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The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models

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INTRODUCTION

In response to fears about the damages global warming may cause in the future, most of the world's nations signed the Kyoto Protocol in December 1997, agreeing to cap human-induced emissions of carbon dioxide and other human-induced greenhouse gases in the United States and 37 other industrial nations beginning in 2008. At that time, they left many details unresolved. Since then, the Bush Administration has indicated it would not submit the protocol to the Senate for ratification, and the other parties have agreed to rules for implementation that will likely result in a much smaller reduction in emissions than originally envisioned by the protocol.[1] Nonetheless, the considerable volume of studies of the Kyoto agreement as originally intended may have some lessons for any future attempts to limit greenhouse gases. This paper reviews those studies in order to assess the economic cost of limiting greenhouse emissions through a system of tradable emissions permits and investigates the impact of alternative rules for trading.

Economists have used a variety of models to estimate the costs of complying with emissions caps. These models assume that a permit system would raise the cost of goods or services that cause greenhouse gas emissions when they are either used or produced. Carbon dioxide from the combustion of coal, oil and natural gas accounts for the bulk of such emissions, so prices of energy and energy-intensive goods and services would rise the most. The higher the price of such goods rose, the fewer of them people would use, until emissions were reduced to the level of the cap.

This paper surveys and synthesizes the predictions of several such economic models of the cost of meeting the Kyoto caps. The models produce a wide variety of cost estimates, depending on many factors. The most important of those factors are differences in the amount of permit trading assumed and different model assumptions about the sensitivity of energy usage to energy prices and the response of the economy to higher inflation. In some cases, differences in the assumed path of baseline emissions, the response of labor supply to the real wage, and the impact of international capital flows are also important. All models are simplifications of reality, and thus to some extent make unrealistic assumptions— often different ones in different models. However, by comparing model assumptions and results, it is possible to assess the effect of those assumptions and to adjust for them. The synthesis presented in this paper provides an integrated view that minimizes the role of unrealistic assumptions, and thus gives a clearer view of the likely economic impact of alternative rules for permit trading.

1. Congressional Budget Office, *The Economics of Climate Change: A Primer* (April 2003).

Depending on how much permit trading is allowed, a wide range of costs is possible. Based on forecasts released in 2000, gasoline prices in the United States could be 12 to 38 cents per gallon (1997 dollars) higher in 2010 than they would without emission limits, depending on trading rules. (Throughout this paper, prices are expressed in 1997 dollars. To convert 1997 dollars into 2002 dollars, multiply by 1.085.) The price of natural gas to households could be 13 percent to 42 percent higher, while the price of electricity to households could be 13 percent to 36 percent higher. Real GDP in the United States under the protocol could be 0.5 percent to 1.2 percent lower in 2010 than otherwise, while real consumption could be 0.4 percent to 1.0 percent lower. In every case, costs are smallest when no restrictions are imposed on international permit trading. (Taking account of uncertainty widens the range of estimates further.)

Although different rules for permit trading would have a large impact on the cost of emissions restrictions, they would have little impact on the environmental benefits, that is, on the reduction in global emissions of greenhouse gases. In most cases, restrictions like those specified in the Kyoto Protocol would reduce global emissions of carbon dioxide in 2010 by about 6 percent from what it would otherwise be, or from 40 percent above 1990 levels to 33 percent above 1990 levels. Only if countries could not sell their excess permits (permits from a cap in excess of baseline emissions) would the reduction in emissions be larger. Unfortunately, costs are also largest in this case. Thus, one of the key findings of this paper is that the United States would be better off the fewer restrictions there were on international permit trading.[2]

If no trading were allowed at all, costs would rise well above those in the worst case scenario for the protocol. On the other hand, if developing and newly developed nations accepted caps on emissions, essentially creating a global market for permits, costs could be reduced to half of what they would be under the best case scenario for the Kyoto Protocol.

The distributional impacts of restrictions on greenhouse emissions could be large. Such limits, if implemented through permits, would essentially transfer income from energy users to permit recipients. (If the permits are auctioned by the government and the revenues recycled as tax cuts or transfer payments, then the recipients are those people who receive the tax cuts or transfers.) To the extent that the users are the same as the recipients, there is no net redistribution. However, the amount at stake is potentially large: depending on the amount of permit trading allowed, the value of permits used in the United States would be between 0.9 percent and 2.0 percent of GDP in 2010.

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2. This finding assumes that there are no additional benefits to reducing greenhouse emissions beyond changes in global climate.

In the interest of simplicity, the models, and thus the model synthesis, leave out certain aspects of the possible costs of emissions caps. For example, most models assume that energy usage will decline in the future by the same percentage amount for a given percentage increase in energy prices as it has in the past. However, opportunities to reduce energy usage today may be either more or less abundant than in the past. In addition, the models assume that emissions can be monitored and permits transacted at no cost, and that countries do not cheat. Also, the models do not estimate how much costs could be reduced by substituting new forest growth for the most costly reductions in emissions.

The estimates in this paper are based on projections of emissions and energy prices released by the U.S. Department of Energy's Energy Information Administration (EIA) in 2000. In more recent projections, EIA has raised its forecasts of both energy prices in the United States and emissions in most signatories of the Kyoto Protocol. Those upward revisions would increase the adverse impact of the protocol on energy prices, GDP, and consumption, but also would increase the impact on emissions. However, the comparative impacts of restrictions on permit trading or of a global market for permits would be similar.

This paper looks only at the costs of emissions restrictions like those in the Kyoto Protocol and their effect on global emissions. A full evaluation of the treaty would also assess the science that underlies the claim that a significant risk of global warming exists, and the benefits of lower emissions. Such an assessment, however, is beyond the scope of this paper.

CHAPTER 1
THE KYOTO PROTOCOL

In December 1997, most of the world's nations signed a draft treaty—the Kyoto Protocol—that would limit human-induced emissions of greenhouse gases in the United States and 37 other industrial nations (listed in Annex B). Other signatories do not face any limitations under the protocol. Instead, they may undertake joint abatement projects with other industrial countries, thereby providing the latter with credit against their national limits in exchange for a fee or other compensation. The protocol enters into force 90 days after 55 signatories have formally ratified it, provided those signatories include nations that emitted at least 55 percent of Annex B's carbon dioxide in 1990. Thus, the protocol cannot go into effect unless either the United States or Russia ratifies the protocol, since those two countries accounted for about half of Annex B's carbon dioxide emissions in 1990.

Recent developments suggest that a much more limited version of this agreement may soon take effect. In early 2001, the Bush Administration indicated that it would not continue to negotiate the terms of the protocol or submit the protocol to the Senate for ratification. In November 2001, the other parties agreed to allow some credit for existing forests, effectively easing the emissions limits. The European Union and Japan ratified the protocol in 2002. As of March 2003, ratification by Russia would bring the treaty into effect within the countries having ratified it.[3]

The Kyoto Protocol covers the six main types of greenhouse gases stemming from human activity: carbon dioxide, methane, nitrous oxide, and three kinds of synthetic gases—hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. The treaty uses the "global warming potential" of each gas—a measure of its contribution to global warming—to translate the raw weight of its emissions into an equivalent weight of carbon dioxide. By convention, scientists further translate that equivalent weight of carbon dioxide into the weight of its carbon alone. For that reason, this paper reports emissions in metric tons (tonnes) of carbon (mtc).

The treaty restrictions apply to net emissions, so a country can receive credit for the carbon dioxide removed from the air by the net growth of forests that meet certain qualifications. To qualify as a Kyoto forest, a woodland must result from human intervention since 1990. However, the signatories have held widely divergent opinions as to what should count under this provision. A key point of contention has been how much credit should be given for "existing effort," or forest growth that

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3. This information, along with further details on negotiations subsequent to the Kyoto Protocol, can be found in Congressional Budget Office, *The Economics of Climate Change: A Primer* (April 2003), pp. 47-48.

would have occurred whether the protocol were ratified or not. In November 2001, the remaining parties to the protocol agreed to grant each participant a specified credit for existing effort. Granting credit for existing effort reduces both the costs and the benefits of the protocol.

For each of the countries listed in Annex B, the protocol specifies a cap on average net emissions during a commitment period. Caps have been specified only for the first commitment period—the five years from 2008 through 2012. Each country's cap for that period is an agreed percentage of its total benchmark year emissions. For most countries, the benchmark year is 1990. Some eastern European nations are given the option of using a different year, and 1995 is the benchmark year for some gases. The United States agreed to a cap of 93 percent of 1990 emissions. As a whole, the Annex B cap is roughly 95 percent of 1990 emissions.[4] The protocol does not specify caps beyond 2012.

Under the treaty, each Annex B nation receives tradable allowances, or permits, that certify the right to release greenhouse emissions up to its respective allowable total for the commitment period. The permits may be distributed any way the country chooses, and they may be bought and sold, at home or abroad. In addition, a country can receive tradable credits for verified greenhouse abatement that it realizes in a country outside of Annex B through the Clean Development Mechanism (CDM). Any permits not used or sold may be banked for use in a future commitment period.

One of the most important details left unresolved by the protocol is how much international permit trading it allows. The treaty merely states that "trading shall be supplemental to domestic actions for the purpose of meeting quantified emission limitation and reduction." The parties have never decided how much "supplementarity" should be allowed. A restrictive set of rules on trading of permits would have a major impact on the protocol's cost.

This paper assesses the potential economic costs to the United States of reducing emissions under several scenarios consistent with the Kyoto Protocol as originally negotiated. Lowest costs prevail under "ideal implementation," in which:

- no cartel manipulates permit prices for its own advantage;
- the provisions for CDM work as intended;
- no restrictions are placed on permit trading; and

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4. A cap of 92 percent of benchmark year emissions was individually and collectively agreed to by the European Union and its members: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and United Kingdom. Other countries agreeing to a 92 percent cap included Bulgaria, Czech Republic, Estonia, Latvia, Liechtenstein, Lithuania, Monaco, Romania, Slovakia, Slovenia, and Switzerland. The following list contains the other Annex B countries (and the limits they agreed to as percentages of benchmark year levels): Australia (108), Canada (94), Croatia (95), Hungary (94), Iceland (110), Japan (94), New Zealand (100), Norway (101), Poland (94), Russia (100) and Ukraine (100).

• caps apply to all greenhouse gases.

Costs rise as, one by one, these assumptions are changed. First, a cartel of former Soviet bloc nations acts to restrict permit supply. Next, the provisions of the CDM fail to work as intended. Then restrictions on each country's permit sales are added. As an alternative, restrictions are placed on each country's permit purchases. Finally, only carbon dioxide is capped; other greenhouse gases remain unregulated. This paper also assesses costs in the illustrative cases of no international permit trading and of an amended Kyoto Protocol in which all countries accept emissions caps.

CHAPTER 2
ECONOMIC MODELS EXAMINED IN THIS SURVEY

The economic models surveyed in this paper treat the economy as an interactive system. Impacts begin in the energy sector, where restrictions on emissions boost the price of energy, reducing the amount of energy used in the rest of the economy. This in turn affects businesses' investment and hiring decisions. To the extent that gross domestic product (GDP) falls in response, demand for energy declines further. Economic models are designed to capture these and other interactions among the various sectors of the economy. In that sense, they differ from purely technology-based models, which focus overwhelmingly on the energy sector.

While most of the economic models surveyed base projected responses of energy users to changes in prices on past responses, several also incorporate choices among specific technologies, especially in electricity generation. In such models, electric utilities are assumed to choose the mix of technologies that meets empirically-based demand for electricity at the lowest cost.

Eleven of the models surveyed in this paper were used during Round 16 of Stanford University's Energy Modeling Forum (EMF-16), which examined the potential economic impact of the Kyoto Protocol (see Table 2-1). Those studies are published in a special issue of the Energy Journal.[5] (That issue contains descriptions of the models.) This survey also includes the results of four other models frequently cited in discussions of the costs of reducing greenhouse gas emissions.[6]

I generally follow the Modeling Forum's convention of referring to the studies by the name of the model that each study uses. In the case of studies produced by private forecasters–DRI, Oxford and WEFA–the model is named for the institution producing the study. The Energy Information Administration (EIA) uses its own model (NEMS) for energy sector results but uses the DRI model for economy-wide results. I denote this combination as EIA. Studies prepared by the Clinton Administration and by Battelle Pacific Northwest National Laboratory both use the SGM model. These studies are referred to as SGM-Administration and SGM-PNNL, respectively.

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5. Weyant, John P., ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999).

6. Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); Standard & Poor's DRI, *The Impact of Meeting the Kyoto Protocol on Energy Markets and the Economy* (Lexington, MA: Standard & Poor's DRI, 1998); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998).

A key difference among the models is that some use a general equilibrium structure, while others use a macroeconometric structure. General equilibrium models assume that the labor market is always in equilibrium, meaning that any worker willing to work at the going wage can always find a job. In those models, monetary and fiscal policies can affect output only by changing worker productivity or labor supply. Macroeconometric models, by contrast, assume that some unemployment is involuntary. These models leave scope for policy to affect output through changes in the utilization of labor and capital. The AIM, CETA, EPPA, GTEM, JWS, MERGE, MS-MRT, RICE, SGM and WorldScan models assume a general equilibrium structure, while DRI, EIA, Oxford and WEFA use macroeconometric models. The G-Cubed model uses a hybrid of these two structures.

Not surprisingly, different models have different strengths and weaknesses. Models that make seemingly unrealistic assumptions in one sector are sometimes better than other models in representing reality in another sector. In addition, assumptions that are unrealistic to use in analyzing the impact of emissions restrictions on the macroeconomy over a ten-year horizon may produce realistic results when applied to another policy or over a longer time horizon.

The Kyoto Protocol specifies that average annual emissions during the 2008-2012 commitment period should equal specified limits, unless emissions credits are "banked" for use in later periods. Several models simply assume that the caps are for 2010, and all models assume there is no banking of permits. To ensure comparability among studies, I focus on results for 2010 and assume no banking of permits. Banking of permits would increase the impact of the protocol on energy prices during 2008-2012, but would reduce it in later years.

The study using the JWS model does not use the emissions cap specified in the Kyoto Protocol, but rather a return to 1990 emissions levels in 2010. While the properties of this model are incorporated into the model synthesis estimates, results from the study that depend on meeting its looser emissions caps are not presented.

CHAPTER 3
PERMIT PRICES UNDER THE KYOTO PROTOCOL

As originally intended by U.S. negotiators, the Kyoto Protocol would limit emissions of greenhouse gases by Annex B countries by creating a system of tradeable permits that firms would be required to hold in order to produce energy from coal, natural gas or petroleum, or to engage in any other activity that produces greenhouse gases. Whether firms purchased permits or received them without charge, the permit price would eventually be passed along to users of energy from fossil fuels and to final purchasers of any other goods or services produced by emitting greenhouse gases.[7] In the end, those higher prices would reduce demand for goods and services that produce greenhouse gases.

Several studies have used economic models to analyze the impact of a such a system of tradeable emissions permits on the economy (see Box 2-1). These models incorporate interactions between the energy sector, which is responsible for most greenhouse gas emissions, and the rest of the economy. Most of the models assume that energy users respond to changes in the price of energy in the same way that they have in the past.

The studies encompass a wide range of outcomes. Differences in outcomes stem from differences in assumptions about the implementation of the permit system, the operation of the economy, and the response of consumers and businesses to higher energy prices. In general, the fewer the restrictions on permit trading and the more sensitive energy users are to energy prices under the protocol, the lower the permit price and the smaller the impact on the economy.

Synthesizing results from several studies, permit prices under the Kyoto Protocol could range from $56 per metric ton of carbon to $178 per metric ton in 2010 (in 1997 dollars), depending on how the protocol was to be implemented.[8] (Appendix B explains how the synthesis results were constructed.) Uncertainty about the size of consumer and business responses to higher energy prices raises the range to $41 to $226 per metric ton of carbon (mtc). Those estimates assume that permits could be traded among industrial countries in Annex B and that the protocol was effective

7. Even if a business received permits free of charge, it would still set prices as if it had paid for the permits. By using the permits, the business foregoes the revenue it could have received from selling the permits, and it will charge its customers a higher price to cover this foregone opportunity.

8. To translate permit prices into more familiar terms, 426 gallons of gasoline contain a metric ton of carbon, so each $100 rise in permit prices adds $100 per 426 gallons, or 23.8 cents per gallon, to the price of gasoline. The actual increase in gasoline prices will be somewhat smaller, because crude oil prices and refining margins will fall. For further details, see the section on energy prices.

in reducing global emissions. If such trade were prohibited, permit prices could be substantially higher, while permit prices could be lower if the protocol were amended to include countries outside Annex B. If Annex B countries received full credit for greenhouse gases absorbed by forest growth and other land use changes, permit prices would be zero in 2010, but the protocol would have no effect on emissions.

As discussed in the introduction, synthesis estimates of permit prices are based on projections of emissions and energy prices released by the Energy Information Administration (EIA) in 2000. More recent projections of emissions and energy prices are higher, meaning that updated synthesis estimates of permit prices would be higher in every scenario.

KEY DETERMINANTS OF PERMIT PRICES

Permit prices will depend primarily on three factors: the required reduction in emissions; the response of households and businesses to an increase in prices of greenhouse gas-related goods and services; and the level of such prices in the baseline. A fourth factor, the effect of the Kyoto agreement on gross domestic product (GDP), is of little importance: even studies that find large GDP losses estimate that lower GDP would produce less than one-seventh of the required reduction in emissions.

Required Reduction in Emissions

The required reduction in emissions can have a significant impact on permit prices. The Kyoto agreement would reduce emissions because the permits would increase the cost of using carbon-energy and goods and services produced using other greenhouse gases. (Following Nordhaus and Boyer, this paper uses the term "carbon-energy" as short-hand for energy from coal, natural gas and petroleum.) Not surprisingly, the larger the required reduction in emissions, the higher the permit price would have to be.

When permits can be traded across borders, the international market determines the permit price in each country unless limits are placed on purchases of permits. So, with international trade of permits, the percentage reduction in emissions in the entire trading bloc, and not just in the United States, determines the permit price. This is true for any commodity that is traded internationally. For example, the price of crude oil in the United States plunged in 1998, even though U.S. consumption rose and production fell, because the price of oil is determined in a global market, and the Asian crisis reduced global demand for oil.

Although the studies present a range of estimates, they agree that the percentage reduction in emissions for the United States without trading would be much larger than the percentage reduction in Annex B or global emissions with trading. If permits could not be traded and the cap applied only to carbon dioxide, the United States would have to reduce domestic emissions by 30 percent to comply with the emissions caps specified in the protocol, according to estimates released in 2000 by EIA (but not reflected in the model results).[9] However, carbon emissions would have to be cut by only 12 percent in the Annex B region if permits were freely traded within that region. If permits were traded globally, world emissions would have to be cut by only 6 percent. The models make qualitatively similar assumptions (see Table 3-1).

The Kyoto caps are easier to reach with trade for two reasons. First, the portion of the U.S. cap attributable to carbon emissions in 1990 is set 7 percent below those levels, while the portion of the cap for the other Annex B countries attributable to carbon emissions in 1990 averages only about 3 percent below those levels. Second, and more important, carbon emissions are expected to grow more slowly between 1990 and 2010 in other Annex B countries than in the United States. That projection stems partly from the expectation that economic activity in the countries of the former Soviet Union will still be below 1990 levels in 2010. In addition, because the communist governments in the former Soviet bloc subsidized fossil fuels heavily and encouraged excessive use, those countries are expected to cut back their use of fossil fuels as they continue their transition toward market economies. Already, carbon emissions per dollar of GDP in Eastern Europe have fallen at almost a 5 percent annual rate from 1990 to 1999. Over the next decade, EIA expects rapid declines in energy intensity to continue in eastern Europe, and to spread to the former Soviet Union.[10]

A few provisions of the Kyoto Protocol can cause Annex B emissions of carbon dioxide to diverge from the portion of the caps attributable to 1990 emissions of carbon dioxide. First, Annex B countries can get credit for certain reductions in non-Annex B emissions under the Clean Development Mechanism (CDM). Second, since the Kyoto caps include all greenhouse gases, reductions in emissions of other greenhouse gases (like methane and nitrous oxide) below the caps can be counted toward a country's obligation to reduce carbon emissions. Finally, countries can receive credits for forest growth. To the extent that countries get credits for forest growth that would have occurred even without the protocol, such credits reduce the environmental benefits of the protocol as well as its economic costs.

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9. Energy Information Administration, *International Energy Outlook 2000*, DOE/EIA-0484 (March 2000). According to the 2002 projection, required reductions in emissions would be larger for both the United States and for the rest of Annex B.

10. Energy Information Administration, *International Energy Outlook 2000*.

Because of questions about how those provisions for the CDM and offsets for other gases and forest growth would be implemented and enforced, many modelers do not include impacts from them. The Clinton Administration assumed larger benefits from these provisions than any other researchers, which is one reason why the Administration's estimate of the cost of the Kyoto Protocol is more optimistic than those of most other modelers.

Price Sensitivity of Emissions

How high must permit prices rise to produce the required decline in carbon emissions? The answer will depend on how much households and businesses respond to an increase in the price of carbon-energy. The larger their response, the lower the permit price would have to be to achieve the Kyoto caps.

The sensitivity of households and businesses to the price of carbon-energy varies significantly among the models, and it is the most important source of differences among the models' estimates of the permit price. For very small changes in emissions, the price sensitivity of a model can be measured approximately as the percentage change in carbon emissions per GDP produced by a one percent increase in the price of carbon-energy. For the United States, estimates of price sensitivity in 2010 differ by a factor of four among the models when there is no international permit trading (see Table 3-2).

Four factors can influence the price sensitivity of carbon emissions at a given point in time in any country: the long-run ability of businesses to substitute low-carbon fuels for high-carbon fuels; the long-run sensitivity of household and business energy usage to higher energy prices; the speed at which these long-run responses occur; and differences in these reactions between countries. The models make a variety of different assumptions about each of these factors. (In addition, the price sensitivity for emissions of other greenhouse gases may differ from that for carbon dioxide. Only two studies, by the Clinton Administration and the EPPA modelers, look at this issue.)

Substitution Among Fuels. One way businesses and households can respond to higher costs of emitting carbon is by substituting low-carbon or no-carbon fuels for high-carbon fuels. Electric generators would make most of these substitutions, replacing coal with other fuels. In fact, fuel substitution by electric generators alone can account for between 24 percent (in DRI's 1997 study) and 48 percent (in EIA's study) of the total reduction in emissions.

The amount of fuel substitution can differ among models for many reasons. First, models may differ on the permit price at which a technology that uses less carbon becomes economical and on the availability of that technology. Unfortunately, many models implicitly assume unrealistically large increases in nuclear and hydroelectric power, given the high cost and political difficulties of new nuclear plants and the lack of potential new dam sites. On the other hand, some models assume that utilities retire existing nuclear plants at the rate currently anticipated no matter how high permit prices go.[11] Assumptions about nuclear and hydro power can cause permit prices to vary by nearly 30 percent.

Second, some models assume that capital and labor can somehow be substituted for fossil fuels in the production of fossil-fuel energy–an assumption that seems implausible. For example, some models allow petroleum refiners and natural gas utilities to substitute labor and capital for petroleum and natural gas. In other words, those models assume that refiners would be able to reduce the amount of crude oil required to produce a gallon of gasoline by using more labor and capital.[12] This assumption can play a significant role in the analysis; in one case, it reduces estimated permit prices by more than 15 percent.

Third, emissions from coal, petroleum and natural gas in some models fall by a much larger percentage than actual combustion of these fuels.[13] This assumption can cause permit prices to be understated by 15 percent.

Long-Run Sensitivity of Overall Energy Demand. Households and businesses would also reduce overall energy demand as energy prices rose. Businesses would substitute capital and labor for energy (factor substitution), while households would substitute purchases of other goods for energy.[14] Many of these responses would only occur slowly over time. For example, many households and businesses would upgrade to

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11. The EPPA, G-Cubed and JWS models implicitly assume unrealistic increases in hydroelectric and nuclear power. The DRI, GTEM and WEFA models assume that nuclear plants are retired at baseline rates no matter what the permit price. AIM, OEF, MERGE, CETA, RICE and WorldScan do not have separate electricity sectors, so it is impossible to know if their implicit assumptions are realistic or not.

