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Costs of Reducing Global Carbon Emissions

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Projecting the costs of reducing carbon emissions is extremely important, and exceedingly difficult. Such projections are an integral component of cost-benefit analyses of alternative policies; for example, for the global climate policy analysis described by William Nordhaus in this symposium. Moreover, the nature of the climate change problem dictates that costs be incurred long before benefits can be realized or accurately measured. Consequently, the political spotlight predictably focuses on the cost estimates whenever specific policy options are contemplated.

Projecting the costs of reducing carbon emissions is difficult because many assumptions must be made about how the world will evolve over a very long period of time with and without a control program. Typically, some of these assumptions, like population growth, are taken from outside sources. Other factors, like the response of energy demand to changes in economic output or energy prices, are the result of modeling the behavior of economic actors in response to exogenous stimuli. Considerable uncertainty exists about both the exogenous factors and the best way to model the behavioral responses.

The global nature of the climate change problem adds yet another complication to the cost analysis. Scientists have concluded that it is the global concentration of carbon in the atmosphere that influences climate. Moreover, since carbon in the atmosphere gets mixed more or less uniformly, emissions anywhere change concentrations everywhere, but with a long lead time. Current global carbon emissions are estimated to be only about 4 percent of the stock of CO_2 in the atmosphere attributable to human activity (and about

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1 percent of total atmospheric carbon). Thus, the cost of reducing global carbon concentrations depends on the collective emissions of all the countries of the world over long periods of time. This makes an analysis of the costs of controlling emissions in any one country or region at any point in time an important guide to appropriate policies for that particular country, but an incomplete one.

For the purposes of surveying a number of assumptions and models, the recently completed Energy Modeling Forum 12 study entitled "Controlling Global Carbon Emissions; Costs and Policy Options," which included a comparison of results from 14 models for 13 standardized scenarios, is helpful in this endeavor (Gaskins and Weyant, 1993a, b). A number of more specialized study groups were also organized during EMF 12 to study dimensions of emissions control policy not considered in the original study design. In total, results from 16 models were included in EMF 12, and over two dozen control scenarios were considered. In addition, several other major studies completed over the last three years are relied upon in developing our conclusions here, in particular the excellent surveys by Nordhaus (1991), Congressional Budget Office (1990), Beoro, Clarke, and Winters (1991), Cline (1992), and Dean et al. (1993).

An important limitation of the existing studies, including those represented in EMF 12, is that they focus almost exclusively on reducing carbon dioxide emissions, and include very little detail on the developing countries. Although carbon dioxide is the most important greenhouse gas, reductions in emissions of other greenhouse gases like methane may ultimately prove more cost effective (Blitzer et al., 1992; Schmalensee, 1993).

Many models are now available for studying emissions reductions in the United States and other OECD countries, and a growing number of global analyses offer some regional detail. In the global studies, however, developing countries are typically treated in a simplistic fashion, or aggregated together because of lack of appropriate data and institutional information for the countries involved, or computational limits on model size. A number of developing countries (including China, India, Brazil, Egypt, Nigeria, Indonesia, and others) have substantial emissions at present and/or emissions levels that are likely to grow rapidly during the first half of the next century. This has led to the development of models that can provide a more realistic picture of the potential for emission reductions in these individual countries (Blitzer et al., 1992, 1993; Pachauri and Khanna, 1992), and valuable insights for the global models.

The next section of this paper discusses the key dimensions of any projection of the cost of reducing carbon emissions. The paper then discusses the projections that have been made, including long-, medium- and short-range time horizons. Finally, the conclusion summarizes what we know and don't know about the costs of controlling carbon emissions and recommends an agenda for future research.

Key Determinants of Cost of Control Projections

Hundreds of projections of the cost of reducing carbon emissions have been published over the past decade, a pace that seems likely to continue. Each projection has four key elements: (1) the baseline input assumptions to the analysis; (2) the specification of the control scenario being considered; (3) the structure of the model employed to make the projection; and (4) the cost measure(s) reported. Knowing a few basics about how these elements are handled in a particular study can go a long way towards helping one understand how its results relate to other available projections.

Baseline Input Assumptions

The assumptions included in the baseline scenario are important because the incremental cost of carbon emission controls are measured relative to them. Any analysis of the cost of reducing carbon emissions must rely on input assumptions in three areas: population and economic activity; energy resource availability and prices; and technology availabilities and costs.

Most of the groups projecting the costs of reducing carbon emissions have relied on population and economic assumptions from other groups. The worldwide population growth projections are commonly from demographic models of the World Bank or the United Nations. For economic assumptions, such studies generally rely on economic growth projections made by others, or on external assumptions about labor force participation, and productivity growth. For either population or economic growth, there is less uncertainty about projections for the developed countries than for the developing countries. Birdsall (1992) offers a discussion of the dependence of the results of global warming analyses on population projections.

