines emissions, thereby reducing bias. Our single equation and our systems estimates are similar. However, when we include an additional regressor in the emissions function to account for structural differences across economies, we find a negative relation between CO_2 emissions and income, contrary to previous research.

The next section reviews the relevant literature. We then present our model. The following section reports estimation results, and compares these to previous estimates. The next section uses the estimated model to simulate the effects of trade in permits.

2 Related Literature

We review three strands of literature that are closely related to our paper. First, we discuss the environmental Kuznets curve. Then we summarize the key issues in emissions trading in general, and recent experience in SO_2 trading. Finally, we discuss previous attempts to estimate the likely range of prices under trade in carbon permits.

2.1 The Environmental Kuznets Curve

Pollution is a by-product of production. As countries move up the ladder of development and increase their output, they are likely to increase pollution. In many cases, pollution damages the environment and decreases utility. If the environment is a normal good, when a country becomes sufficiently wealthy it begins to impose stricter environmental protection and adopts less damaging methods of production, and produces less pollution. Thus, at low income levels we might see a positive relation between income and pollution, and at high levels of income a negative relation between the two variables. This inverted U-shaped relation is known as the environmental Kuznets curve. A number of papers (including [6], [8],[25]) show that the environmental Kuznets curve describes the relation between income and several pollutants such as particulates, sulphur dioxide and water pollutants. For these local pollutants, countries recognize that their emissions determine the amount of pollution that directly affects them. They therefore have an incentive to reduce emissions when they become sufficiently wealthy.

The connection between a country's emissions and the level of pollution it experiences is weaker or even negligible for a transnational pollutant such as CO_2. It might be rational for small countries to take the level of these pollutants as given. In that case, increased income would not induce greater attempts to control emissions. The production effect would remain, but without the offsetting income effect we would observe a monotonically increasing relation between income and emissions. Recent papers ([10], [26]) provide empirical evidence of a monotonically increasing relation between carbon emissions and income.

Most previous estimates of the environmental Kuznets curve treat the level of income as exogenous. However, if income and pollution are jointly determined – as theory suggests – OLS parameter estimates of the environmental Kuznets curve are biased, as Stern et al. [28] note. We can correct this bias by jointly estimating income and emissions.

Other factors in addition to income may be important in determining a country's level of CO_2 emissions. Shafik [26] includes a country specific dummy and a time trend in his emissions regression.[1] Two countries with similar levels of technology and factor endowments may have significantly different industrial structures as a result of past investment decisions. Their aggregate capital levels may be similar, but differences in the composition of capital may lead to differences in the opportunity cost of reducing emissions. A regression of emissions on income, without controlling for the difference in industrial structure, may lead to mis-specification bias. The challenge, of course, is to improve the specification.

2.2 Emissions Trading and CO_2 Reduction

The Kyoto Protocol, if ratified[2] , requires that industrialized countries reduce their collective emissions of greenhouse gasses by 5.2% of 1990 levels by the period 2008-2012. At the 1992 UN Framework Convention on Climate Change industrialized countries agreed to reduce emissions to 1990 levels. The UK and Germany have achieved significant reductions. The UK removed coal subsidies and switched to North Sea gas, and Germany shut

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[1] Some models for local pollutants include explanatory variables in addition to income. For example, [6] uses population density to proxy the health effect of pollution.

[2] The agreement will become legally binding 90 days after it has been ratified by at least 55 developed countries which collectively account for at least 55% of developed countries' emissions [21].

inefficient plants in the former East Germany [3]. Both countries can achieve further substantial reductions: the UK by replacing coal fired power plants with combined cycle gas turbines and Germany by shifting from coal to natural gas [22]. In many countries, including the US, groups which fear an economic loss have opposed government-mandated emissions reductions.

The country-specific targets[3] in the Kyoto Protocol may be difficult for some nations to achieve. There may be considerable cross-country variation in marginal abatement costs, and the strength of environmental lobbies also differs. The Protocol proposes three mechanisms to enable signatories to achieve reductions efficiently. The *Clean Development Mechanism* allows industrialized countries to receive credit for financing emissions-reduction projects in developing nations. *Joint Implementation* enables developed countries to receive credits for emissions-reduction projects in other developed countries. *Emissions Trading* allows developed countries to trade emissions credits amongst themselves. This trade makes sense only amongst those countries that have agreed to quotas, predominately the OECD countries. We therefore include only these countries in our empirical model.

The advantages of emissions trading are widely recognized ([12],[17],[29],[21]). In addition to the static benefits that arise from equating marginal abatement costs across firms and nations, there may be important dynamic benefits. Emissions trading may promote the flow of capital and technology and induce technological change.

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[3] The 5.2% reduction in total developed country emission will be achieved by national reductions of: 8% by Switzerland, many Central and East European states, and the European Union (reductions within the EU will differ); 7% by the US; 6% by Canada, Hungary, Japan, and Poland. Russia, New Zealand, and Ukraine agreed to stabilize their emissions, while Norway is allowed to increase emissions by 1%, Australia by 8%, and Iceland by 10%. See [21].

There are potential disadvantages of emissions trade. By creating global rather than local limits on emissions, trade may lead to high local concentrations ("hot spots"), resulting in more severe local problems. In addition, some environmentalists feel that there are ethical arguments against emissions trading, and refer to it as trade in hot air.[4]

There are also factors that might reduce the gains from trade in permits. Emissions trading is likely to involve governments, which have the potential to exercise market power (Hagem and Westkog [7]). The exercise of this power would reduce trade and decrease efficiency gains. The possibility of high transactions costs may also decrease the gains from trade. These considerations suggest that the gains from trade might be small, but they do not imply that the gains are negative.[5]

The US Acid Rain Program, which allows trade in SO_2 emissions, is an important experiment in tradeable pollution rights. An international market for CO_2 permits may differ significantly from the domestic market for SO_2 permits. International transactions costs may be higher than costs in a domestic market. Offsetting this, a market for SO_2 is probably

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[4] Although we have not seen opponents of tradeable permits make this argument, there is a possiblity that trade might reduce the aggregate amount of abatement. This reduction can occur because trade *increases* the opportunity cost of emissions for some countries. In the absence of trade, countries with low abatement costs and high environmental concern might choose to reduce their emissions below target levels, out of concern for the environment. Without trade, the cost of this altruism is the national abatement cost. For other countries, the targets are binding. In this scenario without trade, aggregate (world) emissions are less than the ceiling. With trade, the opportunity cost of abatement for the environmentally friendly country is the world price, which may be considerably above the no-trade national marginal abatement cost. In this case, the (formerly altruistic) country would increase abatement and sell it's unused quota to a high-cost country, which would make offsetting reductions in abatement. In this scenario with trade, the aggregate level of emissions equals the ceiling. Trade increases aggregate emissions because it increases the opportunity cost of altruism.

[5] Discussions of tradeable permits frequently mention the difficulties of monitoring and enforcing limits. It is important to recognize that these problems are associated with any agreement to limit emissions. They have nothing to do with trade in permits *per se*.

much thinner than the potential market for CO_2. The experience from the US SO_2 program suggests that trade in CO_2 permits could have considerable benefits. The key features of the US program include a national emissions cap, free trading and banking of permits, and strict monitoring. Recent analysis ([24], [27]) concludes that the program decreased costs of achieving emissions. The Government Accounting Office claims that emissions trading halved the cost expected under the previous rate-based standard, achieving larger gains than industry and the government had anticipated [29].