12. Unrealistic substitution of capital and labor for crude oil and natural gas only affects permit prices if emissions are assumed proportional to usage of fossil fuels, as in the AIM and SGM models. Such unrealistic substitutions do not affect permit prices in models that assume emissions are proportional to refined petroleum products and utility natural gas, such as EPPA, G-Cubed, GTEM and JWS.

13. The G-Cubed and SGM models assume that emissions are proportional to gross sales of the coal mining and oil and gas extraction industries, rather than to the net sales of these industries. For example, emissions from coal are assumed proportional to gross sales of coal and coal mining services, including sales of coal and coal mining services from one company to another. These models also assume that such intra-industry sales fall by a larger percentage than net sales of coal to industries that will actually burn the coal. Thus, estimated emissions from coal fall by a larger percentage than actual coal usage.

14. The overall capital intensity of the economy would nonetheless fall. First, businesses would substitute labor for capital, which is produced using energy, as well as capital and labor for energy. Second, the amount of capital used in the energy sector would shrink with the size of that sector.

more fuel-efficient appliances and equipment only when the existing items would normally be replaced.

Most of the models base their expectations of how energy users will react to changes in energy prices from studies about how businesses and consumers have reacted in the past. Because the large price changes of the 1970s and early 1980s produced disproportionately small changes in usage, most models assume that energy users would respond relatively modestly to changes in energy prices.

Three models–G-Cubed, RICE, and WorldScan–assume, for analytical convenience, much larger responses to changes in energy prices, without, however, claiming an empirical basis for this assumption.[15] The use of demand responses out of line with the empirical literature has a larger effect than any other unrealistic assumption, reducing the permit price by 30 percent in the model requiring the smallest adjustment, G-Cubed.

Expectations and Speed of Adjustment. The longer it takes for businesses and households to reduce their energy usage and make fuel substitutions in response to higher carbon-energy prices, the higher energy prices would have to rise in 2010 to achieve a given percentage reduction in emissions. The speed of adjustment can be measured by comparing the price sensitivity in 2010 with that in 2020; the smaller the ratio, the more slowly households and businesses cut emissions (see Table 3-2).

Most models assume businesses would respond gradually, reflecting the fact that an industry can achieve many reductions in energy usage per dollar of output only as it turns over its capital stock. In general, differences in techniques for modeling this gradual response do not appear to have significant effects on the estimates of permit prices.

Some models (CETA, JWS and RICE), however, assume immediate adjustment. These models assume that businesses can, for example, instantaneously transform coal mines into energy-saving industrial equipment, or immediately make existing equipment more energy efficient. In such models, the price sensitivity is roughly the same in 2010 as it is in 2020. This observation also applies to Oxford and WorldScan, which assume that all adjustments to changes in energy prices are complete by 2010.

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15. These models assume a unit elasticity of demand for energy—that is, the percentage change in energy demand is roughly the same (but in the opposite direction) as the percentage change in real energy prices. In the G-Cubed model, this assumption affects only final demands. In the RICE and WorldScan models, a Cobb-Douglas production function (with a unit elasticity) is used to derive energy demand throughout the economy.

The date when people begin to anticipate higher energy prices can also affect the permit price. Other things equal, the longer it takes for a policy change to be announced or ratified, the more slowly people will respond to it. For example, the EIA study that assumes people begin to respond in 2000 finds lower permit prices than the EIA that assumes people begin to respond in 2005.

Speeds of adjustment are a big factor accounting for differences among the models. The long-run price sensitivity in the EIA study appears to be only about 10 percent smaller than that of studies using the SGM model, such as that of the Clinton Administration. A more rapid speed of adjustment in the SGM model thus explains most of the difference in permit prices between the EIA and Administration studies.

Price Sensitivity in Other Countries. When permits can be traded across borders, the U.S. permit price is determined by the price sensitivity of carbon emissions in all the countries trading permits, not that just in the United States.

Most models assume that other countries would be less sensitive to energy prices than the United States (see Table 3-3). Within the Annex B region, other countries generate a larger percentage of their electricity from nuclear and hydroelectric sources than from fossil fuels. As a result, those countries have fewer opportunities for substituting fuels than the United States. And outside of the Annex B region, other countries have not fully demonstrated their ability to use a price mechanism to reduce their energy usage. As a result, emissions in those countries may not respond as much to higher prices for carbon-energy as in Annex B countries.

Baseline Price of Carbon-Energy

The higher the baseline price of carbon-energy, the higher the permit price must be to achieve a given percentage increase in energy prices, for a given price sensitivity (see Table 3-4). The price of carbon-energy is an aggregate of the price per ton of carbon for each type of carbon-energy, such as gasoline, electricity from fossil fuels, and residential natural gas.

The models generally project that the baseline price of carbon-energy would be somewhat lower for the overall Annex B region than for the United States (see Tables 3-4 and 3-5).[16] That result stems from low baseline prices in the former Soviet bloc. Although baseline prices are higher in Japan and western Europe than in the United States, these countries would reduce emissions much less than the former Soviet bloc, and thus receive a smaller weight.

16. The only model for which this is not true, Oxford's, does not include eastern Europe or the Ukraine, and thus gives a smaller weight to the countries of Annex B with low baseline prices of carbon-energy.

The baseline price of carbon-energy is quite a bit lower in non-Annex B countries than in the Annex B region. The main reason is these countries' greater dependence on coal-based energy, which is much cheaper than energy from petroleum and natural gas.

MODEL ESTIMATES OF PERMIT PRICES

Although the studies produce a wide range of estimates for the price of emissions permits, the studies unanimously agree on one point: trading permits across borders will lower their price in the United States. A corollary to this point is that restrictions on trading boost the permit price.

No International Trade of Permits

Although the Kyoto Protocol envisions international trade of permits, assuming no trade provides a useful benchmark. Under this scenario, the models find a wide range of permit prices in 2010, from $91 per metric ton (in 1997 dollars) in the G-Cubed study to $407 in the Oxford study (see Table 3-4). The average permit price is $246 per metric ton, while the median price is $232.

Although many factors influence permit prices, variations in the models' assumptions about price sensitivity account for most of the difference in the estimates. Estimates of price sensitivity vary nearly four-fold across the models. Models with lower-than-average permit prices generally make assumptions that overstate price sensitivity, while some of the models with higher-than-average permit prices make assumptions that understate price sensitivity (see Appendix B). On average, assumptions overstating price sensitivity outweigh those understating it, thus reducing estimates of the permit price.

The other determinants of permit prices are less important. As Table 3-1 shows, the studies are reasonably consistent in their assumptions about how much U.S. emissions would have to be reduced if permit trading were not allowed. Although assumptions about the baseline price of carbon-energy also affect the permit price, they vary less among models than those about price sensitivity and so explain less of the differences in permit price among the models.

Studies that assume the United States can use forest growth and reductions in other greenhouse gases to offset carbon emissions find lower permit prices, other things equal. For example, the EIA study estimates that the permit price would fall from $355 to $300 per metric ton if the United States could use forest growth or reductions in other greenhouse gases to meet the Kyoto cap. Because businesses and consumers do not need to reduce energy usage as much in this case, the protocol can be satisfied with a lower permit price.

Unrestricted Trading of Permits Among Annex B Countries

The Kyoto Protocol envisions permit trading among Annex B countries, and every study cited in this paper finds that trade lowers permit prices in the United States. According to the studies, permit prices would range from $24 per metric ton (in 1997 dollars) to $222 per metric ton, compared with a range of $91 to $407 without trading (see Table 3-5). Permit prices are lower in the United States when permits can be traded among Annex B countries because the overall Annex B emissions cap is easier to hit than the U.S. cap alone. So, other Annex B countries would be willing to sell permits to the United States at prices lower than the U.S. no-trade price.

Much of the variation among studies stems from differences in price sensitivity. For example, the Oxford study predicts a permit price about nine times as large as the WorldScan study, even though both studies assume Annex B must cut carbon emissions by 21 percent. Almost all of the difference stems from different assumptions about how sensitive energy users are to changes in prices. The WorldScan study assumes energy users are unusually sensitive; as a result, only a small permit price is needed to induce them to make large cuts in their energy use. (In addition, the WorldScan study assumes a somewhat lower baseline price of carbon-energy.)

However, unlike the no-trading scenario, differences in assumptions about how much emissions must be reduced to meet the Kyoto Protocol are also important. Models disagree about both how far baseline emissions will be above Kyoto caps in 2010 and what role offsets from CDM, forest growth and cuts in other gases will play. The cut in carbon emissions varies from 8 percent to 21 percent among the studies.

Models that assume higher baseline growth in emissions, and thus larger percentage reductions in carbon emissions, estimate higher permit prices, given the same price sensitivity. For example, SGM-PNNL and GTEM assume similar price sensitivity for Annex B, but SGM-PNNL assumes a smaller percentage reduction in emissions than GTEM and thus estimates a lower permit price.

Models assuming offsets from CDM, forest growth and cuts in other gases find, on average, lower permit prices than those that do not. The impact of offsets is largest in the Clinton Administration study. The Administration assumed lower non-CO_2 greenhouse gases in the former Soviet bloc and very high price sensitivity for these gases at low permit prices. These assumptions make the caps for these gases easier to reach.

Unrestricted Global Trading of Permits

Amending the Kyoto Protocol to include non-Annex B countries would further reduce the permit price. According to the models, prices would range from $13 per metric ton (1997 dollars) to $80 per metric ton with unrestricted global trading of permits, compared with a range of $24 to $222 with only Annex B participation (see Table 3-6). (The range of prices under global trading may be artificially narrow relative to the non-global trading range, because the studies with the highest and lowest prices under Annex B trading did not examine the effects of global trading.)

With global trading of permits, the permit price would be determined by worldwide supply and demand for permits. The worldwide percentage reduction in carbon emissions under global trading would be smaller than the percentage reduction in the carbon emissions of Annex B under Annex B trading. Global trading would spread the Annex B reduction over a broader base, which lowers the percentage reduction. In addition, baseline prices for carbon-energy average lower in non-Annex B countries than in Annex B countries. As a result, most models find that emissions would fall by a larger percentage in non-Annex B countries than in Annex B countries, given the same permit price. The exceptions are those models that assume lower price sensitivity in non-Annex B countries.

Permit prices vary among models because of differences in percentage reductions in emissions, baseline prices of carbon-energy and price sensitivity of users. Not surprisingly, the RICE model, which has the smallest percentage reduction in emissions, the third-highest price sensitivity among Annex B energy users, and the lowest baseline price of carbon-energy among non-Annex B countries, has the lowest permit price. By contrast, the MERGE model has the least responsive energy users, and the highest permit price.

Most studies assume that the caps for non-Annex B countries would be set equal to projected baseline emissions in those countries. (The exception is the MS-MRT model, which assumes that the non-Annex B countries must be given permits in excess of their baseline level of emissions to induce them to participate. This assumption reduces the permit price, but also trims the global reduction in emissions from what it would be if the non-Annex B caps were set at projected baseline levels of emissions.) If caps for non-Annex B countries were set lower than projected baseline emissions, both the permit price and the reduction in global emissions would be higher.

Limitations on Permit Trading

While the Kyoto Protocol envisions permit trading among the Annex B countries, it does not rule out the possibility that trade could be limited by regulation or strategic behavior. Those limits could include restrictions on the purchases of permits by permit-importing countries, controls on sales of permits by permit-exporting countries, and the exercise of market power by permit-exporting countries.[17] The models generally agree that limiting free trade would raise the permit price.

Restrictions on Permit Purchases. Restricting the number of permits the United States could purchase from other countries would boost permit prices in the United States and in other countries facing the same situation.[18] But, permit prices would fall in other (unrestricted) countries, due to lower demand for permits in the international market.

With binding restrictions on permit purchases, the advantages of global trading of permits would nearly disappear. The United States would be unable to take advantage of the lower global price of permits to buy more permits. The domestic permit price would be determined by the tightness of the restriction, rather than by the international permit price. The only remaining advantage would be that a lower international permit price would reduce the cost of purchasing the fixed number of permits allowed.

Although several studies mention the possibility of restricting purchases, only three examine the potential implication of hypothetically restricting each Annex B country's permit purchases to roughly one-third of the difference between its caps and its baseline emissions.[19] Studies using the MERGE and MS-MRT models indicate that such a restriction would boost U.S. permit prices significantly. The MS-MRT study finds that it would boost the U.S. permit price to $166 per metric ton of carbon (in 1997 dollars), from $94 per ton under unrestricted Annex B trading. Starting from unrestricted global trading, the MERGE study finds that restrictions would boost the U.S. permit price from $80 to $167 per metric ton of carbon.

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17. Modelers have also examined the effects of creating a European "bubble" (in which Europe collectively meets its overall target) alongside unrestricted permit trading among the other Annex B countries, but that possibility is not discussed in this paper because it seems somewhat unrealistic.

18. The analysis assumes that the restrictions are binding. If the restrictions were not binding, U.S. permit prices would be unaffected.

19. Studies using EPPA and MERGE assume permit purchases are restricted to one-third of a country's obligation, while the study using MS-MRT assumed purchases are restricted to 30% of a country's obligation. The MERGE study assumes restrictions in the context of global trading of permits, while the other two studies assume restrictions under Annex B trading of permits. In practice, the baseline would not be observed if the protocol were ratified, so the actual restriction would be defined in terms of emissions at some fixed date in the past.

By contrast, a study using the EPPA model finds that such a restriction would be binding on Japan and western Europe, but not on the United States or other regions.[20] Thus, because the restriction would reduce international demand for permits, it would reduce the price of permits to U.S. and other OECD buyers from $180 to $162 per metric ton (1997 dollars). Compared with other studies (including the study using the EPPA model cited in Table 2-1), however, this study assumes higher emissions baselines for other Annex B countries. Lower baseline emissions in other Annex B countries would reduce the international permit price low enough that the United States would want to buy more permits than it was limited to.

Restrictions on Permit Sales. Restricting the ability of permit-exporting countries to sell emissions permits would also boost permit prices. Two studies examined the impact of preventing Russia and other countries of the former Soviet Union from selling the excess permits that arise because their projected levels of emissions in 2010 will be less than their levels in 1990. The MS-MRT model indicates that such a restriction on permit sales would increase permit prices from $94 to $136 per metric ton of carbon. The PNNL study, which uses the SGM model, estimates similar effects. In that study, permit prices rise from $82 to $127 per ton of carbon.

Although restricting the sale of excess permits from Russia and other countries of the former Soviet Union would raise permit prices, it would also increase the environmental benefits of Kyoto because it would effectively tighten the overall emissions cap.

Exercise of Market Power By Permit Exporters. With Annex B trading, the countries of the former Soviet Union could form a cartel to exploit their position as the primary exporters of permits. The impact of such a cartel would depend on its objective. If its objective were to maximize permit revenues from other countries, the cartel would have little impact. Although the former Soviet Union would be the primary exporter of permits, it would still account for only a small share of the permits used in the other Annex B countries. (Such a cartel would have considerably less power than OPEC, which supplies more than half of the oil used in western Europe and Japan and a quarter of the oil used in the United States.) If the former Soviet Union were to restrict permit sales to boost prices, it would lose about as much from lower volume as it gained from higher prices.

However, if a cartel pursued a broader economic objective than simply maximizing permit revenues, permit prices would rise higher. For example, reducing the number of permits exported would reduce permit revenues slightly, but would also increase

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20. A. Denny Ellerman and Annelene Decaux, *Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Cost Curves*, Report Series No. 40 (Cambridge, Mass.: MIT Joint Program on the Science and Policy of Global Change, October 1998).

the supply of permits to the domestic economies of the cartel, reducing energy prices and the associated adverse GDP impacts within those countries. If the former Soviet Union decided to maximize permit revenues less the direct economic costs of higher domestic energy prices, the PNNL study finds that Annex B permit prices would rise 35 percent, from $82 to $111 per metric ton of carbon (1997 dollars). If Eastern Europe joined the cartel, prices would rise to $118 per tonne. A study using the EPPA model, assuming the same cartel objective, finds a much smaller 12 percent price increase. The MS-MRT study, using a broader measure of domestic economic costs, finds that a former Soviet bloc cartel would boost permit prices by 42 percent, from $95 per tonne to $135 per tonne.

Amending the protocol to include all countries would sharply limit the ability of a former Soviet Union cartel to boost permit prices. Any effort by these countries to boost the international price of permits would produce a sharp drop in permit sales from those countries, as other developing countries boosted their own sales. Those other countries could try to form a cartel, but its effectiveness would be limited unless it covered most permit-exporting countries.

ESTIMATES OF PERMIT PRICES UNDER VARIOUS SCENARIOS: MODEL SYNTHESIS

The modelers' results already indicate a general trend: permit prices in the United States are likely to be much higher if no international trading is allowed than if trading is unrestricted. However, the wide range of model results makes it hard to get a quantitative sense of the importance of various sorts of limits on permit trading. This section presents a synthesis of the model results, derived from a reduced-form model created using averages of the properties of the models, adjusted where necessary (see Appendix B for the methodology.)

The synthesis estimates include several outcomes consistent with the Kyoto Protocol, as well as two sets of outcomes that would require amendments to the Protocol: no international trade of permits, and global trading of permits (see Table 3-7). The estimates are derived from model runs that assume a credible commitment to reducing emissions was made or expected by 2001. Given that the United States has not ratified the protocol, energy users will have less time to react, likely pushing permit prices higher.[21]

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21. The estimates also assume that subsidies to energy usage, such as the tax-free treatment of employer-provided parking, are not changed.

A wide range of scenarios is consistent with the Kyoto Protocol, were the United States to ratify it. Depending on how the protocol is interpreted and implemented, permit prices in the United States could range from $56 to $178 per metric ton of carbon in 2010. (All prices in this section are in 1997 dollars. To convert 1997 dollars to 2002 dollars, multiply by 1.085.) Those estimates assume that forest growth has little net impact. If countries received unlimited credits for greenhouse gases absorbed by baseline (non Kyoto-related) forest growth and other land-use changes, permit prices would fall to zero in 2010, but the protocol would have no effect on the amount of greenhouse gases in the atmosphere. This paper does not examine the impact of the limited credits for baseline forest growth agreed to in November 2001, or of Kyoto-related forest growth.

The wide range of scenarios stems from the fact that several important issues are not yet resolved:

- Will permit-exporting countries exploit their market power and raise permit prices above competitive levels?
- Will the clean development mechanism that allows Annex B countries to take credit for emissions reductions in non-Annex B countries actually work?
- Will restrictions will be imposed on a country's ability to purchase or sell its permits to other countries?
- Will the difficulties in monitoring reductions in non-CO_2 greenhouse gases confound efforts to include these gases under the caps?

This section also presents a range of possible error around the model synthesis estimate of the U.S. permit price for each scenario, reflecting the uncertainty present in each model's estimates. Much of this uncertainty stems from estimates of price sensitivity. Modelers must estimate the factors determining price sensitivity, and their estimates have some uncertainty attached. Based on estimates of uncertainty from empirical studies of the price sensitivity of energy demand, the actual permit price for a given scenario would fall within a range running from 27 percent below to 27 percent above the estimated permit price for that scenario. For example, an estimate of $56 per metric ton implies a range of $41 to $71 per metric ton.[22]

Possible errors in projected emissions baselines also add to the uncertainty of the permit price. However, such uncertainty has little impact on the relative sizes of the costs and benefits of reducing emissions. That is because trying to hit the same cap from a lower baseline would mean both a lower permit price and a smaller reduction in emissions. Using an extreme case to illustrate the point, if baseline emissions in

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22. Actually, the range may not be symmetric around the point estimate because price sensitivity has a nonlinear impact on the permit price. A given reduction in price sensitivity boosts the permit price by a larger percentage than a same-sized increase in price sensitivity reduces it. In that case, the range of uncertainty would be 20 percent below the permit price to 34 percent above it. In the example, this would produce a range of permit prices of $45 to $76 per metric ton.

2010 equaled the Kyoto cap, the treaty would have no cost–the permit price would be zero–but also no benefit–emissions would be unaffected. This study provides no estimates of the effect of this type of uncertainty, but it would likely be of a similar magnitude as that coming from uncertainty about price sensitivity.

Scenarios Consistent with the Kyoto Protocol

The Kyoto Protocol envisions a system of emissions permits that would be traded among Annex B countries. However, the protocol is consistent with a variety of alternative outcomes. The range of outcomes would be widened further if some provisions of the protocol proved unworkable.

Ideal Implementation. Ideally, permit-exporting countries make no attempt to exploit their market power, the clean development mechanism works as promised, no restrictions are placed on the United States' ability to purchase permits from abroad, and reductions in other greenhouse gases can be used to offset carbon dioxide emissions. Under that scenario, a synthesis of model results suggests that emissions permits would cost $56 per metric ton in 2010, the lowest estimate of permit prices consistent with the protocol.

That estimate is lower than most model estimates of the impact of the protocol, for three reasons. First, the model synthesis incorporates the positive effect of the clean development mechanism, which puts downward pressure on permit prices. By contrast, only one model (MERGE) incorporates such an effect. Second, most modelers do not account for the impact of offsets from other greenhouse gases. (Without the effects of the clean development mechanism or offsets from other gases, the permit price would rise to $81 per metric ton.[23]) Third, the level of future baseline emissions assumed in the synthesis estimates is significantly lower than that assumed by most modelers. Synthesis assumptions are based on projections prepared by the U.S. Energy Information Agency in 2000, rather than the EIA projections prepared in 1998 that many modelers used. Between 1998 and 2000, the EIA lowered its projected level of emissions, particularly in Europe and the former Soviet bloc. In those countries, emissions projected for 2010 were about 8 percent lower in 2000 than what they had been in 1998. Partly offsetting those three factors, the price sensitivity of carbon emissions assumed in the synthesis estimates is somewhat lower than the model average.

Ideal implementation would reduce global greenhouse emissions in 2010 by about 6 percent of baseline carbon dioxide emissions. (As a percent of baseline greenhouse emissions, the reduction would be smaller, but no one projects a global baseline for

23. Annex B offsets from CDM and other gases total 133 mmtc.

other greenhouse gases.) Global emissions of carbon dioxide would be 33 percent above 1990 levels in 2010, compared with a 40 percent rise in the baseline. The reduction in global emissions would be larger if not for the fact that the protocol would boost emissions in non-Annex B countries, a phenomenon known as leakage (see Box 2-1).

BOX 2-1
EMISSIONS LEAKAGE

Leakage occurs when policies that reduce greenhouse gas emissions in Annex B countries cause emissions to increase in other countries. Leakage can occur in two ways. First, reductions in Annex B usage of crude oil would reduce its price in world markets. In response, non-Annex B countries would increase their purchases of crude oil, although by a smaller amount than the reduction in Annex B purchases.

Second, energy-intensive industries in Annex B countries would relocate some production to countries where energy is cheaper to use, exporting this production back to Annex B countries. Although exchange rates would adjust to offset the impact of such relocations on the overall trade balance of Annex B countries, the composition of Annex B imports would shift toward energy-intensive goods. This would increase emissions in the countries to which the industries relocated.

Provisions in the Kyoto Protocol allowing Annex B countries to trade permits reduce leakage, for two reasons. First, permit trading reduces the price of permits, and thus energy prices, in most Annex B countries. (Energy prices would be higher than in the no-trading case only in the former Soviet bloc.) This reduces the incentive for energy-intensive industries to relocate to non-Annex B countries. On average, the modelers find that increases in non-Annex B emissions would offset 10 percent of Annex B cuts with international trading of permits, but 17 percent without.

Second, trading of permits eliminates leakage to the former Soviet bloc. Any increase in emissions by the former Soviet bloc reduces the number of permits the former Soviet bloc can sell to other Annex B countries. Leakage to the former Soviet bloc would occur within the Kyoto Protocol only if such limits were placed on the number of permits other countries could purchase that the domestic price of permits in the former Soviet bloc fell to zero. On average, the modelers find that, without permit trading, increases in emissions of the former Soviet bloc would offset 7 percent of the cuts in the rest of Annex B.

For similar reasons, amending the Kyoto Protocol to allow unrestricted global permit trading would eliminate leakage. Any increase in carbon emissions by Annex B countries would reduce the number of permits they could sell.

