Distribution of Emissions Allowances as an Opportunity

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Abstract

Much of the debate on climate policy in the United States focuses on the gain or loss to the macroeconomy of alternative policies to reduce greenhouse gas emissions. However, the economy is made up of multiple individuals, not a representative agent. This paper reports the results of alternative ways of distributing emissions allocations across citizens. Macroeconomic effects interact with the policy for distribution, but the distributional weights are more important for the welfare of individual agents than the economy-wide effects of the emissions reductions. Egalitarian distributions of the emissions allowances have the potential to increase the welfare of most people, even if significant emissions reductions are mandated. Focusing on the distribution of emissions allowances (or the revenues generated from an emissions tax) rather than on aggregate GDP may provide guidance in identifying and implementing politically viable solutions to the climate change mitigation problem.

Keywords: Climate policy, greenhouse gas emissions reductions, cap-and-trade, emissions allowances, income distribution, wealth distribution, macroeconomic effects of climate policies, distributional effects of climate policies

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I. Introduction

Much of the climate policy debate in the United States has been devoted to the effect of various emissions-reduction strategies (cap-and-trade, carbon tax, voluntary programs) on aggregate output measured by GDP. Estimates of the total economic burden of various policy proposals are politically salient, even though these estimates do not capture the entire range of issues that must be addressed by climate policy.[1] The value of climate services is ordinarily not included in net cost estimates, largely because the benefits of averting climate change are very difficult to quantify.[2] In addition, it has been recognized since climate change emerged as a major issue that one of the keys to rational climate policy is to approach it as the purchase of insurance against planetary disaster, rather than as a more conventional cost-benefit calculation. The United Nations Framework on Climate Change was set up to avoid "dangerous anthropogenic interference" in the climate system, and the role of risk management in climate policy been a theme of growing importance since then (DeCanio 1997; Hall and Behl 2006; Weitzman 2007 forthcoming).

Bearing these caveats in mind, the output of policy simulations is most frequently presented as a deviation of GDP from its unconstrained path.[3] This is equivalent to positing a "representative agent" as a stand-in for all the consumers in the economy. Yet the members of any modern nation are highly diverse, with very different levels of wealth, income, education, and other characteristics. A critical question is how the emissions-reduction policy might differentially affect people up and down the wealth distribution. By definition, a representative agent model cannot shed any light on this.

Yet it is the effect of the policies on differentially situated agents that is of greatest interest to the agents themselves, and indirectly, to their political representatives. To illustrate this, an examination of the 10 greenhouse gas cap-and-trade bills under consideration by the 110th Congress as of May, 2007, reveals a wide variety of emissions allocation schemes. Some bills leave the authority for determining the allocation to the President; some specify auctioning various percentages of the allocations; some of the bills allocate a fraction of the permits to historical emitters. Many of the bills require consideration of "consumer impact," "competitiveness," "transition assistance," etc. (Pew Center on Global Climate Change 2007). None of these impacts can fully be determined without a disaggregated analysis of the consequences of alternative allocation plans.

II. A Conceptual Model

In order to explore how emissions reductions affect different members of the economy, the model in this paper has five representative agents corresponding to the quintiles of the income distribution, but is stripped down to the simplest kind of representation in every other respect. As such, the model presented here should be thought of as a "conceptual" model rather than being meant to be "descriptive" of the economy.[4] It has only five commodities and three factors of production, and the agents' utility functions as well as the commodities' production functions are all of generic Cobb-Douglas form. Markets are assumed to be perfectly competitive, and there are no distortions of any kind in the economy. Incomes are determined solely by the agents' endowments of the three factors of production (labor, human and tangible capital, and energy), and policy is represented by changes in the total energy endowment and its allocation across the agents. This avoids all complications associated with the interaction of distortionary taxes (as in the "double dividend" debate).[5] There is no intertemporal maximization of utility, and the processes of capital accumulation and technical progress take place outside the model. Institutional arrangements for administration of the emissions allowances are not modeled, so there are no transactions costs associated with the policy.[6] Population (and thus the pure labor input) is held constant so that changes in aggregate or quintile incomes are the same as per capita changes.