A second key set of input assumptions to the models concerns the price and/or availability of energy resources. The prices of fossil fuels like oil, natural gas, and coal tend to be important because they are what generally need to be substituted away from when carbon emissions are restricted. Since gas combustion produces about 60 percent of the carbon produced by coal combustion and 80 percent of the carbon produced by oil combustion per unit of energy consumed, optimistic assumptions about natural gas availability can make carbon emissions targets easier to achieve in the short run. Another key dimension of the energy supply picture is the assumption made about the response of the oil exporters to the imposition of a carbon tax or other policies that reduce the demand for oil imports.

A final set of key assumptions about inputs are those made about the costs and efficiencies of current and future technologies, both for energy supply and energy use. Most analysts use a combination of statistical analysis of historical data on the demand for individual fuels, and a process analysis of individual technologies in use or under development to represent trends in energy technologies. At some point these two approaches tend to look quite similar though, as the end-use process analysis usually runs out of new technology concepts after a couple of decades, and it is then assumed that the efficiency of the most efficient technologies for which there is an actual proposed design will continue to improve as time goes on. Particularly important, but difficult, here is projecting technological progress. Attempts to estimate empirically the dependence of future trends in productivity on factor prices, including energy, are rare. Jorgenson and Wilcoxen (1991) present one prominent attempt to do so.

In the long run, the assumptions made about the cost of substitutes for conventional oil and gas determine the cost of controlling carbon emissions. It is generally assumed that the long-run carbon-based fuel alternatives (for example, coal generated electricity and coal-based liquid synthetic fuels) will be less expensive than non-carbon alternatives (like solar-generated electricity, and liquid fuels made from biomass). If this were not the case, there would be no projected long-run costs of controlling carbon emissions.

Existing emissions controls on fossil fuel combustion, like those on sulfur dioxide included in the U.S. Clean Air Act and its amendments, are represented in the models via their projected impact of fuel choice trends, or by using higher costs for technologies that emit sulfur dioxide in the process analysis approach. Representing these costs can be an important element of the baseline scenario because coal use generally leads to high sulfur *and* carbon emissions. Thus, restricting sulfur emissions can lead to some reductions in coal use and, hence, carbon emissions.

Control Scenario

A control scenario translates a carbon emission control program into model inputs. Several dimensions of the control scenario considered are important. First, the control program must specify a goal, which can be an annual carbon emissions target, an atmospheric CO_2 concentration limit, a rate of carbon taxation, or some combination of these elements. The goal must also include a rate at which the objective is to be achieved—because of the time required to replace energy-producing and -consuming capital equipment, it may be easier to reach a more stringent annual emissions target over a longer period of time than a less stringent one over a shorter period of time.

The instrument to be used to achieve the objective must also be specified. For example, an emissions target may be met via a carbon tax, an emissions permit trading system, energy efficiency standards, or a variety of other policies. For control scenarios involving carbon taxation, some assumption needs to be made about the use of the revenues generated, and about the tax treatment of imports of energy and energy intensive products.

A final crucial element of the control program is the allocation of the allowable emissions among countries or regions. Since developing countries are poorer to begin with and likely to grow faster than the developed countries, they will probably not agree to proportional cuts in emissions by all countries.

The paper by James Poterba in this symposium offers an excellent discussion of "North-South" negotiations.[1]

Model Structure

The models considered here can be classified into six distinct classes, depending on the way the relevant markets are represented. The first three categories are *energy-economy models*: the distinguishing feature of such models is that they treat the energy sector in a more aggregate fashion than the energy models, and instead contain much more detail on markets and/or agents in the rest of the economy or economies. The other three categories are *energy models*, which focus on the various markets for energy—fossil fuels, renewables, electric power, and refined fuels—and on specific energy conversion and/or end-use technologies. They treat the rest of the economy in a more aggregated fashion. (See Beaver, 1992, for a more detailed structural comparison of the EMF 12 models.)

The salient characteristics of each class of model are summarized in Table 1, along with examples of models that are included in each class, the time horizon considered, the amount of foresight assumed, and whether the behavioral parameters included in the model are empirically or judgmentally determined. None of the models considered here incorporates uncertainty about future events in representing decision-making by individual participants in the economy.

One distinction of importance in the three energy-economy approaches lies in the level of disaggregation of the non-energy sectors. Both disaggregated and aggregated economic equilibrium models allow investment levels to be chosen endogenously. However, the disaggregated equilibrium models consider markets by industry category, and allow GDP to be determined, in part, by these interindustry interactions. The aggregate equilibrium models, on the other hand, usually include markets for broad sectors like capital, labor, and energy, and determine GDP with an aggregate production function. The main advantage of the disaggregated approach is that it allows a closer look at non-energy markets; the main advantage of the aggregate approach is that it allows more detail in looking at energy markets.