Exercise of Market Power by Permit-Exporting Countries. Under ideal implementation of the Kyoto Protocol, the developed countries would buy permits from eastern Europe and the Annex B portion of the former Soviet Union. Those latter countries could try to use their position as the only net sellers of permits to boost the international price of permits above competitive levels. The ultimate impact on prices would depend on the objective of the permit-exporting countries in using their market power, and on how the Annex B countries reacted.

If the countries of the former Soviet Union formed a cartel in order to maximize their revenues from the export of permits, the impact on permit prices would be small. Although those countries would supply a dominant share of permit exports, they would supply only a small share of the total permits used in the other Annex B countries.[24] As those countries tried to boost prices, demand for their exports of permits would fall off. A synthesis of model results suggests that those countries would maximize their revenues if the permit price was $67 per metric ton of carbon, which is only modestly higher than permit price of $56 per tonne under the ideal implementation scenario described above.

Permit prices would rise higher if the former Soviet Union instead attempted to maximize its GDP plus revenues from permit exports. Withholding permits from the world market would not only boost the world permit price, but it would also make more permits available for consumption in the countries of the former Soviet Union. That development would mute the rise in energy prices in those countries and thus the loss in their GDP. World permit prices would rise to $85 per metric ton under this scenario.[25]

This scenario would not occur if other Annex B countries could credibly threaten to retaliate, perhaps by imposing quotas on the import of permits. In that case, a more likely outcome would be for the former Soviet Union to restrict exports of permits below the levels in the ideal implementation scenario, but not so far as to trigger retaliation from other countries. For example, if countries of the former Soviet Union and eastern Europe restricted permit exports by enough to hold their domestic permit prices at half the level of international permit prices, the international permit price would be $70 per ton.[26]

<u>No Clean Development Mechanism.</u> If the Clean Development Mechanism proved unworkable, the impact on U.S. energy prices could be small, because, according to the assumption made by the EMF in examining this scenario, the impact of the Clean Development Mechanism itself would be small. Assuming a moderate exercise of market power by the former Soviet bloc, the U.S. permit price could rise from $70 per metric ton to $76 per metric ton of carbon under this scenario.

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24. In the ideal implementation scenario, the countries of the former Soviet Union account for 79 percent of permit exports, but just 12 percent of permits used by permit-importing countries.

25. At that price, the former Soviet Union would sell only "hot air"—permits in excess of baseline emissions—and reduce its domestic permit price to zero.

26. This scenario still implies a significant reduction in emissions in the former Soviet bloc, because of low baseline prices of carbon-energy in those countries. In fact, those countries would be reducing their emissions by a larger percentage from baseline than any of the other Annex B countries.

Restrictions on U.S. Purchases of Emissions Permits. The Kyoto Protocol states that "trading shall be supplemental to domestic actions for the purpose of meeting quantified emission limitation and reduction." Rules governing trading are to be developed at a future "Conference of the Parties." In the past, the European Union has suggested that the term "supplemental" means that limits should be imposed on each country's ability to satisfy its Kyoto obligation by purchasing permits from other countries.

Such limits could have a significant effect on permit prices. If the United States was required to achieve at least 65 percent of its obligation by reducing domestic emissions, the U.S. permit price would jump to $122 per metric ton. (This restriction is roughly equivalent to that proposed by the European Union in 2000.) By contrast, permit prices in the former Soviet Union and eastern Europe would fall very close to zero because those countries could supply the limited demand from the rest of Annex B countries entirely by selling their "hot air"—permits in excess of baseline emissions. A tighter limit on permit purchases would result in a higher permit price, while a looser restriction would result in a lower price. Note that with restrictions on permit purchases, the CDM would have no impact on permit prices. Any credit obtained from a non-Annex B country would reduce the number of permits the United States could purchase from other Annex B countries.

Restrictions on Sales of Emissions Permits. The Conference of Parties could instead impose limits on the amount of permits a country can sell. For example, the countries of the former Soviet bloc could be prevented from selling their hot air. This restriction would be equivalent to changing their permit allocation to match their baseline level of emissions. (This restriction is not as tight as that proposed by the European Union in 2000.) Under this scenario the permit price in Annex B countries would rise to $137 per metric ton of carbon.[27] The value of permit sales by the former Soviet bloc would only decline by 14 percent, from $38 billion to $33 billion (in 1997 dollars), because the higher price would nearly offset the decline in the number of permits sold.

That scenario would reduce global emissions substantially more than other interpretations of the Kyoto Protocol. Global emissions of greenhouse gases in 2010 would fall by the equivalent of nearly 10 percent of baseline carbon dioxide emissions, about one and one-half times as much as in the ideal implementation scenario. Emissions would be lower than under a policy of limited purchases because permit prices would be higher in every Annex B country, including those of the former Soviet

27. This estimate assumes that the countries of the former Soviet bloc would exercise a moderate degree of market power and restrict permit sales so that their domestic price of permits is one-half the international price of permits.

bloc. Nonetheless, global emissions of carbon dioxide would still be 29 percent above 1990 levels in 2010.

In later years, the impact on both the permit price and emissions of a restriction on sales of hot air would fade as hot air disappeared with higher baseline emissions in the former Soviet Union bloc. However, if the restriction on sales were tied to the number of permits sold, rather than to the amount of hot air sold, it could have a permanent effect on permit prices and global emissions.

<u>No Offsets from Other Greenhouse Gases.</u> If other greenhouse gases proved too difficult to monitor, or if other problems arose in imposing permits on sources of these emissions, the U.S. permit price would rise still further. With restrictions on sales of hot air and caps on carbon dioxide equal to the carbon dioxide portion of the overall Kyoto cap, each permit would cost $178 per metric ton of carbon in 2010. Taking account of uncertainty in model estimates of price sensitivity, the permit price would fall in a range of $130 to $226 per metric ton. This permit price would apply only to carbon dioxide, and so would have only a slightly larger impact on the overall level of U.S. prices than a $137 per ton charge on all greenhouse gases.

Permit prices would be higher under this scenario for two reasons. First, other greenhouse gases are cheaper to reduce than carbon dioxide. Second, the percentage difference between baseline emissions and the Kyoto caps is much larger for carbon dioxide than it is for the other greenhouse gases.

<u>Credit for Baseline Forest Growth.</u> In August 2000, the U.S. Department of State argued that countries should receive credits for the change in carbon stocks on managed lands during the commitment period, including changes that would have occurred whether or not the protocol was ratified.[28] (Managed lands include cropland, grazing land and forests, except those not available or appropriate for wood production.) According to estimates submitted by the countries to the United Nations, such credits would slightly exceed the difference between projected baseline emissions and the Kyoto caps in Annex B in 2010.[29] The supply of emissions permits and credits would exceed baseline emissions, driving the permit price to zero in 2010. In later years, if the cap were frozen at its 2010 level, rising baseline emissions would eventually result in positive permit prices.

Although this interpretation of the Kyoto Protocol's provisions on forest growth would eliminate the economic costs of the protocol in 2010, it would also eliminate

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28. Department of State, *United States Submission on Land-Use, Land-Use Change and Forestry*, August 1, 2000 (available at www.state.gov/www/global/global_issues/climate/000801_unfccc1_subm.pdf).

29. United Nations Framework Convention on Climate Change, *Greenhouse Gas Inventory Database*, 2000 (available at www.unfccc.de).

the protocol's environmental benefits in that year. Since the protocol would not impose a cost to emitting greenhouse gases, there would be no reduction in such emissions.

These results assume no limitations on countries' ability to buy and sell permits. With such limits, permit prices would be positive, but far smaller than if credits for baseline forest growth were not allowed. For example, with the limit on purchases described above, the U.S. permit price would fall to $50 per mtc in 2010, from $122 per mtc without credits for forest growth. However, the reduction in global emissions of greenhouse gases in 2010 would fall to 3 percent of baseline carbon dioxide emissions, much lower than in any other Kyoto-consistent case.

In November 2000, the United States, Canada and Japan proposed a somewhat stricter treatment for baseline forest growth, or "existing effort."[30] Under this proposal, baseline forest growth could be used to satisfy about 60 percent of Annex B's required reduction in emissions. In the ideal implementation case, the permit price would drop from $56 per metric ton to $24 per metric ton, but the cut in global emissions would fall from 6 percent to 3 percent of baseline carbon dioxide.

If credits were only given for forest growth that would have occurred in the absence of the protocol, permit prices would be lower than if no credit were given for any forest growth. Countries could substitute forest growth for the most expensive cutbacks in emissions. This would trim the overall reduction in global emissions, but increase absorption of greenhouse gases by the same amount. Unfortunately, it is impossible to use the economic models to determine the effect this would have on permit prices, because none of them include such an effect. One paper finds that such effects could be large.[31]

Scenarios Requiring Amendments to the Kyoto Protocol

Amending the Kyoto Protocol to prevent the international trade of permits or to include countries outside of the Annex B region could produce impacts on permit prices that are larger or smaller than those shown above.

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30. Department of State, *Proposal by United States, Canada, Japan: Phase-in for Forest Management in the First Commitment Period*, November 21, 2000 (available at www.state.gov/www/global/global_issues/climate/cop6/001121_phase-in.html).

31. Bruce A. McCarl, "Carbon Sequestration via Tree Planting on Agricultural Lands: An Economic Study of Costs and Policy Design Alternatives," Internet draft, November 1998 (available at http://ageco.tamu.edu/faculty/mccarl/papers/676.pdf).

No Permit Trading Between Countries. If the United States could not purchase permits from other countries, but could use reductions in emissions of other greenhouse gases to offset reductions in carbon dioxide, emissions permits would cost $216 per metric ton in 2010. If offsets from other greenhouse gases could not be used, the permit price would rise to $264 per metric ton in 2010.

The only advantage of eliminating international trade of permits would be that countries could not use hot air from the former Soviet bloc to reduce their own need to cut emissions. Consequently, global emissions of greenhouse gases would be reduced from baseline 2010 levels by the equivalent of 8 percent of baseline carbon dioxide emissions if no offsets from other gases were allowed and by 9 percent if offsets were allowed. This advantage would disappear over time as higher baseline emissions in the former Soviet Union eliminated hot air.

Global Trading of Emissions Permits. Amending the Kyoto Protocol to include non-Annex B countries could greatly reduce the impact of the protocol on energy prices. If emissions caps for these countries were set equal to projected baseline levels for these countries and there were no limitations on trading, the price of an emissions permit would drop to $28 per metric ton of carbon. Permit prices are lower because global trading allows Annex B countries to substitute low-cost reductions in non-Annex B emissions for more expensive reductions in their own emissions.

The behavior of the former Soviet bloc would have a smaller impact on U.S. permit prices with global trading because non-Annex B countries would provide a large alternative source of permits. If countries of the former Soviet Union and eastern Europe restricted permit exports by enough to hold their domestic permit prices at half the level of international permit prices, the international permit price would only rise to $31 per metric ton. Preventing the sale of hot air would only boost the permit price to $49 per metric ton.

Putting restrictions on permit purchases, however, would boost the permit price to $122 per metric ton, roughly the same as under Annex B trading of permits. The United States would be unable to take advantage of the additional permits non-Annex B countries would be willing to supply. If, in addition, no offsets were available from reductions in other greenhouse gases below target levels (i.e., if the non-carbon dioxide portions of the caps were eliminated), the U.S. permit price would rise still further, to $147 per metric ton.

Expanding the Kyoto Protocol to include non-Annex B countries would reduce global emissions by eliminating leakage to those countries. The global reduction in emissions of greenhouse gases would be 8 to 10 percent larger with global trading of permits than under the Kyoto Protocol.

CHAPTER 4
THE EFFECTS OF THE KYOTO PROTOCOL ON ENERGY PRICES

A system of tradeable permits would reduce emissions by boosting prices of energy made from coal, petroleum and natural gas. Although consumers would not pay for emissions permits directly, permit prices would have a large influence on energy prices, just as prices of crude oil influence gasoline prices even though motorists do not pay for crude oil directly.

According to a synthesis of model results, each $100 per metric ton increase in the permit price would add 17 to 22 cents per gallon to gasoline prices, roughly $1.57 per thousand cubic feet to the price of natural gas, roughly $55 per short ton to the user price of steam coal, and 1.4 to 1.7 cents per kilowatt-hour to the price of electricity.[32] On a percentage basis, gasoline prices would increase the least and coal prices the most.

Several factors determine the impact of permit prices on energy prices. Of these, the direct impact of the permit price is the most important. In addition, lower demand for coal and crude oil depresses their producer prices, offsetting part of the impact of permit prices. Depending on whether demand for natural gas rises or falls, the wellhead price of natural gas will rise or fall, adding to or subtracting from the impact of permit prices. Changing margins for refiners, distributors and electricity generators may also affect energy prices. Finally, changes in the mix of fuels used will help determine how much electricity prices rise.

The estimates of the potential impact of the Kyoto Protocol on energy prices reflect the changes in permit prices found in the previous chapter. Just as different interpretations of the protocol could lead to different permit prices, a wide range of outcomes for energy prices is consistent with the protocol. U.S. gasoline prices could rise anywhere from 12 to 38 cents per gallon higher than they would be otherwise. (All prices in this chapter are in 1997 dollars.) The price of natural gas to households would increase between 13 and 42 percent above baseline levels. Electricity prices to households would be 13 to 36 percent higher than they would be without emissions restrictions. Accounting for the uncertainty present in model estimates of price sensitivity would widen these ranges somewhat.

As discussed in the introduction, synthesis estimates of the change in energy prices are based on projections of emissions and energy prices released by the Energy

32. The change in gasoline prices is not proportional to the permit price because the drop in crude oil prices, due to lower demand, depends on global demand for crude oil rather than the permit price. The change in electricity prices is not proportional to the permit price because the mix of fuels used to generate electricity changes as the permit price rises.

Information Administration in 2000. More recent projections of emissions and energy prices are higher. If synthesis estimates were prepared using the new projections, they would show larger absolute increases in energy prices and larger percentage changes in electricity prices in every scenario. The percentage change in natural gas prices would likely also be higher.

MODEL ESTIMATES OF EFFECTS ON ENERGY PRICES

Although every study provides estimates of permit prices, few translate these prices into changes in energy prices. This section draws heavily on results from the DRI, EIA and WEFA studies, which provide the most detail on energy prices. Differences with other studies are also noted.

Coal Prices

Each $100 per mtc in permit prices directly boosts the price of coal delivered to electric utilities by roughly $55 per short ton, or between 213 and 245 percent (see Table 4-1). Higher grades of coal, which have higher heat content, would face larger absolute price increases, although higher baseline prices for these grades would mean smaller percentage increases.

The modelers expect minemouth prices for each grade of coal to fall due to lower demand. WEFA projects that a permit price of $265 per metric ton would reduce average minemouth prices by $3.60 per short ton. EIA expects average minemouth prices to rise, but only because of shifts in the mix of coal being mined, not because of increases in prices for any grade of coal. For example, a ton of coal from the Powder River basin in Wyoming is cheaper than a ton of Appalachian coal at the minemouth, but contains more carbon and less sulfur per unit of heat. So, as prices of greenhouse permits rise and prices of sulfur dioxide permits fall, Powder River basin coal loses its cost advantage, and the mix of coal used shifts toward more-expensive Appalachian coal, boosting the average minemouth price, even though the price of each grade falls.

Gasoline Prices

The impact of the Kyoto Protocol on the price of gasoline depends on three factors: the direct impact of the permit price; the indirect impact of reduced demand for crude oil on crude oil prices; and the impact of lower volumes on refiner and distributor margins. The first effect boosts the gasoline price, while the other two effects partly offset this increase.

Direct Effects. The carbon content of gasoline alone determines the direct impact of permit prices. Each gallon of gasoline contains about 5.2 pounds of carbon, so that each $100 per mtc (metric ton of carbon) increase in the permit price boosts the price of gasoline by 23.8 cents per gallon, all else equal.[33] The carbon content of other petroleum products is somewhat higher than that of gasoline, so a $100 permit price would directly add almost 26 cents per gallon to jet fuel prices and about 27 cents per gallon to distillate (diesel) prices. The direct impact of permit prices on gasoline prices is smaller in models that assume that capital and labor can be substituted for crude oil in the production of gasoline.

Effects on Crude Oil Prices. Higher prices for petroleum-based energy would lead consumers and businesses to reduce their purchases of it, reducing world-wide demand for crude oil. As the impact of lower Asian demand on world oil markets in 1998 demonstrated, reduced demand would push crude oil prices down. The size of the drop in prices would not depend on the U.S. permit price, but rather on the global reduction in crude oil demand.

On average, the models find that the percentage drop in crude oil prices would be nearly twice as large as the percentage drop in global petroleum consumption. So, a 3 percent drop in worldwide petroleum usage would produce a nearly 6 percent drop in crude oil prices. This works out to 2 to 3 cents per gallon for each $100 per mtc in permit prices.

Margins. Most studies, including those of DRI and WEFA, assume that changes in demand for petroleum-based energy do not impact refiners' profit margins. The EIA study, however, predicts that low capacity utilization would cause refiners to reduce margins in order to compete for business. This would reduce gasoline prices by about 3 cents per gallon for each $100 per mtc increase in permit prices.

Natural Gas Prices

Each $100 per mtc in permit prices directly adds almost $1.50 to the price of a thousand cubic feet of natural gas. In addition, demand for natural gas, unlike that for coal and petroleum, may rise due to higher demand from electric generators, pushing prices up further. Among the modelers publishing natural gas usage, DRI, EIA, SGM-PNNL and WEFA expect an increase in demand from electric utilities to outweigh lower demand for natural gas by households, businesses and governments,

33. Energy Information Administration, *Annual Energy Outlook 2000*, DOE/EIA-0383 (December 1999).

while the G-Cubed, JWS and MS-MRT models predict overall natural gas usage to fall. Estimates of the total impact of a $100 per metric ton permit price on wellhead prices (excluding permit costs) thus range from a drop of about 30 cents per thousand cubic feet to an increase of almost 25 cents.

EIA projects that higher demand for natural gas would boost distributors' margins. This would push the price each natural gas customer faces higher, although because demand would shift from high-margin residential and commercial customers to low-margin utilities, the average price to all users would fall. The DRI, EIA and WEFA studies find that each $100 increase in permit prices would add $1.55 to $1.83 per thousand cubic feet to the residential price of natural gas.

Electricity Prices

Unlike refiners and natural gas distributors, electric utilities can substitute biomass, solar or wind power for fossil fuels and natural gas for coal, substantially lowering the carbon content of a kilowatt-hour of electricity without reducing the amount of electricity generated. In fact, the modelers find that changes in the fuel mix account for reductions in emissions that are at least as large as those from cuts in electricity demand.

Although fuel substitutions reduce the direct impact of the permit program, they introduce a cost as well: fuel and generating costs are higher. (Otherwise, utilities would already be using the new mix of fuels.) As a result, the net impact of the Kyoto Protocol on electricity prices would be smaller than the permit cost of the original mix of fuels, but larger than the permit cost of the final mix of fuels.

Using the baseline mix of fuels, generating technologies, and fossil fuel prices, each $100 per mtc increase in permit prices would boost electricity prices by 1.7 cents per kilowatt-hour, according to the DRI, EIA and WEFA studies. Although shifting from coal lowers the direct impact of the permits on electricity prices considerably, it boosts other costs, eliminating most of the savings. In the EIA study, for example, fuel shifting reduces the costs of the permits to less than 1 cent per kilowatt-hour per $100 permit price, but higher wellhead prices for natural gas add 0.1 cent, and higher fuel and generating costs add another 0.5 cent. In the end, electricity prices rise nearly 1.6 cents per kilowatt-hour per $100 permit price anyway, and they are only 9 percent less than they would be if utilities used the baseline mix of fuels. Savings from switching fuels are smaller in the DRI study and are actually negative in the WEFA study.

The increase in the electricity price is larger than permit costs and a simple estimate of higher generating and fuel costs (discussed in Appendix B) would produce. Part of the reason generating costs are surprisingly high in the DRI and WEFA studies is that these models assume that electric generators' decisions about plant type take into account likely permit costs over the entire service lifetime of the plant. Both studies anticipate that permit prices will rise after 2010, so, while a new natural gas-fired plant may increase costs in 2010, it may nonetheless cost less to operate over the whole life of the plant. Thus, costs and prices may rise by more than the value of permits saved in 2010.

In addition, the studies assume that, at least in some regions, electricity prices are set according to the cost of the last kilowatt-hour generated, rather than according to the average cost of all electricity generated. As coal-fired plants are moved from providing baseload generation to providing marginal generation, marginal costs rise more than average costs, so prices rise more than the average cost of fuel-switching would predict. By 2020, both of these factors are less important, as coal plants are retired.

ESTIMATES OF EFFECTS ON ENERGY PRICES: MODEL SYNTHESIS

Permit prices play a key role in determining the effect of the Kyoto Protocol on energy prices. Scenarios that produce high permit prices, such as limits on international trading of permits, also produce large changes in energy prices (see Table 4-2). Depending on the scenario, U.S. gasoline prices would rise 12 to 38 cents per gallon (in 1997 dollars) above baseline levels in 2010. Natural gas prices to households would rise between 13 and 42 percent above baseline levels, while electricity prices to households would increase between 13 and 36 percent.[34] Scenarios requiring amendments to the protocol, such as global trading of permits or no international trade of permits, could produce smaller or larger impacts. The same uncertainty present in estimates of the permit price is also present in estimates of changes in energy prices.

34. Estimated prices for natural gas and electricity do not include the cost of permits for methane emitted by coal mines and natural gas system, and thus are probably too low.

CHAPTER 5
MACROECONOMIC AND DISTRIBUTIVE EFFECTS OF CUTTING GREENHOUSE GAS EMISSIONS

The various economic studies surveyed find that restrictions on emissions of greenhouse gases by a system of tradeable permits would reduce both output and consumption—and transfer a significant amount of income from producers and consumers of emission-producing goods and services to recipients of permits.[35] However, auctioning permits and using the receipts to cut tax rates could reduce those losses in output and consumption.

The impacts of the Kyoto Protocol on output, consumption and the distribution of income would depend on how the protocol is interpreted and implemented. In particular, the fewer the restrictions on permit trading, the smaller the impacts on the macroeconomy and the distribution of income.

The macroeconomic impact of reducing emissions of greenhouse gases can be measured in several ways. This paper focuses on two: the change in GDP and the change in consumption. The change in GDP measures the effect of emissions reductions on output, while the change in consumption shows the overall impact of emissions reductions on standards of living. A third measure, direct cost, captures only those losses in output suffered directly by consumers and producers of energy. It thus ignores feedback effects on the rest of the economy.

The synthesis of model results suggests that real U.S. GDP would decline between 0.5 percent and 1.2 percent below baseline levels in 2010 under the Kyoto Protocol, and real consumption would fall between 0.4 percent and 1.0 percent, depending on the scenario.[36] The direct cost of the Kyoto Protocol would be between 0.2 percent and 0.4 percent of GDP. The total value of permits used, which indicates the amount of income that would be transferred from producers and consumers of energy to recipients of permits, would total between $108 billion and $245 billion (in 1997 dollars) in 2010, or 0.9 percent to 2.0 percent of GDP. (Many households would both pay and receive funds.) If the government auctioned the permits, its revenues would rise by a comparable amount.

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35. Emission-producing goods and services can produce emissions either when they are used or when they are produced.

36. I interpret the economic impacts in 2010 as representative of impacts over a longer period of time. The actual impacts in 2010 may be larger, while the impacts in some other years during 2005 to 2015 may be smaller. See Appendix B.

Those estimates of losses in GDP and consumption reflect the same uncertainty present in estimates of the permit price. That is, if the price sensitivity of emissions is actually higher than estimated, permit price and losses in GDP and consumption will be lower than estimated, and if price sensitivity is lower than estimated, permit price and losses in GDP and consumption will be higher than estimated. In addition, there is some uncertainty about the effect a given permit price has on GDP and consumption. These latter sources of uncertainty are difficult to quantify, so the ranges of possible error presented in this chapter focus only on uncertainty in the estimate of price sensitivity.

As discussed in the introduction, synthesis estimates of changes in GDP and consumption are based on projections of emissions and energy prices released by the Energy Information Administration (EIA) in 2000. More recent projections of emissions and energy prices are higher, meaning that updated synthesis estimates of the reduction in GDP and consumption would be larger in every scenario.

