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Background Paper

How CBO Estimates the Costs of Reducing Greenhouse-Gas Emissions

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Preface

As part of its mandate to provide the Congress with the objective, timely, and nonpartisan analysis needed to make informed economic and budgetary decisions, the Congressional Budget Office (CBO) prepares cost estimates for legislation under consideration by the Congress. In recent years, a number of legislative proposals have involved efforts to restrict emissions of greenhouse gases in the United States. To estimate the budgetary impact of such proposals, CBO must first estimate the incremental costs to firms and households of mitigating greenhouse gases. This background paper briefly describes the methodology that CBO uses to estimate those incremental costs, the data sources and models used to develop that methodology, and the rationale for using it. In keeping with CBO's mandate to provide impartial analysis, the paper contains no policy recommendations.

The methodology described in this paper was developed by Mark Lasky and Robert Shackleton of CBO's Macroeconomic Analysis Division and by Natalie Tawil of CBO's Microeconomic Studies Division. Robert Shackleton prepared the paper, under the supervision of Robert Dennis, Douglas Hamilton (formerly of CBO), and William Randolph. Paul Cullinan, Rob Johansson, Joseph Kile, and Mark Lasky provided helpful comments on an earlier draft.

Loretta Lettner edited the paper, and John Skeen proofread it. Maureen Costantino prepared the paper for publication. Lenny Skutnik produced the printed copies, Linda Schimmel coordinated the print distribution, and Simone Thomas prepared the electronic version for CBO's Web site (www.cbo.gov).

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How CBO Estimates the Costs of Reducing Greenhouse-Gas Emissions

Introduction

In accordance with the Congressional Budget and Impoundment Control Act of 1974, the Congressional Budget Office (CBO) assists the Congress by providing estimates of the costs the government could expect to incur as a result of enacting various legislative proposals. As the Congress has taken up the issue of addressing the risks associated with climate change, CBO has produced several estimates of the budgetary impact of policies designed to mitigate emissions of greenhouse gases (GHGs). A notable recent example of such legislation was a bill introduced in the Senate, S. 2191, the America's Climate Security Act of 2007—also known as the Lieberman-Warner bill—which would have established a regulatory program aimed at reducing the emission of GHGs in the United States over the 2010–2050 period.[1] To estimate the impact of such proposals on the federal budget, CBO must estimate the marginal, or incremental, cost of reducing emissions of a number of different greenhouse gases at various levels of mitigation and at different points in the future. This background paper describes CBO's methodological approach to estimating such costs, the sources of data and analysis used to develop that approach, and the rationale for using it.

CBO's methodology for estimating the costs of mitigating greenhouse-gas emissions draws on a wide range of public and private sources for data and analysis and involves a relatively simple framework that can be used to evaluate a wide variety of proposed policies. The framework can be adjusted to take into account changes in projections of emissions, other important economic assumptions, and science and policy parameters. In preparing its cost estimates, CBO uses estimates of mitigation costs that, by construction, are in the middle of the range of estimates produced by current state-of-the-art energy-economy models.

As currently implemented, the approach has several important limitations. First, it yields only point estimates and does not provide information about important sources of uncertainty. Second, it does not estimate or incorporate the effects of policies on aggregate economic output. Third, it does not provide detail about which technologies would be adopted more widely or used less because of the policies. Fourth, it does not include modeling of greenhouse-gas emissions or climate policies in other

1. CBO's cost estimates for S. 2191 are available online at www.cbo.gov/ftpdocs/91xx/doc9120/s2191.pdf and www.cbo.gov/ftpdocs/91xx/doc9121/s2191_EPW_Amendment.pdf. CBO also provided a cost estimate for a later version of the bill, S. 3036, entitled the Lieberman-Warner Climate Security Act of 2008, which is available at www.cbo.gov/ftpdocs/93xx/doc9337/s3036.pdf.

countries, which can have significant effects—depending on U.S. policy regarding emission offsets and trade in emission-intensive products—on the costs of controlling emissions in the United States. Those limitations could be addressed by future work that expands on the existing framework, and some of that work is now under way at CBO.

Several aspects of the climate issue serve as a useful backdrop to a description of the technical underpinnings of CBO's methodology. Those elements—discussed below—include the sources of greenhouse-gas emissions, potential approaches to managing those emissions, and the characteristics of recent legislative proposals to address the problem of greenhouse-gas emissions.

Sources of Greenhouse-Gas Emissions in the United States

Households and businesses in a modern industrial economy like that of the United States emit a number of different greenhouse gases through a wide variety of activities—any or all of which might be regulated under a mitigation program. The Environmental Protection Agency (EPA) estimates that, in 2006, U.S. emissions of greenhouse gases amounted to nearly 7.1 billion metric tons of carbon dioxide equivalent (MT CO_2e)—about 85 percent in the form of carbon dioxide (CO_2), 8 percent in the form of methane (CH_4), 5 percent in the form of nitrous oxide (N_2O), and 2 percent in the form of other (mainly fluorinated) gases (see Table 1).[2] About 86 percent of those emissions (including most of the CO_2 emissions) were directly related to the generation and consumption of energy, while the remaining 14 percent came from industrial and agricultural processes as diverse as the production of cement and the management of landfills, wastewater, and agricultural soils. About 94 percent of the CO_2 was emitted directly through the combustion of fossil fuels—40 percent from petroleum products, 35 percent from coal, and 19 percent from natural gas. The generation of electricity accounted for about 34 percent of total greenhouse-gas emissions; if emissions from electricity generation are attributed to the sectors that consume the electricity, industry accounted for about 29 percent of total greenhouse-gas emissions; transportation accounted for 28 percent; commercial and residential activities accounted for about 17 percent each, and agriculture accounted for about 8 percent. Those emissions were partially offset by the net absorption of roughly 900 million metric tons of CO_2 by the nation's forests and soils.

2. Greenhouse gases differ in their contribution to warming per physical unit of gas, and, for simplicity, they are often measured in terms of MT CO_2e—quantities of emissions that, over an arbitrary period of years (usually a century), enhance the greenhouse effect by as much as a metric ton of CO_2. The values cited above are from Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006* (April 15, 2008), available at www.epa.gov/climatechange/emissions/downloads/08_CR.pdf.

Table 1.

U.S. Greenhouse-Gas Emissions by Type of Gas and Economic Sector, Selected Years

(Millions of metric tons of carbon dioxide equivalent)

	1990	1995	2000	2005	2006	Percentage of Total, 2006
Total Greenhouse Gases	6,148	6,494	7,033	7,130	7,054	100.0
By Type of Greenhouse Gas						
Carbon Dioxide	5,069	5,394	5,940	6,074	5,983	84.8
From fossil-fuel combustion	4,724	5,032	5,577	5,731	5,638	79.9
Coal	1,699	1,805	2,053	2,094	2,065	29.3
Natural gas	1,012	1,172	1,221	1,174	1,155	16.4
Petroleum	2,013	2,055	2,303	2,463	2,417	34.3
From other sources	344	362	363	343	345	4.9
Methane	606	599	574	540	555	7.9
Nitrous oxide	383	396	386	370	368	5.2
Fluorinated gases	90	105	133	146	148	2.1
By Economic Sector						
(With Electricity-Related Emissions Attributed to the Electricity-Producing Sector)						
Electric Power	1,859	1,990	2,329	2,430	2,378	33.7
Transportation	1,544	1,686	1,918	1,987	1,970	27.9
Industry	1,460	1,478	1,433	1,354	1,372	19.4
Agriculture	507	524	528	521	534	7.6
Commercial	397	405	390	400	395	5.6
Residential	347	371	388	376	345	4.9
(With Electricity-Related Emissions Attributed to the Electricity-Consuming Sector)						
Industry	2,100	2,141	2,174	2,038	2,029	28.8
Transportation	1,547	1,689	1,921	1,992	1,975	28.0
Commercial	946	1,004	1,142	1,213	1,204	17.1
Residential	952	1,027	1,161	1,242	1,188	16.8
Agriculture	568	593	587	585	596	8.4
Memorandum:						
Net Absorption of CO_2 from Land Use, Land-Use Change, and Forestry[a]	-738	-775	-674	-879	-884	-12.5

Source: Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006, available at www.epa.gov/climatechange/emissions/downloads/08_CR.pdf.

