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How Carbon Dioxide Emissions Would Respond to a Tax or Allowance Price: An Update

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Abstract

In this working paper, the Congressional Budget Office describes its recent update of parameters that characterize the relationship between emissions of carbon dioxide and changes in the price of those emissions. Based on a review of recent studies, CBO evaluated how a change in price induced by a tax or an allowance price on emissions would affect the amount of carbon dioxide released by the combustion of fossil fuels in the electric power sector, the transportation sector, and a composite sector that comprises the residential, commercial, and industrial sectors.

In the electric power sector, price sensitivities of energy-related emissions of carbon dioxide over the first 10 years of a potential tax policy are about three times larger, on average—that is, more sensitive—in CBO's current update than its previous (2010) estimates. In the transportation sector, 10-year average price sensitivities are about 25 percent smaller (that is, less sensitive) in the current update, and they are about the same in the composite sector. Totaled across all three sectors, the projected 10-year reduction in carbon dioxide emissions stemming from a tax on those emissions would be about twice as large as previously estimated, though the increased reductions in the electric power sector would account for nearly all of the additional reductions overall. Because emissions would decline by a larger amount than previously estimated, overall revenues from a prospective tax on energy-related emissions of carbon dioxide would be smaller. Revenues in the electric power sector would be about 25 percent lower over 10 years, but revenues in the transportation and composite sectors would be largely unchanged.

Keywords: climate, emissions, tax, greenhouse gases

JEL Classification: H23, Q48, Q54, Q58

Notes

Numbers in the text, figures, and tables may not sum to totals because of rounding.

Unless this report indicates otherwise, all years referred to are calendar years, and all values are reported in 2020 dollars.

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Introduction

Lawmakers are considering policies that would reduce emissions of greenhouse gases (GHGs)—the majority of which result from the burning of fossil fuels—to forestall climate change. One policy option would impose a price on emissions of carbon dioxide (CO_2) and, possibly, other gases linked to global warming, either by imposing a tax on such emissions or by adopting a cap-and-trade program. To determine the potential effects of those types of policies, the Congressional Budget Office and the staff of the Joint Committee on Taxation project the change in emissions and estimate the budgetary effects on the basis of the projected emissions that would remain.

This working paper describes CBO's 2020 update of a key input into the modeling of emissions responses: the sensitivity of energy-related CO_2 emissions to a change in the price of those emissions.[1] A tax on those CO_2 emissions or an allowance price under a cap-and-trade program would raise the price of fossil fuels (oil, coal, and natural gas) and provide an incentive for consumers and businesses to switch to lower-carbon fuels when possible (from coal to natural gas, for example), invest in energy-efficient upgrades, or reduce their purchases of fossil fuels (among other options). CBO's analysis examines the price sensitivity in three broad sectors—electric power, transportation, and a composite of the residential, commercial, and industrial sectors. Although CBO considers the specific case of the imposition of a tax on energy-related emissions of CO_2, the price sensitivity would apply equally to the case in which allowance prices were introduced on emissions under a cap-and-trade program.

To estimate the relationship between a tax and emissions of CO_2 in each sector, CBO calculated a "price of embedded CO_2"—that is, an average price that final purchasers of fossil fuels (or electricity) implicitly pay for the CO_2 that is emitted when the fuels are burned. In the transportation sector, for example, the price of embedded CO_2 by CBO's calculation was about $310 for each metric ton of CO_2 released in 2020. In other words, one metric ton of CO_2 was released by the combustion of fossil fuels, on average, for each $310 spent on the purchase of gasoline, diesel fuel, and other fuels used for transportation. By raising the prices of fossil fuels, the tax would increase the price of embedded CO_2 and make it more costly to emit.

Among the three sectors that CBO examined, the electric power sector is most responsive to changes in the price of embedded CO_2, largely because electricity producers have relatively extensive opportunities to switch between fuels as relative prices change. A tax on energy-related

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[1] In its recent update, CBO focused on the responsiveness of CO_2 emissions from the combustion of fossil fuels. The agency did not reevaluate the sensitivity of other greenhouse gases because none of the simulations that CBO relied on considered the effects on non–CO_2 gases. For details on the method CBO used to measure the sensitivity of emissions of those non–CO_2 gases and their price, see Congressional Budget Office, *How CBO Estimates the Costs of Reducing Greenhouse-Gas Emissions* (April 2009), www.cbo.gov/publication/41745.