The "energy" input may in this context be thought of as the "energy/emissions" resource.[7] Present ownership of shares in fossil fuel companies or stocks of such fuels can be mapped exactly into emissions allowances according to the energy and carbon content of the different fuels. Because property rights are ultimately defined by the government, it would be straightforward to redefine ownership of the company shares or the physical commodities with the equivalent right to emit the fuels' CO_2 content when they are converted into work. Thus, in the discussion that follows, this input will be referred to as the "energy/emissions" input to the production processes.

Details of the model and numerical values of its parameters are given in the Appendix. Two versions were computed, under different assumptions regarding technological progress and capital accumulation. Changes in the incomes of members of the top quintiles could possibly have an effect on aggregate capital accumulation, so in one version of the model all the economic growth stems from augmentations to the capital assets, while in the other version, the capital endowment is held fixed and economic growth arises solely because of increases in total factor productivity. Results not reported here show that at this level of detail it matters little whether the utility functions differ according to the expenditure shares of the different quintiles.[8]

The initial distribution of the endowments of the factors of production was as follows: The amount of pure labor was equal in each of the quintiles. Human capital was included in the "capital" input, and the initial endowments of capital (human plus physical) and energy/emissions were distributed according to the average of the shares of earnings and wealth by quintiles (Castañeda *et al*. 2003).[9] The model was solved for equilibrium[10] under six scenarios, two base cases and four policy cases. The base cases were the initial period and business as usual (BAU) growth, in which economic growth takes place either because capital grows by a factor of 1.5 and energy by a factor of 1.2 (this will be referred to as the "capital accumulation case"), or because total factor productivity in each of the five industrial sectors increases by a factor of 1.3 (this will be referred to as the "total factor productivity case"). The policy cases all have capital or total factor productivity growing by the same factor as under BAU, while energy/emissions is cut to 0.8 of its initial value by a cap-and-trade emissions permit system. (This amounts to a 33% reduction from BAU in the capital accumulation case.) The difference in the policy cases is in how the emissions endowments are distributed, and whether there is any energy-efficiency enhancement due to elimination of market, institutional, and organizational barriers. The four policy scenarios are: (1) Grandfathering the energy/emissions permits to correspond to the initial distribution of energy/emissions across the quintiles; (2) an egalitarian distribution in which the energy/emissions endowments are equal across the quintiles; (3) a half-and-half case in which the energy/emissions endowments are the average of the grandfathered endowments and the egalitarian endowments; and (4) the half-and-half case but with the energy/emissions efficiency parameters in the manufacturing and transportation sectors increased by 20% from their base values.[11] The distribution of the energy/emissions endowments under these six scenarios are given in Table 1.[12]

Table 1 – Energy/Emissions Factor Endowments under Alternative Scenarios

Scenario	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
Initial period	0.000	0.250	0.910	1.840	7.000
BAU growth due to capital accumulation	0.000	0.300	1.092	2.208	8.400
BAU growth due to total factor productivity	0.000	0.250	0.910	1.840	7.000
Grandfathering	0.000	0.200	0.728	1.472	5.600
Egalitarian	1.600	1.600	1.600	1.600	1.600
Half-and-Half	0.800	0.900	1.164	1.536	3.600
Half-and-Half + Eff.	0.800	0.900	1.164	1.536	3.600