DIRECT COST

The direct cost of abatement measures the economic cost that a cap or tax imposes in the directly-affected market alone—in this case, an implicit market for emissions. It thus excludes feedback effects, for example those stemming from interactions between energy markets and the rest of the economy.

Direct cost consists of two parts: domestic direct cost (the Harberger triangle[37]) and permit purchases from other countries. Domestic direct cost is the loss in value that users and producers would incur because the Kyoto cap would force users to substitute away from fossil energy and products that produce other greenhouse gases. Those substitutions would divert resources from producing fossil energy toward other uses. But the alternative uses of those resources would be less valuable than the baseline uses: if they were as valuable, it would not take positive permit prices to get people to adopt the alternative uses. Permit purchases are the dollar value of permits to emit greenhouse gases purchased from other countries.

Model Results

The models surveyed in this paper find that the Kyoto caps would carry direct costs between 0.2 percent and 0.9 percent of baseline GDP in 2010 if permits could not

37. The Harberger triangle is the area between the supply and demand curves, both constructed excluding taxes, and to the right of actual quantity.

be traded internationally.[38] In most cases, models with the highest permit prices find the highest direct costs, while models with the lowest permit prices find the lowest direct costs.

The studies agree that the direct cost would be lower with unrestricted trading among Annex B countries. Even though trading would incur the cost of purchasing permits from abroad, the direct cost would amount to just 0.1 percent to 0.6 percent of GDP in 2010. International trading of permits reduces the direct cost because trading allows energy users to substitute purchases of foreign permits for more costly reductions in their own emissions. Restricting the trade of permits among Annex B countries would raise the direct cost.

Revising the Kyoto Protocol to permit global trading of permits would reduce total direct cost even further, to 0.1 percent to 0.3 percent of GDP. Although the United States would purchase more permits from other countries under this scenario, permit prices would fall by enough to reduce the cost of permit purchases from other countries. In addition, global trading of permits would reduce the amount of emissions that the United States would have to cut domestically, which would reduce domestic direct costs.

Synthesis of Results

Based on a synthesis of model results, the Kyoto Protocol would impose total direct costs of 0.2 percent to 0.4 percent of baseline GDP in 2010. The precise amount would depend on how the protocol was implemented. Direct cost would be lowest if no restrictions are placed on trade of permits among Annex B countries. In general, restrictions on permit trading mean higher permit prices and higher direct costs.[39] These estimates do not take account of pre-existing taxes on energy; accounting for such taxes increases direct cost by about 30 percent, to a range of 0.3 percent to 0.6 percent of GDP.

Without international trade of permits, total direct cost would be 0.4 percent of baseline GDP in 2010 if the United States had to meet the Kyoto cap for all greenhouse gases; and 0.5 percent of GDP if only carbon dioxide was capped. (These

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38. These calculations assume that there are no pre-existing taxes on energy, such as gasoline taxes. Such taxes increase the adverse impact of additional increases in the price of domestic energy, boosting direct cost. Without international trade of permits, pre-existing taxes boost estimates of the U.S. direct cost by almost a third.

39. With restrictions on permit purchases, the price the United States pays for foreign permits can be anywhere between the permit prices in permit-exporting countries and in the United States. If restrictions on permit purchases push this “import” price down far enough, total direct cost can fall while the permit price and domestic direct cost rise.

estimates do not take account of pre-existing taxes.) By contrast, unrestricted global trading of permits would reduce total direct cost to just 0.1 percent of GDP.

IMPACT ON U.S. GDP AND CONSUMPTION

In general, restricting emissions of greenhouse gases would reduce U.S. gross domestic product (GDP) and consumption. The precise amount is uncertain, and depends on the details of the proposal. Moreover, those losses could be significantly reduced—or possibly eliminated—if the government auctioned the emissions permits (instead of giving them away) and used the revenues from the auction to reduce marginal tax rates. This section and the next assume that permits are given away for free; the following section explores the implication of auctioning permits.

GDP is the total market value of goods and services produced domestically during a given period, and it is the broadest measure of a country's economic output. However, GDP is not a measure of the standard of living. Consumption is a better measure of the standard of living, although it is also imperfect because it does not include the value of non-market activities, like leisure. Nonetheless, estimates of the effects of Kyoto on GDP and consumption are useful benchmarks.

Restrictions on emissions could affect the economy through several channels. First, they would lower potential GDP because higher energy prices would raise the cost of capital (which would reduce investment in new plant and equipment) and lower the real wage (which would discourage work). Second, reduced energy usage would render existing labor and capital less productive, further reducing potential GDP. Third, higher energy prices might hurt the profitability of new investment in some countries more than in others, leading to changes in flows of capital among nations. Fourth, if permits were traded internationally, paying for foreign permits would divert resources from domestic investment and consumption. Fifth, the Federal Reserve might have to raise interest rates temporarily to curb inflationary pressures that stem from higher energy prices. Such interest rate hikes would lead to higher unemployment in the short run. Finally, if the government auctioned the permits, the additional revenue could be used to cut taxes or increase spending, which would affect the economy in different ways.[40]

40. In addition, higher energy prices could affect the pace of overall technological change. However, none of the studies cited in this paper examined this possibility.

Model Estimates of the Impact on U.S. GDP and Consumption

Estimates of losses in GDP and consumption vary widely among studies, depending on the model used and on the degree of international trading of permits assumed. Models that assume inflation and unemployment can vary from baseline levels generally find larger losses than models that do not. And all else equal, models that assume energy usage is very sensitive to prices have smaller losses in GDP and consumption than models that assume energy usage is insensitive.

Permit prices are a key determinant of GDP loss, so the fewer restrictions placed on international trading of permits, the lower the permit price, and the smaller the loss in GDP. International trade of permits also reduces losses in consumption, despite the transfer of income to other countries to purchase foreign permits. When permits are traded, prices of emission-producing goods and services are lower, which outweighs the negative effect on consumption of purchasing foreign emissions permits.

No International Trade of Permits. Every study finds that losses in GDP and consumption would be largest if carbon emissions were reduced without international trade of emissions permits. Among models reporting effects on GDP, the losses in 2010 vary from 0.4 percent to 4.2 percent of baseline GDP (see Table 5-1).[41] Total (private plus government) consumption falls 0.2 percent to 3.1 percent below baseline levels in 2010, except in the G-Cubed model, which shows a rise in consumption.[42] (That model finds that consumption is permanently above baseline levels, while GDP is permanently below baseline levels, a finding that seems implausible.)

Losses in GDP and consumption are generally larger in studies using macroeconometric models than in studies using general equilibrium models. The larger losses come from one of two mechanisms. In some macroeconometric models, higher energy prices lead the Federal Reserve to raise interest rates, dampening demand, raising unemployment, and reducing output. The same mechanism also slows investment and productive capacity. In the DRI model, another mechanism operates: the rise in energy prices directly slows consumption growth by reducing consumers' real incomes without any rise in interest rates.

Among the general equilibrium models, the CETA and JWS models find unusually large GDP losses given their estimates of the permit price (Figure 5-1). In the JWS model, this result is due to a much larger decline in labor supply in response to lower

41. The EPPA, SGM-Administration, SGM-PNNL and WorldScan studies do not report changes in GDP.

42. Many modelers treat private consumption, government consumption and government investment together. This is a close approximation of total consumption. In 1999, 81 percent of government consumption and investment was government consumption.

real wages than that of other models. However, it is unclear why GDP loss is larger in the CETA model than in the MERGE model, since both models use similar assumptions. Among studies using macroeconometric models, Oxford has the smallest GDP losses relative to permit price because Oxford assumes that the reduction in GDP needed to prevent higher inflation is completed before 2010. As a result, by 2010 the relationship between permit price and GDP in the Oxford model is similar to that in the general equilibrium models.

The percentage reduction in consumption is usually smaller than the percentage reduction in GDP. One reason is that the decline in GDP partly mirrors a decline in productive capacity. This means that a smaller share of GDP needs to be devoted to replacing depreciated capital, and that a larger share can go toward consumption. In addition, reduced rates of return cause people to save a smaller share of their income, further softening the impact of lower GDP on consumption. So the general equilibrium models in which lower investment accounts for the largest share of GDP loss (CETA, MS-MRT and RICE) find unusually small losses in consumption given the change in GDP.[43] However, the difference between the percentage declines in consumption and GDP is less apparent in the macroeconometric models, because the more the Federal Reserve would have to raise interest rates in order to subdue inflation, the more equity prices would fall, and the larger would be the decline in consumption. Also, higher interest rates would boost saving, further reducing consumption.

<u>International Trading of Permits.</u> Allowing international trading of permits would reduce the losses in U.S. GDP and consumption associated with reducing greenhouse gas emissions. Permit trading allows the United States to achieve some of its emissions reductions in other countries, where those reductions are cheaper. Every study finds that, under unrestricted permit trading, the reduction in the cost of domestically allocated permits overwhelms the cost of permits purchased from abroad (see Table 5-2). Losses in GDP and consumption would be lowest with global permit trading, because permit prices would be lowest. Limiting trade to a smaller area, as under the Kyoto Protocol, would boost losses, but they would still be far smaller than with no trade. Restricting purchases, so that the U.S. permit price did not equal the international price, would remove many of the benefits of permit trading.

With unrestricted permit trading among Annex B countries, the models estimate that the GDP loss in 2010 would range between 0.2 percent and 2.0 percent of baseline

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43. These models and JWS have the largest ratios of GDP loss to direct cost. Any loss not coming from direct cost must come from lower investment or lower labor supply. In JWS, these other losses come primarily from lower labor supply. In CETA, MS-MRT and RICE, which hold labor supply constant, they come from lower investment.

GDP if permits are not auctioned (see Table 5-3).[44] Those losses are roughly half as large as they would be if permits could not be traded among Annex B countries. Allowing unrestricted global trading of permits would reduce GDP loss further, to between 0.1 percent and 1.0 percent of baseline GDP. Macroeconometric models show larger losses than general equilibrium models.

With unrestricted permit trading among Annex B countries, estimates of the loss in consumption in 2010 range from 0.1 percent to 1.7 percent of baseline levels, also about half as large as they would be without permit trading. (G-Cubed is again the exception; in that model, consumption rises 0.7 percent above baseline levels). Allowing unrestricted global trading of permits would reduce this range to 0.1 percent to 0.9 percent of baseline levels. For most models, the change in consumption is more closely correlated with the change in GDP plus payments for foreign permits than with the change in GDP alone. Permit purchases reflect a loss of purchasing power not captured by GDP.

Restricting international trade of permits would increase the losses to GDP and consumption, because it would push up permit prices and energy prices. The MS-MRT study finds that restricting permit purchases from other countries to 30 percent of the difference between a country's baseline emissions and its cap would boost the loss in U.S. GDP from 0.8 percent to 1.2 percent of baseline GDP in 2010. Removing restrictions on purchases but preventing the former Soviet bloc countries from selling "hot air" would boost U.S. GDP loss to 1.1 percent of baseline GDP in 2010. According to the MERGE model, adding restrictions on U.S. purchases of emissions permits could erase the benefits of an expanded permit market. Exact losses would depend on the price that U.S. importers of permits paid foreign sellers, a price that could fall anywhere between the domestic U.S. price and the domestic price in permit-selling countries. If the price of imported permits equaled the domestic price in permit-selling countries—a "buyers' market"—U.S. GDP loss (0.6 percent of baseline GDP) would be somewhat smaller than if sellers of permits could charge U.S. buyers the same price they paid for domestic permits (0.7 percent of baseline GDP)—a "sellers' market."[45]

44. Most models treat U.S. purchases of foreign permits as a financial transaction, which is excluded from the GDP accounts. The model synthesis estimates also follow this practice. However, the MERGE model treats permit purchases as an import of a service, which thus subtracts from GDP.

45. One should treat the MERGE model's estimates of GDP loss under international permit trading with caution. That model treats purchases of permits as an import, and thus a charge against GDP. This exaggerates GDP loss under international permit trading, and exaggerates the difference in GDP between the buyers' and sellers' markets.

Impact on U.S. GDP and Consumption: Model Synthesis

According to a synthesis of model results (see Appendix B), the Kyoto Protocol would reduce U.S. GDP in 2010 by 0.5 percent to 1.2 percent below its baseline level and U.S. consumption in 2010 by 0.4 percent to 1.0 percent below baseline, depending on how the treaty were implemented (see Table 5-4). (Incorporating uncertainty about the price sensitivity of emissions expands these ranges to a GDP loss of 0.4 percent to 1.5 percent and a consumption loss of 0.3 percent to 1.3 percent.) Without any international trade of emissions permits, U.S. GDP would decline by 1.7 percent to 1.8 percent and U.S. consumption by about 1.2 percent in 2010. By contrast, U.S. GDP and consumption would each decline just 0.2 percent below baseline levels in 2010 with unrestricted global trading of permits.

GDP loss is closely tied to permit prices through their impact on prices of energy and other emission-producing goods and services: the larger the impact on energy prices, the greater the GDP loss. Thus GDP loss is smallest with unrestricted global trading of permits and largest with no international trade of permits. Within the scenarios that are consistent with the Kyoto Protocol, restrictions on international trade of permits raise domestic permit prices and magnify the losses to GDP and consumption. The percentage change in consumption is smaller than the percentage change in real GDP, for the same reasons discussed above.

In the case of no international permit trading, the model synthesis produces estimates of GDP loss that are larger than those from most general equilibrium models, but smaller than those from macroeconometric models. The general equilibrium models do not consider the potential impacts of higher unemployment and lower capacity utilization on GDP, which the synthesis includes. However, the synthesis assumes that the adverse effects of higher unemployment and lower capacity utilization are smaller and spread out over a longer period of time than most macroeconometric models do.

With ideal implementation of international permit trading, the model synthesis produces estimates of GDP loss comparable to those from general equilibrium models, and smaller than those from macroeconometric models. On average, the positive impact of a smaller required reduction in Annex B emissions (and thus a lower permit price) on GDP in the synthesis estimates is offset by the impact of higher unemployment and lower capacity utilization in those estimates.

In the case of a cartel of permit-exporting countries, the size of the GDP loss would depend on the strategy followed by those countries. The figures in Table 5-4 assume that the countries of the former Soviet bloc sell just enough permits to keep their own domestic permit price at half the level of the international price. If, instead, those countries attempted to maximize their gross national income—roughly, GDP plus permit revenues—by selling only their unused permits (known as hot air), losses would be somewhat larger. U.S. GDP would fall by 0.7 percent below baseline levels in 2010, and U.S. consumption would fall by 0.6 percent.

With restrictions on permit purchases, losses in GDP and consumption would be nearly the same under global trading as under Annex B trading, because permit prices in the United States would be the same in both cases. A difference would arise only because the price that the United States paid for foreign permits would likely be lower under global trading, reducing the loss in U.S. income. That price could be anywhere between the domestic permit price in the United States ($122 per metric ton of carbon) and the domestic price in permit-exporting countries (zero), and would depend on the relative bargaining power of buyers and sellers of permits. Since global trading would increase the number of countries selling permits, the bargaining power of buyers would rise, pushing down the price of imported permits and losses in GDP and consumption.

If restrictions were placed on permit purchases and the import price of permits equaled the domestic permit price of $122 per tonne, GDP would fall by 1.0 percent below baseline levels and consumption would fall by 0.8 percent. On the other hand, if the domestic permit price remained unchanged but the price of foreign permits was zero, GDP would fall by 0.9 percent and consumption would fall by 0.6 percent. (The difference in consumption is larger than the difference in GDP because permit imports reduce income, which affects consumption directly but affects GDP only through reduced saving.) The synthesis estimates for restrictions on permit purchases assume that the price of imported permits is zero with global permit trading and halfway between zero and $122 per tonne with Annex B trade of permits.

Among the Kyoto-consistent scenarios, losses in GDP and consumption are somewhat higher under restrictions on permit sales than under restrictions on permit purchases. This is at least partly due to the specific restrictions on sales and purchases chosen. If, for example, the restriction on permit purchases were tightened so that the United States was required to achieve at least 75 percent of its obligation to reduce emissions domestically, then losses in GDP and consumption would be larger than with a prohibition on sales of hot air. Similarly, a looser restriction on permit sales would reduce losses in GDP and consumption in that case below those in the case of restrictions on permit purchases.

Although losing offsets from emissions of greenhouse gases other than carbon dioxide would boost permit prices significantly, it would increase losses to GDP and consumption only slightly. This is because the total number of permits required would fall, since permits would no longer be required for activities that produced greenhouse gases other than carbon dioxide. Losses in GDP and consumption due to reductions in carbon dioxide would rise, but losses due to reductions in other greenhouse gases would be eliminated.

In every scenario, if the United States received credits for carbon sequestered through land use changes that occurred because of the Kyoto Protocol, then losses in GDP and consumption would be smaller than if no such credits were given. Such credits would push permit prices lower than they otherwise would be, and reduce the economic losses from that source. Partly offsetting this gain, GDP would fall by the value of the agricultural products that the reforested land would have otherwise produced, net of the value of farm inputs that would be freed for other uses.

Using revenues from a permit auction to cut tax rates would reduce losses in output and consumption (see Box 5-1). Unfortunately, results from the surveyed models were too few and too varied for me to construct a synthesis estimate of the impact of lower tax rates.

POTENTIAL IMPACTS ON INCOMES

The Kyoto Protocol could have a larger impact on the incomes of permit recipients and of producers and consumers of energy than on the overall level of income, with some households benefitting and some losing. The beneficiaries would be the recipients of emissions rights, if such rights were allocated free of charge, or the recipients of tax cuts or spending increases, if the permits were auctioned and the revenues used to cut taxes or increase spending. The losers would be consumers who paid more for energy and for goods and services produced using energy, and energy producers whose incomes decline from lower demand for their products.[46] Many households would find themselves both winners as stockholders or taxpayers and losers as consumers or energy producers. (In addition, taxpayers would have to cover the higher cost of government purchases and transfers, but would benefit from higher profits taxes if emissions rights were allocated to companies free of change.)

The JWS model is the only one that directly addresses the potential distributional impact of emissions reductions. It finds that wealthy households gain more or lose less than poor households.

46. If greenhouse gases other than carbon dioxide are also capped, then the losers also include consumers of goods and services whose production causes such gases to be emitted, as well as the producers of those goods and services.

BOX 5-1

THE ECONOMIC IMPACT OF AUCTIONING PERMITS

Economic losses could be smaller than estimated in the previous section if permits were auctioned and the revenues used to cut tax rates in ways that improved incentives to work and save. However, the amount by which economic losses are reduced by permit auctions would depend on exactly how auction revenues were used. Studies disagree on the effects different methods of recycling revenues would have. In addition, because the policy discussion has focused on permits given away for free, few studies have looked at the implications of permit auctions. It is thus difficult to determine what the effects of a particular use of auction revenues would be.

In the absence of international permit trading, the JWS model indicates that if auction revenues were used to finance a cut in the corporate tax rate, the GDP loss from reducing emissions to 1990 levels in 2010 would fall from 1.1 percent of baseline GDP with permits given away for free to 0.4 percent. The consumption loss would fall from 0.6 percent to 0.1 percent of the baseline. Although reductions in emissions would still reduce investment below baseline levels, cutting taxes on corporate income significantly eases the impact.

The JWS model also finds that if auction revenues were used to finance a cut in marginal tax rates for individuals, labor hours would jump by 1.1 percent, GDP by 0.4 percent, and private consumption by 0.7 percent above baseline levels in 2010.[47] This result assumes that labor supply responds strongly to real wages and that the policy would raise the marginal after-tax wage rate.[48]

In a paper examining the impact of recycling auction revenues through a cut in the personal tax rate, Parry, Williams and Goulder find much smaller positive effects from recycling than the JWS model does.[49] Although recycling still has a positive impact, it is not enough to overcome the negative impacts of higher energy prices. Those authors find that revenue recycling reduces the direct cost of achieving a 25 percent reduction in emissions (about the same size as the reduction in the JWS study) to roughly half of what it would be if permits were not auctioned.

47. Total consumption (public plus private) would rise 0.9 percent above its baseline level, a larger percentage than private consumption alone. In the JWS model, tax rates are exogenous, so government spending adjusts to hold the deficit at baseline levels. Higher GDP thus boosts government spending, while lower GDP reduces government spending. The SGM model follows the same practice.

48. In addition, it appears that the JWS study may understate the rise in consumer prices, and thus the fall in real wages, from a rise in permit costs. The JWS study reports that permits would add $1.20 per million Btu (1996 dollars) to prices of refined petroleum in 2010. Starting from EIA's baseline price for refined petroleum of $7.94 per million Btu (1996 dollars) in 2010, a $1.20 per million Btu carbon charge would boost the price of refined petroleum by 15.1 percent. (This increase is likely an underestimate of the percentage impact of permit costs on refined petroleum prices in the JWS study, both because the EIA baseline includes gasoline taxes, which are not included in the output price for the refined petroleum industry used by JWS, and because the real price index for refined petroleum falls between 1996 and 2010 in the JWS study but is roughly unchanged in the EIA study.) The JWS study finds that non-permit costs of petroleum refiners fall 4.0 percent. Adding the 15.1 percent rise in permit costs would mean a 10.5 percent rise in the price of refined petroleum. However, the JWS study finds that the price of refined petroleum rises just 3.8 percent. Consumer prices of items containing refined petroleum may thus be understated.

49. Ian W. H. Parry, Roberton C. Williams, III and Lawrence H. Goulder, "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets," *Journal of Environmental Economics and Management*, vol. 37, no. 1 (1999), pp. 52-84.

BOX 5-1
(continued)

The JWS model and the Parry, Williams and Goulder model assume that workers are more responsive to changes in the marginal after-tax wage than empirical work examined by CBO does.[50] On the other hand, most of the other models assume there is no response at all. Thus, most models would find a much smaller beneficial impact from a cut in personal tax rates than these two models.

The EIA study finds that using auction revenues to reduce Social Security tax rates of both employers and employees would cut GDP losses by almost half. Reducing employer-paid Social Security tax rates would cut labor costs and thus prices, which in turn would offset about half of the increase in consumer prices from higher energy prices. With lower inflation, the Federal Reserve would not have to tighten as much and unemployment would not rise as much. In addition, a lower Social Security tax for workers would raise their after-tax real wage, causing them to increase their labor supply. The net result is that losses in GDP and consumption would be much smaller than if the permits were given away for free.

Using the same macroeconomic model as EIA, DRI finds that, in the absence of international permit trading, the gain from recycling permit revenues would be smaller if the revenues were used to increase the federal surplus than if they were used to cut marginal tax rates. The positive effects from increasing the surplus stem from the boost to national saving. However, national saving would not improve by much. While federal government savings would rise, business saving (profits) would fall because businesses would no longer receive permits free of charge. Without international trade of permits, DRI estimates that losses in both GDP and consumption in 2010 would only be 0.2 percent smaller than if permits were given away for free.

Only two studies examine the implications of permit auctions with international trading of permits. The EIA study finds that using the auction revenues to cut the Social Security tax rate would reduce losses in GDP and consumption by roughly half in scenarios that correspond to Annex B trading of permits and global trading of permits. Parry, Williams and Goulder find that auctioning permits and using the revenues to cut personal tax rates would reduce the direct cost of achieving a 15 percent reduction in U.S. emissions by just over 50 percent of what it would be if permits were not auctioned.

End of Box

An analysis of which households gain and which households lose and how much they gain or lose is beyond the scope of this paper. (CBO has analyzed that issue in another study.[51]) However, it is easy to estimate how much could be redistributed. The total amount gained is just the value of permits issued to U.S. households, directly and indirectly, which is the volume of permits issued (the emissions cap) multiplied by their price. (With restrictions on permit purchases from abroad, the value of import quotas would also be part of the gains.) The amount lost is the value of permits issued plus the value of permits purchased from abroad, less losses by

50. Congressional Budget Office, *Labor Supply and Taxes*, CBO Memorandum (January 1996).

51. Congressional Budget Office, *Who Gains and Who Pays Under Carbon-Allowance Trading? The Distributional Effects of Alternative Policy Designs* (June 2000).

foreign energy producers. In every study, the value of permits issued and used is larger than the change in GDP. Consumers, rather than energy producers, bear the lion's share of the losses. However, consumer losses are more evenly distributed across the population than producer losses are.