2.3 Estimates of Carbon Permit Prices

There have been many attempts to estimate the costs of reducing carbon emissions, and several attempts to synthesize the estimation results. If countries were allowed to trade emissions quotas, the equilibrium price would be determined by the costs of reducing emissions. We use the estimates from previous costs studies as a basis for comparison of the estimates of quota prices that we obtain from a simple econometric model.

Nordhaus [18] surveyed three categories of studies: estimates of cost reductions obtained by substituting specific low-CO_2 for high-CO_2 technologies; econometric models; and optimization models of the energy sector. He collected the different estimates of marginal costs of abatement and estimated a relation between these costs and the percentage reduction of emissions.

Bohm and Larsen [2] use this relation to estimate the price of tradeable permits and the efficiency gain for intra-European trade when emissions are cut by 20% of the projected levels in the year 2010. They estimate an equilibrium price of \$240 per ton of carbon if only Western European countries trade. Including the remaining OECD countries, China, Eastern Europe and the former Soviet Union causes the supply to rise by more than the demand, resulting in a fall in price to $33.5 per ton of carbon. Larsen and Shah [13] use the same cost function and calculate the price of emissions if all countries participate in trade ($58 per ton of carbon) and if only OECD countries participate ($181 per ton). This experiment assumes that the emissions levels projected for the year 2000 are reduced to 1987 levels.

Decanio [4] describes two recent attempts to estimate abatement costs. The Energy Modeling Forum at Stanford University ran a number of models under a common set of assumptions. In order to achieve a 20% reduction from 1990 levels, by the year 2010, the models require a tax of between $50 and $260 per metric ton of carbon with an average of $170 per metric ton. A similar exercise by the Interagency Analytical Team of the US government, using three models, estimated that a tax of between $89 and $160 per metric ton would stabilize emissions at 1990 levels, by the year 2010.

Coppock [3] describes an American Petroleum Institute study that estimates an abatement cost of $200 per ton of carbon for the US to achieve 1990 levels by the year 2010. The Environmental Energy Technology division at the Lawrence Berkeley Laboratory estimated that the US could achieve half of the abatement needed to meet 1990 levels at a cost of $50 per ton.

3 The Model

We estimate a revenue function and an emissions function using 1975-1990 panel data for 24 OECD countries. Appendix A describes the data. For the first equation we assume that GDP and CO_2 emissions are joint products, produced by country-specific factors: capital, labor and technology. This joint production function implies an efficiency frontier, which defines the trade-off between emissions and GDP for given levels of factors. We refer to this frontier as the revenue function.

We refer to the second relation as the "emissions function". This function, which determines the equilibrium point on the efficiency frontier, can be viewed as the equilibrium condition of a political economy model involving producers, environmentalists and policy-makers. More simply, it can be viewed as a first order condition to a policy-maker's utility function, as in Antweiler *et al.* [1].

To conserve notation we suppress time and country subscripts in describing the model. The joint production function is $F(Y, E) = G(C, K, L, T, Pop)$, where: Y = GDP (measured in constant 1987 US\$); E = Industrial CO_2 Emissions (in kt, i.e. thousands of metric tons)[6] ; C is a country specific dummy; K = Physical Capital Stock (in constant 1987 US\$); L = Labor force; T = Patent applications (a proxy for technology[7]); and Pop = Country Population. We invert the relation $F() = G()$ to obtain the revenue function $Y =$

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[6] These include emissions arising from burning fossil fuels and manufacturing cement, and contributions from other solid, liquid and gas fuels and gas flaring. The data also includes emissions from commercial and residential sources, but not from changes in land-use [23],[30]. This data accounts for approximately 94% of the measure of "Total anthropogenic emissions excluding land-use change and forestry" found in [21].

[7] Gardner and Joutz [5] discuss the relative merits of using patent applications and R&D expenditures as proxies for technological innovation, and recommend the former.

$f(C, K, L, T, Pop, E)$, which represents the feasible trade-off between income and emissions, for given levels of the other variables. We divide all variables (except the dummy) by Pop to obtain per capita variables, and estimate a log-linear relation.

The estimation equation for the revenue function is

$$y_{is} = c_i + \alpha_1 k_{is} + \alpha_2 l_{is} + \alpha_3 t_{is} + \alpha_4 e_{is} + \epsilon_{1is}. \tag{1}$$

Lower case variables y, k, l, t and e are logarithm of the per capita of the corresponding upper case variables, c_i is the country specific dummy, ϵ_{1is} is the error associated with country i in period s and the parameters α_j, $j = 1, 4$ are to be estimated. We view Y and E as endogenous and we treat K, L, T and Pop as exogenous[8] . We include the country dummy to account for country-specific variables such as arable land and cultural factors.

The revenue function describes the technological trade-off between emissions and income. A second relation, the emissions function, describes the "social trade-off" between income and emissions. We can view this relation as a reflection of either a political economy equilibrium or of a policymaker's preferences. In either case, this relation is constrained by limitations in the policy menu, such as the ability to make income transfers. In principle, the emissions function should include variables which proxy political constraints (e.g., membership in environmental groups, relative income of workers in "dirty" industries). Much of

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[8] The explanatory variables K, L, T and Pop are stock variables. Thus, we treat the levels of these variables as predetermined in a period. Of course, the *change* in these levels is likely to be endogenous. Most of the empirical growth literature estimates equations like the revenue function in first differences, rather than levels. Mankiw [14] discusses the endogeneity problems that arise when the explanatory variables are changes in stocks. Most of the literature on the environmental Kuznets curve (which usually relies on cross sectional data) estimates a relation between levels rather than first differences. In order to determine the effects of tradeable permits, we need to know the relation between levels, rather than the relation between first differences.

this kind of information is not available for our sample. The social trade-off also depends on the opportunity cost of emissions, and thus the type of capital that is available, rather than simply the aggregate level of capital. An economy with a large service sector may be able to obtain a given level of income with lower emissions, compared to an economy with a large manufacturing sector.

In an effort to improve the specification of the emissions function and maintain identification, we include commercial energy use (kt of oil equivalent), N, as a regressor in the emissions function. We view N as a proxy for the structure of the economy, i.e. an indication of the opportunity cost of reducing emissions. Although energy consumption (like most variables) is not genuinely exogenous, it does seem like a reasonable proxy for those variables which affect a country's ability to reduce emissions. Energy consumption and emissions are highly correlated, but it is possible to reduce one without reducing the other. By switching technologies (e.g. from coal-fired to gas-fired power generation) an economy can consume the same amount of energy while producing fewer emissions. We are interested in whether richer economies are more likely to make such a switch, for a given level of energy-dependence.

We estimate a log-linear specification of the emissions function

$$e_{is} = d + \beta_1 y_{is} + \beta_2 y_{is}^2 + \beta_3 n_{is} + \epsilon_{2is}. \tag{2}$$

The variable n_{is} is the log of per capita energy consumption in country i, year s, d is a constant, and ϵ_{2is} is the error term.

A more familiar specification treats energy, rather than emissions, as a regressor in the revenue function. For purposes of comparison we also estimate that model. However, equations (1) and (2) are preferable on theoretical grounds. In view of the magnitude of trade in oil, it makes sense to treat energy as a purchased input, much like other internationally traded inputs (e.g. steel, grain). We want to estimate the GNP-emissions frontier as a function of factor endowments, rather than the level of traded inputs. In other words, we think of CO_2 emissions as representing "environmental services", a factor of production whose supply is endogenous. With this interpretation, the regressors in equation (1) consist of factors of production, not tradeable inputs.

