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Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE" Model

By WILLIAM D. NORDHAUS *

The threat of anthropogenic climate change has become a major economic and political issue, symbolic of growing concerns that humans are making irreversible and potentially calamitous interventions in global life-support systems. Climatologists and other scientists have warned that the accumulation of carbon dioxide (CO_2) and other greenhouse gases (GHG's) is likely to lead to global warming and other significant climatic changes over the next century. Setting optimal policies for the control of GHG's poses daunting problems of data, modeling, uncertainty, international coordination, and institutional design.

A growing body of literature considers issues of cost effectiveness of different policies as well as the role of "carbon taxes" in reducing GHG emissions. The present study extends earlier work and shows the results of an integrated model that incorporates both the dynamics of emissions and climate-change impacts and the economic costs of policies to curb emissions. It is called the "DICE" model as an acronym for a *d*ynamic *i*ntegrated *c*limate-*e*conomy model.[1] This new model extends earlier studies by integrating the economic costs and benefits of GHG reductions with a simple dynamic representation of the scientific links of emissions, concentrations, and climate change. This paper sketches the DICE model, presents the major results, and inquires into alternative approaches to recycling carbon-tax revenues.

I. Model Description

Existing empirical studies of the interaction between climate change and economic growth have generally been of a partial-equilibrium or static nature. The present study constructs an empirical Ramsey model of optimal economic growth with the addition of a climate sector and estimates the optimal path for both capital accumulation and GHG-emissions reductions. The resulting trajectory can be interpreted as either the most efficient path for slowing climate change or as the competitive equilibrium among market economies where the externalities are internalized using the appropriate social shadow prices for GHG's.

The DICE model is designed to choose levels of investment in tangible capital and in GHG reductions that maximize a social-welfare function that is the discounted sum of the utilities of per capita consumption. The emphasis is upon the intertemporal choice, where there is in every period a choice between current consumption, investment in reproducible capital, and GHG abatement.

The version presented here considers an aggregate global economy; while this is a restrictive assumption, preliminary work with a more complete multiregion model suggests that aggregation does not affect the major conclusions. The composite economy is endowed with an initial stock of capital, labor, and technology, and all industries behave competitively. Output is produced according to a Cobb-Douglas production function in capital, labor, and technology. Population growth and technological change are exogenous, while capital accumulation is

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*The author is A. Whitney Griswold Professor of Economics and on the staff of the Cowles Foundation, Yale University, Box 1972 Yale Station, New Haven, CT 06520. This research was supported by the National Science Foundation.

[1] The complete model is presented in a background paper (Nordhaus, 1992a), and an abbreviated version appears in Nordhaus (1992b). Full results will be forthcoming as a monograph.

determined by optimizing the flow of consumption over time.

In addition, the model introduces a number of relationships that attempt to capture the major forces affecting climate change. This part includes an emissions equation, a concentrations equation, a climate equation, a climate-damage function, and a GHG-reduction cost function. Emissions represent all GHG emissions, although they are most easily interpreted as CO_2. Uncontrolled emissions are a slowly declining fraction of gross output; this assumption is consistent with more complete assumptions about the underlying production and demand functions and trends in technology.

Atmospheric concentrations are increased with emissions, with concentrations having an atmospheric residence time of 120 years. Climate change is represented by realized global mean surface temperature, which uses an equilibrium relationship drawn from the consensus of climate modelers and a lag given by recent coupled ocean-atmospheric models.

The model contains two policy variables: conventional investment and the rate of emissions reduction. The latter represents the fractional reduction of emissions relative to the uncontrolled level. The model determines the optimal control rate along with its dual variable, the derivative of the objective function with respect to emissions, which is the "carbon tax."

Two key parts of the model are the climate-damage function and the GHG-reduction cost function. Estimating the damages from greenhouse warming has proved to be extremely difficult. The DICE model assumes that a 3°C warming would lower world output by 1.3 percent and that the impact increases in a quadratic fashion with the temperature increase.[2]

The other difficult economic relationship is the GHG-reduction cost function. This is the one area that has been extensively studied, and while not without controversy, the general shape of the cost function has been sketched on a number of occasions.[3] Based on existing studies, the DICE model assumes that an efficient program (one with lump-sum taxation or costless regulation) could achieve the first 10-percent reduction in GHG emissions at little cost while a 50-percent reduction in GHG emissions will cost about $200 billion per year, or around 1 percent of world output, in today's global economy.