Winners: The Value of Permits Allocated

The studies indicate that the value of permits issued in the United States would be large (see Table 5-5). With unrestricted trading of permits among Annex B countries, the models find that the value of permits issued would be between $32 billion and $281 billion (in 1997 dollars) in 2010. Eliminating international trade of permits would boost permit prices, raising the value of permits issued to $114 billion to $524 billion. Global trading of permits would reduce permit prices, reducing the value of permits issued in the United States to $17 billion to $105 billion. Those amounts would go to recipients of the permits if permits are distributed free of charge, or to the recipients of tax cuts or spending increases if the permits are auctioned and the proceeds used to cut taxes or increase spending.

Using the synthesis model, I estimate that the value of permits allocated to the United States under the Kyoto Protocol would range from $86 billion to $223 billion (in 1997 dollars) in 2010, or 0.7 to 1.8 percent of GDP, depending on how the protocol was interpreted and implemented (see Table 5-6). The lower estimate is almost 7 percent as large as CBO's January 2001 projection of revenues from individual income taxes in 2010, and 36 percent as large as CBO's projection of revenues from corporate income taxes. The upper estimate is 17 percent as large as CBO's projection revenues from individual income taxes in 2010, and 94 percent as large as CBO's projection of revenues from corporate income taxes. Thus, with restrictions on permit sales by the former Soviet bloc and no offsets from reductions in other greenhouse gases, receipts from a permit auction would be large enough to finance a 17 percent reduction in tax rates on individual income.

If a limit were placed on permit purchases, a quota system would be needed to hold permit purchases below the limit. In that case, the total value of permits issued would include the value of emissions permits and the value of import permits (quotas). The value of each quota would equal the difference between the U.S. permit price and the price charged by the foreign seller. The latter price could be anywhere between zero and the U.S. price of emissions permits, putting the value of quotas between zero and $25 billion (in 1997 dollars), according to a synthesis of model results. (That estimate assumes that the United States would be constrained to achieve at least 65 percent of its Kyoto obligation with cuts in domestic emissions.)

Without international trading of permits, the value of permits would rise to $331 billion (1997 dollars) in 2010, or 2.7 permit of GDP, 25 percent as large as CBO's January 2001 projection of revenues from individual income taxes in 2010, and 39 percent larger than CBO's projection of revenues from corporate income taxes. If the Kyoto Protocol were amended to include all countries, however, the value of permits would be much smaller. The value of permits would be smaller than under the existing Kyoto Protocol, as long as significant limits were not put on U.S. purchases of foreign permits.

Losers: The Value of Permits Used

These gains would come at the expense of energy producers and households consuming goods and services whose production or use causes greenhouse gases to be emitted. Consumers would suffer most of these losses. Under the Kyoto Protocol, higher prices for U.S. consumers would account for between 94 percent and 96 percent of the value of permits used, and income losses by energy producers would account for the remaining amounts.[52] Moreover, if restrictions on permit trading were imposed, permit prices would rise proportionately more than crude oil prices fall, so that the consumer share of the total loss would also rise. Thus, eliminating international trade of permits would boost consumers' share of the loss to 96 percent of the value of permits used, while unrestricted global trading of permits would reduce it to 90 percent.

Foreign producers would absorb more than half of producers' share of losses. The biggest source of loss for producers would be lower oil prices. (The United States is projected to import more than two thirds of the crude oil it uses in 2010.) Both domestic and foreign refiners would have excess capacity and would be forced to trim their margins. The price of coal would also fall, resulting in lower incomes for miners and mine owners. On the other side, if usage of natural gas rose, natural gas prices would rise, raising incomes of natural gas producers. Most natural gas used in the United States is also produced here, so this factor would primarily help raise U.S. incomes.

With international trade of permits, wealth would be transferred from the United States to other countries, on net. That is, the value of permits purchased from abroad would greatly exceed the drop in foreign income from lower prices for fossil fuels consumed in the United States. Without international trade of permits, payments for foreign permits would disappear, but there would be a small net inflow from foreign

52. This includes only lower margins of energy producers, e.g., lower wage rates for coal miners who retain their jobs and lower profit margins for oil producers. It does not include reductions in incomes of labor and capital no longer employed in the energy industry, such as laid-off coal miners or abandoned coal mines. These are not redistributed to anyone, but are simply lost.

crude oil producers to U.S. consumers of petroleum products. As noted above, however, the transfer from domestic energy consumers to permit recipients would grow significantly.[53]

53. The issue of net transfers is complicated by foreign ownership of stock in U.S. companies that receive permits and domestic ownership of stock in foreign companies that receive permits.

APPENDIX A
THE PRICE SENSITIVITY OF EMISSIONS AND THE PRICE OF CARBON-ENERGY

The price sensitivity of carbon emissions measures how carbon emissions change in response to changes in the price of carbon-energy due to emissions charges. The price of carbon-energy is the price that users of energy generated from coal, oil and natural gas pay per metric ton of carbon embodied in these fuels and emitted when they are burned. This appendix defines these concepts in more detail, shows how they are used in this study and how they were calculated from the models' results.

Price Sensitivity of Carbon Emissions

The price sensitivity of carbon emissions equals the logarithm change in carbon intensity (carbon emissions divided by real GDP), divided by the logarithm of one plus the ratio of the permit price to the baseline price of carbon-energy. This is equivalent to dividing the logarithm change in carbon emissions minus the logarithm change in GDP by the logarithm of one plus the ratio of the permit price to the baseline price of carbon-energy. Mathematically,

$$s = \left[\ln\left(\frac{E_{final}}{GDP_{final}} \right) - \ln\left(\frac{E_{baseline}}{GDP_{baseline}} \right) \right] \Big/ \ln\left(1 + \frac{T}{P} \right)$$

$$= \left[\ln\left(\frac{E_{final}}{E_{baseline}} \right) - \ln\left(\frac{GDP_{final}}{GDP_{baseline}} \right) \right] \Big/ \ln\left(1 + \frac{T}{P} \right),$$

where s is price sensitivity, E is carbon emissions, T is the permit price, and P is the baseline price of carbon-energy. Price sensitivity is a negative number.

Logarithms are preferred to percentage changes because the percentage increase in the price of carbon-energy needed to reduce emissions by a given percentage amount rises as the level of emissions falls. That is, doubling the permit price leads to less than a doubling of the amount of carbon emissions mitigated.

If one knows price sensitivity, one can rearrange the above formula to determine the level of emissions produced at a given permit price:

$$E_{final} = E_{baseline} \times \left(\frac{GDP_{final}}{GDP_{baseline}} \right) \times \left(1 + \frac{T}{P} \right)^{s}.$$

Alternatively, the same formula can be rearranged to show what permit price is required to achieve a given reduction in emissions:

$$T = P \times \left\{ \left[\left(\frac{E_{final}}{E_{baseline}} \right) \Big/ \left(\frac{GDP_{final}}{GDP_{baseline}} \right) \right]^{\frac{1}{s}} - 1 \right\}.$$

The definition of price sensitivity assumes that, all else equal at a given time, emissions are proportional to real GDP. That is, an extra one percent of GDP will push emissions up one percent. Most economic models make assumptions about energy usage that guarantee a similar result. For the models that do not report GDP—EPPA, SGM and WorldScan—I used direct cost as an estimate of the loss in real GDP in calculating price sensitivity. Direct cost almost certainly understates the actual loss in GDP, and thus leads to an overstatement of price sensitivity in these models. That is, the less of the reduction in emissions explained by lower GDP, the more explained by higher energy prices.

The price sensitivity of carbon emissions is similar in many ways to a demand elasticity for carbon-energy, but there are two important differences. First, the price sensitivity of emissions captures both changes in demand for carbon-energy and substitutions between fuels with different carbon contents. Second, price sensitivity measures the response of emissions to the permit price, rather than to changes in the price of carbon-energy, and thus includes supply effects. Differences in supply prices (the price of energy excluding permit costs) cause differences between the permit price and the change in the price of carbon-energy. For example, if lower demand causes the price of crude oil to fall, the change in the price of carbon-energy will be smaller than the permit price. The first factor will make the price sensitivity of carbon emissions larger than the elasticity of demand for carbon-energy, while the second factor will partially offset this effect.

The Baseline Price of Carbon-Energy

The price of carbon-energy is calculated from the prices paid by the end users of energy. Except for the case of fuel-switching by electric utilities, the amount of emissions produced is determined by these end users. For example, motorists base their decisions on the type of car to buy and how much to drive it on the price they pay at the pump. The price of crude oil will affect their consumption of gasoline, and the emissions from it, only to the extent that it affects the retail price of gasoline. Similarly, consumers of coal-based electricity will base their usage of electricity on the price of that electricity, not on the price of the coal used to make it, except to the extent that the coal price affects the electricity price.

The baseline price of carbon-energy must be aggregated from the prices of many individual energy products, such as gasoline, diesel fuel, jet fuel, heating oil, delivered natural gas, and electricity, each with their own price per metric ton of emissions.

Since emissions data are only available by fossil fuel type and by broad industrial category from any of the models, the first step in the aggregation is to create a price of carbon-energy for each fuel—coal, natural gas and petroleum. This is done by dividing total dollars spent on final energy from each fuel by emissions from that fuel.

The second step aggregates prices of energy from each fuel into a single price of carbon-energy that can be used in calculating the price sensitivity of emissions. For this purpose, I assume that the price sensitivity of each fuel, excluding substitution between fuels, is equal, and that the effect of substitution between fuels on emissions can be captured mathematically by an expression that relates the permit price to the overall price of carbon-energy. That is,

$$\frac{E}{GDP}\left(1+\frac{T}{P}\right)^{s}=\frac{E_c}{GDP}\left(1+\frac{T}{P_c}\right)^{r}+\frac{E_n}{GDP}\left(1+\frac{T}{P_n}\right)^{r}+\frac{E_p}{GDP}\left(1+\frac{T}{P_p}\right)^{r}+z\,\frac{E}{GDP}\left[\left(1+\frac{T}{P}\right)^{x}-1\right],$$

where r is the price sensitivity of emissions of each fuel, excluding the effects of substitution between fuels, the subscripts c, n and p denote coal, natural gas and petroleum, respectively, and E_i and P_i denote baseline emissions from fuel i and the baseline price of energy from fuel i. The parameter z is a rough approximation of the total share of emissions that can be eliminated by fuel substitution, and the parameter x governs how this substitution relates to the permit price. Each side of the equation is an expression for economy-wide emissions intensity (the ratio of emissions to GDP).

Because the above equation is nonlinear, there is no single P that, given the prices for each fuel, will satisfy this equation exactly for all permit prices T. For the sake of simplicity, this study defines the equation to hold around a permit price of zero. In other words, starting from a permit price of zero, the baseline price of carbon-energy is defined so that the left- and right-hand sides of the equation both produce the same ratio of emissions to GDP for small increases in the permit price. Taking derivatives of both sides of the above equation with respect to T, and then setting T to zero yields the following equation:

$$(s-xz)\frac{E}{GDP}\frac{1}{P}=r\,\frac{E_c}{GDP}\frac{1}{P_c}+r\,\frac{E_n}{GDP}\frac{1}{P_n}+r\,\frac{E_p}{GDP}\frac{1}{P_p}.$$

The reduction in overall emissions intensity (from s) less the reduction in emissions intensity from substitution effects (from xz) equals the reduction in emissions intensity from higher costs of using each type of fuel (the right-hand side of the equation).

An expression for P can be obtained by solving this equation for P and setting s equal to r plus xz, i.e., s-xz=r. Thus,

$$P=\left(\frac{E_c}{E}P_c^{-1}+\frac{E_n}{E}P_n^{-1}+\frac{E_p}{E}P_p^{-1}\right)^{-1},$$

a CES (constant elasticity of substitution) weighting of energy prices, with the substitution parameter equal to 1. The baseline price for carbon-energy is the reciprocal of a weighted average of the reciprocals of the prices of energy from each fuel.

The same formula is used to aggregate baseline energy prices across countries. In this case, the subscripts refer to countries instead of fuels. The baseline price is the reciprocal of a weighted average of the reciprocals of the prices of energy from each country. This aggregation assumes that the price sensitivity in each country being aggregated is the same.

In theory, there are two reasons the results could be distorted, though any distortion seems likely to be small. First, as the permit price rises and emissions fall, the relative weight of the higher-cost fuels rises, because reductions in the lower-cost fuels are disproportionately large. Second, as the permit price rises, opportunities for further reductions in emissions from fuel-switching disappear faster than opportunities for further reductions in final use of carbon-energy. Both of these should tend to cause the estimated price sensitivity of emissions to decline as permit prices rise, and consequently the price sensitivity should be lowest when no permit trading is allowed. However, the models give mixed results: roughly one-third find this expected relationship, another third find that trading lowers price sensitivity, and another third find that trading has a negligible impact on price sensitivity (less than a 5 percent change).

Constructing the Baseline Price of Carbon-Energy for the United States. The price of carbon-energy is the price that users of energy generated from coal, oil and natural gas pay per metric ton of carbon emissions. For each fuel, I calculate this price by dividing the market value of the energy produced by that fuel by the carbon emissions generated by that fuel. For the non-electricity portion of the energy from each fuel, the market value is the amount of energy delivered to end-users times the average sales price of that energy. (For petroleum, I exclude the value of non-energy products such as asphalt, most plastics and motor oil, since these do not produce carbon emissions.) For the electricity portion, the market value for a given fuel is that fuel's share of the total inputs to electricity generation times the total market value of electricity. This implicitly assumes that electricity from every source is sold at the same price.

Several studies provide all or most of the data needed for these calculations. The EIA study and editions of the EIA's Annual Energy Outlook used by SGM-Admin and SGM-PNNL contain all the requisite data. The DRI and WEFA studies contain most of the data needed. Missing data on shares of each type of fuel going to various end uses were filled in using data from the EIA study.

Several other studies—those using the AIM, EPPA, G-Cubed, GTEM, JWS, MS-MRT and Oxford models—provide price indexes for electricity, refined petroleum (or gasoline) and natural gas, but incomplete or inconsistent data for quantities of fuels.[54] These prices are converted to prices for final users by assuming that real distribution costs and indirect taxes (most important in the case of refined petroleum) are constant in real terms.[55] Emissions and quantities of energy used are taken from EIA's Annual Energy Outlook 1998 (AEO98), which contains data very similar to that used in the EIA study. The estimated price of carbon-energy is not very sensitive to the choice of data source for emissions and energy use.

One model, RICE, contains its own measure of the price of carbon-energy. This equals the wholesale price of carbon-energy, which is assumed to be constant across all regions, plus a markup over the wholesale price, which varies by region. Historical values of the price of carbon-energy for the United States are somewhat larger than I calculate, while historical values for some developing countries are smaller.

Data for energy prices were not available for the studies using the CETA, MERGE and WorldScan models. For these general equilibrium models, I use the average price of carbon-energy from the eight general equilibrium models for which a price of carbon-energy can be calculated. (RICE is not included in this average, since its historical values are inconsistent with those assumed for the other models.)

Constructing Baseline Prices of Carbon-Energy for Other Countries. None of the studies contain energy forecasts for other countries with the same detail as that used to construct the baseline price of carbon-energy for the United States. To construct forecasts of the baseline price of carbon-energy for other countries, I essentially calculate historical differences in prices of carbon-energy between the United States and other countries, and then add these to the forecast for U.S. prices.

The International Energy Agency provides price data for electricity to households and industry, regular and premium gasoline, light fuel oil for industry, commercial and non-commercial diesel fuel, high sulphur fuel oil to industry, and natural gas to industry and households for several foreign countries.[56] Data for 1996, denominated in foreign currencies, are converted to U.S. dollar values using 1996 exchange rates.

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54. One study projects lower consumption of each fossil fuel in 2010 than the EIA study, but at the same time projects higher carbon emissions.

55. In the EPPA, price data are in units of efficiency labor. I assume that the price of efficiency labor rises at the same rate as the GDP price index.

56. International Energy Agency, *Energy Prices & Taxes: Quarterly Statistics*, no. 1 (1999). Countries covered include the United States, OECD Europe (including the Czech Republic, Hungary and Poland), Australia, Canada, China, India, Indonesia, Japan, Kazakhstan, South Korea, Mexico, New Zealand, Romania, Russia, Slovakia, South Africa, Taiwan, Thailand, Turkey and Venezuela.

Value added tax is removed from prices subject to it.[57] For each country, prices per Btu of fossil fuel for various end uses of that fuel are weighted together using EIA data on end use consumption by country, or using U.S. weights where country data are missing. For countries for which price data is unavailable, price data from similar countries or countries in the same region are used.[58] These steps produce estimates of the price of energy per Btu of fossil fuel by fuel and by country for 1996.

To obtain the price of carbon-energy by fuel and country, I then multiply these estimates by the U.S. ratio of the price of energy per metric ton of carbon to the price of energy per Btu, for each fuel. These estimates of the price of carbon-energy for each fuel by country are then aggregated to estimates of the price of carbon-energy for each fuel for broader regions using the same formula used to aggregate the price of carbon-energy across fuels.

To obtain model-specific forecasts of the baseline price of carbon-energy in 2010, it is assumed that the difference between foreign and U.S. prices of carbon-energy, by fuel, are the same in 2010 as in 1996. In other words, the differences obtained above for 1996 are added to each model's 2010 estimate for the price of carbon-energy, by fuel. (In cases where differences lead to unrealistically low prices in China and the former Soviet Union, a multiplicative adjustment is made.) These prices are then aggregated across fuels using the CES aggregation formula developed above, to obtain estimates of the baseline price of carbon-energy for Annex B and the non-Annex B countries. Finally, these estimates are converted to 1997 dollars.

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57. The value added tax (VAT) would be applied to the permit component of final energy prices, just as it is to the non-permit (baseline) components of energy prices. To make the baseline price comparable to the permit price, one therefore must remove VAT from both.

58. The Czech Republic, Hungary, Poland, Romania and Slovakia are used for unavailable eastern European countries, Kazakhstan and Russia are used for unavailable countries of the former Soviet Union, Indonesia, Thailand and Taiwan are used for missing Asian countries, excluding the Middle East, Brazil is used for missing Central and South American countries, South Africa is used for the rest of Africa, excluding the Middle East, and the oil exporters Indonesia, Mexico and Venezuela are used for the Middle East, excluding Turkey.

APPENDIX B
ORIGINS OF MODEL SYNTHESIS ESTIMATES

This appendix shows how the various estimates of the effects of emissions reductions on the U.S. economy were synthesized into a single estimate using a simple reduced-form model. The guiding principle of this model is to base its properties on the properties of the models wherever possible. In some cases, that principle meant making adjustments to models that made unrealistic assumptions. In other cases, it meant using only the subset of models that examined a particular issue, such as emissions leakage. In cases where modelers use other sources, it meant using updated projections from those sources.

Emissions Baselines and Caps

Few modelers claim special expertise in forecasting baseline emissions of carbon dioxide. Instead, many of them base their estimates on work done by the EIA. This paper uses the projections of carbon dioxide emissions from EIA's March 2000 report.[59] For consistency, I used estimates of carbon dioxide caps for the Kyoto protocol from the same publication. Because EIA's projections of emissions for many countries were lower in 2000 than they had been when modelers prepared their analysis in 1998, smaller percentage reductions in emissions are required in the model synthesis estimates than in most of the studies. Since 2000, however, EIA has revised its emissions projections up, pushing required reductions in emissions higher again.

Unfortunately, EIA does not project emissions of the five other greenhouse gases: methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons, and sulfur hexaflouride. However, studies from three modelers—EPPA, SGM-Administration and SGM-PNNL—do.[60] For Annex B countries, I used the average emissions baselines and Kyoto caps for other gases from those three studies. None of the studies provided estimates of other greenhouse gases for non-Annex B countries, but instead assumed that any extension of the Kyoto Protocol to include non-Annex B countries would exempt emissions of these gases in those countries. I made the same assumption.

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59. Energy Information Administration, *International Energy Outlook 2000*, DOE/EIA-0484 (March 2000).

60. The EPPA estimates are from John Reilly, Ronald G. Prinn, Jochen Harnisch, Jean Fitzmaurice, Henry D. Jacoby, David Klicklighter, Peter H. Stone, Andrei P. Sokolov and Chien Wang, *Multi-Gas Assessment of the Kyoto Protocol*, Report Series No. 45 (Cambridge, MA: MIT, Joint Program on the Science and Policy of Global Change, January 1999).

Forest Growth. Baseline estimates of greenhouse gases sequestered by cropland, grazing land and managed forests are based on country submissions to the United Nations Framework Convention on Climate Change.[61] The estimate of credits for carbon sinks in 2010 is the amount of carbon sequestered in the most recent year for which an estimate is available in that document. For most Annex B countries, this is 1998.

GDP and Emissions. The model synthesis uses CBO's January 2000 projection of real GDP for the United States, and EIA projections for other countries. Although CBO's projection for U.S. GDP in 2010 is nearly 9 percent higher than EIA's, it is difficult to determine whether CBO's higher GDP would imply higher emissions than EIA's. For example, if the extra output in CBO's projection stems from higher investment in computers and semiconductors, emissions would probably be similar to EIA's. Consequently, I simply used EIA's emissions projection without adjustments. A higher emissions projection would mean higher permit prices and greater losses in GDP and consumption, but a greater environmental benefit. The baseline price of carbon-energy was derived as described in Appendix A.

Price Sensitivity of Carbon Emissions

Every study surveyed in this paper estimates what permit prices would be in the United States without international trade of permits. Thus, this case provides a useful benchmark. I use estimates of price sensitivity from that benchmark to develop estimates of price sensitivity for the other trading scenarios and for other countries.

U.S. Price Sensitivity, with no International Trade of Permits. To develop an estimate of the price sensitivity of U.S. carbon emissions, I adjusted the price sensitivities of each model for known problems (if possible), and then took a geometric average of the resulting price sensitivities (see Table B-1). My adjustments attempt to deal with four types of problems found in some of the models:

- theoretical assumptions about responses to energy prices contradicted by the empirical evidence;
- reductions in carbon dioxide emissions that exceed the reduction in the consumption of carbon-energy;
- unrealistically large or small implied increases in nuclear and hydroelectric power; and
- responses to the expected rise in energy prices that either begin too late or are completed too quickly.

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61. United Nations Framework Convention on Climate Change, *Greenhouse Gas Inventory Database*, 2000 (available at www.unfccc.de).

Another possible factor that artificially inflates price sensitivity in at least one model, but is not explored here, is the treatment of lower coal exports as a reduction in U.S. emissions. Coal exports do not count as emissions under the Kyoto Protocol.

The G-Cubed, RICE and WorldScan models assume that the elasticity of energy demand is 1.0; that is, each one percent rise in energy prices produces a one percent fall in demand. This estimate of the elasticity of energy demand is much higher than that in the empirical literature. In G-Cubed, this assumption affects only final demand, through a Cobb-Douglas utility function. The RICE and WorldScan models use Cobb-Douglas production functions to determine energy demand throughout the economy.[62] Since price sensitivities in those two models depend entirely on this assumption, they are excluded from the synthesis calculations. G-Cubed uses estimated elasticities in industry production functions, and so provides some empirically-based information, but the adjustment required for the demand elasticities is large.

Several models assume that the percentage reduction in emissions can exceed the percentage reduction in carbon-energy. This assumption can take different forms. For example, some models assume that refiners can produce the same amount of gasoline by using more labor and capital and less crude oil. (If a model assumes that emissions are proportional to sales of refined products rather than crude oil, then unrealistic assumptions about crude oil usage do not affect estimated emissions or price sensitivity.) In the AIM and SGM models, such substitution can take place in both the petroleum refining and natural gas utility industries. In EPPA, the amount of substitution is greater, but it takes place only in the natural gas utility industry, which is lumped together with the electricity industry.