CO_2 could lead to a large reduction in emissions because less electricity would be produced using coal and more would be generated using natural gas or, over longer time frames, renewable sources, such as wind and solar power. (Combustion of natural gas releases about half the emissions of CO_2 for an equivalent amount of electricity produced as does the combustion of coal, and renewable power releases no emissions.)

The transportation sector, in contrast, is less responsive to changes in the price of embedded CO_2, because it is overwhelmingly dependent on petroleum-based liquid fuels and has few cost-effective alternatives available. In addition, the stock of capital in transportation—the number and the composition of cars and trucks, aircraft, and other forms of transportation—changes slowly, so CO_2 emissions in that sector are much less responsive than in the electric power sector. The responsiveness of emissions in the composite sector is more comparable to the responsiveness of emissions in transportation than in the electric power sector because productive capital in the composite sector—industrial equipment and machinery, commercial building space, residential housing, and other long-lived assets—is costly to update or replace.

CBO previously updated its price sensitivities in 2010. Several developments since then raise the possibility that the relationship between emissions of CO_2 and the prices of embedded CO_2 may have changed. For example, the lower costs of producing renewable power within the electric power sector, the increase in the supply of oil and natural gas from shale and the downward pressure that has had on the prices of those fuels, and the changing composition of U.S. economic activity in which fewer emissions are being released per dollar of economic output have affected the potential response of GHG emissions to a change in the price of embedded CO_2.

Composition and Distribution of Greenhouse Gas Emissions in the United States

The Environmental Protection Agency (EPA), the agency tasked with accounting for GHG emissions in the United States, estimates that those emissions amounted to nearly 6.6 billion metric tons of carbon dioxide equivalent (MT CO_2e) in 2019 (the latest year for which EPA reports emissions), about the same level as in 1990 but about 12 percent below the 2007 peak (see Figure 1).[2] Emissions were partially offset by the net absorption of about 800 million metric

[2] Greenhouse gases differ in their contribution to warming per physical unit of gas. For simplicity, they are often measured in terms of MT CO_2e—quantities of emissions that, over a period of years (usually a century), contribute to the greenhouse effect by as much as a metric ton of CO_2. See Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019*, EPA 430-R-21-005 (April 2021), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

tons of carbon dioxide equivalent (MMT CO_2e), or nearly 12 percent of all emissions, by the nation's forests and soils; that net absorption is not shown in Figure 1.[3]

About 80 percent of GHG emissions in 2019 (about 5.3 billion metric tons) were carbon dioxide, and the remainder were methane, nitrous oxide, and other (mainly fluorinated) gases. Of those CO_2 emissions, about 92 percent (about 4.9 billion metric tons) resulted directly from the combustion of fossil fuels. The other 8 percent of CO_2 emissions were from sources not related to fossil fuel combustion, such as those from industrial, agricultural, and waste management processes in which emissions are released as a byproduct (during the production of cement or ammonia, for example).[4]

Among the three broad sectors for which CBO calculated price sensitivities, transportation accounted for the largest share of CO_2 emissions from fossil fuel combustion in 2019, at 38 percent. In turn, the electric power and the composite sectors accounted for 33 percent and 29 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2019 (see Figure 2).

CBO's Methodology for Estimating the Sectoral Responses to Changes in Emissions Prices

The procedure that CBO used in 2020 to estimate the relationship between energy-related emissions of CO_2 and an emissions tax is similar to the one the agency used in 2010.[5] First, CBO reviewed a number of studies of how sectoral CO_2 emissions from the combustion of fossil fuels for energy would be affected by different levels of emissions taxes. Next, CBO calculated the price of embedded CO_2 for each modeled sector and determined how that price would change when a tax was introduced. Then, CBO combined those prices of embedded CO_2 with the emissions predicted by those models to econometrically estimate the implied price sensitivity—the relationship between changes in the prices of embedded CO_2 and changes in energy-related emissions of CO_2—for each sector.