The disaggregated energy-economy models can be further subdivided into long-run growth and short-run macroeconomic adjustment variants. The macroeconomic adjustment models include multiple sectors and explicitly represent the processes by which unemployment and inflation are created and influence the level of economic output.

In the three classes of energy models—energy-sector equilibrium, optimization, and energy demand simulation models—the major distinction is the manner of modeling prices in the energy sector. An energy-sector equilibrium model examines simultaneous equilibria in all energy sector markets: fossil fuel, renewable energy, electricity, and so on. Contrary to the first three model

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[1] See also Chichilnisky (1993).

Table 1

Model Types and Distinguishing Characteristics

Market Representation	*Model Author(s)*	*Scope*	*Time Horizon*	*Fore-sight*	*Param*
Disaggregated Economic Equilibrium	CRTM (Carbon Rights Trade Model) Rutherford (1992)	World	2100	M	J
	DGEM (Dynamic General Equilibrium Model) Jorgenson/Wilcoxen (1991)	U.S.	2050	P	E
	GOULDER Goulder (1993)	U.S.	2030	P	J
	GREEN (General Equilibrium Environmental) Burniaux/Martin/Nicoletti/ Oliveira-Martins (1991)	World	2050	M	J
Disaggregated MacroEmetric Adjustment	DRI McGraw-Hill Brinner, Shelby, Yanchar, Christofaro (1992)	U.S.	2010	M	E
	LINK Kaufman/Li/Pauly/Thompson (1991)	World	2010	M	E
Aggregate Economic Equilibrium	CETA (Carbon Emissions Trajectory Assessment Model) Peck/Teisberg (1992a)	World	2100	P	J
	GLOBAL 2100 Manne/Richels (1992a)	World	2100	P	J
Energy-sector Equilibrium	GEMINI Decision Focus, Inc. (1990)	U.S.	2030	P	J
	FOSSIL2 AES Corporation (1990)	U.S.	2030	M	J
	GLOBAL MACRO ICF, Inc. (1988)	World	2100	M	J
	ERM (Edmonds-Reilly Model) Edmonds/Reilly (1985); Edmonds and Barns (1991)	World	2095	M	J
	MWC (Model of Warming Commitment) Mintzer/Schaper (1992)	World	2095	M	J
	EDS (IEA Energy Demand System) International Energy Agency (1991)	World	2005	M	E
Energy-sector Optimization	MARKAL (MARket ALlocation Model) Morris/Solomon/Hill/Goldstein (1990)	U.S.	2025	P	J
Energy Demand Simulation	T-GAS (Trace Gas Accounting System) Piccot, et al. (1990)	World	2010	M	E

Key: M is myopic; P is perfect; J is judgmental; E is econometrically estimated.

types, this type of model does not include any markets for non-energy goods. These models generally offer a regional analysis of the nation or globe, along with great detail on energy technology.

The objective of an energy-sector optimization model is minimization of total U.S. energy sector costs, given the demands for energy services from the rest of the economy. Although this optimization approach contains within it an implicit equilibrium, it does not actually use explicit market prices. This approach usually allows energy use to be reduced only through the introduction of more efficient technologies, and employs a great deal of detail about such technology. However, it does not examine economic effects outside the energy sector—even questions like what effect higher energy prices would have on the quantity of energy demanded.

The energy demand simulation approach uses projections of energy prices and economic activity, together with econometrically estimated parameters representing the behavioral response of industry and consumers to these factors, to estimate how much energy will be consumed. This approach has no explicit representation of supply, and thus does not model an explicit equilibrium in energy markets.

Two other features of the models are important in understanding and assessing differences in model projections: the assumption made about the foresight employed by economic agents in making decisions, and the source of key parameters employed in representing economic behavior. In some models it is assumed that economic agents base current consumption, production, and investment decisions on current prices only (myopic expectations), while others assume that they base these decisions on perfect information about the price projections produced by the model.

The substitution parameters used in the models are either judgmental (although generally calibrated to the available empirical literature in some way) or econometrically estimated with historical data. Reflecting the typical practice of including only a limited number of aggregate parameters whose values can easily be changed in sensitivity analyses in them, the models with judgmentally determined parameters are sometimes also referred to as "parametric" models.