Notes: Greenhouse gases differ in their contribution to warming per physical unit of gas and, for simplicity, are often measured in terms of metric tons of carbon dioxide (CO_2) equivalent—quantities of emissions that, over an arbitrary period of years (usually a century), enhance the greenhouse effect by as much as a metric ton of CO_2. EPA uses 100-year global-warming potentials to measure CO_2 equivalents for other gases.

Details may not sum to totals because of rounding. The enumeration by type of fossil fuel excludes a very small quantity of emissions from geothermal energy that is included in the fossil-fuel-combustion total; and the enumeration by economic sector excludes a small quantity of emissions coming from U.S. territories that is included in the total.

a. Not included in total.

Potential Approaches to Managing Emissions

Several different approaches, or combinations of approaches, could be used to manage emissions, including "command-and-control" regulations that would require the use of specific technologies or would set specific emission standards for various kinds of activity or equipment; cap-and-trade restrictions that would set an overall limit on specific types of emissions but allow emitters to buy and sell allowances to emit; and taxes that would directly raise the price of emitting gases.[3]

Experts generally consider the latter two "market-based" approaches—a cap-and-trade system or a tax, both of which would give businesses and households economic incentives to reduce the production and consumption of such emissions—to be particularly promising for managing many types of pollution. Each approach would allow emissions to be reduced through the decentralized decisionmaking of the participants in the relevant markets, increasing the likelihood that the reductions would be achieved at minimum cost. Moreover, experts generally agree that either approach could be used to efficiently manage the great majority of U.S. greenhouse-gas emissions—especially those that come from the combustion of fossil fuels. There being no domestic restrictions on such emissions at present, households and firms emit gases up to the point at which their marginal benefit equals the private cost of those emissions. Taxes or tradable caps on emissions—but not, in general, command-and-control regulations—would lead households and firms to cease emission-causing activities that yielded the least economic benefit per ton of emissions while continuing activities that yielded particularly large benefits. Those who acquired the right to emit gases under a cap-and-trade system would have, in effect, an asset whose value would be determined by the economic benefits of the last ton of allowable emissions. Legislation that imposed a tax on emissions would have a similar effect. Households and firms would continue emission-causing activities whose benefits per ton of emissions were greater than the tax rate and pay the tax, but they would cease activities that yielded benefits lower than the tax.

In principle, a given tax rate would yield a specific reduction in emissions; conversely, an emissions cap that required an equivalent reduction using tradable allowances would create, in effect, a right to emit whose value would be equal to the corresponding tax rate. Experts also generally agree that because of the uncertainties that society faces about the marginal benefits and marginal costs of averting climate change, a tax on emissions would have several economic advantages over a cap-and-trade approach.[4]

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3. In addition, policymakers could provide incentives to develop new technologies that produced fewer emissions.

4. For further discussion, see Congressional Budget Office, *Policy Options for Reducing CO_2 Emissions* (February 2008), available at www.cbo.gov/ftpdocs/89xx/doc8934/02-12-Carbon.pdf.

Management through market-based approaches would be particularly straightforward for CO_2 emissions produced during the combustion of fossil fuels (which accounts for about 80 percent of U.S. emissions of greenhouse gases) because the quantity of emissions from any fuel is directly related to its carbon content, which is easily measured. As a result, a cap or tax could be easily implemented by monitoring and controlling activities that indirectly lead to emissions (such as the production, sale, or purchase of fuels) rather than by monitoring actual emissions during combustion. Regulators could therefore control emissions by tracking fuels at a relatively small number of specific points prior to combustion—for coal, at the point of extraction; for petroleum products, at the point of import or refining; and for natural gas, at the pipeline. With somewhat greater difficulty, regulators could track nearly all emissions from the combustion of fossil fuels used in power plants in the utility sector or in large boilers in the industrial sector, both of which are already subject to a continuous emission monitoring system (CEMS) under existing regulation.[5]

However, not all U.S. emissions of greenhouse gases would be as straightforward to manage as CO_2 emissions from the combustion of fossil fuels. A significant share of the remaining 20 percent of U.S. emissions, which come from a variety of relatively minor sources, are much more difficult to monitor or ascribe directly to human activity and, therefore, would be difficult to control under either a cap-and-trade system or a tax. The same is true for the large movements of carbon dioxide and other gases in and out of the nation's forests and soils.

The gap between the ease of controlling some types of greenhouse-gas emissions and the difficulty of controlling others raises complex issues about which emissions to control and how to do so. Moreover, if more than one management approach might be appropriate, depending on the gas and its source, the issue of how to integrate different management approaches for different types of emissions in a single framework would have to be addressed. Such issues can complicate the design and implementation of effective management and the analysis of proposals that involve multiple approaches. CBO's methodology is intended to provide enough flexibility to permit the analysis of a wide variety of such proposals.

Characteristics of Recent Legislative Proposals

Recent Congressional proposals for which CBO has provided cost estimates would regulate the bulk of U.S. greenhouse-gas emissions through various types of cap-and-trade systems. The proposals typically involve the allocation or sale by the federal government of a limited number of allowances, each of which would give its holder the right either to emit a certain quantity of greenhouse gases or to produce or sell products whose consumption would ultimately result in that quantity of emissions. For any potential source of emissions covered under a given proposal, some agent in the chain of production or consumption leading to emissions would be required to

5. See www.epa.gov/ttn/emc/cem.html for further description of CEMS.

submit an allowance either for the emissions or for the production or sale of precursors. Generally, the proposals would allow nearly anyone to buy, hold, and sell the allowances, whether or not they actually were required to submit allowances under the regulation. That flexibility would open the potential market for allowances to a large number of agents, helping ensure that information about emissions and their effective control would be quickly incorporated into the allowance price.

S. 2191, the Lieberman-Warner bill, provides a useful illustration of the mechanics of a cap-and-trade system and of the complexities that can arise in the process of designing and analyzing such a system. Broadly speaking, S. 2191 would have required the Environmental Protection Agency to establish two cap-and-trade programs aimed at reducing the emission of GHGs in the United States over the 2010–2050 period.[6] One program would have covered the bulk of emissions, requiring nearly all entities that burned coal to submit an allowance for each ton of CO_2e emitted. By contrast, the program would have required entities that manufactured or imported petroleum or petroleum-based fuels to submit allowances for each quantity of fuel produced that would yield a ton of CO_2e emissions when the fuel was burned (presumably mainly by entities other than the manufacturer or importer). Thus, under S. 2191, consumers of gasoline would not have needed to submit allowances for the CO_2 emitted by their cars and trucks. However, importers and refiners could not produce and sell the gasoline to consumers without submitting allowances, effectively bringing the consumers—the ultimate emitters—under the program as well by increasing the scarcity of gasoline and raising its price. The same allowance program under S. 2191 would have required the submission of allowances for entities' CO_2e emissions of several other greenhouse gases from a number of sources (or for the production of goods whose consumption would result in emissions).