Emissions reductions can also exceed reductions in consumption of fossil fuels in models in which emissions from fossil fuels are assumed proportional to total sales of refined products, including intra-industry sales. The problem in these models is that intra-industry sales frequently do not generate emissions. For example, when gas utilities sell less gas to each other or coal mines buy fewer services from mining service companies, the total amount of emissions does not change. In the G-Cubed and JWS models, however, reductions in such sales are assumed to reduce emissions. Those models assume that firms cut back on intra-industry sales disproportionately as the permit price rises, which artificially reduces emissions. For example, in the G-Cubed model, total sales of coal fall by 45 percent in 2010 without international trade of permits, while non intra-industry sales of coal fall by just 40 percent. Thus, coal

62. DRI uses a Cobb-Douglas production function to determine the impact of labor, capital and energy on potential GDP, but not to determine the demand for energy. While this is internally inconsistent, it allows energy demand to be modeled consistently with the empirical evidence.

emissions are estimated to fall by 45 percent, even though net coal usage declines only 40 percent.

Any model that does not separate electricity by fuel source may inadvertently assume unrealistically large increases in electricity from non-fossil sources. In making my adjustments, I make the judgment that any increases in electricity from nuclear and renewable sources (e.g., wind and biomass) that are 50 percent larger than those found by EIA at a similar permit price in 2020 are unrealistically large. Instead, I assume that the additional electricity would be generated by natural gas instead. (Assuming generation by coal would increase the adjustment.) Such adjustments are required for EPPA, G-Cubed, and JWS. Although the MS-MRT model does not break out electricity by fuel source, it does not appear to imply unrealistically large increases in electricity from non-fossil sources.

Other models assume that nuclear energy remains at baseline levels when the costs of using fossil fuels rise, an assumption that seems somewhat unrealistic given that the lifetime of nuclear plants can be extended. To address this issue, I made small adjustments to estimates of price sensitivity from the DRI, GTEM, Oxford and WEFA models, by assuming the same increase in nuclear generation over baseline levels as in the EIA model.

The CETA, JWS, RICE and WorldScan models all assume that capital and labor can be adjusted immediately at no cost. In other words, businesses can change the energy efficiency of existing equipment at no cost, and can transform coal mines and mining equipment into nuclear power plants at no cost. Although such adjustments are nearly costless in the long run (when existing equipment has depreciated and decisions about new investment have to be made), they are not costless in the short run. I adjusted the estimates of price sensitivity in these models by the average ratio of price sensitivity in 2010 to that in 2020 for the other models (see Table 3-2). (This adjustment is conservative, since many models assume adjustments continue after 2020.) Such ratios range between 0.48 in the EPPA model, in which adjustment takes place most slowly, to 1.00 in the Oxford model, in which adjustments are not immediate but are nonetheless completed by 2010.

In its original study, EIA assumes that households and businesses outside the electric generating sector do not begin to respond to the prospect of higher energy prices until 2005. In a later study, EIA assumes those responses begin in 2000. For EIA, I use the estimate of price sensitivity derived from the latter study.

I use the geometric mean of the adjusted estimates of price sensitivity from all but the RICE and WorldScan models to develop an estimate for the model synthesis. That estimate is -0.536, which is lower than the geometric mean of the unadjusted estimates because most of the adjustments made to estimates from the studies reduce price sensitivity. To avoid counting the SGM model twice, results from the studies by the Administration and Battelle PNNL are averaged together. Although the CETA, MERGE and MS-MRT models share many parameters, the adjusted price sensitivities in these models are close enough to the model synthesis estimate that averaging these models would have little impact. DRI and EIA use the same model for GDP results, but they use different models for energy demand, and thus are treated separately.

<u>U.S. Price Sensitivity, with International Trade of Permits.</u> I use the same price sensitivity for the United States with permit trading as without permit trading. Although theory suggests that price sensitivity might be higher at lower permit prices (see Appendix A), the models provide little support for this proposition. On average, price sensitivity is 4 percent higher with Annex B trade of permits but 12 percent lower with global trade of permits than without international trade of permits. (These figures are not comparable, since fewer models examine global trade of permits than Annex B trade of permits.) One way to interpret this observation is that fuel substitution becomes more economical above a threshold permit price (somewhere around $100 per metric ton of carbon), but that opportunities for fuel substitution are slowly exhausted at higher prices. Since the variations in price sensitivity are small, I use a single estimate for all scenarios.

<u>Empirical Estimates of the Price Sensitivity of Carbon Emissions in the United States.</u> The estimate of price sensitivity thus derived from the models agrees closely with the available empirical evidence. In 1993, Carol Dahl surveyed estimates of energy demand elasticities from more than 400 studies, providing summary estimates of short-run and long-run own-price and cross-price elasticities for coal, oil, natural gas and electricity in the residential, commercial, industrial and transportation sectors.[63] I obtained medium-run elasticities by averaging the long-run and short-run elasticities. These elasticities were then combined with changes in energy prices from the EIA scenarios to determine what emissions would be if EIA's NEMS model used these elasticities instead of its own. (Fuel substitution in electricity generation was assumed to occur at the same rates as in EIA's early start study.) Using this emissions data, price sensitivities could then be calculated for the various scenarios consistent with Dahl's summary estimates of price elasticities.

The estimates of price sensitivity derived from this exercise are surprisingly close to those obtained from the models. Price sensitivity averages -0.53 over the EIA scenarios, about the same as the adjusted model average. As in the models, price sensitivity roughly equals this value with no international trade of permits (a permit

63. Carol Dahl, "A Survey of Energy Demand Elasticities in Support of the Development of the NEMS" (working paper, Colorado School of Mines, October 1993). In using the estimates from this survey, I set negative cross-price elasticities to zero, and reduced large positive cross-price elasticities so that they were equal in absolute value to the corresponding own-price elasticities.

price of about $350 per metric ton of carbon), is somewhat lower (-0.49) with global trade of permits (a permit price of $70 per metric ton), and is slightly higher (-0.55 to -0.56) in intermediate cases (permit prices of $130 to $300 per metric ton).

Those price sensitivity estimates assume that energy users begin to anticipate higher future energy prices in 2000 or 2001. If energy users began to anticipate higher energy prices at a later date, energy users would have less time to respond, and demand elasticities would be closer to the short-run estimates, pushing price sensitivity lower. On the other hand, if caps applied to 2020 instead of 2010, demand elasticities would be closer to the long-run estimates, pushing price sensitivity higher.

The Price Sensitivity of Carbon Emissions in Other Countries. The models disagree on whether price sensitivity in other Annex B countries would be lower or higher than in the United States. Most models assume price sensitivity would be lower in other countries, but some models, most notably GTEM and WorldScan, assume price sensitivity would be much higher in other countries than in the United States. Thus, while the median ratio of price sensitivity in overall Annex B to that in the United States is 0.89, GTEM and WorldScan push the geometric average ratio up to 1.02.[64] The geometric average of the ratio is 0.95 if one excludes those two models and the two models with the lowest ratios of price sensitivity in overall Annex B to that in the United States (RICE and SGM). That is the assumption used in the model synthesis.

The models also disagree about the price sensitivity in countries outside of Annex B. Some models (AIM, CETA and MERGE) assume price sensitivity would be much lower among non-Annex B countries than within Annex B, while SGM assumes it would be much higher. Other models looking at non-Annex B emissions with global trade of permits (G-Cubed, MS-MRT and RICE) assume price sensitivity outside Annex B would be no more than 11 percent above or below its value inside Annex B. On average, the models find price sensitivity somewhat lower outside Annex B than inside it.

In calculating model synthesis estimates, I assume that price sensitivity in both overall Annex B and in the non-Annex B countries is 95 percent as large as in the United States. In addition to the model evidence, theory suggests two reasons why price sensitivity should be lower outside the United States than inside it. First, because of their greater dependence on nuclear power, Japan and Europe have fewer opportunities for fuel substitution in the electricity industry. Second, energy users in the former Soviet bloc and the non-Annex B countries may not respond as readily to

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64. These figures do not include results from the study using the G-Cubed model. For the former Soviet bloc, that study uses results from the SGM model, which are not consistent with those that would be obtained using the G-Cubed model for this region.

changes in energy prices as energy users in the United States, who have a long experience with free markets.

Price Sensitivity of Emissions of Other Greenhouse Gases

While many economists have implicitly examined how carbon dioxide emissions respond to changes in prices of carbon-energy, few if any have studied how emissions of other greenhouse gases respond to changes in their price. The economic models surveyed in this paper take two approaches: either they assume that emissions of other greenhouse gases respond the same as emissions of carbon dioxide (SGM-PNNL), or they use technology-based estimates of how much emitters theoretically could reduce emissions at various prices (SGM-Administration and a recent study using EPPA[65]). Neither of these approaches seems appropriate. The first option makes no use of available information from technology-based studies; the second option treats the information from the technology-based studies as consistent with information on carbon emissions from economic studies.

This paper takes a different approach: I derive a synthesis estimate of the price sensitivity of emissions of other greenhouse gases by adjusting the price sensitivity of carbon emissions obtained from the economic studies by the ratio between estimates of price sensitivities of carbon dioxide and methane obtained from two representative technology-based studies. (Methane is the most important of the other greenhouse gases.) In other words, the percentage reduction in methane in one technology-based study is higher than the percentage reduction in carbon dioxide in another technology-based study, so I assume that the price sensitivity of other greenhouse gases is larger than the price sensitivity of carbon dioxide by a similar amount. This procedure assumes that the excess of price sensitivity in technology-based models relative to that in economic models is the same for all greenhouse gases.

A technology-based study of carbon emissions by five scientific laboratories finds that a permit price of $50 per metric ton of carbon equivalent produces a 23 percent reduction in emissions.[66] An EPA technology-based study of methane emissions finds

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65. John Reilly, Ronald G. Prinn, Jochen Harnisch, Jean Fitzmaurice, Henry D. Jacoby, David Kicklighter, Peter H. Stone, Andrei P. Sokolov and Chien Wang, *Multi-Gas Assessment of the Kyoto Protocol* Report No. 45 (Cambridge, MA: MIT, Joint Program on the Science and Policy of Global Change, January 1999). See also John Reilly, Monika Mayer and Jochen Harnisch, *Multiple Gas Control Under the Kyoto Agreement* Report No. 58 (Cambridge, MA: MIT, Joint Program on the Science and Policy of Global Change, March 2000).

66. Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies, *Scenarios of U.S. Carbon Reductions: Potential Impacts of Energy-Efficient and Low Carbon Technologies by 2010 and Beyond* (Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and Argonne National Laboratory,

that the same permit price yields roughly a 35 percent reduction in emissions.[67] Using EIA's baseline price of carbon emissions for the sake of comparability, these numbers imply price sensitivities of -1.66 for carbon dioxide and -2.74 for methane. Thus, I assume the price sensitivity for other greenhouse gases is 1.65 (2.74 divided by 1.66) times as large as the price sensitivity for carbon dioxide, or -0.88 for the United States.[68]

Range of Uncertainty for Estimates of Permit Prices

This study only examines the uncertainty in permit prices coming from uncertainty about the estimate of price sensitivity. (As explained in Chapter 2, errors in the forecast of baseline emissions would change both the costs and benefits of the Kyoto Protocol in the same direction.) This uncertainty is best measured by looking at standard errors from estimates of the elasticity of energy demand. Using the range of model estimates of price sensitivity would not provide a good measure of uncertainty, since differences in these estimates stem more from model assumptions than from uncertainty about how responsive energy users are to changes in the price of energy.

The range of uncertainty in permit prices presented in Chapter 2 roughly corresponds to one standard error above and below the estimate of price sensitivity. According to Dahl's study, the median standard error of estimates of all types of energy demand in the medium run is 0.07. Surprisingly, the average standard error between studies, roughly 0.13, is much larger. I use the average of these standard errors, 0.10, and then augment it to account for uncertainty about fuel substitution, which is not reflected in the elasticity of energy demand. Assuming that the error for fuel substitution is of the same magnitude as, but uncorrelated with, the error for total energy demand, the final standard error is somewhat less than 0.13. Reducing the absolute magnitude of price sensitivity of carbon emissions by 0.13, from -0.53 to

September 1997).

67. Environmental Protection Agency, Office of Air and Radiation, *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions* (September 1999). That study looks at reductions in methane that would be profitable with a permit price of $50 per metric ton of carbon equivalent on methane, but no price charged on the carbon dioxide emitted when the methane is burned. Under the Kyoto Protocol, such a charge would be imposed when methane from natural gas systems or coal mining is burned. The resulting carbon dioxide would cost $6.55 for each $50 of methane emissions prevented. For these sources, I use the percentage reduction in methane at a permit price of $43.45 per ton as the EPA estimate of methane reductions at a permit price of $50 per ton.

68. This estimate of the price sensitivity of other greenhouse gases is consistent with the use of the baseline price for carbon emissions. If the true baseline price for other greenhouse gases is lower than that for carbon dioxide, then price sensitivity for those gases is correspondingly lower.

−0.40, boosts permit prices by 34 percent, while a price sensitivity of -0.66 reduces permit prices 20 percent. The average error is thus 27 percent.

Impact of the Clean Development Mechanism

It is difficult to gauge how effective the clean development mechanism (CDM) would be in reducing emissions in non-Annex B countries. The only study that quantifies the impact, the study using MERGE, uses the EMF-16 assumption that 15 percent of the non-Annex B reductions made under global trading would be available as CDM projects under Annex B trading. I use this assumption in developing model synthesis estimates. CDM projects would then provide 43 mmtc of emissions reductions in the ideal implementation scenario.

Domestic Direct Cost

Domestic direct cost is calculated as the area under the marginal abatement cost curve. This curve plots the permit price against the corresponding reduction in domestic emissions, excluding reductions due to lower GDP. When accounting for the impact of pre-existing taxes in energy markets, the marginal abatement cost curve plots the permit price plus pre-existing taxes against the reduction in emissions. Eliminating pre-existing taxes reduces the U.S. baseline price of carbon from $298 to $264 per metric ton of carbon.

Impact on GDP

If restrictions were placed on emissions, GDP losses could flow from six sources:

- domestic direct cost;
- a lower capital stock because of higher prices for plant and equipment;
- impacts of capital flows;
- reduced labor supply;
- a lower capital stock because of the decline in income arising from buying permits from abroad; and
- impacts of higher interest rates on unemployment and the capital stock.

Unfortunately, the studies provide no estimates of the impact of any individual factor on GDP. Nonetheless, enough information can be gleaned from available model evidence to develop synthesis estimates of GDP loss.

Domestic Direct Cost and Higher Prices for Plant and Equipment. One can use GDP loss in general equilibrium models in the case of no international trade of permits as an estimate of the combined impact of domestic direct cost and higher prices for plant and equipment on GDP. Removing permit trading eliminates the effect of permit purchases from other countries. In addition, most general equilibrium models have small or nonexistent capital flows and exogenous labor supply and unemployment, so they effectively remove these effects on GDP. One exception is G-Cubed, in which the United States has a capital inflow and higher unemployment. However, those factors have roughly offsetting effects on GDP, so GDP loss yields a rough estimate of the effects of domestic direct cost and higher capital prices in this model as well. Another exception is the JWS model, which has large labor supply responses. In that model, the GDP loss combines the impacts of domestic direct cost, lower investment and lower labor supply.

With no international trade of permits, the geometric mean of the ratio of GDP loss to domestic direct cost is 2.5 in the general equilibrium models that report GDP, except JWS. These ratios range from 1.5 in AIM to 4.8 in CETA. However, as permit prices fall, domestic direct cost declines proportionately faster than the decline in investment. Thus, the ratio of GDP losses stemming from domestic direct cost and higher investment costs to domestic direct cost rises as permit prices fall. Consequently, a method other than a simple ratio to domestic direct cost must be used to determine the impact of domestic direct cost and higher investment costs on GDP when countries can trade permits. Fortunately, theory provides a way to quantify those two effects on GDP.

The loss in GDP stemming from domestic direct cost differs from domestic direct cost for three reasons. First, a portion of domestic direct cost reflects reduced consumer surplus, and thus does not affect GDP.[69] Second, domestic direct cost as calculated by the models ignores the impact of pre-existing taxes on energy, and thus understates the impact on GDP. These two factors happen to roughly offset each other in the case of no international permit trading, leaving a loss in GDP roughly equal to domestic direct cost. Third, however, this loss in GDP reduces income and thus saving, feeding back into investment and causing a further loss in GDP. Overall, the loss in GDP from domestic direct cost should be between 1.3 and 1.4 times as large as domestic direct cost.

The permit price affects investment through its impact on the cost of producing new plant and equipment. In the DRI model, a permit price that raises the overall price level by one percent boosts capital prices by a little more than 0.5 percent, and thus reduces the desired capital stock by roughly the same percentage. Using information on the effect of the capital stock on potential GDP and on the feedback effects of resulting changes in saving on investment, one can determine the impact of emissions restrictions on GDP through lower investment. For the case of no international trade

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69. In a model that uses chain-type aggregation to determine real GDP, real consumption can reflect changes in consumer surplus. None of the general equilibrium models use this type of aggregation, however.

of permits, this impact is between 1.1 and 1.2 times as large as domestic direct cost. Adding this to the effect from domestic direct cost produces a GDP loss about 2.5 times as large as domestic direct cost in the case of no international permit trading, the same as the estimate from the models.

Capital Flows. G-Cubed is the only model in which capital flows have a large impact on GDP. In the study using this model, the United States has lower permit prices than the other developed countries when there is no international trade of permits, and so draws capital flows from those countries. These flows boost investment, and thus GDP.

According to the model synthesis, however, only Japan would have a higher permit price than the United States when there is no international trade of permits allowed. And with Annex B trade of permits, only Australia, Canada and the former Soviet bloc would see a larger percentage increase in their overall price level, a plausible measure of the increase in the cost of doing business, and thus of the reduction in the return to capital. Thus, if anything, the Kyoto Protocol would likely lead to capital outflows from the United States. Given the difficulty of judging the size or effect of these flows, the possible impact of capital flows on GDP has been left out of the model synthesis.

Reduced Labor Supply. Most of the general equilibrium models assume that labor supply is exogenous—that is, it does not respond to changes in the marginal after-tax real wage. On the other hand, the JWS model assumes that labor supply is highly responsive to the marginal after-tax real wage, with an elasticity of about 1.0.[70] The actual response would be between these two extremes.

In a memorandum looking at the empirical evidence, CBO concluded that "a 10 percent increase in after-tax wages would raise total hours of work by between zero and 3 percent," indicating a labor supply elasticity of 0 to 0.3. The study went on to state that "those estimates may somewhat overstate the responsiveness of the economy's labor supply," because they did not account for how married men and women would respond to changes in a spouse's after-tax wage rate.[71] The labor supply elasticity in the DRI model, 0.06, falls in this range, although below its midpoint. Consequently, this estimate is used to calculate the change in labor supply and the resulting impact on GDP in the model synthesis results. Using the midpoint elasticity of 0.15 instead would boost estimates of GDP loss by about 15 percent.

70. Much of the large response of labor supply in the JWS model results from the assumption of a representative consumer with an infinite lifetime. This exaggerates the intertemporal tradeoff of labor and leisure beyond what it would be in a model assuming consumers with finite lifetimes.

71. Congressional Budget Office, *Labor Supply and Taxes*, CBO Memorandum (January 1996).

Permit Purchases from Other Countries. Unless purchases of permits from other countries are counted as an import of a service, such purchases have no direct impact on GDP. However, the permits must ultimately be paid for with higher net exports. Those purchases reduce the share of GDP going to investment, which in turn reduces potential GDP. This impact is similar to the feedback effects of lower saving on GDP discussed above, and is likewise small.

Impacts of Higher Interest Rates on Unemployment and Investment. The timing of GDP loss from higher interest rates depends strongly on when the increase in the general price level stemming from higher energy prices is assumed to occur, and how long unemployment remains above baseline levels in response to that increase. This can be seen most clearly in the two EIA studies, which use the same model. In the study in which energy prices begin to rise in 2005, unemployment is still well above baseline levels in 2010, and real GDP falls 4.2 percent below its baseline level. If energy prices begin to rise in 2000, however, unemployment is back to baseline levels in 2010, and real GDP falls less than one third as much, 1.2 percent, even though the permit price is nearly as large as in the other case.

I interpret the economic impacts in 2010 as representative of impacts over a longer period of time. A simple-minded focus on the economy's response in 2010 alone would exaggerate the effect on GDP of fighting higher inflation over this longer period. According to the Kyoto Protocol, permits would first be imposed in 2008, so the effect on unemployment would be near its peak in 2010. Instead, the model synthesis estimates assume that the effect of fighting higher inflation on GDP is spread evenly over a ten year period, so that the estimated effect in 2010 will be representative of this longer period of time.

The Federal Reserve would focus on the portion of inflation that it believed would be permanent if not counteracted by higher interest rates. In the DRI model, a one-time 1.0 percent upward shock to the general price level would trigger a permanent 0.11 percentage point rise in the inflation rate if not offset by higher unemployment and lower capacity utilization. Thus, the 3.3 percent increase in the general price level occurring with no international trade of permits would lead to a permanent 0.37 percentage point rise in the inflation rate.

Eliminating this extra inflation would reduce real GDP by an average of nearly 0.5 percent per year over 10 years. A loss of nearly 0.3 percent per year would be directly associated with the higher unemployment and lower capacity utilization needed to bring inflation back down. An additional 0.2 percent per year would be lost because the higher interest rates needed to slow the economy would hurt investment, reducing potential GDP. The 0.5 percent reduction in GDP from macroeconometric effects in the no-trade case is smaller than those in the DRI and WEFA studies and the first EIA study (which assumes responses begin in 2005) but larger than those in the Oxford study and the second EIA study (which assumes responses begin in 2000).

GDP Losses in Other Countries. The model synthesis estimates assume that GDP loss in other countries is determined in the same way that GDP loss in the United States is. This is not likely to hold exactly, because inflation may respond differently to unemployment in other countries than in the United States, among other things. However, GDP loss in other countries only affects the U.S. results insofar as lower GDP in those countries reduces their demand for permits and thus the international permit price. Those effects will be small, so using a reasonable approximation for foreign GDP loss should not have much effect on permit price or GDP estimates for the United States.

Impact on Consumption

Without international trade of permits or reductions in greenhouse gases other than carbon dioxide, the ratio of the percentage drop in consumption to the percentage drop in GDP averages 0.70 among the models.[72] (To avoid double-counting the DRI model, this average uses only the ratio from the original EIA study. The ratio in the DRI study is higher, while that in the EIA early start study is lower). In most models, as international trade of permits is added, the ratio of the percentage change in consumption is more closely tied to the percentage change in GDP less permit purchases than to the percentage change in GDP alone. That is, an extra $100 of lost GDP has about the same effect on consumption as an extra $100 spent on foreign permits. The model synthesis estimates thus assume that the ratio of the percentage change in consumption to the percentage change in GDP less permit purchases declines gradually from 0.70 without international trade of permits or sinks to 0.60 with unrestricted global trade of permits—the average estimates from the models.

Change in Global Emissions

The change in global emissions from baseline levels in 2010 under the Kyoto Protocol would equal emissions reductions in countries constrained by the protocol less emissions increases in countries unconstrained by the protocol. Such increases in emissions, resulting from greater oil consumption in response to lower global oil prices and a relocation of energy-intensive industries from constrained to

72. For studies publishing both private and government consumption (DRI, EIA and WEFA), this ratio is calculated using the percentage change in total (private plus government) consumption. The model synthesis estimates assume that the percentage change in private consumption is the same as the percentage change in government consumption. This seems a more realistic long run assumption than assuming that government consumption and investment do not respond to changes in GDP.

unconstrained countries, are known as leakage. Leakage would boost emissions in any country with a domestic permit price of zero. Such countries would include the former Soviet bloc if limits were placed on permit imports or international trade of permits were blocked altogether, and would include non-Annex B countries if there were no global trade of permits. (Leakage to non-Annex B countries would also occur under global trade of permits if limits were placed on permit imports.) In the discussion that follows, the leakage rate is defined as the increase in emissions in unconstrained countries as a percentage of the decline in emissions in constrained countries.

The leakage rate depends on the permit price in countries where emissions are constrained. The higher the permit price in these countries, the more leakage there will be. Thus, on average, the models find that the leakage rate to non-Annex B countries drops from 17 percent with no international trade of permits to 10 percent with unrestricted Annex B trade of permits. (These averages exclude models that assume no leakage or that do not specify emissions in countries other than the United States.) Model synthesis estimates of leakage are calculated using the relationship between leakage rates and permit prices established by these two data points in cases where the permit price in non-Annex B countries is zero. In models in which the permit price in the former Soviet bloc is also zero when there is no international trade of permits, leakage to these countries is 40 percent as large as leakage to the non-Annex B countries. So leakage to the former Soviet bloc is assumed to be 40 percent as large as non-Annex B leakage when permit prices in the former Soviet bloc are zero.