Cost Measure

The cost of carbon emission reductions are reported using at least four alternative cost measures: (1) the *carbon tax* required, which measures the marginal cost of the last ton of emissions reduced; (2) the *total direct cost*, which measures the marginal cost of the reductions integrated over all emissions reductions; (3) the loss in *gross domestic product* (GDP), which measures the reduction in the total goods and services produced by the economy, and thus may include the impact of the carbon emission reductions on capital accumulation and technological progress, and (4) *compensated income variation*, which measures how much consumers would have to be compensated to make them as well off in terms of their own utility after the imposition of the emissions reduction program as in the baseline scenario. Not all models can produce results for all cost measures, which further complicates comparisons. For example, energy sector models cannot produce compensated income variation results (since they do not examine the broader economy in that way), and the total direct cost is generally not reported by general equilibrium modelers. These measures tend to move together, but departures from this general rule can be significant. For example, general equilibrium models may project lower carbon taxes required to achieve an emissions target, but greater GDP losses than energy sector models if they include a strong negative influence of higher energy prices on economic growth. This lowers baseline emissions, but increases the share of emissions reductions that comes from lower economic growth rates rather than reductions in energy intensity or fuel switching.

Along with the problem of measuring the cost of emissions reductions along different dimensions, cost measures are often discussed according to their time frame. The next section of this paper discusses "long-run" costs, defined as those costs which remain after a transition to primary reliance on non-fossil fuel sources of energy can be completed. The following section will address "short-to-intermediate-run" costs, which occur until that transition is completed. Both sorts of costs are likely to be important to policy-makers. Although the total annual costs of carbon emission reductions are generally projected to be higher in the long run, the marginal costs of control can be higher in the short run. In addition, the relative importance of short- and long-run costs depends on the rate at which future costs are discounted, which is an ongoing debate as mentioned by Richard Schmalensee in his introduction to this symposium. Throughout the discussion here, the goal is to describe results that appear to be robust across all sets of input assumptions and models, and when the results differ, to figure out why.

Long-Run Cost Projections

The transition period to a low-carbon world is likely to take 40 to 60 years, even if it started today. This results from the long life of energy-producing and -consuming capital stock, and the long lead time required to develop, refine, and phase in new carbon-free technologies. Every carbon emission control study must come to grips with this fact.

Common Conclusions

Three major general conclusions can be drawn about the cost of controlling carbon emissions in the existing long-run economic studies, defined here as those extending beyond 2040: controlling global carbon emissions over this time horizon will require a significant amount of international cooperation; if such cooperation can be achieved, a control program that is phased in gradually need not slow world economic growth appreciably, but will be expensive in absolute terms; and a system of international emissions trading can improve the efficiency of a global control program and significantly reduce its cost. Each of these points is explored in turn.

A significant amount of international cooperation will be required to control carbon emissions in the long run. Manne and Richels (1992a) observe that it will probably be impossible to limit global carbon emissions to 1990 levels by the middle of the next century if China does not participate in the control program—even if *all* other countries reduce their emissions to zero! Although China is responsible for only about 11 percent of global carbon emissions today (650 million tons out of world total of 6 billion tons) that percentage is expected to grow as the Chinese economy develops and uses its substantial coal reserves as part of that development process. If carbon emissions in China grow at 4 percent per year, which is not a particularly high baseline projection, in 56 years the emissions in China alone will equal total world emissions today. Efforts to limit global carbon emissions may start with the developed countries, but they cannot end there.

The costs of stabilizing global carbon emissions appear likely to be in the range of about 4 percent of GDP per year by the year 2100. For example, consider four key control scenarios from the EMF 12 study. Each includes participation by all major carbon emitters. In the "Stabilize Global Emissions" scenario, the countries of the OECD and the former Soviet Union are assumed to reduce emissions by 20 percent relative to 1990 levels by 2010 and maintain them at that level through 2100, while the rest of the world is restricted to increasing their emissions by no more than 50 percent relative to 1990 levels through 2100. This allocation of emissions rights leads to global emissions in 2010 and thereafter that are no greater than those in 1990. In the "Reduce Global Emissions" scenario the OECD and former USSR reduce emissions by 50 percent relative to 1990 by 2050, and the rest of the world is again limited to no more than a 50 percent increase relative to 1990 levels; this leads ultimately to about a 15 percent reduction in global carbon emissions. In the "Slower Growth in Global Emissions" scenario, the developed countries limit emissions to 1990 levels by 2000 and the developing countries are again limited to no more than 50 percent more than today's emissions levels, resulting in about an 18 percent increase in global emissions relative to 1990. Finally, the "Phased-In Tax" scenario includes a carbon tax imposed by all countries that increases from $15 per metric ton of carbon in 1990 at 5 percent per year. This is approximately the tax trajectory that would result from limiting *cumulative* world emissions over the next 50 years to 50 times 1990 emissions.