4 Estimation Results

For purposes of comparison we estimate equations (1) and (2) singly using ordinary least squares (OLS), and then jointly using three stage least squares (3SLQ). Estimation using 3SLQ accounts for correlation between the errors ϵ_{1is} and ϵ_{2is}, in addition to the endogeneity of the explanatory variables [11]. The sample correlation between any two of the three variables n, e and y is 0.99. Given this degree of multicollinearity, we would expect to be unable to reject the two simple hypotheses that β_1 and β_3 equal 0, and we would also expect the OLS and 3SLQ estimates to be nearly the same. We strongly reject the hypotheses that $\beta_1 = 0$ and $\beta_3 = 0$; our simulation results and some statistical results suggest that the OLS and 3SLQ estimates are significantly different.

Tables 1 and 2 report the results of OLS estimation of equations (1) and (2), with t statistics in parentheses. (Appendix B contains the estimates of the country dummies.)

$\boldsymbol{\alpha}_1$ (k)	$\boldsymbol{\alpha}_2$ (l)	$\boldsymbol{\alpha}_3$ (t)	$\boldsymbol{\alpha}_4$ (e)	R^2
.534 (21.874)	.3385 (15.336)	.0558 (8.49)	.0452 (3.53)	.99

Table 1: OLS Estimates of Equation 1

β_1 (y)	β_2 (y^2)	β_3 (n)	R^2
-.1968 (-5.1)	-.0016 (-3.12)	1.1631 (31.33)	.996
1.0072 (160.3)	-.0031 (-3.09)		.986
-.21 (-5.4)		1.17 (31.36)	.996

Table 2: OLS Estimates of Equation 2

The elasticities in equation (1) are highly significant and have reasonable magnitudes. Their sum is .9735. The t statistic for the null hypothesis that their sum is 1 equals 7.4, so we reject the hypothesis of constant returns to scale in capital, labor, technology and "environmental services".

We estimate three OLS versions of equation (2): first, using the three regressors y, y^2 and n and then excluding either y^2 or n. Although $\beta_{2,}$ the coefficient of y^2, is statistically significant, its magnitude is small, and the turning point of the graphs of e against y are (vastly) higher than GDP in our sample. Thus, for both versions that include y^2, emissions are monotonic in GDP over the range in our sample. When we exclude n our estimates imply that emissions increase with GDP, in agreement with [10] and [26]. However, when we include n, our estimates imply that emissions *decrease* with income. In this specification the point estimate of the income elasticity of emissions is approximately -0.2 and is highly significant.

These contrasting results are consistent with two quite different interpretations. If we think that per capita energy consumption is chiefly determined by income, then we should treat n as endogenous. In this case, the interesting relation is between e and y, allowing n to vary endogenously. This view – which appears to be the conventional wisdom – implies that CO_2 emissions are likely to increase with income. However, if we think that per capita energy consumption is partly the result of the structure of the economy (e.g. the relative importance of manufacturing and services), then it becomes interesting to consider the relation between e and y, holding n fixed. This view implies that CO_2 emissions are likely to fall with income. (For a given level of per capita energy consumption, higher income is associated with cleaner technology and lower emissions.)

Tables (3) - (5) give the point estimates (and t-statistics) using 3SLQ for the three variants of equation (2): including both y^2 and n (Table 3); excluding n (Table 4); and excluding y^2 (Table 5). For the estimation in Tables 3 and 4 we treat y^2 as exogenous in order to be able to use a linear package and facilitate comparison with other specifications. Thus, we have eliminated only part of the bias resulting from correlation between the regressors and the error in equation (2). We expect this bias to be small, because the correlation between y^2 and the error is likely to be relatively small, but in any case we use the results in Tables 3 and 4 principally to gauge the sensitivity of our estimates.

Excluding n from equation (2) changes the sign of the coefficient of y, as was the case with the OLS estimates. In addition, this exclusion leads to implausible (and insignificant) estimates of some parameters of equation (1) (a negative elasticity of GDP with respect to

$\alpha_1(k)$	α_2 (l)	α_3 (t)	α_4 (e)	β_1 (y)	β_2 (y^2)	β_3 (n)
.5096 (20.14)	.2646 (8.78)	.0653 (9.02)	.1315 (5.17)	-.199 (-5.16)	-.0016 (-3.13)	1.165 (31.4)

Table 3: 3SLQ, Including y**2 and n

α_1 (k)	α_2 (l)	α_3 (t)	α_4 (e)	β_1 (y)	β_2 (y^2)	β_3 (n)
.3242 (1.78)	-.318 (-.51)	.141 (1.58)	.797 (1.19)	1.01 (161)	-.003 (-3.1)	

Table 4: 3SLQ, Including y**2, excluding n

labor, α_2). We therefore reject the model that excludes n (Table 4). The coefficient of y^2 in Table 3 is significant, but its magnitude is small and the remaining coefficients in Tables 3 and 5 are similar. We will use the coefficient estimates α_i to simulate the effects of allowing tradeable permits. Because of the possible bias that results from treating y^2 as exogenous, we hereafter concentrate on the model reported in Table 5. We use the results in Table 3 for sensitivity comparisons in the next section.

There is little difference between the OLS and 3SLQ estimates of equation (2), which is not surprising in view of the high correlation between n and e. It is not clear whether a systems estimator is important for equation (1). The sum of the elasticities under OLS (Table 1)and under 3SLQ (Table 5) are virtually the same (.973 and .972, respectively), and for both methods we reject the hypothesis of constant returns to scale in capital, labor, technology and emissions. However, the 3SLQ estimate of the income elasticity with respect

α_1 (k)	α_2 (l)	α_3 (t)	α_4 (e)	β_1 (y)	β_2 (y^2)	β_3 (n)
.517 (20.82)	.287 (9.44)	.0625 (8.74)	.106 (4.07)	-.216 (-5.55)		1.179 (31.47)

Table 5: 3SLQ, Excluding y**2, including n

to emissions (α_4) is double the OLS estimate. This parameter is key in simulating the efficiency gains and equilibrium price under tradeable permits.

A formal test of whether the two sets of α_i (in Tables 1 and 5) are equal is complicated because the two estimates rely on the same data set and are obviously correlated. However, we can use standard tests for a set of related hypotheses. We reject the hypothesis (under 3SLQ) that $\alpha_4 = .0452$ (= the value in Table 1); the t statistic is 2.42. We fail to reject the joint hypothesis (under 3SLQ) that the set of α_i equal the corresponding OLS values in Table 1; the χ^2 statistic is 5.84 and the critical χ^2 is 13.28 at the 1% significance level. On the other hand, we reject the joint hypothesis (under OLS) that the set of α_i equal the corresponding 3SLQ values in Table 5; the F statistic is 5.7 and the critical F(4,356) at the 1% significance level is 3.32.