III. Results

Before presenting the main results on the effects of the alternative policy scenarios on welfare and the income distribution, it is worth reviewing the model equilibrium in the context of other computable general equilibrium (CGE) exercises. First, the GDP reductions from emissions restrictions in the policy cases are similar to the GDP reductions found in other models for similar scenarios.[13] In the initial period (before any economic growth takes place), if energy/emissions is cut 20% with the allocations grandfathered and the other endowments held constant, GDP falls by approximately 2.4% when measured in initial prices. In prices of the initial period, the emissions-restricted cases show GDP in the final period about 4.2% lower than BAU in the capital accumulation case and 2.4% lower than under BAU in the total factor productivity case.[14] If the time period between the initial year and the final year of the BAU case is 20 years, then the annual growth rate of (per capita) GDP over that period is about 1.3-1.4% under business as usual. The index number problem associated with the price changes that occur under different scenarios (Füssel 2007) is just detectable; in the capital accumulation case, the ratio of final GDP to initial GDP is 1.314 using the prices of the initial period and 1.311 using the prices of the final period. As would be expected, the price of energy/emissions rises substantially when its supply is constrained by policy relative to BAU; the average energy/emissions price increase (relative to its BAU price) across the four policy scenarios in the capital accumulation case is 47%; in the total factor productivity case the average energy/emissions price increase is 24%.

The model economy looks similar to the actual economy in terms of some standard indicators. The initial and BAU factor shares of the model economy are: labor, 0.270 (recall that this share does not include the fraction of wage and salary compensation due to human capital); human and tangible capital, 0.622; energy/emissions, 0.108. The Gini index of income inequality in the initial period is 0.456, comparable to the 0.462 recent value of the 2002 Gini index of household income for the United States (DeNavas-Walt *et al*. 2003, p. 14).

The equilibrium utilities and incomes under each of the six scenarios are shown in Tables 2 and 3. The salient features of these tables are:

(1) In all scenarios and for all agents, both utility[15] and income are substantially greater at the end of the period than they are at the beginning of the period.

(2) If the energy/emissions endowments are grandfathered, utilities and incomes of all agents are lower than in the BAU scenario.

(3) However, under each of the other three scenarios, utilities and incomes of the three agents at the lower end of the income distribution are *higher* than their utilities and incomes under BAU. For example, in the capital accumulation case utility for the bottom quintile is increased by 35% and income by 34% with the egalitarian assignment of energy/emissions allowances, relative to BAU. In the half-and-half case without efficiency enhancement of the energy/emissions input, both the utility and the income of the bottom quintile increase by 15% relative to BAU. In the total factor productivity case utility and income of the bottom quintile increase by 37% relative to BAU, and the income of this quintile increases by 17% relative to BAU for the half-and-half case.

(4) In the policy cases (and for both economic growth scenarios), utility and income of the four bottom quintiles are higher under the non-grandfathered than under the grandfathered energy/emissions allocations. That is, if the government decides to undertake an emissions-reduction policy of this magnitude, four-fifths of the population would be better off if the energy/emissions allocations were not grandfathered.

(5) The enhancement of energy efficiency increases incomes and utilities across the board; both utility and income are higher for each agent in the half-and-half plus efficiency case relative to the half-and-half case. GDP is slightly more than 1% higher in the H&H + Efficiency case than in the H&H case, even though the energy efficiency gains are confined to a modest 20% in only two sectors over a 20-year period.

(6) Tables 2 and 3 are very similar; the results are being driven by the differences in the distribution of the energy/emissions allowances, not by differences in the sources of economic growth.

Table 2 – Utilities and Incomes of Agents/Quintiles under Alternative Policies, Capital Accumulation Case

	Utilities					
	Base Cases		Policy Cases			
	Initial Yr.	BAU	Grndfthr	Egalitarian	Half & Half	H&H + Eff.
Agent 1	0.519	0.687	0.658	0.921	0.789	0.800
2	0.664	0.873	0.834	1.052	0.943	0.957
3	1.110	1.458	1.394	1.530	1.462	1.483
4	1.741	2.284	2.183	2.203	2.193	2.225
5	5.427	7.116	6.816	6.166	6.491	6.579
	Incomes, in Prices of Initial Year					
	Base Cases		Policy Cases			
	Initial Yr.	BAU	Grndfthr	Egalitarian	Half & Half	H&H + Eff.
Agent 1	2.729	3.616	3.470	4.856	4.162	4.214
2	3.654	4.812	4.605	5.808	5.206	5.278
3	6.095	8.020	7.677	8.425	8.051	8.161
4	9.535	12.519	11.988	12.098	12.043	12.205
5	28.619	37.577	36.041	32.607	34.325	34.756
GDP	50.632	66.544	63.781	63.794	63.788	64.614

Source: See text.