For the runs presented here, the model operates in steps of 10 years centered on 1965, 1975, 1985, ... 2095, ... The model is calibrated by fitting the solution for the first three decades to the actual data for 1965, 1975, and 1985 and is then optimized for capital accumulation and GHG emissions in the future. The utility function is assumed to be logarithmic, and the rate of social time preference is taken to be 3 percent per year. This preference function leads to predictions of the rate of return on capital and the gross savings rate that are close to observed levels.

The DICE model contains many parameters and assumptions that will affect the projections and policy conclusions. The present study presents the central or "best-guess" case and does not at this stage include sensitivity analyses. Work underway suggests that there is great uncertainty about

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[2] A thorough review of impacts by William Cline (1992) finds quantified impacts for the United States of 1.1 percent of GNP for a 2.5°C warming as opposed to the estimate of 1 percent for 3°C warming by the present author. A more recent unpublished study by Samuel Fankhauser (1992) estimates total impacts of a doubling of CO_2 would lead to a 1.3-percent cost to the United States, a 1.4-percent cost to the OECD, and a 1.5-percent cost to the world. Because estimating the impacts of climate change has proved to be elusive, the author is undertaking a survey of experts on the economic impacts of climate change.

[3] The most systematic study is the model comparison study of the Stanford Energy Modeling Forum 12, under the general direction of John Weyant, presented in this session (see Darius W. Gaskins and Weyant, 1993).

TABLE 1—RESULTS OF ALTERNATIVE APPROACHES

Run	Control Rate, 1995 [percent][a]	Carbon Tax, 1995, [$/*t C*, 1990 $][b]	Annualized global impact [billions, 1990 $/year][c]
1. Optimal policy[d]	8.80	5.24	16.39
2. 20-percent cut in emissions from 1990 levels[d]	30.80	55.55	−762.50
3. Tax with wasteful spending	0.30	0.02	−0.56
4. Tax recycled by lowering burdensome taxes	31.70	59.00	205.97

[a] Reduction of GHG emissions below baseline as percentage of baseline.

[b] Tax on GHG emissions in dollar per ton of CO_2 equivalent emissions, carbon (C) weight.

[c] Present value of difference between run and no-control case annualized at a 6-percent real interest rate.

[d] These policies assume that any revenues are returned through lump-sum or nondistortionary rebates.

future conditions but that *today's* optimal policies are robust to all major assumptions and parameters except the rate of social time preference.

II. Policies and Results

A. *Alternative Levels of Control*

I now describe the different scenarios or policy experiments to which the model is applied. I begin by examining the impact of two alternative control strategies: (1) First is the *optimal policy* in which emissions are reduced so as to maximize the objective function. (2) In the second, following the suggestions of many governments, I have investigated a *20-percent emissions reductions from 1990 levels*; although this policy has no particular analytical, scientific, or economic merit, it enjoys the virtue of simplicity.

Table 1 shows the overall evaluation of the different policies. The first column shows the GHG control rate, and the second shows the rate of carbon tax that would support the program. The last column shows the annualized value of the program *relative to a no-controls case*; it is measured as the discounted value of consumption times the first-period real interest rate of 6 percent. The optimal policy in row 1 has a global benefit relative to no controls of $16 billion annually globally; this policy would have a GHG control rate of slightly under 10 percent in the first period. The optimal carbon tax would rise steadily over the coming decades, reaching about $20 per ton by the end of the next century.

The environmentally correct policy of a 20-percent cut would impose significant net global costs of $762 billion in annualized terms. The control rate in the environmentalist policy is higher than the optimal rate, around 30 percent in the first period, and would require a carbon tax of $56 per ton *C*.[4]

It is instructive to compare these results with those from other economic studies. The studies of Alan S. Manne and Richard G. Richels (1992) and Stephen C. Peck and Thomas J. Teisberg (1992) have conclusions that are roughly similar to those reported here. All these studies contain explicit or implicit relationships between emissions control rates and carbon taxes; the relationships are broadly similar to those found by the DICE model, although papers with more detailed energy sectors have more complex dynamics than those seen here. The studies by Dale W. Jorgenson and Peter J. Wilcoxen (see especially Jorgenson and Wilcoxen [1991]) show a lower set of carbon taxes needed to reduce GHG emissions than those shown here, in part because of the induced innovation in the Jorgenson-Wilcoxen model.