We will use the parameter estimates to simulate the effect of tradeable permits. Therefore, a reasonable way of determining whether a systems estimator is important, is to compare simulations using single equation and systems estimators. However, if we had chosen to begin with a single equation model, equation (1) would not have been most readers' obvious choice. As we mentioned in the previous section, a more familiar model treats income as a function of the usual factors and energy (rather than emissions). That is, we replace equation (1) with

$$y_{is} = c_i + \alpha_1 k_{is} + \alpha_2 l_{is} + \alpha_3 t_{is} + \alpha_4 n_{is} + \epsilon_{3is}. \tag{3}$$

We can use the relation between emissions and energy,

$$E = \gamma_0 + \gamma_1 N + \epsilon_{4is} \tag{4}$$

α_1 (k)	α_2 (l)	α_3 (t)	α_4 (n)	γ_0 (constant)	γ_1 (N)
.502 (19.13)	.312 (12.71)	.054 (8.48)	.106 (4.18)	719 (.26)	2.52 (353)

Table 6: OLS Estimates of Equations (3) and (4)

to translate restrictions on emissions to restrictions on energy. (Upper case letters represent levels, and lower case letters represent the log of per capita levels.) Table 6 contains the OLS parameter estimates and t statistics for these two equations. The R^2 for both equations equal .99. The OLS estimate of α_4 in Table 6, using n rather than e as a regressor, is much closer to the 3SLQ estimate (Table 5) than to the OLS estimate (Table 1). The estimate for γ_0 is not significantly different from 0.

Our estimates for equations (1) or (3) are comparable to the augmented Solow growth model estimated by Nonneman and Vanhoudt [20] for OECD countries. Their estimated production function is $Y = K^{.33}L^{.4}\tilde{T}^{.08}H^{.15}$, where their measure of technology, $\tilde{T}$, uses R&D expenditures and H is a measure of human capital. We experimented with including human capital, proxied by average years of education. The signs of the coefficients did not change, but the coefficients of labor, technology, and human capital were not significantly different from 0.[9] Our estimate of the elasticity with respect to capital is larger, and our estimate of the labor elasticity is smaller, relative to [20]. Although we use a different variable to measure technology, our elasticity estimate is similar to theirs.

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[9] There was very little variation over time in mean years of education for most countries. Thus, we expect that the country dummy would pick up the human capital effect. Mankiw *et al.* [15] also find that including human capital in the Solow model leads to low t values for investment and population growth for the OECD countries. Nonneman and Vanhoudt [20] find that human capital appears to be less important than previous studies had estimated.

5 Simulation Results

We begin with a brief discussion of the reduced form of the model and then explain how we can use the structural model to simulate the price and the efficiency effect of tradeable permits. We also calculate the maximum feasible reduction in aggregate emissions, together with the allocations of permits, that is consistent with holding all countries at a given level of income.

First, we consider the reduced form of the model. We solve the deterministic versions of equations (1) and (2) (with $\beta_2 = 0$) to obtain an expression for country i's equilibrium (reduced form) level of emissions:

$$\begin{aligned} \ln E_i &= \eta_0 + \eta_1 \ln F_i + \eta_2 \ln Pop_i + \eta_3 \ln N_i \qquad (5) \\ F_i &\equiv \exp(c_i) K_i^{\alpha_1} L_i^{\alpha_2} T_i^{\alpha_3}; \eta_0 \equiv \frac{d}{1-\beta_1\alpha_4}; \eta_1 = \frac{\beta_1}{1-\beta_1\alpha_4}; \\ \eta_2 &= \frac{\beta_1(1-\Sigma_j\alpha_j)+1-\beta_1-\beta_3}{1-\beta_1\alpha_4}; \eta_3 = \frac{\beta_3}{1-\beta_1\alpha_4}. \end{aligned}$$

The "factor index" F_i is a function of capital, labor, and technology. The parameter estimates in Table 5 imply point estimates for the elasticities of emissions with respect to F, Pop, and N of: $\eta_1 = -.21$, $\eta_2 = .03$ and $\eta_3 = 1.15$. An increase in factors of production raises GDP, and based on our estimated negative value of β_1, leads to a decrease in emissions. Other things equal, a 10% increase in population leads to a .3% increase in emissions. However, a population increase is usually associated with an increase in labor and thus an increase in F, so our estimates imply that the net effect of higher population may be to decrease emissions. The elasticity of emissions with respect to N exceeds 1.

Using equations (1) and (2) (with $\beta_2 = 0$), the reduced form (deterministic) equation for income is

$$\begin{aligned} \ln Y_i &= \theta_0 + \theta_1 \ln F_i + \theta_2 \ln Pop_i + \theta_3 \ln N_i \qquad (6) \\ \theta_0 &\equiv \alpha_4 \eta_0; \theta_1 \equiv 1 + \alpha_4 \eta_1; \theta_2 \equiv (1 - \Sigma_j \alpha_j) + \alpha_4 \eta_2; \theta_3 \equiv \alpha_4 \eta_3. \end{aligned}$$

The parameter estimates in Table 5 imply point estimates for the elasticities of income with respect to F, Pop, and N of: $\theta_1 = .978$, $\theta_2 = .031$, $\theta_3 = .122$. The elasticity of income with respect to the index of factors, F, is nearly 1 and the elasticity with respect to N ($\theta_3 = .122$) is similar to the elasticity we obtained by estimating the reduced form, reported in Table 6 ($\alpha_4 = .106$).

Our estimates imply that increased emissions are associated with a change in the structure of the economy, proxied by N, rather than from larger supplies of capital, labor and technology. For example, our point estimates imply that if energy consumption increases by 20%, CO_2 emissions increase by 23% and GDP increases by 2.4%.

Now we explain how we will use the structural model – particularly the revenue function, equation (1) – to estimate the effect of trade in permits. It is convenient to rewrite equation (1) as

$$Y_i = A_i E_i^{\alpha_4}; \text{with } A_i \equiv F_i Pop_i^{\sigma}; \sigma \equiv (1 - \Sigma_j \alpha_j). \qquad (7)$$

The positively sloped solid curve in Figure 1 shows the graph of the revenue function for a particular country in the year 1990, and the negatively sloped solid curve shows the emissions function. The intersection of these curves, point x, represents the 1990 equilibrium.

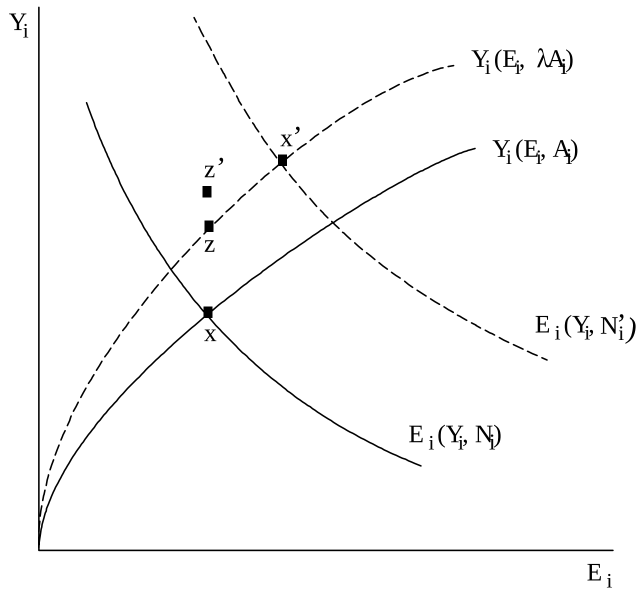

Figure 1: Equilibrium with and without quotas

If factors of production and population [and thus the variable A defined in equation (7)] increase, then the revenue function shifts out as shown by the upwardly sloping dashed curve in Figure 1.