[3] Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019*, EPA 430-R-21-005 (April 2021), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

[4] Ibid. Under the Environmental Protection Agency's definition, emissions of carbon dioxide in agriculture from energy-related fossil fuel combustion are included with industrial sector emissions. Other greenhouse gas emissions in agriculture—almost exclusively methane and nitrous oxide—are related to land and livestock use and are aggregated as a separate agricultural sector.

[5] CBO's methodology for estimating sectoral price sensitivities was first detailed in Congressional Budget Office, *The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models*, Technical Paper 2003-03 (May 2003), www.cbo.gov/publication/14414. In 2010, CBO used that methodology to update its carbon dioxide price sensitivities.

How Energy-Related Emissions of Carbon Dioxide Would Respond to a Tax or an Allowance Price

Based on the results of recent policy simulations, CBO updated its estimated relationship between the imposition of a tax and changes in the quantity of CO_2 emitted from fossil fuel combustion. Those simulations projected that the quantity of CO_2 emissions would change significantly, particularly in the electric power sector, when a tax on such emissions was imposed. An emissions tax would raise the prices of fossil fuels used in combustion, causing consumers and businesses to decrease the amount of fuel they purchased or to purchase lower-carbon fuels in place of higher-carbon ones, for example, thereby reducing emissions.

CBO measured that effect by calculating price sensitivities. Those price sensitivities reflect changes in the demand for carbon-intensive fuels that would result from the imposition of a tax or an allowance price, the substitution among fuels with different carbon contents, and changes in production decisions made by fuel producers. In short, the price sensitivities measure the full equilibrium response of the tax, including feedback effects among the different sectors of the economy.[6]

To measure the relationship between the price and quantity of CO_2 emissions, CBO calculated a sectoral average, referred to as the price of embedded CO_2. That average relates total spending by consumers and businesses on fossil fuel energy within a sector to the CO_2 emissions attributable to that sector when those fuels are burned. Changes in that average that come from imposing a tax or allowance price form the basis of CBO's assessment of the sensitivity of emissions. The imposition of a tax or an allowance price would increase the prices of individual fossil fuels, thus raising the price of embedded CO_2, so final users would pay more for fossil fuel energy under such a policy and would adjust their purchases of energy accordingly.

Policy Simulations of Emissions Taxes. To update its price sensitivities, CBO relied on the results of nearly a dozen models, most of which came from the Energy Modeling Forum (EMF), a working group of research economists established at Stanford University that periodically evaluates the effects of energy market policies. The EMF convened a group of modelers to examine the market implications of alternative tax rates on emissions of CO_2.[7] Their 2017 study, referred to as EMF-32 (because it is the 32nd study the group conducted since its founding in 1976), consisted of 11 carbon dioxide tax modeling efforts intended to describe the range of

[6] CBO's price sensitivity of emissions is similar to an elasticity of demand for energy produced from fossil fuels, though there are important differences. Whereas the price sensitivity measures the full equilibrium response by consumers and producers to a tax on emissions, a demand elasticity measures only the demand-side change in the use of fossil fuel energy that stems from a change in its price, holding everything else fixed. Those effects do not include supply-side changes in the composition of fossil fuel energy used to produce electricity, for example, nor do they reflect feedback effects among different sectors of the economy, among other equilibrium effects.

[7] See Energy Modeling Forum, Stanford University, https://emf.stanford.edu/.

outcomes from a common set of policies.[8] CBO relied on the results of 10 of those models as well as the 2020 *Annual Energy Outlook* (AEO) from the Energy Information Administration (EIA); one study from EMF-32 was omitted because it was insufficiently detailed for CBO's needs (see Table 1).[9]

The EMF-32 study considered the effects of four distinct tax policies involving two different initial taxes and two different growth rates: taxes on CO_2 emissions starting in the first year of the policy of about $30 per MT CO_2 and $59 per MT CO_2 (equivalent to $25 per MT CO_2 and $50 per MT CO_2 in 2010 dollars), each of which grew in real (inflation-adjusted) terms over a 31-year horizon (2020 through 2050) by 1 percent per year and 5 percent per year, respectively.[10] In the least stringent case, emissions taxes grew from about $30 to $40 per MT CO_2 between 2020 and 2050; in the most stringent case, they grew from about $59 to $255 per MT CO_2 over that period.