In addition, the legislation would have required EPA to establish a separate allowance program that applied only to the production and import of hydrofluorocarbons (HFCs). Altogether, the entities that would have been covered under the two programs were responsible for about 87 percent of total estimated emissions (unrelated to forestry and agriculture) in 2005, including nearly all emissions from the combustion of fossil fuels.

S. 2191 also called for more complex regulatory processes that would have provided credits to entities that reduced any of the wide variety of emissions (including net emissions from forestry and agriculture) not covered under the two cap-and-trade programs. Under those processes, entities could negotiate with regulators to establish projected emission baselines and then receive credits for reductions relative to those

6. In preparing recent cost estimates, such as that for S. 2191, CBO has relied on determinations by the Climate Change Division of EPA's Office of Atmospheric Programs as to which gases emitted from which economic sectors would be covered by the proposed legislation. EPA provides information on historical emissions by category as well as detailed information about coverage and the ease with which the emissions could be monitored and measured.

baselines. Examples include reducing emissions emanating from landfills, sequestering GHGs on croplands and rangelands, altering tillage practices, planting winter crops, or reducing the use of nitrogen fertilizer. Through such actions, entities could earn allowances that could be sold to and submitted by entities that were covered under the primary allowance program (that is, that were required to submit allowances for their emissions). Covered entities could thus, in effect, emit more gases than they would be allowed to otherwise, but those higher emissions would be offset by reductions elsewhere in the economy. S. 2191 limited the number of such offset allowances that could be submitted in place of emission reductions to no more than 15 percent of the total allowances submitted by a covered entity in any given year.

S. 2191 also would have allowed covered entities to purchase emission allowances from the greenhouse-gas regulatory programs of other countries, as long as the Administrator of EPA determined that the foreign program imposed mandatory quantitative controls on greenhouse-gas emissions and that the program was of "comparable stringency" to that proposed under S. 2191. As with offset allowances, S. 2191 would have limited the submission of international allowances to no more than 15 percent of total allowances submitted by a covered entity in any given year.

All recent legislative proposals would mandate a gradual decrease over time in the number of emission allowances allocated or sold annually—or, what is largely equivalent, a gradual increase in the tax rate on emissions. In the case of S. 2191, the number of allowances allocated under the main program would have declined from 5,775 million metric tons of CO_2e in 2012 to 1,732 million metric tons of CO_2e in 2050, at which point the number of allowances would be equal to about 28 percent of 2005 emissions (or about 16 percent of baseline 2050 emissions, as projected by CBO) in sectors covered by the program. The number of allowances allocated under the HFC program would have declined from 300 million metric tons of CO_2e in 2012 to 90 million metric tons of CO_2e annually from 2037 to 2050. Such decreases in the number of allowances would make the right to emit or sell products associated with emissions an increasingly scarce resource over time, and thus would increase its economic value at the margin—and its market price. Under any such program, the rising prices of increasingly scarce allowances would be largely incorporated into the prices of products associated with emissions and passed along to consumers of those products, so that the entity required to submit an allowance or pay a tax would tend to bear only a fraction of the ultimate cost. Rising prices of such products (relative to the prices of other goods and services) would, in turn, induce firms and households to reduce their consumption of those products and seek cheaper alternatives (in other words, those with lower associated emissions).

Although recent proposals typically would assign each emission allowance to a particular year, they would not require that all allowances be submitted in the year to which they were assigned. Usually, the proposals would limit the extent to which entities could "borrow forward"—that is, submit allowances prior to the assigned year and pay some penalty for doing so. However, proposals would generally allow entities to bank allowances more or less indefinitely and submit them many years after they were initially allocated. Such provisions would give regulated entities or other agents the opportunity to undertake significant reductions in emissions during early years of a regulatory program so that they would have more allowances available in later years as the program's increasingly stringent caps drive up the costs of mitigation. They also raise the analytic issue of what rate of return firms would require to undertake reductions for the purpose of banking.

Legislative proposals have included a wide array of provisions for the allocation of allowances, with many proposals calling for the sale of some allowances (either at auction or at a fixed price) and the free allocation of others (to covered entities, to states, or to firms or households—for instance, as rewards for various kinds of actions or as compensation for the costs of the program). A large body of economic literature concludes that the method of allocation could significantly affect the aggregate economic costs of the system, as well as the distribution of those costs within the population.[7] Specifically, the overall costs could be substantially moderated if allowances were sold at auction and the revenues were used to reduce marginal rates of taxes on capital and labor. However, the method of allocation would probably have at most a minor impact on the allowance price under a given cap.

Some proposals have included provisions that would effectively set a ceiling on the price of emission allowances, thus allowing the cap to be exceeded if mitigation costs threatened to rise above the ceiling. For example, S. 1766, the Low Carbon Economy Act of 2007, would have established a "technology accelerator payment" (or TAP) starting at $12 per metric ton of CO_2e in 2012 and rising by 5 percent annually (in inflation-adjusted terms) thereafter. In any given year, if regulated entities found that the market price of emission allowances was higher than the TAP for that year, they could elect to pay the TAP rather than submit an allowance. Other proposals have included provisions that would set a floor on the allowance price, such as the floor of $10 per metric ton of CO_2e mandated under S. 3036, the final version of the America's Climate Security Act of 2007 (which did not pass). Such provisions would prevent the price from sinking below the floor in the event of unexpectedly low energy demand and would ensure that emission reductions cheaper than the floor would be undertaken even during such periods.

Because the production of emission-intensive goods can easily migrate from one country to another, restrictions on emissions in any single country could easily result in a transfer of production to (and an increase in emissions in) other countries. Such

7. For discussions of such impacts, see Congressional Budget Office, *Policy Options for Reducing CO_2 Emissions*; Congressional Budget Office, *Trade-Offs in Allocating Allowances for CO_2 Emissions*, Issue Brief (April 25, 2007), available at www.cbo.gov/ftpdocs/89xx/doc8946/04-25-Cap_Trade.pdf; and Congressional Budget Office, "Comments on *Design Elements of a Mandatory Market-Based Greenhouse Gas Regulatory System,*"letter to the Honorable Jeff Bingaman (March 13, 2006), available at www.cbo.gov/ftpdocs/70xx/doc7068/03-13-CommentsOnWhitePaper.pdf.

“leakage” of emissions from controlling countries to others would result both in output losses in the controlling countries and in lower environmental benefits. To counteract such developments, several legislative proposals have included provisions that would restrict the importation of goods whose production was associated with significant quantities of greenhouse-gas emissions. For example, S. 2191 would have established a program that, beginning in 2020, would have required importers to purchase from the government “international reserve allowances” for the emissions embodied in imports of certain emission-intensive goods from countries that did not have in place emission-reduction policies comparable to those of the United State. The number of allowances required would have been determined by the amount of GHG emissions that went into producing those goods, and the cost of the allowances would have been determined by the cost of emission allowances in the domestic market.