Table 3 – Utilities and Incomes of Agents/Quintiles under Alternative Policies, Total Factor Productivity Case

	Base Cases		Policy Cases			
Utilities						
	Initial Yr.	BAU	Grndfthr	Egalitarian	Half & Half	H&H + Eff.
Agent 1	0.519	0.675	0.659	0.922	0.791	0.801
2	0.664	0.863	0.841	1.061	0.951	0.965
3	1.110	1.443	1.407	1.544	1.476	1.498
4	1.741	2.264	2.209	2.229	2.219	2.251
5	5.427	7.055	6.889	6.233	6.561	6.650
Incomes, in Prices of Initial Year						
	Base Cases		Policy Cases			
	Initial Yr.	BAU	Grndfthr	Egalitarian	Half & Half	H&H + Eff.
Agent 1	2.729	3.548	3.466	4.850	4.157	4.213
2	3.654	4.750	4.633	5.843	5.238	5.315
3	6.095	7.923	7.730	8.483	8.106	8.224
4	9.535	12.395	12.095	12.206	12.150	12.324
5	28.619	37.205	36.336	32.875	34.607	35.069
GDP	50.632	65.821	64.260	64.257	64.258	65.145

Source: See text.

Comparison of these results to previous calculations in the literature of the distributional impact of a carbon tax reveals that the main differences are accounted for by how the carbon revenues are treated. For example, Barnes and Breslow (2003) computed the net effect (as % of mean household income) by income decile of a cap-and-trade system combined with per capita distribution of the carbon charges that would meet the 2010 U.S. emissions targets of the Kyoto Protocol. They found that seven of the ten deciles (including the bottom six) would experience a net gain in income ranging from 5.1% for the bottom decile to 0.2% for the eighth decile. Deciles 7, 9, and 10 would experience a net loss, the largest in percentage terms being 0.9% of income for the top decile.[16]

More recently, the Congressional Budget Office recently estimated the effects of various dispositions of the revenues from a carbon tax that would achieve a 15% cut in CO_2 emissions in 2010 (Dinan 2007). The CBO's calculations show that if the carbon tax revenues were distributed equally as lump-sum payments, the average income of the bottom quintile would increase by 1.8% and of the second quintile by 0.7%. The top three quintiles would experience small losses, of 0.1%, 0.6%, and 0.7%, respectively. GDP would fall by 0.34% under this scenario. The two notable differences between the CBO study and the results shown in Tables 2 and 3 of the present paper are (1) the CBO cuts occur in the relatively near future, so that there is no economic growth from capital accumulation or technological progress to cushion the reduction in the energy/emissions input, and (2) the distribution of the tax revenues occurs as lump-sum rebates which do not offset any tax distortions. In other calculations reported by the CBO, if the tax revenues are used to cut corporate taxes or payroll taxes, the net loss to GDP is lower although the effect on income distribution is regressive.[17]

Some earlier studies of the distributional impact of a carbon tax or energy tax found that such taxes, if enacted without any other tax reforms, would generally be regressive (Bull, Hassett, and Metcalf 1994).[18] However, it is relatively straightforward to design a tax shift that makes the environmental taxes combined with other tax cuts distributionally neutral or progressive (Metcalf 1999).

IV. Discussion and Implications for Policy

Several policy implications emerge from this simple conceptual model. It should be emphasized that these results are not meant to be exact predictions; a conceptual model is intended to outline the underlying gross features of the economy with a particular emphasis – in this case, the effects of alternative allocations of emissions allowances.