By the year 2040, all four scenarios would cause the world GDP on average to drop by about 2 percent of GDP per year, plus or minus half a percent. By 2100, they would reduce global GDP by 4 percent per year, plus or minus 1 percent. However, all of these scenarios represent a significant departure from the historical trend in carbon emissions. The baseline projection, without any of these policy changes, is that carbon dioxide emissions will have doubled by 2040, and increased by a factor of nearly six-fold by 2100. The "Phased-In Tax" scenario would reduce emissions rather sharply by the year 2100, while the other three scenarios would keep carbon emissions within about 20 percent of their present level over the next century.

The cost of a long-run global carbon emissions control program designed to limit emissions to their 1990 level (about 6 billion metric tons), is projected to be about 2.5 percent of world GDP by the year 2043, plus or minus 1 percent. If world GDP were projected to grow at 2.3 percent per year over the next 50 years in the absence of a control program, a control program phased in over that period would only lower that growth rate to 2.25 percent per year. Thus, if climate change turns out to be a very serious problem, it can be controlled without eliminating or even noticeably reducing long-run economic growth. On the other hand, 2.5 percent of the almost $90 trillion dollar world economy in 2043 (in 1990 dollars) would amount to about $2.25 trillion dollars per year (2.5 percent of current world GDP is over half a trillion dollars). Given other pressing world problems, this sum represents a substantial long-run commitment of societal resources.

These cost estimates have so far generally assumed that the emissions reductions are achieved efficiently in each region as, for example, through the use of a tax on the carbon content of fossil fuels. Given institutional constraints in both the developed and developing countries, this assumption may ultimately turn out to be overly optimistic, but the results obtained for the carbon tax cases provide useful benchmarks on what might be achievable.

A growing number of analysts have studied the potential for international trading of emissions rights to reduce the cost of a global carbon emissions control program. In such a program, one country can pay for emissions reductions in another country, if that is less expensive than the available domestic options. In EMF 12, an emissions trading program was considered relative to the global emissions stabilization scenario, where the initial allocation of emissions rights is 20 percent lower than current emissions for the developed countries and 50 percent more than current emissions levels for the developing countries. Results from four models show that this strategy can reduce the costs of control by one-third or more, by equalizing the marginal cost of control across all nations.[2] Allocation of emissions rights by population or GDP per capita would lead to even greater benefits from international emissions trading (Yamaji and Okada, 1992; Edmonds et al., 1993). At some point, the technology of energy production and use may become homogeneous enough to eliminate these advantages, but until that point an international emissions trading program will be worth serious negotiating efforts; in fact, it may be the only way to solve the participation problem noted above.

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[2] For example, the four models included in EMF 12 that attempted the International Emissions Trading Scenario—ERM, OECD-GREEN, Global 2100, and CRTM—project a decrease of 30 percent to 40 percent in the initial cost of Stabilize Global Emissions scenario with trading with respect to the no trading case.

Significant Differences in Assumptions and Models

Although the long-run cost of controlling carbon emissions seems fairly similar in many published studies, there are some differences as well. First, the estimated cost of reducing emissions to achieve any CO_2 emission or concentration target depends on the baseline emissions projection of carbon emissions, which in turn depends on the projected rates of economic growth, income elasticities for energy demand, and rates of non-price induced shifts in energy efficiency. Second, the degree to which "backstop" technology assumptions—advanced technologies with high cost and unlimited supply—are employed has a large impact on the cost of control estimates. Third, in lieu of backstops, some analysts use resource supply curves with large flat segments at higher prices, and differences in these assumptions can be significant. Again, each of these three points will be examined in turn.

Most long-run projections of the costs of controlling carbon emissions foresee a major role for coal in the future baseline energy mix, and since coal is abundant on a global basis, this assumption limits future energy price increases. As a result, the major determinants of long-run energy demand turn out to be population growth, economic growth, the income elasticity of demand for energy, and the non-price-induced rate of change in energy demand per unit of economic output. Very few modelers make their own projections of long-term worldwide economic growth, worldwide income elasticities, or long-term energy efficiency trends. Thus, most researchers rely on the few estimates that are available, most of which are for just the United States or the other members of the Organization for Economic Cooperation and Development (OECD).

Even when the assumptions about GDP growth rates are standardized, a wide range of reference case emissions projections are produced by the models. By the year 2100, projections of world CO_2 emissions from eight different models range all the way from a tripling to a seven-fold increase over 1990 levels.[3] The reason for this variation is simple enough: relatively small differences in model parameters lead to large differences when their effects are compounded over more than a century. Much of the difference in projections from the models for 2100 can be explained by differences in the assumed rate of decrease in energy use per unit of economic output independent of energy price changes. The Global 2100 model uses a value of .5 percent per year for this parameter, while the Edmonds-Reilly model employs 1.0 percent per year assumption. This single difference explains virtually all of the nearly factor of two difference in the baseline emissions projections from these two models in 2090 (Dean et al., 1993; Gaskins and Weyant, 1993b). The more disaggregated assumptions made in the Global Macro model imply about a 1.25 percent rate of decrease in energy use (per unit of output). Estimates of this aggregate parameter based on historical data range from a rate of decrease of about .5 percent per year to an *increase* at about that rate (Jorgenson and Wilcoxen,

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[3] The eight models are ERM, Glob-Macro, Global 2100, OECD, IEA, CETA, MWC, and CRTM.