Estimating the Costs of Mitigation

Given the basic characteristics of the relevant legislation outlined in the previous section, estimating the marginal costs of reducing emissions—which ultimately would determine the price of allowances—requires several steps:

- Construction of a base case that includes projections of future greenhouse-gas emissions in the United States in the absence of any new federal policies to control them, as well as projections of future prices of fossil fuels, electricity, and other products and services closely associated with such emissions.

- Development of estimates of how extensively and rapidly firms and households would respond to increases in the prices of fossil fuels and other sources of GHG emissions. That response can involve a combination of lowered demand for energy and energy-intensive goods and services, and the development and deployment of energy-efficient and low-emission energy technologies.

- Assessment of the impact of an array of provisions that would influence the market price of allowances. The most important such provisions involve regulatory coverage, subsidies for various emission-reducing activities, and opportunities for firms to bank allowances in one year and use them in another, as well as to purchase domestic or international offsets.

CBO follows a set of general rules when preparing its cost estimates. Those estimates generally do not reflect any net effect that a bill under consideration might have on aggregate economic activity, as measured by the inflation-adjusted gross domestic product (or real GDP), or any feedback effect on the budget from such changes in output. In the case of policies as far-reaching as those contained in recent proposals to reduce emissions, the impact on real GDP is likely to be fairly significant over several decades, even it is likely to be modest over the 10-year budgetary window. Moreover, a considerable body of economic research suggests that the allocation of emission allowances—or the disposition of revenues from the sale of allowances—could influence the magnitude of a policy's effect on GDP, although the impact of any induced changes in GDP on allowance prices would probably be modest. Nevertheless, in projecting the impact of climate legislation, CBO follows its standard practice of not estimating output effects or feedbacks from changes in output to changes in the budget.

Congressional procedures also require that CBO provide estimates of the budgetary effects of proposed legislation primarily over a 10-year window. Nevertheless, firms' expectations about long-term developments in the allowance market could lead them to undertake additional emission reductions in early years so that they could bank allowances for use in later years. Such banking could strongly affect allowance prices within that 10-year period. As a consequence, a realistic estimate of prices in the initial years of a regulatory program requires estimates of prices in later years as well. In making those estimates, CBO assumes that laws currently in place will remain in place indefinitely.

Projecting a Base Case

For its base-case projections of economic output, prices, and GHG emissions, CBO relied primarily on projections from the Energy Information Administration (EIA), which regularly produces and publishes the most detailed and comprehensive long-term projections of U.S energy use available.[8] EIA's projections, which currently extend to 2030, include estimates of the supply of, demand for, trade of, and prices of different types of energy services throughout the United States and, with lesser detail, the rest of the world. EIA also develops projections for GHG emissions unrelated to energy, which it uses when it receives requests to analyze proposals to regulate such emissions.[9]

A potential source of concern is that EIA's projections of real GDP could differ considerably from those of CBO, resulting in baseline projections for greenhouse-gas emissions that are inconsistent with CBO's economic projections. However, in recent years, EIA's projections have been sufficiently similar to CBO's that no adjustments were deemed necessary.[10] Should EIA's projections deviate substantially from CBO's in the future, CBO will continue to use EIA's annual ratios of emissions to real GDP

8. As of this writing, EIA's most recent projections for energy use and energy-related emissions are available at www.eia.doe.gov/oiaf/servicerpt/stimulus/aeostim.html.

9. EIA's most recent such projections, undertaken for its analysis of S. 2191, can be found at www.eia.doe.gov/oiaf/servicerpt/s2191/index.html.

10. In its 2008 *Annual Energy Outlook*, for example, EIA's average annual growth rate for GDP between 2008 and 2030 differs from that used in CBO's long-term projections for Social Security by 0.03 percent. CBO's projections are available at www.cbo.gov/doc.cfm?index=9649; EIA's projections are available at www.eia.doe.gov/oiaf/aeo/index.html.

by type and source of gas but will adjust EIA's emission projections to be consistent with CBO's projections for real GDP.

EIA's inventory of current emissions and projections of future emissions are based on a methodology that differs somewhat from that used by EPA, which publishes an inventory of emissions every year as part of the federal government's commitment to report U.S. emissions to the Intergovernmental Panel on Climate Change.[11] As the EPA inventory is considered the official U.S. estimate for purposes of international negotiations and agreements, CBO adjusted EIA's projections to align them with EPA's estimates of actual emissions for 2005, while retaining EIA's projected growth rates for specific greenhouse gases emitted from specific types of sources.

CBO also adjusted its projections to take into account recent updates to estimates of how emissions of gases other than carbon dioxide are most appropriately converted to carbon dioxide equivalents. EPA's current practice, consistent with international protocol, is to use the carbon dioxide equivalent (CO_2e) measures of the global warming potentials (or GWPs) of other gases that are reported in the *Second Assessment Report of the Intergovernmental Panel of Climate Change*, published in 1996, and, in particular, to use 100-year GWPs—that is, estimates of the amount of warming that those gases would cause over a century, relative to the warming that an equivalent quantity of carbon dioxide would cause over the same period.[12] However, CBO believes that, over the next few years, the relevant domestic and international agencies are likely to adopt the updated GWP measures reported last year in the *Fourth Assessment Report* and that any regulatory program for greenhouse-gas emissions that is adopted in the next few years will use those updated measures.[13] CBO therefore used the updated values in its projections, while continuing to follow the convention of using 100-year GWPs.

CBO's adjustments modestly changed the estimates of quantities of particular gases emitted in 2005, compared with EIA's inventory and base-case projections. Altogether, the adjustments increased the estimate of total greenhouse-gas emissions for 2005 (not including CO_2 emissions from forests and soils) by about 1.2 percent,

11. As of this writing, EPA's most recent such publication, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006*, EPA 430-R-08-005 (April 15, 2008), is available at www.epa.gov/climatechange/emissions/downloads/08_CR.pdf.

12. Ibid., p. ES–3. For the source of GWP estimates, see D. Schimel and others, "Radiative Forcing of Climate Change" in J. T. Houghton and others, eds., *Climate Change 1995: The Science of Climate Change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (New York. Cambridge University Press, 1996), p. 121.

13. The updated GWPs can be found in Piers Forster and others, "Changes in Atmospheric Constituents and in Radiative Forcing" in Solomon and others, eds., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, England: Cambridge University Press, 2007), pp. 212–213.

compared with EIA's inventory, and by about 1.9 percent, compared with EPA's inventory. Those differences carry over into projected emissions as well.

CBO did not develop an explicit projection for net emissions of CO_2 from forests and soils. Instead, as discussed in the next section, CBO developed estimates of potential sequestration (that is, storage of carbon in plants and soils) in those sectors without relating those estimates to an explicit baseline. Nor did CBO develop emission projections for other countries; as of this writing no cost estimate has required the development of supply curves (estimates of the quantities supplied at different prices) for foreign emission reductions or emission allowances.

An additional complication is that some legislation proposes to regulate the production of certain greenhouse gases that will not be emitted until several years after they (or the products in which they are embodied) are produced. The analysis of such proposals—as in the case, for example, of S. 2191's regulation of HFCs—requires baseline projections of the production (rather than the emissions) of the relevant gases. For such analyses, CBO developed projections based on information provided by industry sources and by EPA.