From the standpoint of the *well-being of the individual agents*, the manner of distribution of the energy/emissions allowances is much more important than the macroeconomic consequences of the emissions restriction. The distribution of wealth in the contemporary U.S. economy is quite unequal – the top quintile owns approximately 70% of the wealth. The consequence is that *virtually any allocation of emissions allowances that moves in a more egalitarian direction will improve the material well-being of a majority of the agents, even without taking into account the environmental benefits of the emissions reductions*. This is demonstrated by the result that in all the non-grandfathering policy scenarios, the utilities and incomes of the bottom three quintiles of the income distribution increase relative to the unconstrained emissions BAU case. This model shares with other general equilibrium models the property that if one of the productive factors is restricted by policy, aggregate output will fall. Nevertheless, the allocation of the emissions allowances can overcome this macroeconomic loss for most members of the economy. However, if the energy/emissions permits are grandfathered, everyone's income and utility is reduced relative to business as usual.

This result is obtained in a first-best equilibrium situation, and does not depend on the outcome of the so-called "double dividend" debate. Treatment of the distribution of the rents/revenues resulting from emissions reductions by assigning the allowances directly as part of the agents' endowments bypasses questions about the interaction of tax distortions associated with an emissions tax and other taxes. In the simple conceptual model developed here, the policy implications follow transparently from the distributional characteristics of the assignment of the emissions allowances because there are no distortionary taxes in the model and all feedbacks are taken into account.

Overcoming organizational, institutional and cognitive barriers to efficiency (sometimes inaccurately referred to as "market barriers") can partially or wholly offset the energy/emissions constraint. This is, or course, almost a truism – these barriers are the source of the "no regrets" possibilities that have been documented many times before,[19] and their relaxation has been incorporated into a two-stage macroeconomic framework (with first-order optimizing conditions prevailing in the first stage and efficiency improvements in a second stage) before as well (see Sanstad *et al*. 2001). In the present model, an increase in energy/emissions efficiency of a factor of 1.5 in the capital accumulation case (this would be expressed by setting the parameters of Appendix equations A-1 and A-2 so that $e_i = 1.5$, $i = 1,\dots 5$) in all sectors would offset the 20% reduction in the resource from its baseline value (i.e., for the energy/emissions input, $1.5 \times 0.8 = 1.2$) and result in an equilibrium that, from the point of view of all the agents, would be equivalent to the BAU scenario.

There are two issues associated with the transition from the BAU equilibrium to a policy equilibrium that deserve discussion. First, the conceptual model presented here, like every other general equilibrium model, is one in which all resources are fully employed. However, any climate policy of significant impact would be likely to have both permanent and transitory effects. The transitory effects include job losses – more properly characterized as the destruction and creation of jobs as capital and labor are reallocated in response to the policy. The general equilibrium framework is not suited to address the timing or magnitude of these transitory effects, because equilibrium by definition is a state in which all resources are fully employed. The model abstracts from transitory effects.

Second, the increase in the energy/emissions price associated with its restriction in the policy scenarios should not be thought of as "inflationary," even though this price does increase by 47% in the capital accumulation case and 24% in the total factor productivity case relative to the baseline. Inflation properly defined is a monetary phenomenon, and the model is entirely "real." The price of the numeraire good remains the same through all the scenarios (and in the two baseline cases as well). If the government were to embark on a climate policy involving energy/emissions reductions, it would not be appropriate for the Federal Reserve to tighten the money supply in response to the "inflation" associated with the increased energy/emissions price. Instead, the Fed would fulfill its policy obligations by implementing monetary policies to minimize the transition costs. It is beyond the scope of the present analysis to discuss what those policies might be, but it is clear that they would not entail an automatic tightening of the money supply to combat the "inflation" associated with higher real energy/emissions costs.