Three other studies—those of Cline (1992), Charles D. Kolstad (1992), and Peck and Teisberg (1992)—as well as earlier

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[4] It will be useful to calibrate the carbon taxes in terms of more familiar units. A $10-per-ton carbon tax will raise coal prices by $7 per ton, an increase of about 25 percent at current U.S. coal prices. The same carbon tax would translate into about $1.20 per barrel of oil, or about 15 cents per thousand cubic feet of natural gas.

studies by the present author (Nordhaus, 1979, 1991) also determine the optimal emissions-control rates and carbon taxes, although the modeling of the climate system in the first two papers is less complete than in the DICE model. With the exception of Cline (1992), all the earlier studies show optimal policies close to those determined here. The study of Cline (1992), by contrast, has much higher control rates. The more stringent controls in the Cline study are due to a number of features: primarily, however, because the Cline result lacks an explicit intertemporal optimization and because it assumes a rate of time preference that is lower than would be consistent with observed real interest rates.

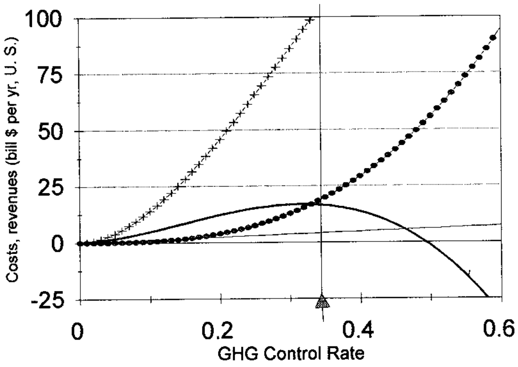

FIGURE 1. RECYCLING REVENUES

B. *Revenue Recycling*

The economic model used here presumes that decisions are optimally taken and that any carbon taxes are recycled using lump-sum rebates. The next two policies examine the impact of alternative fiscal assumptions. In row 3 of Table 1 I assume *wasteful spending or regulation*, with half the carbon-tax revenues wastefully deployed (say, in investments with a rate of return half of that in the private sector).[5] The table shows that if half the revenues are wasted, climate programs should be abandoned. The optimal carbon tax and control rates are essentially zero.

The fourth row of Table 1 examines a more optimistic approach, *reducing burdensome taxes*, in which carbon-tax revenues are used to reduce other taxes. At present, virtually all federal taxes are levied on "goods" such as capital, leisure, or consumption. Such taxes will impose deadweight burdens on the economy because taxes will create wedges between the marginal private value and the marginal social value of goods. The exact value of the marginal deadweight loss of taxes in the United States is controversial, but some have estimated it as high as $0.50 per $1.00 of revenue. Case 4 assumes that the initial carbon tax has no deadweight loss; that carbon-tax revenues are returned in a manner that reduces burdensome taxes; and that the burdensome taxes have a marginal deadweight loss of 0.3 (i.e., for every extra dollar of revenue, there is an additional deadweight loss of 30 cents).

The surprising result of this experiment is that the gain from the efficient use of green taxes is quite substantial. The optimal control rate rises from 8.8 percent to 32 percent, and the optimal carbon tax rises from $5.24 per ton to $59 per ton in the first decade. At current levels of GHG emissions from the United States, this represents a base emissions of about 2.39 billion tons of CO_2 equivalent; with the tax rate and emissions reductions in this example, carbon-tax revenues would be $97 billion per year. Because of the enhanced efficiency of the tax system, this run has a net annualized gain of around $200 billion annually.

Figure 1 shows the components of the result for the United States for the 1990's. The net effect equals the climate gain minus the cost plus some fraction of the revenues. The peak of the carbon-tax Laffer curve (not shown) comes at a tax of over $200 per

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[5] For example, it seems likely that controls will be more tightly imposed in high-income countries than in poorer countries. Another example is the use of "environmental adders" in regulation of electrical generation in the United States, where companies may be required to impute a cost to GHG's in making their investment decisions, whereas no imputation is required outside these decisions.

ton. In case 4, with a deadweight gain of 30 percent of the revenues, the solid line shows the net gain as a function of the control rate. The importance of revenue recycling is surprising and striking. These findings emphasize the critical nature of designing the instruments and use of revenues in a careful manner. The tail of revenue recycling would seem to wag the dog of climate-change policy.

In conclusion, it must be emphasized that the present analysis has a number of qualifications. A central concern is that the damage function, particularly the response of developing countries and natural ecosystems to climate change, is poorly understood at present. Furthermore, the calculations omit other potential market failures, such as ozone depletion, air pollution, and R&D, which might reinforce the logic behind greenhouse-gas reduction or carbon taxes. Finally, this study abstracts from issues of uncertainty, in which risk aversion and the possibility of learning may modify the stringency and timing of control strategies. Notwithstanding these qualifications, the optimal-growth approach may help clarify the questions and help identify the scientific, economic, and policy issues that must underpin any rational decision.

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