Most commentators assume that in the absence of an agreement, emissions would increase over time. Given our parameter estimates, an increase in both emissions and in factors of production (F) requires that the emissions function shifts out (e.g., due to an increase in N). The dashed curve labelled $E_i(Y_i, N_i')$ represents the future (e.g., year 2010) emissions function, and the point x' is the equilibrium combination of emissions and income in the absence of an agreement to constrain emissions.

An international agreement changes the regime that determines the level of emissions. If the agreement restricts emissions in the year 2010 to its 1990 level, the country's level of income without trade is given by the point z. If a country receives an allocation equal to its 1990 emissions, but is able to trade permits, it can achieve a higher level of income, such as the point z'.[10]

In order to use the model to calculate the equilibrium price of tradeable permits, we need an estimate of how A_i will change over the period 1990 - 2010. We propose two alternatives. The *simplest* alternative is to assume that A_i remains constant. In this case, the change in emissions, absent an agreement, is due solely to the shift in the emissions function. A more plausible alternative is to assume that the increase in A_i is positive, but is the same for all countries. That is, $A_{i,2010} = \lambda A_{i,1990}$ for $\lambda > 1$.

Although we do not attempt to estimate the value of λ, a simple calculation suggests a magnitude that is consistent with our model and data and with projections for the increase in emissions in the absence of an agreement. Over the period 1975 - 1990 the average yearly increase in GDP for countries in our sample was 2.9%. If this average were maintained over the period 1990 – 2010, there would be a 77% increase in each country's GDP. US emissions, in the absence of an agreement, are expected to increase by 25% - 35% over the same period [3]. A 30% increase in E and a 77% increase in Y is consistent with a 72% increase in A in equation (7), given our "preferred" estimate, $\alpha_4 = .106$. Thus, our back-of-the-envelope calculation suggests that $\lambda = 1.72$ is a reasonable order of magnitude.

There is a simple relation, described below, between the equilibrium price of permits and

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[10] The horizontal coordinate of z' represents the country's quota allocation, which differs from its actual emissions by the amount of trade. The vertical coordinate repesents the value of production $Y_i(E_i, \lambda A_i)$ net of the value of sales of quota licenses.

the value of λ. Therefore, in the next section we report the simulated equilibrium price under the (implausible) assumption that $\lambda = 1$. The reader can adjust these prices depending on the value of λ that seems reasonable. We show that the efficiency gains due to trade are independent of the value of λ (i.e., independent of the growth of factors of production).

5.1 Equilibrium Prices and Efficiency Gains

With tradeable emissions and perfect competition, the value of marginal product of emissions in each country equals the world price of permits, denoted P. Using equation (7), country i's value of marginal product (its equilibrium inverse demand) for emissions is $P = \alpha_4 A_i E_i^{\alpha_4 - 1}$, which implies the demand

$$E_i = \left(\frac{P}{\alpha_4 A_i}\right)^{\frac{1}{\alpha_4 - 1}}. \tag{8}$$

Using our preferred point estimate (Table 5) $\alpha_4 = .106$, the elasticity of demand (both for a single country and for the aggregate of all countries) is 1.12. Summing equation (8) over i and setting the result equal to the aggregate level of emissions $\bar{E}$ gives the equilibrium price $P^*(\bar{E})$ as the solution to

$$\bar{E} = \Sigma_i E_i = \sum_i \left(\frac{P^*}{\alpha_4 A_i}\right)^{\frac{1}{\alpha_4 - 1}}. \tag{9}$$

To estimate the price using equation (3) [rather than equation (1) as above] we first use equation (4) to calculate the level of $\bar{N}$ that corresponds to a particular level of $\bar{E}$. We then calculate the equilibrium price for rights to use N using equations analogous to (8) and (9), but with different parameter values. We convert the price of N to a price of E using (4).

Table 7 reports the simulated price (1987 US$ per metric ton of CO_2) when OECD aggregate emissions and country i's factors (and thus A_i) equal their 1990 levels, for different

coefficients from Table	1	3	5	6
price per metric ton of CO_2	\$57.5	\$171.25	\$156.8	\$134.3
price per metric ton of carbon	\$210. 84	\$627. 92	\$574.94	\$492. 48

Table 7: Simulated Prices

sets of parameter estimates. (That is, we set $\lambda = 1$.) The first row of Table 7 reports the table (and thus the model) that we used for the coefficient estimates; the second row reports the simulated price for CO_2; and the third row converts this into a price of carbon.[11] The price estimates summarized in Section 2.3 refer to tons of carbon, so the third row of Table 3 should be used for comparison.

The price estimates based on the different models differ by a factor of three $\left(\frac{171}{57}\right)$, despite the fact that many of the underlying parameter estimates are similar. (The price estimates of the two single equation models differ by a factor of $\frac{134}{57} = 2.\,3$.) We prefer Model 5 on theoretical grounds but recognize that Model 6 might strike many readers as an obvious choice because it is the most familiar. (The price estimates of models 5 and 6 differ by a factor of only $\frac{157}{134} = 1.\,2$.) Model 3 errs by treating y^2 as exogenous in estimating the second equation. Model 1 is the least justifiable: the rationale for using emissions (rather than energy consumption) as a regressor for GDP relies on the assumption that GDP and emissions are joint outputs, and thus requires a simultaneous equations model. The estimates in Model 1 ignore the simultaneity. However, of the four choices, Model 1's estimates are closest to those of the previous literature, summarized in Section 2.3.

We also calculated the equilibrium price if emissions are reduced by 20% of 1990 levels.

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[11] CO_2 has a molecular weight of $12 + 2(16) = 44$. Thus the ratio of the weight of CO_2 to carbon is $\frac{44}{12} = 3.\,666\,7$.

Using the estimates in Table 5, the price of a metric ton of CO_2 (carbon) is \$191 (\$670). Again, this price is much higher than those suggested by the simulations carried out by the Energy Modeling Forum at Stanford University [4], which calculate that a tax of between \$50 and \$260 (averaging \$170) supports a 20% reduction in carbon emissions.

The estimated equilibrium prices are primarily useful as a means of comparing our results with the previous literature. The more interesting economic question concerns the welfare effects of allowing trade in permits. Fortunately, the answer to this question is independent of the value of λ.

In order to estimate the efficiency gain due to tradeable permits, we compare a country's estimated GDP with and without tradeable permits, given a quota allocation of their 1990 emissions level. Denote Y_i^* as country i's GDP when it uses the efficient level of emissions, denoted E_i^* [i.e., the value given by equation (8)]. ($Y_i^* = A_i E_i^{*\alpha_4}$.) The value of its exports of permits, given an allocation equal to its actual 1990 emissions, $E_{i,1990}$, is $P^*(E_{i,1990} - E_i^*)$, where P *is the equilibrium price from equation (9). Under tradeable permits country i's total income is Y_i^{TP} :

$$Y_i^{TP} = Y_i^* + P^*(E_{i,1990} - E_i^*). \tag{10}$$

The estimated level of income without trade is $Y_{i,1990} = A_i E_{i,1990}^{\alpha_4}$. A measure of the efficiency gain due to trade is thus $\frac{Y_i^{TP} - Y_{i,1990}}{Y_{i,1990}}$.