Several legislative proposals have included provisions that would permit the limited borrowing and unlimited banking of allowances. Under such provisions, expectations about long-term market developments could strongly affect allowance prices within the 10-year budgetary window for which CBO provides estimates, so that estimates of those prices could require estimates regarding the allowance market in later years as well. Since some of the proposals extend as far as 2050, CBO extended EIA's projections from 2030 to 2050, assuming that emissions would grow at the same annual rates, by type of greenhouse gas and source, beyond 2030 as they grew in the preceding decade, between 2020 and 2030. Since publishing its cost estimates for S. 2191 and S. 3036, CBO has adjusted its methodology so that the projected growth rates beyond 2030 of emissions by type of gas and source are more explicitly tied to economic activity, reflecting trends in both GDP and in the ratios of emissions to GDP. That is, CBO now assumes that emissions per unit of GDP will grow (or decline) at the same rate beyond 2030 as they are projected to grow in the preceding decade. Applied to the baseline CBO used for the cost estimates for S. 2191 and S. 3036, that approach would have raised aggregate emissions of greenhouse gases over the 2031–2050 period by about 1 percent.

Estimating the Response of Firms and Households to Emission Prices

CBO used several different methods for estimating the responsiveness of firms and households to changes in the price of emissions, depending on the source and type of emissions, as well as on the availability of appropriate data.

Carbon Dioxide Emissions from the Combustion of Fossil Fuels. For energy-related carbon dioxide emissions, CBO developed a method that averages a number of estimates from different models of the aggregate responsiveness of all end users of carbon-based energy to the pricing of CO_2 emissions.[14] The approach does not directly draw on highly detailed data of energy supply and demand in specific markets, but it incorporates the aggregate responses from a number of different models that generally treat energy markets in much greater depth. Thus, the approach can utilize a significant amount of detailed information about energy markets without explicitly addressing those details.

The method assumes that the consumption of fossil fuels depends on the end-use price (that is, the price paid by final users) of energy obtained from those fuels. Controls would reduce emissions by changing the end-use price of those products. For example, drivers base their vehicle purchases and driving decisions on the retail price of gasoline. A cap or tax on emissions would influence their consumption of (and emissions from) gasoline only to the extent that it affected that retail price. An increase in the end-use price of electricity generated from coal would reduce coal usage through two channels. First, consumers of coal-fired electricity would change their electricity consumption to the extent that emission controls, by changing the price of coal, influenced the retail price of electricity. Second, electricity generators would shift toward other fuels as the cost of electricity generated from coal rose relative to the cost of electricity generated from those other fuels. (Most models conclude that the bulk of emission reductions in the early years of a program would come from fuel switching in the utility sector.)

With energy consumption distributed across a large variety of fuels and uses, a practical simplification is to calculate end-users' and utilities' aggregate response to changes in the aggregated price of carbon-based energy products. Following that logic, CBO's method consists of three main steps. The first step is to calculate base-case end-use prices of distinct energy products, such as retail gasoline and diesel fuel, delivered natural gas, and retail electricity, in terms of the emissions that result from the consumption of those products. For example, a gallon of gasoline contains about 5.3 pounds of carbon, which, when burned, forms 19.6 pounds—or about 0.009 metric tons—of CO_2. (One pound of carbon, when burned, creates 3.67 pounds of CO_2.) Thus, when the retail price of gasoline is $2 per gallon, the retail price of carbon dioxide embodied in gasoline is $2 divided by 0.009, or about $225 per metric ton of carbon dioxide. (The calculation excludes the CO_2 emissions that result from the extraction, refining, and transportation of an energy product prior to its sale; an extension of the concept of "embodied" CO_2 that included such emissions would yield a somewhat lower price.)

In practice, data on prices, consumption, and emissions—from actual economic activity as well as from projections generated using models—are easily available only in relatively large aggregates, such as broad fuel types used in broad categories of economic

14. The methodology is described in detail in Mark Lasky, *The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models*, Congressional Budget Office Technical Paper 2003-3 (May 2003), available at www.cbo.gov/ftpdocs/41xx/doc4198/2003-3.pdf.

activity—for example, the consumption of natural gas in the residential sector. Thus, the cost per metric ton of CO_2 is calculated for each of those aggregates by dividing the market value of the energy produced using each type of fuel by the total emissions from the combustion of that fuel. For the portion of each fuel type that is not used to generate electricity, the market value is the quantity of fuel delivered to end users times the average sales price per unit of fuel. (The calculations exclude products, such as asphalt and plastics, that are not combusted and so do not yield carbon emissions.) For the portion of each type of fuel that is used to generate electricity, the market value for the energy produced from a given fuel type is calculated as that fuel's share of the total energy inputs to electricity generation times the total market value of electricity—a calculation that implicitly assumes that electricity from every source is sold at the same price.

The second step is to aggregate the resulting prices for each fuel into a single base-case price of energy derived from the combustion of fossil fuel (or carbon-energy). Ideally, the interaction of the allowance price and the baseline price of carbon-energy incorporates estimates not only of the elasticities of demand for each fuel but also of the elasticities of substitution between them.[15] To accomplish that, CBO adopts a constant elasticity of substitution (CES) weighting of the price of energy from each fuel, with the substitution parameter equal to 1. In this form, the baseline price for carbon-energy is the reciprocal of a weighted average of the reciprocals of the prices of energy:

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

where P represents an end-use price, E represents end-use energy, and the subscripts c, n, and p represent end-use coal, natural gas, and petroleum products, respectively.

The third step is to use information from a base-case and a policy-case scenario to calculate an aggregate sensitivity of the carbon-energy-CO_2 intensity of aggregate activity to the allowance price—that is, the sensitivity of CO_2 emissions per unit of economic output to an explicit price on those emissions:

$$s = \left[\ln\left(\frac{E_{policy}}{GDP_{policy}}\right) - \ln\left(\frac{E_{base}}{GDP_{base}}\right)\right]\ln\left(1 + \frac{T}{P}\right)$$

where s represents the sensitivity, E carbon-energy-CO_2 emissions, GDP real gross domestic product, P the aggregate end-use price, and T the allowance price. This approach to calculating the price sensitivity assumes that, all else being equal at a given time, emissions are proportional to real GDP. It also yields a measure that can

15. An elasticity is a quantitative measure of the response of one variable to changes in another, such as the change in the quantity of gasoline demanded that results from a change in the price. It is defined as the change in the natural log of the first variable divided by the change in the natural log of the other.

be used to estimate a response and allowance price that are consistent with the assumption that the nation's total output remains constant.

The calculated price sensitivity is similar to an elasticity of demand for carbon-energy, but in addition to reflecting changes in demand for carbon-energy, it also reflects substitutions among fuels with different carbon contents. In addition, because it measures the response of emissions to the permit price rather than to explicit changes in the price of carbon-based energy, the sensitivity implicitly includes supply effects. For example, if restrictions on emissions led to a decline in the price of crude oil, the price of carbon-energy would fall below the base-case price on which the price sensitivity is calculated. That is, the price of carbon-energy in the policy case would be less than the baseline price of carbon-energy plus the allowance price. The calculated price sensitivity would reflect changes in emissions resulting from such changes in supply prices.