It is difficult to be certain whether these leakage estimates are consistent with the model synthesis estimates of price sensitivity. The amount of leakage per dollar of permit price and the price sensitivity of emissions should be positively correlated: the more easily emissions can move from one country to another, the greater price sensitivity will be in a given country. However, these concepts show little correlation across the models.

Gasoline Price

The change in gasoline prices consists of three pieces: the direct impact of the permit price; the impact of lower demand for gasoline on refiner margins; and the impact of lower global oil demand on crude oil prices. The direct impact is 23.8 cents a gallon per each $100 per metric ton increase in the permit price, according to data from EIA. Refiner margins fall by 0.8 cents a gallon per each $100 per metric ton increase in the permit price, according to averages from the DRI, EIA and WEFA studies. The percentage change in the price of crude oil is found by combining model responses of crude oil prices to global demand for crude oil with estimated changes in global demand for crude oil. According to the model average, the global elasticity of supply for crude oil is between 0.5 and 0.6 over a ten-year horizon.

Price of Natural Gas

The change in the price of natural gas also consists of three pieces: the direct impact of the permit price; the impact of higher natural gas demand on wellhead prices; and the impact of lower residential and commercial demand on distribution costs. Permits directly add $1.48 per thousand cubic feet per each $100 per metric ton increase in the permit price. The increase in wellhead prices is calculated by combining the responses of wellhead prices to U.S. demand for natural gas in the DRI, EIA and WEFA studies with the rise in demand implied by the model synthesis estimates. (The model synthesis estimates focus on changes in U.S. demand because of the difficulties of transporting natural gas overseas.) This rise in natural gas demand is smaller than in the EIA study, because the drop in non-electricity usage is larger.[73] Finally, distribution costs per cubic foot of gas delivered to residential and commercial customers would rise as the same fixed costs were spread over a smaller consumption base.

Electricity Prices

In the model synthesis estimates, electricity prices rise for two reasons: the direct impact of the permit price; and the higher generating costs associated with fuel switching. These both depend on the amount of fuel switching. A shift from coal to natural gas or non-fossil sources reduces the direct impact of the permit price but increases generating costs. However, generators will only want to switch fuels if the increase in generating costs is smaller than the savings in permit expenses.

Determining the change in the price of electricity requires several calculations. First, I calculate a change in emissions from electricity generation consistent with model-based and empirical estimates of overall price sensitivity and the price sensitivity of non-electricity emissions. Multiplying the permit price by the resulting level of emissions yields the total value of permits required to produce electricity. Model-based and empirical estimates of the price sensitivity of electricity demand are combined with the change in emissions from electricity generation to determine the portion of the drop in electricity emissions resulting from fuel switching. The total

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73. According to Dahl's demand elasticities, demand for natural gas would fall below baseline levels, so wellhead prices for natural gas would drop. However, the Dahl elasticities also imply smaller reductions in petroleum than the model synthesis, reducing the drop in crude oil prices. Thus, using the Dahl elasticities for individual fossil fuels would produce higher gasoline and lower natural gas prices than the elasticities implied by the models.

increase in generating costs due to fuel switching is assumed to equal the change in emissions resulting from fuel switching times the average permit price at which those switches are made, i.e., one half the permit price. Adding together the direct impact of the permit price and the increase in generating costs due to fuel switching and dividing by final electricity consumption yields the rise in electricity prices per kilowatt-hour. (The change in electricity consumption is calculated from the change in electricity emissions that does not result from fuel switching.)

These calculations assume that three possible additional impacts on electricity prices are negligible. First, there is no net impact from changes in fossil fuel prices. That is, the increase in natural gas costs from higher wellhead prices is assumed to offset the reduction in coal costs from lower minemouth prices. Second, the change in marginal cost is assumed to equal the change in average cost. The EIA study instead argues that marginal costs would rise more than average costs, pushing prices higher than what this paper assumes. Third, all customers are assumed to face the same absolute increase in electricity prices. The DRI study assumes this, and the WEFA study assumes something close to it. The EIA study, however, assumes that the percentage increase in electricity prices is roughly the same for all customers, meaning that the absolute increase for residential customers is much larger than the increase for other customers. If this is true, the model synthesis estimates understate the percentage increase in residential electricity prices.

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Table 2-1. Studies Analyzing the Impact of Emissions Reductions, by Model and Institutions of Authors

Model	Institutions of Authors
AIM[a] (Asian-Pacific Integrated Model)	NIES (National Institute for Environmental Studies, Japan) and Kyoto University
CETA[a] (Model for Carbon Emissions Trajectory Assessment)	EPRI (Electric Power Research Institute) and Teisberg Associates
DRI (DRI Macro Model)	Standard & Poor's Data Resources, Inc.
EIA Energy sector impacts: NEMS (National Energy Modeling System); Macro impacts: DRI	Energy Information Administration
EPPA[a] (Emissions Prediction and Policy Analysis Model)	MIT (Massachusetts Institute of Technology)
G-Cubed[a] (Global General Equilibrium Growth Model)	Australian National University, Brookings Institution, Environmental Protection Agency, and University of Texas
GTEM[a] (Global Trade and Environment Model)	ABARE (Australian Bureau of Agricultural and Resource Economics)
(JWS) (Jorgenson-Wilcoxen-Slesnick Model)	Dale W. Jorgenson Associates
MERGE[a] (Model for Evaluating Regional and Global Effects of Greenhouse Gas Reduction Policies)	EPRI (Electric Power Research Institute) and Stanford University
MS-MRT[a] (Multi-Sector Multi-Region Trade Model)	Charles River Associates and University of Colorado
Oxford[a] (Oxford Global Macroeconomic and Energy Model)	Oxford Economic Forecasting
RICE[a] (Regional Dynamic Integrated Model of Climate and the Economy)	Yale University
SGM-Administration (see SGM-PNNL)	Clinton Administration
SGM-PNNL[a] (Second Generation Model)	Batelle Pacific Northwest National Laboratory
WEFA Macro Model	Wharton Econometric Forecasting Associates
WorldScan[a] (Model of the World Economy for Scenario Analysis)	RIVM (National Institute of Public Health and the Environment, Netherlands)

NOTES:

a. Participants in Round 16 of Stanford University’s Energy Modeling Forum.

Table 3-1. Percentage Reduction in Emissions of Carbon Dioxide in 2010 Required in Various Regions Under Alternative Permit-Trading Scenarios (Percentage Reduction from Baseline)

Model	Emissions Reduction in U.S. with No International Permit Trade	Total Emissions Reduction in Annex B Countries with Permit Trading Among Annex B Countries	Global Emissions Reduction with Global Permit Trading
	Models with No Offsets		
AIM	25	13	7
CETA	29	8	5
DRI	29	n.a.	n.a.
EIA	30	n.a.	n.a.
EPPA	29	18	n.a.
G-Cubed	30	17	9
GTEM	28	20	n.a.
MS-MRT	30	15	7[a]
Oxford	31	21[b]	n.a.
RICE	25	10	5
WEFA	27	n.a.	n.a.
WorldScan	27	21	n.a.
	Models with Offsets		
EIA	27	n.a.	n.a.
MERGE	29	16	10
SGM-Administration	28	11	7
SGM-PNNL	29	14	10
Memorandum			
Average of All Models	29	16[c]	8

SOURCE: Author's calculations, using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); Standard & Poor's DRI, *The Impact of Meeting the Kyoto Protocol on Energy Markets and the Economy* (Lexington, MA: Standard & Poor's DRI, 1998); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communications from Richard Richels and John Weyant.

NOTES: For the United States, the 2010 cap is 93 percent of 1990 emissions. Percentage reduction refers to the percentage reduction in 2010 baseline emissions required to meet the cap. In some models, the actual percentage reduction differs slightly from this figure.
Offsets are the amount of carbon dioxide offset by forest growth and reductions in other greenhouse gases beyond their share of the cap.
The model average assumes no offsets. Targets for non-Annex B countries equal baseline emissions in those countries.
n.a. = not available

a. The MS-MRT scenario for global trade of permits assumes that emissions caps for non-Annex B countries are the emissions they produce when the Annex B countries meet their caps without international trade of permits.
b. Oxford data for Annex B excludes Ukraine, eastern Europe, Australia and New Zealand.
c. This average excludes Oxford, which does not have data for all of Annex B.

Table 3-2. Impact on U.S. Carbon Emissions of a 1 Percent Increase in the Price of Carbon-Energy, Assuming No International Trading of Permits, Selected Years

Model	Percentage Change in Carbon Emissions from Baseline in		Impact in 2010 as a Percentage of the Impact in 2020
	2010	2020	
AIM	-0.68	-1.01	68
CETA	-0.67	-0.75	89
DRI[a]	-0.49	-0.59	84
EIA[b]	-0.41	-0.60	68
EIA-early start[b]	-0.47	-0.67	71
EPPA	-0.73	-1.53	48
G-Cubed	-1.54	-2.10	74
GTEM	-0.40	-0.49	81
JWS[c]	-1.28	-1.26	101
MERGE	-0.53	-0.72	73
MS-MRT	-0.51	-0.62	83
Oxford	-0.42	-0.42	100
RICE	-0.90	-0.83	108
SGM-Administration	-0.68	n.a.	n.a.
SGM-PNNL	-0.69	-0.74	93
WEFA	-0.42	-0.54	78
WorldScan	-1.17	-1.13	104

SOURCE: Author's calculations, using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); DRI/McGraw-Hill, *The Impact of Carbon Mitigation Strategies on Energy Markets, the National Economy, Industry, and Regional Economies* (study prepared for UMWA-BCOA, Lexington, MA, July 1997); Energy Information Administration, *Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); Dale W. Jorgenson, Richard J. Goettle, Peter J. Wilcoxen and Daniel T. Slesnick, *Carbon Mitigation, Permit Trading and Revenue Recycling* (prepared for the Environmental Protection Agency, November 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communications from Richard Richels and John Weyant.

NOTES: All models assume the 2020 emissions cap is the same as the 2010 cap.

These numbers provide an estimate of how energy users adjust their use of carbon-based energy in response to changes in its price. That price sensitivity is negative because energy use falls as its price rises. Larger absolute values indicate a larger response. The numbers are calculated by using logarithms (see Appendix A for details). Because price sensitivity is nonlinear, these numbers should not be scaled up for larger price changes using simple multiplication.

n.a. = not available

a. Data for DRI are geometric weighted averages of results from two scenarios assuming the Kyoto target is 90 percent and 100 percent, respectively, of 1990 emissions.

b. In these scenarios, EIA assumes emissions of carbon dioxide are reduced 7 percent below 1990 levels.

c. This model assumes emissions return to 1990 levels.

Table 3-3. Impact of a 1 Percent Increase in the Price of Carbon-Energy on Carbon Emissions in 2010 Under Alternative Permit-Trading Scenarios, By Region
(Percentage Change from Baseline Emissions)

	Annex B Permit Trading		Global Permit Trading		
	United States	All Annex B Countries	United States	All Annex B Countries	Rest of World
AIM	-0.62	-0.73	-0.57	-0.72	-0.34
CETA	-0.52	-0.45	-0.58	-0.51	-0.30
DRI	-0.48[a]	n.a.	n.a.	n.a.	n.a.
EIA	-0.41[b]	n.a.	-0.29[c]	n.a.	n.a.
EIA early start	-0.47[b]	n.a.	-0.34[c]	n.a.	n.a.
EPPA	-1.05	-0.88	n.a.	n.a.	n.a.
G-Cubed	-1.43	-1.09	-1.17	-1.03	-1.15
GTEM	-0.33	-0.59	n.a.	n.a.	n.a.
MERGE	-0.56	-0.49	-0.54	-0.46	-0.23
MS-MRT	-0.50	-0.55	-0.46	-0.46	-0.41
Oxford	-0.50	-0.47	n.a.	n.a.	n.a.
RICE	-0.86	-0.68	-0.83	-0.68	-0.69
SGM-Administration	-0.73	-0.65	-0.70	-0.66	-1.14[d]
SGM-PNNL	-0.80	-0.57	-0.82	-0.55	-1.02
WorldScan	-2.12	-3.06	n.a.	n.a.	n.a.

SOURCE: Author's calculations, using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); Energy Information Administration, *Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); Standard & Poor's DRI, *The Impact of Meeting the Kyoto Protocol on Energy Markets and the Economy* (Lexington, MA: Standard & Poor's DRI, 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communications from Richard Richels and John Weyant.

NOTES: These numbers provide an estimate of how energy users adjust their use of carbon-based energy in response to changes in its price. That price sensitivity is negative because energy use falls as its price rises. Larger absolute values indicate a larger response. The numbers are calculated by using logarithms (see Appendix A for details). Because price sensitivity is nonlinear, these numbers should not be scaled up for larger price changes using simple multiplication.
Only the Annex B trading scenario is consistent with the Kyoto Protocol.
n.a. = not available

a. Case 2 in DRI's study of Annex B trading of permits.
b. U.S. emissions are reduced to a level 9 percent above 1990 levels.
c. U.S. emissions are reduced to a level 24 percent above 1990 levels.
d. Includes only China, India, Korea and Mexico.

Table 3-4. Model Estimates of U.S. Permit Prices in 2010, Without International Trade of Permits

Models	Permit Price (in 1997 dollars per mtc)[a]	Key Determinants of Permit Prices: Percentage Change in Carbon Emissions	Percentage Change in GDP	Price Sensitivity of Carbon Emissions	Baseline Price of Carbon-Energy (in 1997 dollars per mtc)
		Models Using Kyoto Targets without Offsets			
AIM	184	-25	-0.5	-0.68	362
CETA	201	-29	-1.9	-0.67	332[b]
DRI[c]	254	-29[d]	-2.3	-0.49	274
EIA	355	-31[d]	-4.2	-0.41	296
EIA early start	322	-30[d]	-1.2	-0.47	296
EPPA	232	-29	n.a.[e]	-0.73	387
G-Cubed	91	-30	-0.4	-1.54	361
GTEM	389	-28	-2.0	-0.40	340
MS-MRT	287	-30	-1.9	-0.51	300
Oxford Econ.	407	-30[d]	-1.8	-0.42	334
RICE	184	-25	-1.0	-0.90	496
WEFA	270	-27[d]	-3.2	-0.42	291
WorldScan	101	-27	n.a.[e]	-1.17	332[b]
		Models Using Kyoto Targets with Offsets			
EIA	300	-27[d]	-3.5	-0.41	296
MERGE	286	-29	-1.0	-0.53	332[b]
SGM-Admin.	192	-28	n.a.[e]	-0.68	314
SGM-PNNL	189	-29	n.a.[e]	-0.69	298
		Memo: Model Targeting 1990 Emissions without Offsets			
JWS	70	-25	-1.1	-1.28	292

SOURCE: Author's calculations using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); DRI/McGraw-Hill, *The Impact of Carbon Mitigation Strategies on Energy Markets, the National Economy, Industry, and Regional Economies* (study prepared for UMWA-BCOA, Lexington, MA, July 1997); Energy Information Administration, *Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); Dale W. Jorgenson, Richard J. Goettle, Peter J. Wilcoxen and Daniel T. Slesnick, *Carbon Mitigation, Permit Trading and Revenue Recycling* (prepared for the Environmental Protection Agency, November 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communications from Richard Richels and John Weyant.

NOTES: Price sensitivity of carbon emissions is a measure of how energy users adjust their use of carbon-based energy in response to 1 percent change in its price. I use logarithms in preparing the estimate, so it cannot be scaled up for larger percent changes by simple multiplication (see Appendix A for details). Price sensitivity is negative because energy use falls as its price rises. Larger absolute values indicate a larger response.
mtc=metric ton of carbon
n.a. = not available

a. Permit prices were converted from other base years to 1997 dollars using the GDP price deflator.

b. The data needed to calculate the price of carbon-based energy are unavailable from these studies. I used the average price of carbon-based energy in eight other studies using general equilibrium models.

c. Emissions and GDP data for DRI are weighted averages of results from two scenarios assuming the Kyoto target is 90 percent and 100 percent, respectively, of 1990 emissions.

d. Emissions in 2010 differ from target levels by small amounts.

e. The change in GDP is not available for these models. Price sensitivity is calculated using direct cost.

Table 3-5. Model Estimates of Annex B Permit Prices in 2010, with Permit-Trading Among Annex B Countries

		Key Determinants of Permit Prices in Annex B			
Models	Permit Price (in 1997 dollars per mtc)[a]	Percentage Change in Carbon Emissions	Percentage Change in GDP[b]	Price Sensitivity of Carbon Emissions	Baseline Price of Carbon-Energy (in 1997 dollars per mtc)
Models Using Kyoto Targets without Offsets					
AIM	78	-13	0[c]	-0.73	364
CETA	55	-8	-0.8	-0.45	305[d]
EIA	166	n.a.	n.a.	n.a.	n.a.
EIA early start	152	n.a.	n.a.	n.a.	n.a.
EPPA	91	-18	n.a.[e]	-0.88	364
G-Cubed	64	-17	0[c]	-1.09	344
GTEM	128	-20	-0.6	-0.59	293
MS-MRT	94	-15	0.2	-0.55	266
Oxford Econ.	222	-21	-0.9	-0.47	351
RICE	41	-10	-0.3	-0.70	274
WorldScan	24	-21	n.a.[e]	-3.06	291[d]
Models Using Kyoto Targets with Offsets					
DRI	115	n.a.	n.a.	n.a.	n.a.
MERGE	116	-16	-0.7	-0.50	299[d]
SGM-Administration	54	-11	n.a.[e]	-0.65	270
SGM-PNNL	82	-14	n.a.[e]	-0.57	269

SOURCES: Same as Table 3-3.

NOTES: With Annex B trade of permits, the U.S. permit price equals the Annex B permit price.
Price sensitivity of carbon emissions is a measure of how energy users adjust their use of carbon-based energy in response to 1 percent change in its price. I use logarithms in preparing the estimate, so it cannot be scaled up for larger percent changes by simple multiplication (see Appendix A for details). Price sensitivity is negative because energy use falls as its price rises. Larger absolute values indicate a larger response.
mtc=metric ton of carbon
n.a. = not available

a. Permit prices were converted from other base years to 1997 dollars using the GDP price deflator.
b. Regional percentage changes in GDP are weighted together using emissions data.
c. These changes round to zero.
d. Data needed to calculate the price of carbon-based energy are unavailable from these studies. For the United States, I use the average price of carbon-based energy in eight other studies using general equilibrium models. Prices for Annex B then incorporate regional differences in emissions between studies.
e. The change in GDP is not available for these models. Price sensitivity is calculated using direct cost.

Table 3-6. Model Estimates of Global Permit Prices in 2010, with Global Permit Trading

Models	Permit Price (in 1997 dollars per mtc)[a]	Key Determinants of Permit Prices: Percentage Change in Carbon Emissions		Percentage Change in GDP		Price Sensitivity of Carbon Emissions		Baseline Price of Carbon-Energy (in 1997 dollars per mtc)	
		Annex B	Other	Annex B	Other	Annex B	Other	Annex B	Other
		Models Using Kyoto Targets without Offsets							
AIM	46	-8	-5	0[b]	0.2	-0.72	-0.34	364	259
CETA	31	-5	-8	-0.2	0.1	-0.51	-0.30	305[c]	202[c]
EIA[d]	68	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
EIA early start[d]	63	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
G-Cubed[e]	24	-7	-12	-0.2	-0.4	-1.03	-1.15	344	210
MS-MRT[f]	32	-5	-8	-0.1	0[b]	-0.46	-0.41	266	139
RICE	13	-3	-7	-0.2	-0.2	-0.68	-0.69	268	134
		Models Using Kyoto Targets with Offsets on Annex B Emissions							
MERGE	80	-11	-8	-0.4	-0.9	-0.46	-0.23	299[c]	199[c]
SGM-Administration	22	-5	-15	n.a.[g]	n.a.[g]	-0.66	-1.14	270	144
SGM-PNNL	29	-6	-16	n.a.[g]	n.a.[g]	-0.55	-1.02	269	159

SOURCES: Author's calculations, using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); Energy Information Administration, *Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communications from Richard Richels and John Weyant.

NOTES: Price sensitivity of carbon emissions is a measure of how energy users adjust their use of carbon-based energy in response to a 1 percent change in its price. CBO uses logarithms in preparing the estimate, so it cannot be scaled up for larger percent changes by simple multiplication (see Appendix A for details). Price sensitivity is negative because energy use falls as its price rises. Larger absolute values indicate a larger response.

mtc = metric ton of carbon

n.a. = not available

a. Permit prices were converted from other base years to 1997 dollars using the GDP price deflator.

b. These changes round to zero.

c. Data needed to calculate the price of carbon-based energy are unavailable from these studies. For the United States, I use the average price of carbon-based energy in eight other studies using general equilibrium models. Prices for other countries then incorporate regional differences in emissions between studies.

d. EIA does not specify which scenario corresponds to global permit trading. These data are from EIA scenarios which assume U.S. emissions of carbon dioxide are 24 percent above baseline levels in 2010.

e. The G-Cubed modelers assume that Mexico and OPEC do not participate in reducing emissions.

f. MS-MRT assumes that non-Annex B countries are given targets equal to their emissions under no international permit trading, rather than their lower baseline emissions.

g. The change in GDP is not available for these models. Price sensitivity is calculated using direct cost.

Table 3-7. Model Synthesis Estimates of Permit Prices and Reductions of Emissions in 2010 Under Various Scenarios

	U.S. Permit Price (1997 dollars per mtc)	Reduction in Global Emissions[a] (Percent of baseline emissions of CO_2)
Kyoto-Consistent Scenarios		
Ideal Implementation	56±15	6
Cartel[b]	70±19	6
Plus: No CDM	76±21	6
Plus: Restrictions on Permit Sales[c]	137±37	10
Plus: No Offsets from Reductions in Other Greenhouse Gases[d]	178±48	9
Restrictions on Permit Purchases[e]	122±33	6
Full Credit for Baseline Forest Growth[f]	0	0
No International Trading of Permits		
Ideal Implementation	216±58	9
No Offsets from Reductions in Other Greenhouse Gases[d]	264±71	8
Global Trading of Permits[g]		
Ideal Implementation	28±8	7
Cartel[b]	31±8	7
Plus: Restrictions on Permit Sales[c]	49±13	11
Restrictions on Permit Purchases[e]	122±33	6
Plus: No Offsets from Reductions in Other Greenhouse Gases[d]	147±40	6

SOURCE: Author's calculations.

NOTES: CDM= Clean Development Mechanism, by which Annex B countries can take credits for projects that reduce emissions in non-Annex B countries.
mtc = metric ton of carbon
CO_2= carbon dioxide
To convert 1997 dollars to 2002 dollars, multiply by 1.085.
Estimates of the U.S. permit price include a range of possible error, reflecting uncertainty about exactly how much businesses, consumers and government would adjust their energy usage in response to higher prices.

a. Reductions are measured from the 2010 baseline. In this baseline, global emissions of carbon dioxide in 2010 are 40 percent above 1990 levels.
b. The countries of the former Soviet Union and eastern Europe are not permitted to sell permits they receive in excess of their baseline emissions. This is equivalent to reducing their allocation of permits to baseline levels.
c. Countries cannot offset emissions of carbon dioxide by reducing emissions of other greenhouse gases below target levels.
d. Each country must achieve at least 65 percent of its obligation to reduce emissions domestically.
e. Each country receives credit for the change in carbon stocks on cropland, grazing land, and forests, except those not available or appropriate for wood production.
f. The global trading cases assume partial exercise of market power by permit-exporting countries within Annex B. Non-Annex B countries are assumed not to control emissions of other greenhouse gases, and their caps are assumed equal to their baseline emissions of carbon dioxide.