1991; Manne and Richels, 1992a). Researchers who have attempted to extrapolate the types and efficiencies of energy-using equipment into the future have argued that the potential exists for a rate of decrease in energy use per unit of economic output from 1 percent per year to over 2 percent per year without any increase in energy prices.

Some analysts use the backstop technology concept (introduced by Nordhaus, 1973) to represent the idea that at a high enough price for energy, one or more technologies will combine to provide a virtually unlimited supply of energy. The inclusion of such technologies puts a cap on the ultimate cost of carbon emissions reductions. In fact, Manne and Richels (1990), who include both a carbon-based backstop (like synthetic oil from coal) and a carbon-free energy backstop (like synthetic oil from biomass) in their analysis, have observed that the long-run carbon tax in such a set-up can be calculated on the back of an envelope, as the difference between the costs of the carbon-free and carbon-based backstops divided by the carbon emissions rate of the carbon-based backstop.[4]

Analyses that do not include backstop technologies per se generally include long-run supply curves for carbon free resources that become very flat at high cost levels. The resources included and extent of high-cost carbon-free resource availability vary from one analysis to another, but each serves to limit the long-run cost of carbon emission reductions.

Short-to-Intermediate Run Costs

In the short-to-intermediate run, the economy must face the costs of transition away from primary reliance on carbon-based energy. Again, some commonalities among the results of these transition studies are reviewed, and then some differences.

Common Results

Several common themes emerge from a review of the cost of control projections for the short-to-intermediate term. First, if the emissions target requires moving faster than the natural rate of capital stock turnover and technology development, significant additional adjustment costs are likely to be incurred. Second, recycling the revenues obtained from carbon taxation in a way that reduces less efficient ways of raising government revenues can significantly reduce the net cost of the control program. Third, if some major carbon emitters fail to participate in the control program, the downward pressure on oil prices and the supply of carbon-intensive goods in the participating coun-

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[4] For example, in EMF 12 a carbon-based non-electric backstop costing \$50/BBL, a non-carbon non-electric backstop at \$100/BBL, and a carbon emission for the carbon-based backstop of .24 metric tons carbon/barrel oil were specified. Thus, the long-run carbon tax produced by the Global 2100 model is (\$100–\$50)/.24 = \$208/metric ton carbon.

tries will cause increases in carbon emissions by non-participants relative to their baseline levels, somewhat offsetting any gains.

Studies of the cost of controlling carbon emissions show that incremental reductions in allowable emissions cost more as the absolute level of allowed emissions in any particular year is reduced. This finding is especially true in the short- and intermediate-run, up to about 2040, before old fossil-fuel based energy producing and consuming equipment can be fully retired and new carbon-free technologies can be fully introduced. For example, in EMF 12 the cost of stabilizing U.S. carbon emissions (reducing them an average of 30 percent relative to the no control baseline) ranged from .2–.75 percent of GDP in 2010, while the cost of reducing emissions by 20 percent in that year (or an additional 15 percent relative to baseline emissions on average) range from .9–1.7 percent of GDP. In other words, a 20 percent additional reduction in emissions relative to 1990 levels (and, on average, a 15 percent reduction relative to 2010 baseline emissions) could more than double the cost.

Existing studies also demonstrate that trying to reach fixed emissions targets faster—say by 2010 rather than 2040—imposes significant additional adjustment costs. Short- to intermediate-run carbon tax projections from the models that significantly exceed their long-run levels provide the most dramatic evidence of situations where these additional adjustment costs are likely to be incurred.[5] This result is observed in results from models that take a long-term perspective; it is still larger in the medium-term models that try to track year by year energy-using and energy-producing capital stock adjustments over the next 20–40 years; and amplified still further in the short-run econometrically estimated demand models that focus primarily on projecting energy demand over the next 5–15 years. These adjustment costs result from a combination of empirically and judgmentally estimated adjustment rate parameters, as well as actual data on existing technologies and capital equipment in place. Despite the heterogeneity in modeling approach adopted, each leads to a projection that substantial adjustment costs are likely to be incurred in this scenario. Extensive sensitivity analyses by Petersen et al. (1992) show that even a ten-year delay in the date by which the global stabilization target must be achieved can reduce the peak in the carbon tax projections dramatically. In addition, Manne and Richels (1992b) show that the peak is virtually eliminated in Global 2100 model by limiting total emissions over a 50-year time period to fifty times the 1990 levels, and letting the model decide when the emissions should occur to maximize the discounted utility of consumers. This optimization results in more emissions than required to stabilize annual emissions in the short run, and less emissions than required to stabilize annual emissions in the long run.