The EMF-32 study also considered several alternative methods to return (or "recycle") tax revenues back to consumers: lump-sum payments, reductions in taxes collected on labor, and reductions in taxes collected on returns from capital. Most of the models evaluated all three methods of recycling revenues, so 12 policy scenarios (each lasting 31 years) were evaluated in all. The method of recycling revenues, although probably important for changes in the distribution of income and certain economic elements, did not significantly affect projections of the amount of CO_2 emissions.

To ensure comparability, all EMF-32 models were calibrated to a common baseline in which no emissions taxes are present. Those baselines were intended to closely reflect EIA's most-current baseline projection, which at the time was from the 2016 AEO.[11] Although the EMF-32 models reasonably approximate that common EIA baseline, variation in modeling assumptions and parameters resulted in some differences in baseline projections of emissions and economic variables.

For this analysis, CBO also relied on a recent examination of CO_2 taxes by EIA in its 2020 energy outlook.[12] EIA considered three paths for emissions taxes: They would start at $15, $26,

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[8] John Weyant, Energy Modeling Forum, "EMF 32: US GHG and Revenue Recycling Scenarios," https://emf.stanford.edu/projects/emf-32-us-ghg-and-revenue-recycling-scenarios.

[9] Warwick J. McKibbin and others, "The Role of Border Carbon Adjustments in a U.S. Carbon Tax," *Climate Change Economics*, vol. 9, no. 1 (2018), www.worldscientific.com/doi/abs/10.1142/S2010007818400110.

[10] Most models, but not all, considered those four combinations.

[11] Energy Information Administration, *Annual Energy Outlook 2016* (September 2016), www.eia.gov/outlooks/archive/aeo16/.

[12] Energy Information Administration, *Annual Energy Outlook 2020* (January 2020), www.eia.gov/outlooks/archive/aeo20/.

or \$36 per MT CO_2 (equivalent to \$15, \$25, or \$35 per MT in 2019 dollars), they would increase in real terms at a rate of 5 percent per year, and all revenues would be recycled back to households in the form of lump-sum transfers. CBO included that study in its analysis, in part because it provided another observation of a common carbon policy and in part because of the additional granularity in the 2020 AEO. Unlike most of the EMF-32 models, which provided results in five-year increments, the 2020 AEO provided annual projections.

Prices of Embedded Carbon Dioxide. CBO's method of relating emissions taxes (or allowance prices in the case of cap-and-trade programs) to CO_2 emissions involves calculating the price of embedded CO_2 on the basis of the prices paid by final users of the energy obtained from fossil fuels. By affecting the end-use prices of those fuels—both by raising prices of individual fossil fuels but also by changing their prices relative to one another—a tax would reduce emissions.

In the transportation sector, for example, the retail price of gasoline determines in part what vehicles drivers decide to purchase and how much they choose to drive. To the extent that retail prices increased, an emissions tax would influence drivers to lessen their consumption of (and the emissions from) gasoline.

In the electric power sector, a tax would reduce emissions through two channels. First, consumers would decrease their use of electricity to the extent that taxes raised its retail price. Second, utilities would reduce their costs by shifting power generation away from coal and toward less carbon-intensive fuels, which would experience smaller price increases from the tax on emissions. (Most of the models CBO surveyed conclude that the bulk of emissions reductions in the early years of a policy would come from fuel switching in the electric power sector.)