In closing, it should be clear that none of the scenarios considered here constitutes a fundamental overturning of the economic status quo. To the extent that happiness in a wealthy country like the United States is based on material factors, it depends as much on relative economic status as on absolute consumption levels (see Brekke and Howarth 2002 and the literature they cite from economics and other fields). Assignment of energy/emissions allowances along the lines of any of the policy scenarios would hardly affect the relative situation of anyone whose wealth is diversified. Of course, any decent policy to reduce fossil fuel use drastically would need to incorporate provisions for compensation to coal miners and a few others whose industries would be shrunk by the policies (see Krause *et al*. 2003 for further discussion). Compensation to investors in fossil fuels is far less justifiable; it is difficult to imagine how any rational investor today would not already have discounted the value of fossil fuel assets heavily in anticipation of future climate policy measures.[20] It is important to note that reassignment of energy/emissions allowances would not constitute arbitrary confiscation of wealth created through work and investment, because the crucially valuable “right” to dispose of CO_2 combustion waste has historically been “owned” by fossil fuel extractors *only as a result of the absence of property rights in the atmospheric commons, not because of any effort or expenditure on their part*.

In the egalitarian scenario least favorable to the top quintile, utility and income of this group fall by 12-13% relative to BAU, depending on which version of the model is run. However, the utility and income of the top quintile in this scenario are 14-15% *above* their initial values. In the half-and-half plus efficiency case (which is probably the most politically plausible of the scenarios),[21] the utility and income of the top quintile fall by 5.7-7.5% relative to BAU (and are 21-23% higher than their initial values). Utility and income of the fourth quintile fall by 0.6-2.6% relative to BAU, and are 28-29% higher than their initial values. The classical rationales for the more well-to-do members of society to bear proportionally more of the burden of addressing the climate problem can be invoked here, especially given that the sacrifices that would be asked of the rich are modest and would neither distort their incentives to save and work nor close off continuing increases in their wealth and incomes. Also, if the emissions allowance assignments were introduced gradually, there would be no time at which the incomes of the top quintiles would actually fall. Economic growth is ongoing in all scenarios, and the utilities and incomes of the top quintiles are significantly higher after the reassignment of energy/emissions allowances than in the initial period.

These calculations suggest that two aspects of climate policy deserve greater prominence than they have received. First, the distribution of the emissions allowances is very important, and its effects for most members of the economy outweigh the macroeconomic losses that the economy may experience as a result of energy/emissions restrictions.[22] Second, more attention should be paid to the offsetting potential of enhancements to energy efficiency. These gains can come about through overcoming the cognitive, organizational, and institutional barriers to full maximization by firms and consumers.[23] Gains in efficiency improve outcomes across the entire income distribution, and even modest gains in the energy-intensive sectors have noticeable effects. Forging a political consensus to undertake the actions that are necessary to stabilize the atmosphere will not be easy, but awareness of the potential for judicious assignment of emissions allowances and stimulation of energy efficiency to ameliorate or actually improve the economic circumstances of lower-income citizens should make agreement easier to achieve.

Appendix – Model Details

The basic equations of the model are Cobb-Douglas functions with constant returns to scale.[24]

Utility Functions:

$$U_i = x_{i1}^{\varphi_i} x_{i2}^{\psi_i} x_{i3}^{\mu_i} x_{i4}^{\eta_i} x_{i5}^{\theta_i}, \quad i = 1,2,\ldots 5 \qquad (A-1)$$

where x_{ij} is the consumption of commodity j by agent i.[25]

Production Functions:

$$X_j = B_j L_j^{\alpha_j} K_j^{\beta_j} (e_j J_j)^{\gamma_j}, \quad j = 1,2,\ldots,5 \qquad (A-2)$$

where L_j, K_j, and J_j are the factors (labor, capital, energy/emissions) allocated to the production of commodity j. The B_j and e_j are "efficiency parameters" for each industry as a whole and for the energy/emissions input, respectively.