[5] In EMF 12, the average carbon tax required to reduce U.S. carbon emissions in 2010 to 20 percent below their 1990 level is about $350 per metric ton, while the same goal can be achieved in 2050 with an average carbon tax of slightly over $200 per metric ton.

If a carbon tax is used to reduce emissions, the way in which revenues from that tax are used has an important impact on the projected GDP loss. Models that do not explicitly represent the tax system often assume tacitly that the revenues simply accrue to the government, with no particular incentive affects, like the revenue from a lump sum tax. However, carbon tax revenues could be used to reduce existing taxes that discourage economic activity, particularly capital formation. This is not a prescription to overhaul fiscal policy to minimize the impact of a carbon tax on the economy, but a more general observation regarding the relationship between taxation and economic growth. It emerges in the carbon emission control context because it helps explain differences in model results and identifies the way in which carbon tax revenues are recycled as an important consideration in evaluating them as a potential policy instrument. As part of the EMF 12 study, simulations with four models of the U.S. economy (DRI McGraw-Hill, LINK, DGEM, and Goulder) indicate that from 35 percent to as much as 100 percent of the U.S. GDP losses for the phased-in carbon tax could ultimately be offset by recycling revenues through cuts in existing taxes (Shackleton et al., 1992). On the other hand, if the revenues are used to fund low return government projects, the cost of achieving the carbon emission reductions could be substantially *greater* than when they are recycled in lump sum fashion (Nordhaus, 1993).

If the OECD or any other group of countries unilaterally implements a carbon reduction program, resulting changes in international energy prices will cause carbon emissions in other countries to increase relative to baseline levels (Rutherford, 1992; Nicoletti and Oliviera-Martins, 1992; Horton, Rollow, and Ulph, 1992; Rutherford et al., 1992). Increased carbon emissions by non-participating regions occur both as a result of increased energy intensity of economic activity domestically (that is, through the use of more energy intensive production processes and demands for more energy intensive products) and through the migration of energy-intensive production into unconstrained regions. Carbon restrictions place countries who control at a competitive disadvantage in energy-intensive industries. Thus, the cost to countries who control emissions increases with the level of cutback, but the impact on global emissions may drop off sharply if large groups of countries fail to cooperate. In comparing model results, we will generally assume universal participation because that is what most existing studies have assumed. Edmonds et al. (1993) and Nicoletti and Oliviera-Martins (1992) also consider some of the implications of partial participation on control costs.

Significant Differences

The most significant differences in short-to-intermediate term cost projections result from differences in the rate of achieving emission targets, introduction rates for new technologies, and retirement rates for existing facilities; economic growth projections; the treatment of pre-existing taxes on energy and on other inputs to the economy; and assumptions about natural gas availability and price.

If a fixed annual emissions rate target is specified, cumulative costs can be reduced with some increase in short-term emissions either by allowing more time for reaching the target, or by phasing in more gradually the instrument(s) used to achieve the target (like a carbon tax). The cost reduction can be particularly significant if the target date and rate of implementation are set to allow new carbon-free technologies to be phased in smoothly. The timing issue has been explored through extensive sensitivity analysis by Petersen et al. (1992) and Manne and Richels (1992b). Similar issues involving the rates of technology introduction and retirement have also been explored through sensitivity analysis by Petersen et al. (1992).

Different projections of economic growth can lead to different estimates of carbon control costs. The EMF 12 study design includes a 2.2 percent growth rate in GDP for the U.S. over the next 30 years. However, one of the models included in the study (DGEM) produced an independent GDP projection of 1.4 percent per year over that time frame (for a description of the methodology employed see Jorgenson and Wilcoxen, 1991, 1992). The lower growth rates result in lower carbon taxes being required to meet any particular emissions target. Interestingly, though, the computed GDP losses from such carbon taxes are not significantly less than in the other models, because higher carbon taxes lead to higher energy prices, which significantly diminish capital accumulation and productivity growth.[6]

Models that include preexisting energy taxes generally require a larger increase in energy prices and, therefore, a higher carbon tax to reach a fixed emissions target (for example, Kaufman, 1992). In countries with higher existing energy taxes, a larger carbon tax must be utilized to achieve a given percentage increase in retail energy price levels. Moreover, most models exhibit increasing marginal costs of energy demand reductions with respect to decreases in the level of energy demand. In addition, Goulder (1993) has observed that general equilibrium models can include preexisting taxes on all factors of production which results in carbon taxes being more costly to the economy. Carbon taxes lead to less energy use which makes other factors less productive, but if these factors are already taxed, the marginal productivity loss will be greater than if there were no preexisting taxes on the other factors. In effect, a carbon tax operates as an implicit factor tax; higher preexisting taxes elsewhere increase the propensity of the carbon tax to generate further distortions in factor markets. This effect also serves to blunt the effectiveness of