Figure 2 shows the efficiency gains for the countries in our sample, using our preferred parameter estimates (Table 5) of equation (1). For most countries the gains are below 2% of GDP; only three countries gain more than 3%. For some countries, e.g. Germany, the gain is negligible; the United States gains 0.53%. The unweighted average of the gains for the 24 countries is 1.36%.

Our preferred estimate of the elasticity of GDP with respect to emissions, $\alpha_4 = .106$, implies that a 50% reduction in emissions reduces income by 5.3%. Nordhaus' surveys ([18],[19]) suggest a much smaller estimate of the cost of this level of emissions reduction (about 1% of GDP). The estimates in those surveys assume that the reduction is phased in over time, whereas our estimate based on the short run elasticity assumes an immediate reduction in emissions. In view of this difference, the magnitude of the difference in estimated costs is reasonable. Decanio [4] discusses the fact that econometric approaches tend to give much higher estimates of abatement costs, relative to engineering approaches.

If we assume that cutting emissions from the year 2010 "Business as Usual" level to the year 1990 level requires a 30% reduction[12] , then our elasticity estimate implies a 3.2% fall in income in the absence of tradeable permits. Thus, if the United States really gains 0.53% of GDP because of tradeable permits, this would represent nearly 17% of the US costs of emissions reductions. In other words, the estimated efficiency gains due to tradeable permits are substantial.

In order to obtain additional perspective on the magnitude of our estimated efficiency gains, we mention two other sets of numbers. Hoel and Karp [9] survey estimates of the costs of damages resulting from a doubling of greenhouse stocks. These damage estimates are even more speculative than the estimates of abatement costs; most estimates are within the range

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[12] This reduction of 30% is the estimate that we used in our "back-of-the-envelope" calculation of λ, and is based on [3].

of 1% to 5% of world GDP. Martin and Winters [16] report that the trade liberalization achieved by the Uruguay Round of GATT negotiations is estimated to increase world GDP by 0.2% to and 0.9%. Viewed in the light of these numbers, our estimated efficiency gains are substantial.

The results above held A_i at its (estimated) 1990 level. As we discussed above, this assumption provides the simplest but not the most plausible means of using our model to estimate the effect of tradeable permits. If, A_i increases in the future (the time at which the quota becomes binding) the equilibrium price would be higher. For example, suppose that A_i is replaced by λA_i, $\lambda \geq 1$ to represent an increase in factors of production and population. Using equation (8) and the equilibrium condition $\bar{E} = \Sigma_i E_i$, it is easy to show that $\frac{dP^*}{P^*} = \frac{d\lambda}{\lambda}$. The previous subsection suggested that $\frac{d\lambda}{\lambda} = .72$ is a reasonable estimate. With this estimate, all of the simulated prices (Table 7) should be increased by 72%.

The estimated equilibrium shares and efficiency gain are independent of λ (provided that the value of λ is the same for each country). In the absence of trade, income is $\lambda A_i E_{i,1990}^{\alpha_4}$. With equal proportional growth in A_i for all i, each country's demand for emissions shifts up by the same amount, and its equilibrium share with trade remains the same. Since the percentage increase in price equals the percentage increase in λ, income under trade (Y_i^{TP}) increases by the same proportion as income in the absence of trade: the efficiency gain due to tradeable permits is independent of λ.

5.2 Maximal Emissions Reductions and Quota Shares

Another way to measure the efficiency gains of permit trading is to calculate the maximum additional reduction in emissions that can be achieved by allowing trade, without reducing income. For example, suppose that initially all countries agree to reduce their emissions to 1990 levels, but *trade in permits is not allowed.* Country i's income under this agreement is $Y_i = \lambda A_i E_{i,1990}^{\alpha_4}$. This in the income level given by point z in Figure 1. Countries *subsequently agree to allow trade in permits.* They return to the bargaining table and seek a further aggregate reduction in emissions, together with an allocation of permits, such that no country is worse off than under the initial agreement. Aggregate emissions are lower but each country's income level (inclusive of the value of net imports of permits) is unchanged.

If the new (with trade) aggregate target is $\bar{E}$ and country i's share is μ_i, the constraint that no country is worse off can be written

$$\lambda A_i E_i^{*\alpha_4} + P^*(\bar{E};\lambda)(\mu_i \bar{E} - E_i^*) \geq \lambda A_i E_{i,1990}^{\alpha_4}. \tag{11}$$

The first term on the left side of (11) is the value of domestic production, given the efficient level of emissions (a function of P^*). The second term is the value of net exports of permit. The equilibrium price $P^*(\bar{E};\lambda)$ is proportional to λ and the equilibrium shares E_i^* are independent of λ. Therefore we can divide both sides of (11) by λ and write the constraint on income as independent of the growth parameter λ.

The optimization problem that determines the new agreement is

$$\min_{\bar{E},\mu_i} \bar{E}, \quad \text{subject to} \quad \Sigma_i \mu_i = 1, \text{ and equation } (11)\,. \tag{12}$$

The equilibrium price and each country's equilibrium use of emissions depend on $\bar{E}$, but are independent of the allocation of quota rights. However, a country's income, and thus it's willingness to sign an agreement, does depend on the allocation.

The solution to (12), i.e the minimal level of $\bar{E}$, is 8.06% lower than 1990 levels.[13] ' Thus, tradeable permits makes it possible to achieve a significantly higher reduction in emissions without a loss in income. We know from elementary principles that trade makes it possible to achieve larger reductions in emissions without greater economic cost. Our empirical result give us an idea of the likely order of magnitude of the benefits from trade. Some environmentalists oppose emissions trading. There are a number of valid reasons for this opposition, but their view may also be colored by a skepticism of markets. Results such as this may help generate more enthusiasm for markets.

Our results probably overstate the actual gain, because we ignore transactions costs and adjustment costs which would undoubtedly be associated with a reallocation of emissions. Thus, all of our estimates of gains should be viewed as plausible upper bounds, rather unbiased estimates.

Figure 3 shows: the actual *shares* of emissions in 1990; the equilibrium shares when aggregate emissions are fixed at 1990 levels and trade in permits is allowed (identified as "Simulation 1"); and the optimal shares μ_i implied by the solution to equation (12) (identified as "Simulation 2"). Figure 4 shows the corresponding *levels* of emissions in these three scenarios.

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[13] Recall that in the 1992 Framework Convention on Climate Change, industrialized countries set a target for the year 2010 at 1990 levels. The Kyoto Protocol set a target at 5.2% of 1990 levels.

We do not constrain $\mu_i \geq 0$, but Switzerland is the only country that receives a (small) negative allocation. (Imposing the non-negativity constraint on shares leads to a negligible change in the solution.) A negative share implies that a country pays a fixed cost for the right to use any level of emissions. The value of the marginal product of emissions in Switzerland was much higher than the equilibrium world price at 1990 emissions levels. Switzerland obtains a substantial increase in income from increasing it's emissions. Figure 2 shows that Switzerland has the largest proportional efficiency gain amongst all OECD countries. By increasing emissions, Switzerland's income increases by enough to offset the cost of paying for emissions.

Although Switzerland is the only country that obtains a negative share, several countries (notably Japan and France) receive a share of quota rights (μ_i) less than their actual share in 1990. However, they emit more under the equilibrium implied by the solution to equation (12) than they did in 1990. For the United States, on the other hand, the optimal quota share under the solution to (12) exceeds it's historical 1990 share, but the equilibrium share of emissions is lower. Thus, Japan and France are net buyers of quota rights, and the United States is a net seller.