The endowments of labor, capital, and energy/emissions of agent i are given by ε_{iL}, ε_{iK}, and ε_{iJ}, respectively. Each agent maximizes utility subject to the budget constraint that the agent's total income equals the income received from ownership of his endowment (possibly zero) of each factor of production. Factor prices (equal to the value of the marginal products in each industry) are equalized across industries. The equilibrium consists of the four commodity prices, p_2, p_3, p_4, p_5 (commodity #1 is set as numeraire with $p_1 = 1$), three factor prices w, r, and s (of labor, capital, and energy/emissions, respectively), factor allocations to production for each industry (15 values) and consumption allocations for each agent (25 values), for 47 equilibrium values in all. There are just this many equations determined by the first-order conditions, the factor pricing equations, the budget constraints, and the market-clearing equations, after eliminating redundancies.

The five commodities may be thought of as corresponding roughly to “food,” “shelter,” “manufactured goods,” “transportation,” and “services.” The parameters of the utility functions for each agent were based on commodity expenditure shares for each of the five quintiles, calculated from the 2005 Consumer Expenditure Survey (U.S. Department of Labor, BLS 2005).[26]

For the production functions, the share of wages and salaries for each of the five industries was calculated from the industry input and output data prepared by the Current Industry Analysis Division of the Bureau of Economic Analysis (U.S. Department of Commerce 2006). Wages and salaries include the return to the human capital of employees, so to convert them to shares for pure “labor power” alone, the wage and salary shares were cut in half (except in the case of the very low labor share for “shelter”) so that the average labor share was approximately 25%. This is consistent with the pure labor share calculated by Barro and Sala-i-Martin (1995, p. 38) in their discussion of what labor and capital shares are consistent with international data on income convergence. The share of energy/emissions was determined more or less arbitrarily to satisfy two requirements: (a) the “manufacturing” and “transportation” sectors were made the most energy/emissions-intensive, and (b) the average energy/emissions share was made to be about 10% of GDP. These shares were scaled roughly on expenditure shares for energy in those sectors, consistent with (a) and (b). The parameters of the utility and production functions are given in Tables A-1 and A-2.

Table A-1 – Utility Function Parameters

Commodity Expenditure Share (i=1,2,3,4,5)	Food φ_i	Shelter ψ_i	Manufacturing μ_i	Transportation η_i	Services θ_i
Agent/Quintile 1	0.181	0.234	0.205	0.143	0.237
Agent/Quintile 2	0.161	0.199	0.195	0.184	0.261
Agent/Quintile 3	0.154	0.195	0.183	0.190	0.278
Agent/Quintile 4	0.148	0.179	0.171	0.193	0.309
Agent/Quintile 5	0.123	0.182	0.169	0.173	0.353

Table A-2 – Production Function Parameters

	Factor Input Elasticities		
Goods	Labor α_j	Human and Physical Capital β_j	Energy/Emissions γ_j
Food, etc.	0.256	0.694	0.050
Shelter	0.065	0.885	0.050
Manufacturing	0.291	0.518	0.191
Transportation	0.326	0.435	0.239
Services	0.351	0.599	0.050

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Endnotes

[1] For example, if per capita GDP is projected to grow at 2% per annum, a permanent drop in per capita GDP of 1% caused by a carbon tax or cap-and-trade system has a present value measured in hundreds of billions of dollars, yet represents only a 6-month delay in achieving any particular future standard of living. Whether this represents at large or small economic consequence thus is partly a matter of how the question is framed.

[2] For a recent effort to estimate these benefits, see the *Stern Review* (HM Treasury 2006).

[3] It should be noted that there is uncertainty even over the sign of the GDP effect of Kyoto-sized GHG reductions (Barker and Ekins 2004; Krause et al. 2002; Repetto and Austin 1997).

[4] See DeCanio (2005) for further discussion of this distinction.

[5] See Repetto (2001) and the references therein.

[6] For a theoretical treatment of the potential impact of transactions costs, see Stavins (1995). For a recent empirical study of transactions costs in EU emissions trading, see Frasch (2007).

[7] Abstracting here from all energy sources that are not fossil fuels, and from the different emissions-to-energy ratios of the different fuels.