The sensitivity can then be used to determine the amount of emissions generated at a given allowance price or tax:

$$E_{policy} = E_{base} \times \left(\frac{GDP_{policy}}{GDP_{base}}\right) \times \left(1 + \frac{T}{P}\right)^{s}$$

or to determine the allowance price or tax required to achieve a given emission target:

$$T = P \times \left\{ \left[\left(\frac{E_{policy}}{E_{base}}\right) / \left(\frac{GDP_{policy}}{GDP_{base}}\right) \right]^{\frac{1}{s}} - 1 \right\}$$

CBO used the method described above to calculate price sensitivities for carbon-energy in a number of economic models that are currently used in the United States to analyze energy consumption and GHG emissions, including models used by EIA and EPA as well as a number of models used by academic researchers. (See Box 1 for a list of the models used.)

The models differ substantially in their baseline projections of economic growth, energy consumption and prices, and greenhouse-gas emissions. Their time steps also vary: Some models produce output for every year of the projection, some for every fifth year, and some once per decade. Most important, the models vary a great deal in their estimates of the sensitivity of households' and businesses' energy use to changes in the cost of using fossil fuels. In general, a model's price sensitivity results from three critical factors: the modeled long-run ability of households, manufacturers, and utilities to substitute low-carbon fuels for high-carbon fuels for a given amount of energy consumption; the long-run sensitivity of those entities' energy usage to higher energy prices; and the speed at which those long-run responses unfold. In addition, a given model's sensitivity can vary with the severity of the restrictions imposed on energy use or emissions.

Box 1.

Models Used to Develop CBO's Synthesis

After reviewing recent studies in the field of energy modeling, the Congressional Budget Office (CBO) concluded that, for the purposes of analyzing market and policy developments in the United States, the current state of the art was best represented by a core of six models. Those models are as follows:

- The National Energy Modeling System (NEMS) developed by the Energy Information Administration (EIA);[1]
- The Emissions Prediction and Policy Analysis (EPPA) Model used by climate researchers at the Massachusetts Institute of Technology;[2]
- The Applied Dynamic Analysis of the Global Economy (ADAGE) Model developed at RTI International and used by EPA;[3]

1. Full documentation of the NEMS model is available at www.eia.doe.gov/oiaf/aeo/overview/index.html.
2. For documentation of EPPA, see Sergey Paltsev and others, "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4," Report No. 125 (Cambridge, Mass.: MIT Joint Program on the Science and Policy of Global Change, August 2005), available at web.mit.edu/globalchange/www/MITJPSPGC_Rpt125.pdf.
3. For documentation of ADAGE, see Martin T. Ross, "Documentation of the Applied Dynamic Analysis of the Global Economy (ADAGE) Model," Working Paper 07_02 (Research Triangle Park, N.C.: RTI International, April 2007), available at www.rti.org/pubs/adage-model-doc_ross_apr07.pdf.

Continued

To develop a single, year-by-year estimate of price sensitivity, CBO calculated a geometric mean of the price sensitivities for the years 2015, 2020, 2025, and 2030 for each of the models available, using one or more representative climate-policy scenarios from each model.[16] In a few cases—the ADAGE and MiniCAM models—CBO concluded that the models' high price sensitivity reflected an overly optimistic assessment of how rapidly energy-consuming capital stock—existing vehicles, equipment, structures, and electricity-generating capacity—could be replaced and adjusted the sensitivities to be consistent with its own assessment of the pace of capital-stock turn-

16. Unlike an arithmetic mean (or average), the geometric mean of a set of *n* numbers is calculated by multiplying them together and taking the *n*th root of their product.

Box 1. Continued

Models Used to Develop CBO's Synthesis

- The Second Generation Model (SGM) and MiniCAM models developed and used by the Joint Global Change Research Institute;[4]
- The Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) developed by Stanford University and EPRI (formerly known as the Electric Power Research Institute);[5] and
- The Multi-Region National–North American Electricity and Environment (MRN–NEEM) Model developed and used by CRA International.[6]

The teams that developed and run those models kindly provided a variety of data and other information to CBO for the development of its estimates.

4. Primary documentation for SGM can be found in Antoinette L. Brenkert and others, "Model Documentation: The Second Generation Model," PNNL-14256 (Richland, Wash.: Pacific Northwest National Laboratory, October 2004), available at www.globalchange.umd.edu/data/models/SGM-Model_Documentation.pdf. Further documentation for SGM is available at www.globalchange.umd.edu/models/sgm/. A brief description of the MiniCAM model is available at www.globalchange.umd.edu/models/minicam/; further documentation is available in L. Clarke and others, "Documentation for the MiniCAM CCSP Scenarios," Battelle Pacific Northwest Division Technical Report PNNL-16735 (Richland, Wash.: Battelle 2007).
5. Documentation for MERGE is in Alan S. Manne and Richard G. Richels, "MERGE: An Integrated Assessment Model for Global Climate Change," available at www.stanford.edu/group/MERGE/GERAD1.pdf.
6. Documentation for MRN-NEEM is in "Appendix: CRA International's MRN-NEEM Integrated Model for Analysis of US Greenhouse Gas Policies," available at www.crai.com/uploadedFiles/RELATING_MATERIALS/Publications/BC/Energy_and_Environment/files/MRN-NEEM%20Integrated%20Model%20for%20Analysis%20of%20US%20Greenhouse%20Gas%20Policies.pdf.

over. In other cases—the EPPA and SGM models—CBO adjusted the sensitivity upward in the early years to reflect the models' lack of forward-looking behavior. A few of the models did not generate results for the years 2015 and 2025; for those years, CBO adjusted the sensitivities calculated using the models that did generate results for those years by the 2020 and 2030 ratios of the price sensitivity calculated using all the models to the sensitivity calculated using only those models that produced results in all years. Finally, CBO interpolated price sensitivities for intervening years and extrapolated back to 2012 and forward to 2050 using estimates of the rates at which capital would probably be replaced in the electric utility sector and in other sectors of the economy.

Thus, CBO's price sensitivities essentially reflect those embodied in the reviewed models, with adjustments to assumptions about the pace at which firms and households would likely replace existing capital stock with newer items that used less energy or emitted smaller quantities of GHGs. The resulting series of estimated annual price sensitivities begins at about -0.4 in 2012 and grows at a decelerating pace to about -1.5 by 2050. Given CBO's baseline, the sensitivity for the year 2015—nearly -0.6—implies that an increase of 10 percent in the average price of end-use energy generated by fossil fuels in that year would induce about a 5 percent reduction in CO_2 emissions. With sustained restrictions on emissions, however, by 2025, a 10 percent increase would result in a nearly 9 percent reduction in emissions, with the sensitivity continuing to increase over time at a gradually decreasing rate.

For CO_2 emissions not associated with energy use—about 6 percent of total CO_2 emissions in 2005—CBO found little research available on mitigation costs and applied the price sensitivities estimated for energy-related CO_2 emissions.

CBO's approach has some important limitations that could be addressed by future work that expands on the existing framework. First, it does not incorporate the effects of changes in aggregate economic output, whereas significant restrictions on emissions could affect aggregate output over the long term. Although estimates of output effects for any given proposal vary widely across models, it appears likely that proposals of the magnitude of S. 2191 could reduce real GDP by a few percent below its projected base-case level by 2050. Such impacts, in turn, could dampen energy demand sufficiently to reduce the estimated allowance price by a few percent as well.