A common perception is that the United States would buy emissions rights, and that the ability to trade might induce it to accept a smaller quota. When we restrict attention to OECD countries, our results suggest that in an optimal (emissions-minimizing) solution the United States would export quota rights. In view of the historical level of US emissions, it is plausible that some of these are wasteful, and that US abatement costs are lower than elsewhere. However, in order to induce the United States to make these reductions, it would need to be compensated with a large share of quota rights. In 1990 the United States accounted for nearly half of OECD emissions. Although its *quota share* under the solution to equation (12) exceeds it's actual 1990 share, its *equilibrium share of emissions* is much less than its 1990 levels. The United States also sells emissions permits in Simulation 1, which held fixed aggregate emissions at 1990 levels.

The Cobb Douglas functional form for income implies that a country's equilibrium share of emissions, $\frac{E_i^*}{\Sigma_j E_j^*}$, equals it's equilibrium share of income from production, $\frac{Y_i^*}{\Sigma_j Y_j^*}$. Since the United States has approximately 35% of OECD GDP (in 1990), its share of emissions is approximately 35% for all the experiments.

6 Conclusion

We estimated a structural model to assess the likely effects of tradeable permits for CO_2 emissions. One equation in our model describes the relation between GDP and factors of production, including CO_2 emissions. We view these emissions as representing "environmental services", the supply of which is endogenous. The second equation uses income and energy consumption (a proxy for the structure of the economy) to explain the equilibrium supply of these "services". When we include energy consumption in our model, we find a negative relation between income and emissions, contrary to previous studies.

Our estimates of the price and efficiency effects of tradeable permits use only the parameters of the revenue function. Thus, it is possible to estimate these price and efficiency effects using a single equation model. For purposes of comparison, we estimated two singe equation models, one with emissions and the other with energy consumption as explanatory variables. Despite the high correlation between emissions and energy consumption, the parameter estimates of the two models are quite different, and the resulting estimates of quota prices differ by a factor of 2.3. We regard the simultaneous equations model as theoretically more defensible, since it takes into account the endogeneity of emissions.

We assumed that an international agreement supersedes the mechanism that would, in the absence of the agreement, determine the endogenous supply of environmental services (the level of emissions). We used our estimated revenue function to simulate the equilibrium price and efficiency gains of tradeable permits, given a particular level of aggregate emissions. Our estimated carbon prices are two or three times as large as previous estimates, without accounting for growth in demand (due to growth in factors of production). When we do account for this growth, the equilibrium prices increase by a further 72%.

For the United States, the estimated gain in efficiency attributable to trade in emissions is over 0.5% of GDP, or approximately one-sixth of the estimated cost of a 30% reduction in emissions. For many countries the efficiency gain is much higher, although for some countries (e.g. Germany) the gain is negligible.

Some proposals aim to reduce year 2010 aggregate emissions to 1990 levels. Our results suggest that an additional 8% reduction in aggregate emissions could be achieved, without income loss, by appropriate distribution of emissions rights. This distribution gives the United States a larger share than it's historic level, but the US exports permits, leading to smaller US emissions. Since we ignore transactions costs and adjustment costs, we interpret these measures of the gains from trade as plausible upper bounds, rather than unbiased estimates.

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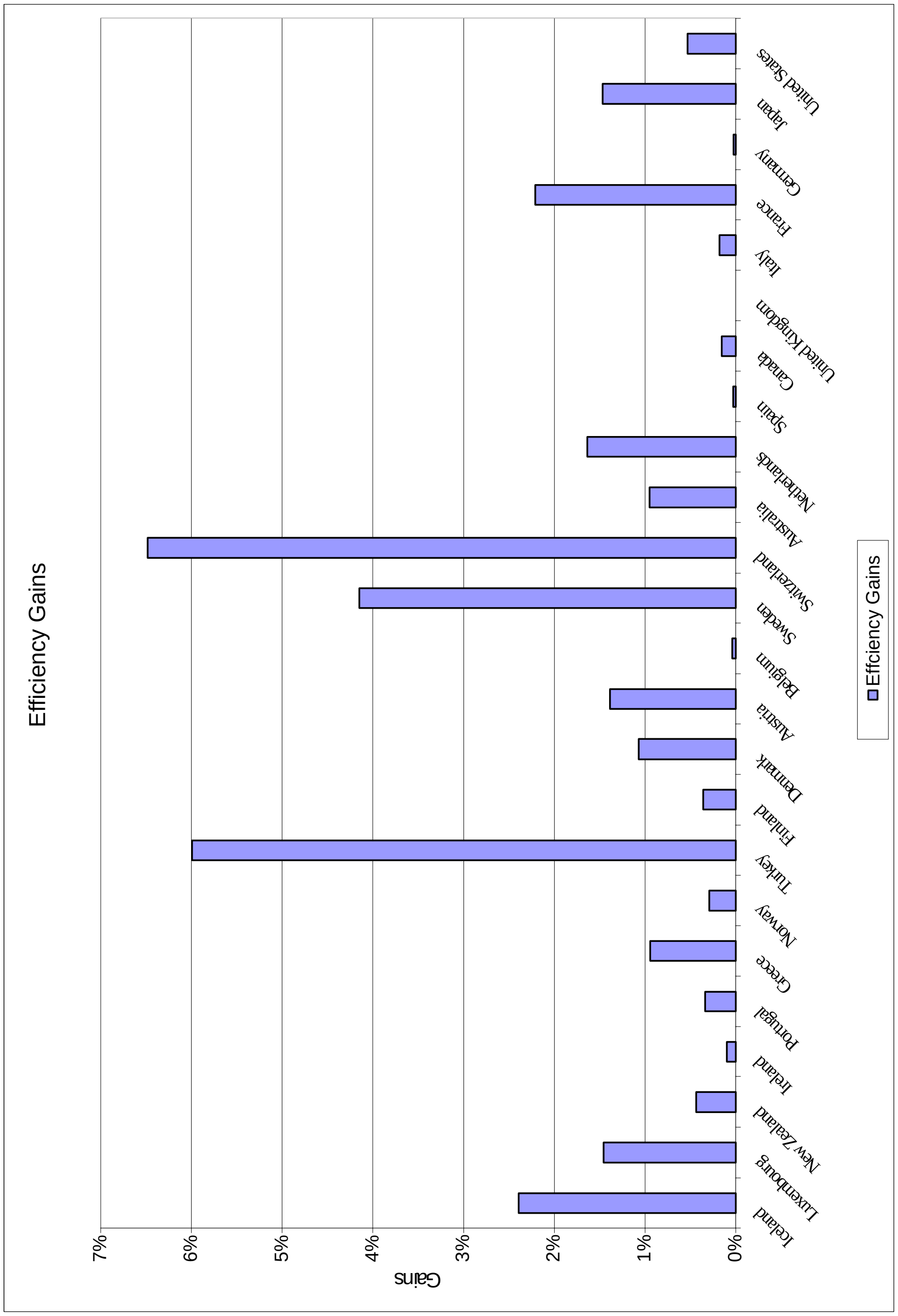
Figure 2