[8] The philosophical question of whether individuals differ in their "tastes" will not be explored here. See Stigler and Becker (1977) for a statement of the position that the starting point for analysis should be that "tastes" are identical across individuals.

[9] Using the distribution of tangible wealth only would skew the distribution in the direction of too much inequality; on the other hand, the earnings data are before-tax labor incomes and do not include government transfers or income from capital. Hence the average of the two distributions was used. The shares of both earnings and wealth for the first quintile were adjusted from their slightly negative values in Castañeda *et al.* to values of zero. The earnings and wealth distributions in Castañeda et al. are based on calculations and sources given in Díaz-Giménez et al. (1997).

[10] The equations of the model were solved simultaneously using FindRoot in Mathematica (2007). Because all the utility and production functions are Cobb-Douglas, the equilibrium is unique (Kehoe 1998, citing Mas-Colell 1991).

[11] In all the scenarios reported here, the other energy-efficiency parameters were set equal to one. Limiting efficiency gains only to the two energy-intensive sectors is quite conservative. The framework was designed to allow investigation of the consequences of allowing the other efficiency parameters to reflect gains.

[12] The total labor endowment in all scenarios was 10; the total initial capital endowment 100, and the total initial energy/emissions endowment 10. Note that the scale or units of these endowments do not matter because all the production functions are Cobb-Douglas. Changes in units could be handled by changes in the constant terms of the production functions and in the units of the factor prices.

[13] Of course, computable general equilibrium models have the built-in property that if one of the inputs to the production process (e.g., energy) is restricted, real output will fall. This is a consequence of the full employment of productive resources at any interior solution of such a model.

[14] This is similar to the 1.4-4.2% range of GDP reductions estimated by the Energy Information Administration for the "cost of Kyoto" in the case of domestic emissions reductions with no international permit trading (EIA 1998).

[15] Of course, the percentage changes in "utility" should not be taken literally, because the equilibrium of the observable prices and quantities is invariant under monotonic transformations of the utility functions.

[16] These are their "middle-range" scenario estimates.

[17] See also Dinan and Rogers (2002) for a similar analysis including more details.

[18] Bull *et al*. also cite Poterba (1991) on this point, and show that the regressivity of such taxes is much reduced if lifetime incidence is considered. Boyd and Uri (1991) found that the incidence of broad-based energy taxes would be spread rather evenly over six household categories ranked by income.

[19] See IPCC, Contribution of Working Group III (1996, Chapters 8 and 9), Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies (2000, summarized in Brown et al. 2001), and Brown (2001).

[20] Such compensation to shareholders because of possible political necessity has been discussed by Bovenberg and Goulder (2000) and Parry (2003).

[21] But it should be noted that egalitarian distribution has been proposed (globally) by EcoEquity (Athanasiou and Baer, 2001) and (domestically) by Barnes (2001). Barnes (2006) expands on the idea of creating trusts in common assets with the proceeds to be distributed primarily on a per capita basis.

[22] The centrality of the equity issue in the distribution of emissions allowances has been recognized by Baer *et al*. (2000).

[23] See the treatment of these barriers in DeCanio (1993). Conventional CGE models also lack the capacity to treat in a sophisticated way economies of scale, learning by doing, and transactions costs as factors in the diffusion of new technologies.

[24] The assumption of constant returns to scale in production omits some possibilities for path dependence and multiple equilibria. These phenomena are related to the barriers to efficiency (and to opportunities for removing those barriers in a cost-effective way) cited earlier.

[25] The utility functions have no initial constant because the prices and quantities in equilibria are invariant to monotonic transformations of the utility functions.

[26] The "food" category contains food, alcoholic beverages, tobacco products and smoking supplies; manufacturing contains utilities, fuels and public services, housekeeping supplies, household furnishings and equipment, and apparel and services; services includes health care, entertainment, personal care products and services, reading, education, miscellaneous, cash contributions, and personal insurance and pensions.