Second, as currently implemented, the approach yields only a point estimate of responsiveness over several decades that does not speak to the range of uncertainty inherent in such calculations. In reality, the economy's response to restrictions on emissions could be significantly stronger or weaker than is projected by CBO.[17]

Third, CBO's approach does not provide insight into the exact ways in which producers and consumers of energy would meet the caps, or into the mix of technological developments that might contribute to that increasing responsiveness. Each of the various models from which the approach draws yields different combinations of ways of reducing emissions; indeed, in some cases, a given model may yield a range of ways

17. Lasky estimates a standard deviation for earlier estimates of such sensitivities of roughly ±25 percent, based on the standard errors of estimates of elasticities of energy demand surveyed in Carol Dahl, *A Survey of Energy Demand Elasticities in Support of the Development of the NEMS* (report submitted under contract DE-AP01-93EI23499 to the Department of Energy, October 19, 1993). (See footnote 14.)

(and a range of estimates of the cost) to achieve a specific goal for emissions, depending on assumptions about what technologies might be available, at what cost, and at what point in time. Every model projects significant reductions from fuel-switching in the electricity sector, with coal-fired generation replaced by some type of low- to zero-emission generation or (after 2020 or so) by technologies designed to capture CO_2 emissions from coal and store them underground. However, the mix of replacement technologies varies significantly among models, as does the mix of fuel-switching in electricity generation, vehicle replacement in the transportation sector, and conservation in those and other sectors. CBO's approach does not require an explicit choice of (or provide explicit conclusions about) which technologies would be used to achieve the emission reductions implied by its price responsiveness.

Fourth, CBO's approach does not include the modeling of other countries' greenhouse-gas emissions or climate policies, which could both have significant effects on the cost of controlling emissions in the United States. For example, higher emissions in developing countries could provide more opportunities for inexpensive offsets, but more-stringent policies in other developed countries could result in greater competition and higher prices for such offsets. In addition, the extent of emission controls in other countries could influence movement of emission-intensive production out of the United States and the impact of trade measures intended to mitigate such movement.

Emissions from Other Sources. To develop estimates of the cost of mitigating greenhouse gases other than carbon dioxide, as well as the cost of activities to sequester carbon dioxide through agricultural and forestry activities, CBO drew on two EPA studies that present estimates of the engineering costs of reducing emissions using a variety of technologies either currently available or projected to be available in coming years.[18] Those studies are considered by many experts to be the best comprehensive reviews of mitigation costs for such sources and form the basis for essentially all recent analyses of the costs of mitigating GHGs in the United States.

For the years 2010 and 2020, EPA presents estimates of the potential percentage reduction in total projected emissions of a particular gas from a particular sector at various prices per unit of greenhouse gas emitted—for example, the percentage reduction in emissions of methane (CH_4) from landfills or in nitrous oxide (N_2O) emissions generated during the production of nitric and adipic acids if the price was \$20 per metric ton of CO_2e. In a number of cases, EPA's estimates of mitigation costs for non-CO_2 gases suggest that at least some reductions could be undertaken at negative cost; that is, firms could adopt advanced technologies that would not only reduce emissions but would also yield a profit. CBO concluded that such extensive profit opportunities were unlikely to exist and that the estimates most likely failed to take

18. See Environmental Protection Agency, *Global Mitigation of Non-CO_2 Greenhouse Gases*, EPA 430-R-06-005 (June 2006), and Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*, EPA 430-R-05-006 (November 2005).

into account transaction costs and other factors that result in positive mitigation costs overall. CBO therefore adjusted EPA's cost estimates accordingly, so that mitigation costs, though often quite low compared with its estimates of mitigation costs for energy-related CO_2 emissions, were nonetheless invariably positive.

CBO also adjusted EPA's cost estimates to include estimates of the rates at which relatively new technologies are likely to penetrate markets. CBO drew on an analysis that was published by EIA and based on studies of technology penetration by Edwin Mansfield and A. Wade Blackman to calculate annual aggregate penetration rates (N_t) for the technologies available to mitigate emissions of each source and type of gas. The penetration rates are estimated as a function of the initial penetration rate (N_0), the magnitude of the profitability of the investment, relative to other investments that a representative firm could undertake (*P),* and of the size of the investment, relative to a representative firm's total investment *(S)*.[19] The calculated equations thus take the form:

$$N_t = 1/[1 + e^{\{-(-\ln((1-N_0)/N_0)) - (z + a_1 P + a_2 S)^* t\}}]$$

where the parameters z, a_1, and a_2 are based on estimates by Mansfield.[20]

CBO used the resulting calculations of market penetration by year and price of emissions to estimate a general translog equation of the form:

$$N_t = e^{(b_0 + b_1 \ln p_t + b_2 \ln t + b_3 \ln p_t \ln t + b_4 (\ln p_t)^2 + b_5 (\ln t)^2)}$$

where the *b*s are the estimated parameters. That equation is of a sufficiently general form that it can capture the curvature of almost any function of time and price that results from the market penetration calculations described above.

For emissions of CO_2, N_2O, and CH_4 from agriculture and forestry, CBO drew on a separate EPA publication that presents estimates of average annual sequestration or net emissions (in millions of metric tons of CO_2) per decade for two price paths for emissions. For N_2O, and CH_4, EPA provides baseline projections, making it possible to estimate regressions of the form described above, with the percentage reduction from the baseline in place of the percentage of market penetration. For CO_2, CBO interpolated a series of price paths between the two paths published by EPA and used

19. See Energy Information Administration, *Outlook for Biomass Ethanol Production and Demand*, available at www.eia.doe.gov/oiaf/analysispaper/pdf/biomass.pdf. Spreadsheet analysis provided to CBO by Daniel Skelly of EIA in December 2007.

20. Following EIA's procedures, CBO used these parameters: a_1 = 0.53; a_2 = -0.027; *P* is a rising linear function of price, with *P* = 0.75 when the emissions price is zero and 1.0 when the emission price is \$20 per MT CO_2e; N_o = 0.35; and *S* = 0.05.

the interpolated series to estimate a translog regression of sequestration (*SQ)* as a function of time and emission price:

$$SQ_t = e^{(b_0 + b_1 \ln p_t + b_2 \ln t + b_3 \ln p_t \ln t + b_4 (\ln p_t)^2 + b_5 (\ln t)^2)}$$

The estimated equations imply that sequestration in any given year is a nearly linear function of the price but that a constant price for emissions will yield logistic growth of absorption of carbon in forests and soils (net of absorption that would occur in the absence of a price), with a rapid initial increase in sequestration that peaks after about 20 years and then gradually tapers off to about 60 percent of the peak after 50 years and about 11 percent after a century.[21] A rising path for emission prices will induce more planting, yielding a path of sequestration that rises more rapidly and tapers off later and more slowly.