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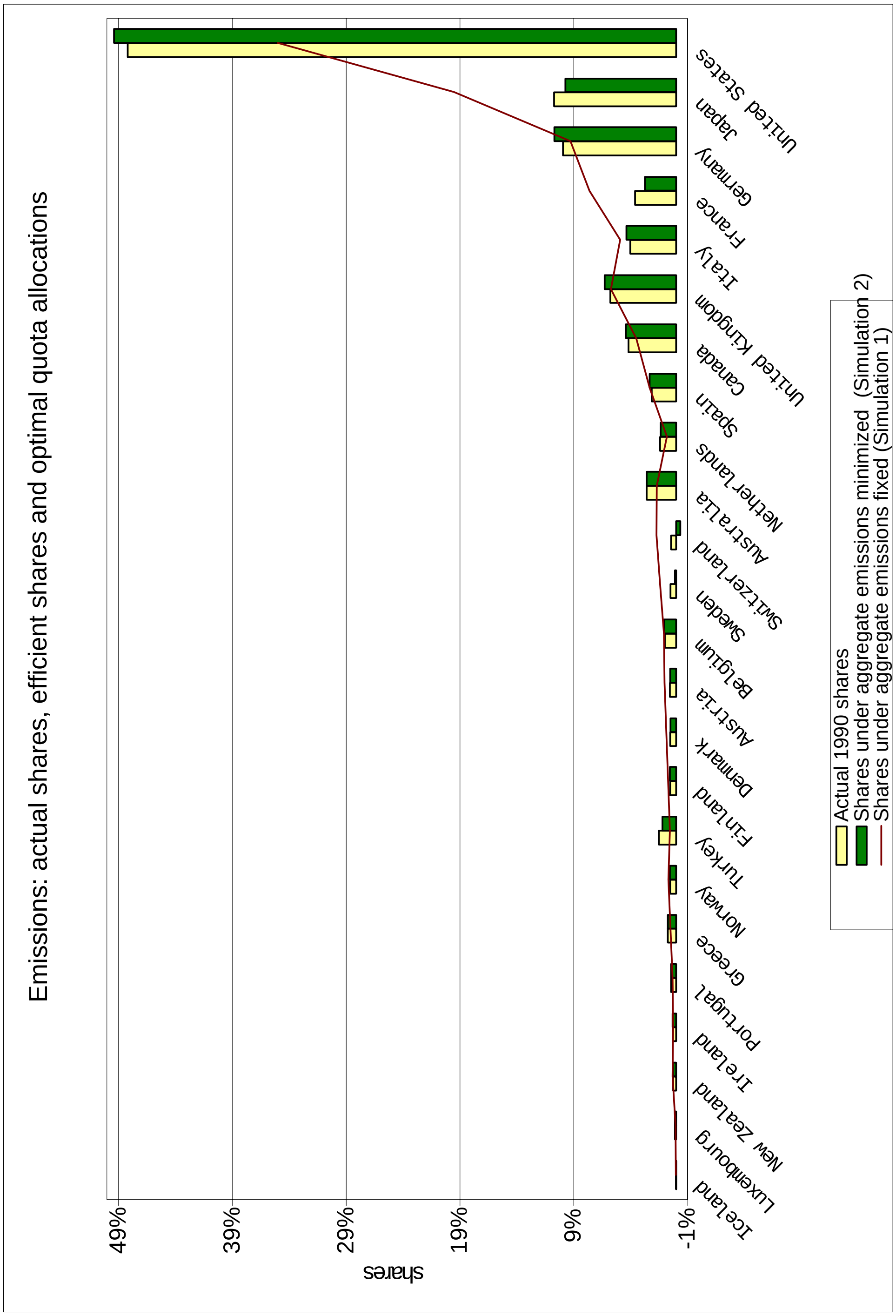

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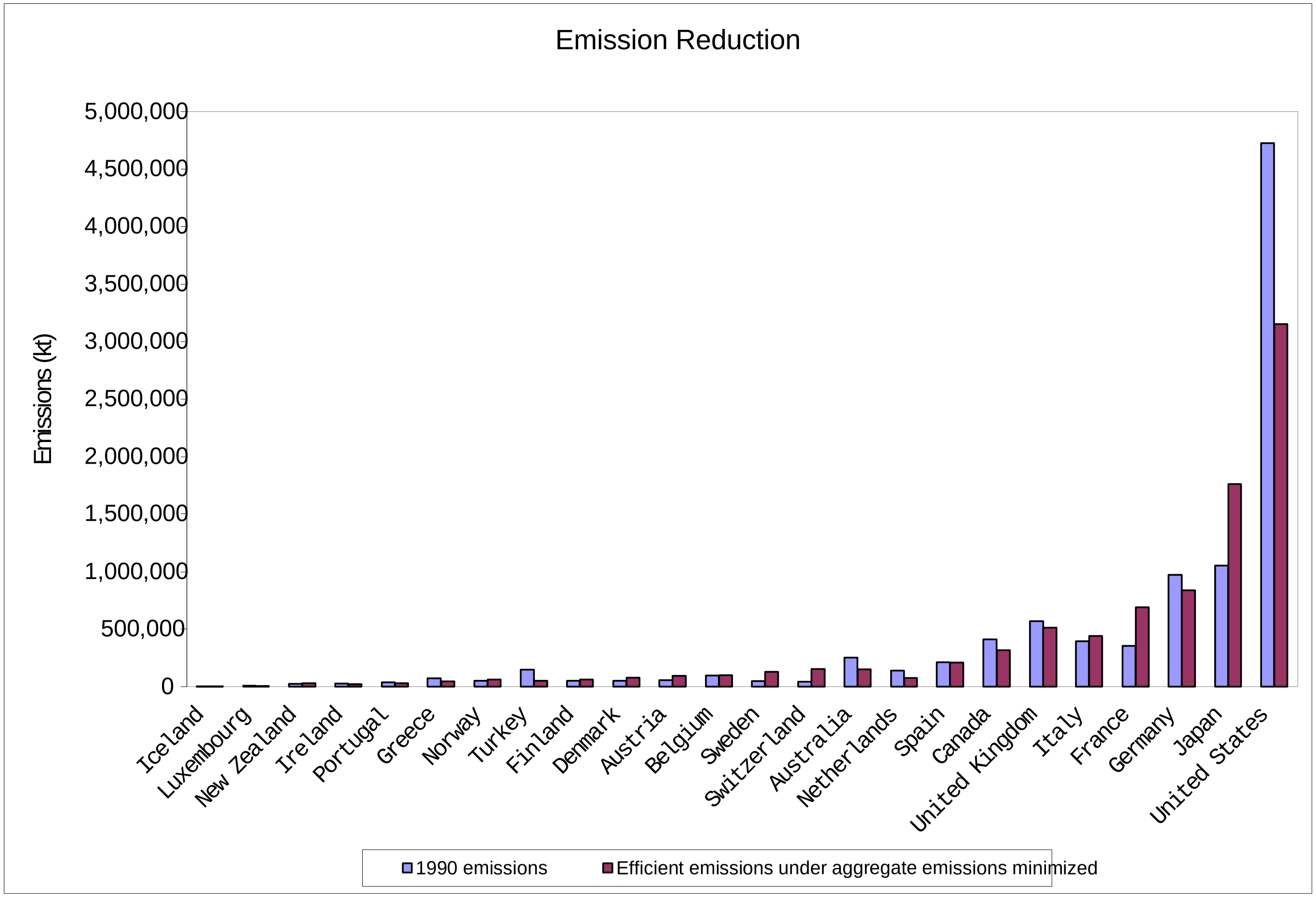

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