Table 4-1. Impact on Energy Prices of a $100 per mtc Permit Price
(Change from Baseline Prices unless Otherwise Noted)

	Price of Coal to Utilities (Dollars per short ton)	Price of Gasoline (Cents per gallon)	Price of Natural Gas to Households (Dollars per thousand cubic feet)	Price of Electricity to all Users (Cents per kwh)
Direct Impact[a]	55	23.8	1.48	0.9 to 1.4
Change in Fossil Fuel Prices	-1 to 1	-2 to -4	0.05 to 0.23	0 to 0.1
Other	-1	-3 to 0	0 to 0.12	0.2 to 0.5
Total Impact[a]	53 to 56	19 to 22	1.55 to 1.83	1.6-1.7
Memorandum:				
Baseline Price in 2010, in 1997 Dollars	23 to 25	127 to 136	5.83 to 6.30	5.1 to 6.3
Total Impact (Percent of Baseline Price)	213 to 245	14 to 17	25 to 31	26 to 33

SOURCES: DRI/McGraw-Hill, *The Impact of Carbon Mitigation Strategies on Energy Markets, the National Economy, Industry, and Regional Economies* (study prepared for UMWA-BCOA, Lexington, MA, July 1997); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); WEFA, Inc., *Global Warming: The Economic Cost of Early Action, National Impacts* (Eddystone, PA: WEFA, Inc., 1997).

NOTES: kwh = kilowatt hour
mtc = metric ton of carbon

a. Direct impact figures for coal, gasoline, and natural gas are from the EIA study only. Total impact figures are taken from the studies. Thus, the three components of total impact may not add up to the total impact.

Table 4-2. Model Synthesis Estimates of the Impacts on Energy Prices in 2010 of Various Scenarios to Restrict Greenhouse Gases

	U.S. Permit Price (in 1997 dollars per mtc)	Gasoline Price (Change from Baseline in 1997 cents per gallon)	Price of Natural Gas to Households (Percent Change from Baseline)	Price of Electricity to Households (Percent Change from Baseline)
		Kyoto-Consistent Scenarios		
Ideal Implementation	56±15	12±3	13±4	13±4
Cartel[a]	70±19	15±4	16±4	15±4
Plus: No CDM	76±21	16±4	18±5	17±5
Plus: Restrictions on Permit Sales[b]	137±37	29±8	32±9	29±8
Plus: No Offsets from Reductions in Other Greenhouse Gases[c]	178±48	38±10	42±11	36±10
Restrictions on Permit Purchases[d]	122±33	26±7	29±8	26±7
Full Credit for Baseline Forest Growth[e]	0	0	0	0
		No International Trading of Permits		
Ideal Implementation	216±58	47±13	51±14	43±12
No Offsets from Reductions in Other Greenhouse Gases[c]	264±71	57±15	62±17	50±14
		Global Trading of Permits[f]		
Ideal Implementation	28±8	5±1	7±2	6±2
Cartel[a]	31±8	6±2	7±2	7±2
Plus: Restrictions on Permit Sales[b]	49±13	9±2	11±3	11±3
Restrictions on Permit Purchases[d]	122±33	26±7	29±8	26±7
Plus: No Offsets from Reductions in Other Greenhouse Gases[c]	147±40	32±9	34±9	31±8

SOURCES: Author's calligraphy calculations.

NOTES: CDM=Clean Development Mechanism, by which Annex B countries can take credits for projects that reduce emissions in non-Annex B countries.
Estimates include a range of possible error, reflecting uncertainty about exactly how much businesses, consumers and government would adjust their energy usage in response to higher prices.
To convert 1997 dollars into 2002 dollars, multiply by 1.085.
mtc = metric tons of carbon

a. The countries of the former Soviet Union and eastern Europe are assumed to limit exports of permits such that the domestic price of emissions permits is one-half the international price.
b. The countries of the former Soviet Union and eastern Europe are not permitted to sell permits they receive in excess of their baseline emissions. This is equivalent to reducing their allocation of permits to baseline levels.
c. Countries cannot offset emissions of carbon dioxide by reducing emissions of other greenhouse gases below target levels.
d. Each country must achieve at least 65 percent of its obligation to reduce emissions domestically.
e. Each country receives credit for the change in carbon stocks on cropland, grazing land, and forests, except those not available or appropriate for wood production.
f. The global trading cases assume partial exercise of market power by permit-exporting countries within Annex B. Non-Annex B countries are assumed not to control emissions of other greenhouse gases, and their caps are assumed equal to their baseline emissions of carbon dioxide.

Table 5-1. Impact of Emissions Reductions on U.S. GDP and Consumption in 2010, with No International Permit Trading and Non-Auctioned Permits (Percentage Change from Baseline)

	Percentage Change in		Memo:
	GDP	Consumption	Permit Price (1997 dollars per mtc)
	General Equilibrium Models		
AIM	-0.5	-0.4[a]	184
CETA	-1.9	-0.6	201
G-Cubed	-0.4	1.4	91
GTEM	-2.0	-2.1	389
MERGE	-1.0	-1.1	286
MS-MRT	-1.4	-0.4	287
RICE	-1.0	-0.2	184
SGM-PNNL	n.a.	-0.7[a]	189
	Macroeconometric Models		
DRI[b]	-2.9	-2.9	254
EIA	-4.2	-3.1	355
EIA early start	-1.2	-0.5	322
Oxford	-1.8[c]	-2.5[a]	407
WEFA	-3.2	-1.8	270

SOURCE: Author's calculations, using: DRI/McGraw-Hill, *The Impact of Carbon Mitigation Strategies on Energy Markets, the National Economy, Industry, and Regional Economies* (study prepared for UMWA-BCOA, Lexington, MA, July 1997); Energy Information Administration, *Analysis of the Impacts of an Early Start for Compliance with the Kyoto Protocol* (July 1999); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communication from John Weyant.

NOTES: Consumption is private consumption plus government consumption and investment, unless noted otherwise.
Except for G-Cubed, general equilibrium models assume that unemployment and inflation cannot vary from baseline levels. Macroeconometric models and G-Cubed assume that unemployment and inflation can vary from baseline levels.
Estimates assume emissions of carbon dioxide in 2010 are cut to 93% of 1990 levels.
Studies using the EPPA, SGM and WorldScan models do not publish changes in GDP, and only the SGM-PNNL study publishes the change in consumption.
n.a.=not available
mtc = metric tons of carbon

a. Percentage change in private consumption only.
b. Data for DRI are derived from a weighted average of two scenarios assuming the Kyoto target is 90 percent and 100 percent, respectively, of 1990 emissions.
c. The 1.8 percent decline in actual GDP is smaller than the 2.5 percent decline in potential GDP shown in the Oxford study.

Table 5-2. Model Estimates of the Cost of Emissions Permits in the United States in 2010, With and Without International Permit Trading
(Billions of 1997 dollars)

Model	No International Permit Trading	Annex B Trading of Permits: Domestically Allocated Permits: Value	Domestically Allocated Permits: Change from No Trading	Permit Purchases	All Permits: Value	All Permits: Change from No Trading
AIM	218	93	-125	16	109	-109
CETA	253	69	-184	20	89	-164
EIA	441	207[a]	-235[a]	36[a]	243[a]	-198[a]
EPPA	297	117	-180	15	132	-165
G-Cubed	114	80	-34	10	90	-24
GTEM	524	173	-351	41	214	-310
MERGE	373	152	-221	27	179	-194
MS-MRT	359	118	-242	29	146	-213
Oxford	516	281	-235	25	307	-209
RICE	237	53	-183	13	67	-170
SGM-Admin	291[b]	82[b]	-209[b]	17[b]	99[b]	-192[b]
SGM-PNNL	291[b]	127[b]	-165[b]	20[b]	147[b]	-144[b]
WorldScan	136	32	-104	6	38	-98

SOURCES: Author's calculations, using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communication from John Weyant.

NOTES: With no international trading of permits the value of domestically allocated permits equals the value of all permits.
Unless otherwise indicated, figures are for the value of carbon dioxide permits only.
n.a.= not available
To convert 1997 dollars into 2002 dollars, multiply by 1.085.

a. Under Annex B trading of permits, U.S. emissions are reduced to a level 9 percent above 1990 levels.
b. These figures include the value of permits for all greenhouse gases.

Table 5-3. Impact of Emissions Reductions on U.S. GDP and Consumption in 2010, with International Permit Trading and Non-Auctioned Permits
(Percentage Change from Baseline)

	Annex B Trading of Permits		Global Trading of Permits	
	GDP	Consumption	GDP	Consumption
		General Equilibrium Models		
AIM	-0.3	-0.3[a]	-0.2	-0.2[a]
CETA	-0.7	-0.4	-0.4	-0.3
G-Cubed	-0.2	1.0	-0.1	0.6
GTEM	-0.4	-1.0	n.a.	n.a.
MERGE	-0.6	-0.5	-0.3	-0.2[a]
MS-MRT	-0.9	-0.3	-0.4	-0.1
RICE	-0.3	-0.1	-0.1	-0.1
SGM-PNNL	n.a.	-0.4[a]	n.a.	-0.1[a]
		Macroeconometric Models		
DRI	-1.1	-1.6	n.a.	n.a.
EIA[b]	-2.0	-1.7	-1.0	-0.9
EIA early start[b]	-0.7	-0.4	-0.5	-0.4
Oxford	-1.0[c]	-1.4[a]	n.a.	n.a.

SOURCE: Author's calculations, using: Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); Standard & Poor's DRI, *The Impact of Meeting the Kyoto Protocol on Energy Markets and the Economy* (Lexington, MA: Standard & Poor's DRI, 1998); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communication from John Weyant.

NOTES: Consumption is private consumption plus government consumption and investment, unless noted otherwise.
Except for G-Cubed, general equilibrium models assume that unemployment and inflation cannot vary from baseline levels. Macroeconometric models and G-Cubed assume that unemployment and inflation can vary from baseline levels.
Studies using the EPPA, SGM and WorldScan models do not publish changes in GDP, and only the SGM-PNNL study publishes the change in consumption.
n.a.=not available

a. Percentage change in private consumption only.
b. EIA does not specify which of its scenarios correspond to Annex B and global trading of permits. This table uses the EIA scenario in which U.S. emissions of CO_2 are 9 percent above 1990 levels in 2010 for Annex B trading and the scenario in which U.S. emissions of CO_2 are 24 percent above 1990 levels in 2010 for global trading.
c. The 1.0 percent decline in actual GDP is smaller than the 1.4 percent decline in potential GDP shown in the Oxford study.

Table 5-4. Model Synthesis Estimates of the Effect of Emissions Reductions on U.S. GDP and Consumption in 2010 Under Various Scenarios, with Non-Auctioned Permits
(Percentage Change from Baseline)

Scenario	Percentage Change in GDP	Percentage Change in Consumption
Kyoto-Consistent Scenarios		
Ideal Implementation	-0.5±0.1	-0.4±0.1
Cartel[a]	-0.6±0.2	-0.5±0.1
Plus: No CDM	-0.6±0.2	-0.5±0.1
Plus: Restrictions on Permit Sales[b]	-1.1±0.3	-0.9±0.2
Plus: No Offsets from Reductions in Other Greenhouse Gases[c]	-1.2±0.3	-1.0±0.3
Restrictions on Permit Purchases[d]	-1.0±0.3	-0.7±0.2
Full Credit for Baseline Forest Growth[e]	0	0
No International Trading of Permits		
Ideal Implementation	-1.7±0.5	-1.2±0.3
No Offsets from Reductions in Other Greenhouse Gases[d]	-1.8±0.5	-1.2±0.3
Global Trading of Permits[f]		
Ideal Implementation	-0.2	-0.2
Cartel[a]	-0.3±0.1	-0.2
Plus: Restrictions on Permit Sales[b]	-0.4±0.1	-0.4±0.1
Restrictions on Permit Purchases[d]	-0.9±0.2	-0.6±0.2
Plus: No Offsets from Reductions in Other Greenhouse Gases[c]	-0.9±0.2	-0.6±0.2

SOURCE: Author's calculations.

NOTES: CDM= Clean Development Mechanism, by which Annex B countries can get credits for projects that reduce emissions in non-Annex B countries.
Estimates include a range of possible error, reflecting uncertainty about exactly how much businesses, consumers and government would adjust their energy usage in response to higher prices.

a. Eastern Europe and the former Soviet Union are assumed to limit exports of permits such that their domestic price of emissions permits is one-half the international price.
b. The countries of the former Soviet Union and eastern Europe are not permitted to sell permits they receive in excess of their baseline emissions. This is equivalent to reducing their allocation of permits to baseline levels.
c. Countries cannot offset emissions of carbon dioxide by reducing emissions of other greenhouse gases below target levels.
d. Each country must achieve at least 65 percent of its obligation to reduce emissions domestically.
e. Each country receives credit for the change in carbon stocks on cropland, grazing land, and forests, except those not available or appropriate for wood production.
f. The global trading cases assume partial exercise of market power by permit-exporting countries within Annex B. Also, non-Annex B countries are assumed not to control emissions of other greenhouse gases.

Table 5-5. Model Estimates of the Value of Emissions Permits Allocated and Used in the United States in 2010
(Billions of 1997 dollars)

Model	No International Permit Trading	Annex B Trading of Permits		Global Permit Trading	
	Allocated and Used	Allocated	Used	Allocated	Used
AIM	218	93	109	54	67
CETA	253	69	89	39	52
DRI	314[a]	150[b]	167[b]	n.a.	n.a.
EIA	441	207[c]	243[c]	85[d]	114[d]
EPPA	297	117	132	n.a.	n.a.
G-Cubed	114	80	90	30	40
GTEM	524	173	214	n.a.	n.a.
MERGE	373	152	179	105	130
MS-MRT	359	118	146	41	55
Oxford	516	281	307	n.a.	n.a.
RICE	237	53	67	17	23
SGM-Admin	291[e]	82[e]	99[e]	34[e]	44[e]
SGM-PNNL	291[e]	127[e]	147[e]	45[e]	59[e]
WEFA	337	n.a.	n.a.	n.a.	n.a.
WorldScan	136	32	38	n.a.	n.a.

SOURCES: Author's calculations, using: Council of Economic Advisors, *The Kyoto Protocol and the President's Policies to Address Climate Change* (July 1998); DRI/McGraw-Hill, *The Impact of Carbon Mitigation Strategies on Energy Markets, the National Economy, Industry, and Regional Economies* (study prepared for UMWA-BCOA, Lexington, MA, July 1997); Energy Information Administration, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (October 1998); William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press, 2000); Standard & Poor's DRI, *The Impact of Meeting the Kyoto Protocol on Energy Markets and the Economy* (Lexington, MA: Standard & Poor's DRI, 1998); WEFA, Inc., *Global Warming: The High Cost of the Kyoto Protocol, National and State Impacts* (Eddystone, PA: WEFA, Inc., 1998); John P. Weyant, ed., *The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of the Energy Journal* (Cleveland, OH: Energy Economics Educational Foundation, Inc., 1999); and personal communication from John Weyant.

NOTES: With no international trading of permits, the value of permits allocated to U.S. businesses and households equals the value of permits used by U.S. businesses and households.
Unless otherwise indicated, figures are for the value of carbon dioxide permits only.
n.a.= not available
To convert 1997 dollars into 2002 dollars, multiply by 1.085.

a. Data are derived from a weighted average of two scenarios assuming the Kyoto target is 90 percent and 100 percent, respectively, of 1990 emissions.
b. Case 2 in DRI's study of Annex B trading of permits.
c. U.S. emissions are reduced to a level 9 percent above 1990 levels.
d. U.S. emissions are reduced to a level 24 percent above 1990 levels.
e. These figures include the value of permits for all greenhouse gases.

Table 5-6. Model Synthesis Estimates of the Value of Emissions Permits Allocated and Used in the United States in 2010

Scenario	Allocated: Billions of 1997 Dollars	Allocated: Percent of GDP	Used: Billions of 1997 Dollars	Used: Percent of GDP
Kyoto-Consistent Scenarios				
Ideal Implementation	86	0.7	108	0.9
Cartel[a]	106	0.9	131	1.1
Plus: No CDM	116	1.0	142	1.2
Plus: Restrictions on Permit Sales[b]	208	1.7	231	1.9
Plus: No Offsets from Reductions in Other Greenhouse Gases[c]	223	1.8	245	2.0
Restrictions on Permit Purchases[d]	186-211[e]	1.5-1.7	211	1.7
No International Trading of Permits				
Ideal Implementation	329	2.7	329	2.7
No Offsets from Reductions in Other Greenhouse Gases[c]	331	2.7	331	2.7
Global Trading of Permits[f]				
Ideal Implementation	43	0.3	56	0.5
Cartel[a]	48	0.4	63	0.5
Plus: Restrictions on Permit Sales[b]	74	0.6	94	0.8
Restrictions on Permit Purchases[d]	186-211[e]	1.5-1.7	211	1.5-1.7
Plus: No Offsets from Reductions in Other Greenhouse Gases[c]	184-210[e]	1.5-1.7	210	1.7

SOURCE: Author’s calculations.

NOTES: CDM= Clean Development Mechanism, by which Annex B countries can get credits for projects that reduce emissions in non-Annex B countries.

To convert 1997 dollars into 2002 dollars, multiply by 1.085.

a. Eastern Europe and the former Soviet Union are assumed to limit exports of permits such that the domestic price of emissions permits is one-half the international price.

b. The countries of the former Soviet Union and eastern Europe are not permitted to sell permits they receive in excess of their baseline emissions. This is equivalent to reducing their allocation of permits to baseline levels.

c. Countries cannot offset emissions of carbon dioxide by reducing emissions of other greenhouse gases below target levels.

d. Each country must achieve at least 65 percent of its obligation to reduce emissions domestically.

e. These estimates include the value of import quotas. The lower number in the range assumes that the United States buys foreign permits at the domestic U.S. permit price. The higher number assumes that the United States buys permits in their domestic price in permit-exporting countries.

f. The global trading cases assume partial exercise of market power by permit-exporting countries within Annex B. Also, non-Annex B countries are assumed not to control emissions of other greenhouse gases.

Table B-1.
Adjustments Made to Model Estimates of Price Sensitivity in Constructing the Model Synthesis Estimates

Model	Model Estimate of Price Sensitivity	Multiplicative Adjustment for: Final Demand for Energy Too Sensitive	Multiplicative Adjustment for: Reductions in Emissions Exceeding Reductions in Carbon-Energy Usage	Multiplicative Adjustment for: Implicit Increases in Nuclear and Hydroelectric Power That Are Too: Large	Multiplicative Adjustment for: Implicit Increases in Nuclear and Hydroelectric Power That Are Too: Small	Multiplicative Adjustment for: Responses to Higher Energy Prices That: Begin Too Late	Multiplicative Adjustment for: Responses to Higher Energy Prices That: Are Ended Too Soon	Adjusted Price Sensitivity
AIM	-0.68		0.91					-0.62
CETA	-0.67						0.77	-0.52
DRI	-0.49				1.06			-0.52
EIA	-0.41					1.16		-0.47
EPPA	-0.69		0.84	0.83				-0.51
G-Cubed	-1.54	0.73	0.78	0.82				-0.72
GTEM	-0.40				1.06			-0.42
JWS	-1.28		0.89	0.80			0.77	-0.71
MERGE	-0.53							-0.53
MS-MRT	-0.51							-0.51
Oxford	-0.42				1.06			-0.44
SGM-Administration	-0.68		0.93					-0.64
SGM-PNNL	-0.69		0.93					-0.65
WEFA	-0.42				1.07			-0.45

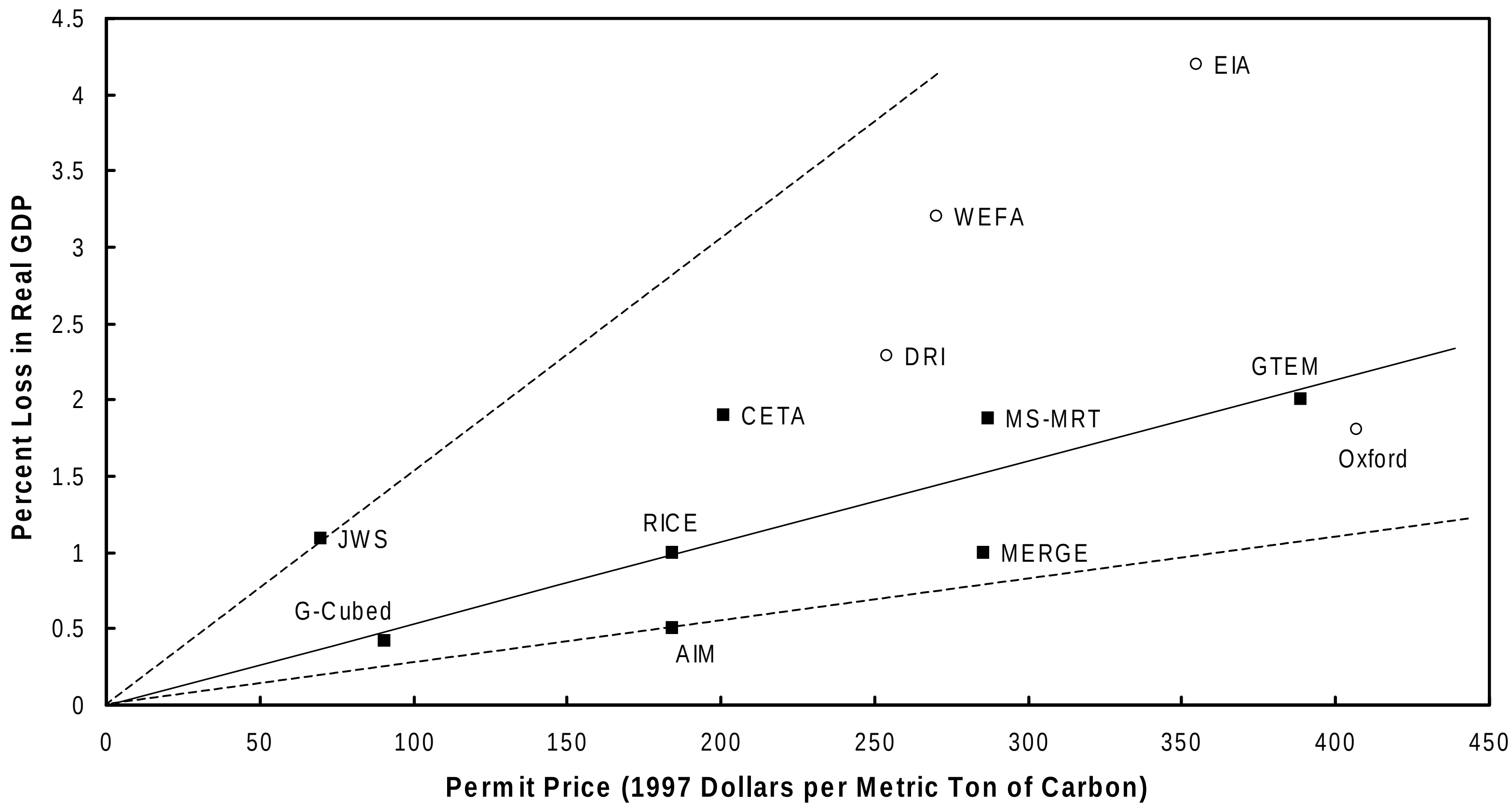
SOURCES: Table 3-2 and author's calculations.

NOTES: Price sensitivity provides an estimate of how energy users adjust their use of carbon-based energy in response to changes in its price (see Appendix A for details). That sensitivity is negative because energy use falls as its price rises. Larger absolute values indicate a larger response.

Except for JWS, all calculations assume that U.S. emissions in 2010 are reduced 7 percent below 1990 levels. JWS assumes U.S. emissions in 2010 are reduced to 1990 levels.

RICE and WorldScan models assume a unit elasticity of demand for energy. Because it is difficult to know how to adjust estimates of price sensitivity from these models for this factor, these models are not included in the table.

Figure 5-1. Model Estimates of Permit Price and Percent Loss in GDP in 2010, with No International Permit Trading



■ General Equilibrium Models

○ Macroeconometric Models

—— Regression Line Relating Percent Loss in GDP to Permit Price for General Equilibrium Models with Kyoto Consistent Caps

- - - - Maximum and Minimum Ratios of GDP Loss to Permit Price

Note: JWS assumes a cap equal to 1990 emissions, instead of a Kyoto-consistent cap.