Fluorinated Gases. CBO found very little information available on the likely cost of reducing the production of fluorinated gases, the bulk of which are hydrofluorocarbons (HFCs). Following discussions with analysts at EPA and within the industry, CBO concluded that the price for production allowances in an HFC program was likely to be driven by responses to increasing prices of HFCs, by prices paid for the recycling of HFCs, and, over time, by prices of substitutes that would only gradually become available and be incorporated into the design and production of HFC-using equipment. Caps or taxes would tend to raise the price of HFCs, reducing the quantity demanded. Higher prices also would encourage recyclers to meet some of the demand by removing existing HFCs from older products, processing them, and making them available for sale. Over time, restrictions would encourage the development and deployment of new types of HFCs with lower GWPs, and products designed around them. However, such innovations would take time to penetrate markets, and it is difficult to estimate the extent to which they are likely to displace the demand for existing products over the next decade. Thus, CBO anticipated that in the early years of the program, importers and exporters of HFCs would most likely turn to recycling their HFCs—currently costing roughly $8 per pound—as a primary means of meeting the restrictions imposed by the cap set under that legislation. In later years, alternative products of roughly similar costs would probably displace the supply for HFCs in new equipment. CBO assumed that, in the short term, demand for HFCs would be relatively inelastic—roughly as responsive to price increases as the demand for gasoline is, with a price elasticity of -0.2—but that demand would become increasingly responsive to rising prices over time as alternatives became available and equipment was replaced, increasing the elasticity by -0.05 per year until it reached -1.5.

21. Logistic growth follows an S curve, beginning relatively slowly, accelerating rapidly, and then gradually tapering off. For example, an emission price (in 2006 dollars) of $25 per metric ton of CO_2e, beginning in 2006, would yield peak sequestration of about 500 million metric tons of CO_2 in about 2026, tapering off to about 60 million metric tons of CO_2 by 2100.

Analyzing Legislative Provisions

Legislative proposals to restrict emissions can include not only a variety of provisions that specify the structure of a cap-and-trade system (such as provisions for the borrowing or banking of allowances) but also a number of other provisions (such as emission standards and subsidies for technology development) that would affect the growth of emissions. Both types of provisions would influence the market price of allowances under the cap-and-trade system. In addition to the provisions of S. 2191 discussed below, future legislative proposals could include, for example, efficiency standards in the automotive or electric utility sectors, which would require additional analysis to determine the influence of those standards on emissions and allowance prices.

Determining Firms' Response to Opportunities for the Banking of Emission Allowances. Provisions that allow entities to bank allowances for use in years other than the year in which they are issued may create opportunities for firms to profit from such banking. If, in the absence of such provisions, the inflation-adjusted price of allowances rose at a sufficiently rapid rate, firms could earn greater profits by undertaking extra GHG mitigation efforts in the initial years of the program, when the prices were relatively low, banking the remaining allowances, and submitting those allowances in later years, when the increasing stringency imposed by the program's declining caps would drive prices considerably higher.

That possibility raises the analytic issue of what constitutes the normal expected rate of return that would have to be exceeded to induce firms to bank allowances. Various studies that estimate allowance prices under banking provisions have used inflation-adjusted expected rates of return ranging from 4 percent (somewhat higher than the historical returns to bonds) to 8 percent (roughly the historical return on corporate equity). A lower rate implies a slower rate of growth of the allowance price, more banking, and a higher estimated allowance price in the early years of the program, compared with prices in a program without banking. The price would be lower in later years than it would be without banking; the inflection point is determined by the period of analysis.

An important requirement of the appropriate rate of return is that the risk characteristics of the relevant investment should be similar to those of investing in emission allowances. That is, the probabilities of the return being substantially higher or lower than the expected (or average) return should be similar to the probabilities of the future allowance price being substantially higher or lower than expected. For example, allowance prices and returns on allowances could be affected by monetary shocks, higher- or lower-than-expected economic growth, unexpected technological developments or supply shocks in the energy sector and elsewhere, and substantial changes in the regulatory framework. CBO concluded that those risks are very similar to the risks faced by typical investments in the U.S. nonfinancial corporate sector and that, as a rule, holders would bank allowances up to the point at which the expected rate of return for doing so—that is, the expected rate of increase of mitigation costs over time—was equal to the expected rate of return from firms' alternative investment opportunities in that sector.

To calculate the real rate of return in the U.S. nonfinancial corporate sector, CBO employed the methodology underlying its estimates of the long-run real rate of interest on 10-year Treasury notes.[22] To prepare those estimates, CBO uses the concept of the "natural rate of interest," a rate that is based on estimates of the economy's underlying ability to produce output from its capital stock. To obtain an estimate appropriate for the 2012–2050 period covered by S. 2191, CBO used inputs for 2018 (the most distant year available) from its January 2008 forecast of the U.S. economy. That approach yielded a real return of about 6 percent, consistent with CBO's long-run economic forecast.

Treatment of Trade Measures for Carbon-Intensive Goods. For S. 2191, CBO did not estimate the amount of revenues that might be generated from the provision requiring importers to purchase international reserve allowances for emissions embodied in certain types of imports from countries that do not restrict emissions. The provision was not to take effect until 2020 and thus had no budgetary implications within the 10-year budgetary window for which CBO provides estimates. However, in future cost estimates, CBO will estimate revenues and outlays resulting from any provision that would apply trade measures to imports or exports of emission-intensive goods within the budgetary window. Such estimates will require detailed estimates of emissions embodied in different types of products produced in other countries. Because detailed information on the emission intensity of production is not available for most countries, CBO will develop proxy estimates based on the emission intensity of manufactured goods currently produced in the United States, using data on energy use and gross output by industry from input-output tables developed by the U.S. Department of Commerce's Bureau of Economic Analysis as well as estimates of emissions from manufacturing industries developed by EIA.[23] Such estimates will be adjusted to account for expected future changes in emission intensities, on the basis of past trends.

Determining Firms' Response to Subsidies for Carbon Capture and Storage Technology.
CBO generally makes no assumptions about the extent to which subsidies for specific technologies would affect allowance prices. However, in the case of carbon capture and storage (CCS) technology, nearly all of the models used to develop CBO's estimate of the sensitivity of emissions to allowance prices include the technology as a mitigation option, and several of the models project that subsidies for the technology would influence the evolution of allowance prices under a mitigation policy as strin-

22. For a discussion of that methodology, see Congressional Budget Office, *How CBO Projects the Real Rate of Interest on 10-Year Treasury Notes* (December 2007).

23. Data published by the International Energy Agency on the emission intensities of aggregate output of other countries could also be used to scale estimates of sector-specific emission intensities for non-U.S. goods.

gent as that proposed in S. 2191. After analyzing those model results, CBO concluded that subsidies for early investments in CCS technology, if sufficiently large, could encourage enough sequestration to influence allowance prices.

To analyze that potential influence, CBO reviewed projections of the pace of implementation of CCS under different allowance prices in several models, particularly the NEMS and SGM models. On the basis of that review, CBO developed estimates of the maximum realistic rate at which CCS technology could be installed (roughly 14 gigawatts of capacity per year), as well as an estimate of the level of allowance prices, in the absence of subsidies, that would offset the incremental cost of using CCS in the generation of electricity and that would thus trigger the adoption of CCS technology. (The required allowance prices would place a sufficiently high discounted present value on CO_2 sequestered over the assumed lifetime of CCS capacity to offset the incremental cost of CCS.) Using those estimates, CBO developed a process for calculating the additional increment of CCS capacity that would be installed in response to subsidies, measured in terms of dollars per metric ton of sequestered CO_2, subject to the constraint on the installation of CCS capacity.