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[6] The lower GDP growth rate was adopted for a "Low GDP Growth" sensitivity scenario. This scenario does lead to a significant reduction in the cost of control because it directly reduces the reference level of emissions projected by each model. In addition, when all the models are run with the low GDP growth rate assumptions, they produce carbon taxes that are more closely consistent with those projected by the lower growth models.

revenue recycling as a means of reducing the net costs of imposing a carbon tax to reduce carbon emissions.

Finally, the cost of the transition to the non-carbon-based energy technologies can be significantly affected by the availability of natural gas resources. Since natural gas has a lower carbon emissions rate than oil or gas, more fossil energy can be consumed within any emissions constraint if the use of natural gas can be increased. The "High Natural Gas Resources" scenario included in EMF 12 postulates a quadrupling of natural gas resources in each region, an optimistic assumption that thus gives an upper bound on the importance of this factor. In any event, this assumption does lead to a 30 to 40 percent reduction in the discounted cost of stabilizing emissions over the next 20 years.

Conclusions and Directions for Future Research

Regardless of one's view on the magnitude of the global climate change problem and preferred carbon emissions control objective, two things appear to be paramount in any attempt to minimize the cost of any control program—international cooperation and time for existing energy-related facilities to be retired and for new technologies to be phased in. A carefully designed revenue recycling program and set of trade policies can also reduce the costs of the control program significantly. The long-run cost of stabilizing global carbon emissions at 1990 levels appears to be about 4 percent of world GDP per year (plus or minus 1 percent). Although this cost is very high in absolute terms, it implies only a minor reduction in the rate of economic growth if the control program is phased in gradually. On the other hand, if policy were to focus on some convenient but arbitrary earlier goal—like stabilizing or decreasing emissions rates by 2000 or 2010 relative to 1990 levels—the increase in costs could be substantial.

Given the timing and coordination issues discussed here (involving coordination with fiscal and trade policies, as well as with control programs in other nations), a look at the cost side of the equation suggests the advantages of a more gradual control policy, unless the damages resulting from the small amount of additional emissions over the next half century can be argued to be worth the relatively large incremental cost of eliminating them. Reducing the growth rate of emissions might not only be beneficial itself, but also put us in a better position to control emissions more aggressively in the future, if that should become necessary.

Additional research in several areas could significantly improve our ability to understand the costs of reducing carbon emissions, and thus to evaluate alternative policy options.

1. Information about the potential for technologies that improve energy efficiency is incomplete and often inconsistent, and there is little conclusive analysis regarding their likely rate of adoption. However, this factor is a major

determinant of baseline emissions levels, a major source of differences in emissions projections between the models, and a major determinant of the cost of achieving any emissions target. Particularly important here are assessments of market imperfections or distortions that impede the introduction of more efficient technologies. For example, energy pricing in China, the developing countries, and the former Soviet Union has been far below world market levels.

2. The existing long-run population and economic projections display some considerable differences. In particular, relatively little is known about likely economic and population growth in the future in such important and diverse countries as China, India, Brazil, Nigeria, and the independent states of the former Soviet Union.

3. The adjustment costs that result from any control strategy depend on the availability and cost of energy sources that do not emit carbon. Many of these are "renewable" resources like solar or wind power. Such technologies are not currently cost-effective, but they could easily become competitive in the future—say, if carbon taxes reach $100 per metric ton. The models included in this study all represent these adjustment costs in one way or another, but often the approaches lead to markedly different results. This suggests the value of additional work on data and models of new technology availability dates and introduction rates, as well as of technology transfer to the developing countries.

4. Some possible offsets to carbon emissions are not directly part of energy production or use; for example, tree planting or slowing deforestation, or reducing other greenhouse gas emissions like methane from natural gas system leaks, coal bed seams, or ruminants. These approaches might be as effective as carbon emissions reductions in slowing climate change.[7]

5. The value of additional work on the linkages between environmental policies and international trade in energy and non-energy goods is high. See McKibbin and Wilcoxen (1992) and Manne and Rutherford (1992) for promising new work in this direction.

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[7] Herzog et al. (1993) argue that a large scale *long-run* program of carbon sequestration may not ultimately prove feasible. A small interim program could, however, provide much needed time for the world's economies to make the adjustments necessary to transition to non-carbon based energy fuels. See, for example, Callaway et al. (1993) and Richards et al. (1993).

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