Because energy consumption is distributed across a large variety of fuels and uses, a practical simplification in calculating the price of embedded CO_2 is to estimate end-users' overall response to changes in the average price of carbon-based energy products in each sector. To calculate that average price, CBO divides total sectoral spending on fossil fuels by final users by the total emissions of CO_2 in the sector. The resulting measure is the amount of dollars spent by final users on fossil fuel energy for each metric ton of CO_2 emissions released during combustion. For example, a gallon of gasoline yields about 19.6 pounds—or about 0.009 metric tons—of CO_2 emissions when burned.[13] Thus, the price of CO_2 embedded in gasoline when the retail price is \$3 per gallon is \$3 divided by 0.009, or about \$335 per MT CO_2. The analogous measure for a sector as a whole includes all fossil fuels used in that sector and the emissions they release when those fuels are burned.

[13] One pound of carbon, when burned, combines with oxygen to create 3.7 pounds of carbon dioxide. A gallon of gasoline contains about 5.3 pounds of carbon, so 19.6 pounds of carbon dioxide are released when that fuel is burned.

The first step in estimating a representative sectoral price for CO_2 is to calculate baseline end-use prices for distinct energy products—retail gasoline and diesel fuel, delivered natural gas, and retail electricity, for example—in terms of the CO_2 emissions released when they are burned. Specifically, the price of embedded CO_2 for a fuel used in a particular sector on a certain date is calculated as:

$$P_f^s(t) = \frac{V_f^s(t)}{E_f^s(t)}$$

Here, $P_f^s(t)$ denotes the price of embedded CO_2 in sector s for fossil fuel f at date t, $V_f^s(t)$ denotes sales of fossil fuel f to end users (valued at final prices), and E_f^s denotes CO_2 emissions in sector s from the combustion of that fuel, all on a particular date t. For the petroleum fuels used in the transportation sector in 2020, for example, $V_f^s(t)$ denotes the approximately \$565 billion spent on those fuels in that year, and $E_f^s(t)$ denotes the approximately 1,820 MT CO_2 released when those fuels were burned, so $P_f^s(t)$ equals about \$310 per MT CO_2 embedded in the petroleum fuels used in transportation.[14]

The second step is to aggregate the price of CO_2 for each fossil fuel into a single measure for each sector. That aggregate measure—roughly all final spending on fossil fuels burned in the sector divided by the resulting emissions—is provided by the harmonic mean:

$$P^s(t) = \left(\frac{E^s(t)}{\frac{E_c^s(t)}{P_c^s(t)} + \frac{E_n^s(t)}{P_n^s(t)} + \frac{E_o^s(t)}{P_o^s(t)}} \right)$$

Here, $E^s(t)$ is total emissions in the sector on date t; $E_c^s(t)$, $E_n^s(t)$, and $E_o^s(t)$ are emissions from coal, natural gas, and oil in that sector (so that $E^s(t) = E_c^s(t) + E_n^s(t) + E_o^s(t)$); and $P_c^s(t)$, $P_n^s(t)$, and $P_o^s(t)$ are, as above, the date t sectoral prices of embedded CO_2 for coal, natural gas, and oil. That harmonic mean is effectively an average of the prices of embedded CO_2 for individual fossil fuels weighted by the CO_2 emissions from those fuels.

CBO calculated that the prices of embedded CO_2 for 2020 are as follows:

- About \$310 per MT for transportation,

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[14] CBO's calculation excludes fugitive CO_2 emissions—that is, emissions from leaks, venting, or flaring that are released during the extraction, refining, and transportation of energy products before they are sold. An extension of the concept of "embedded" CO_2 that included such emissions would yield a somewhat lower price; the same total spending for final uses would be associated with additional emissions, so the final price per ton of emissions would be lower.

- About $135 per MT for electric power, and
- About $100 per MT for the composite sector.

CBO used EIA's 2020 AEO reference case as the basis for its most recent assessment of potential revenues from an emissions tax.[15] See the appendix for details on the computation of those prices.

Implied Price Sensitivities of Energy-Related Emissions of Carbon Dioxide From Policy Simulations of Emissions Taxes. An emissions tax would raise the price of embedded CO_2 by increasing prices for final energy. In addition to the tax itself, those price increases jointly reflect overall changes in the quantities of energy used, the substitution of lower-carbon fuels for higher-carbon ones, and supply responses from fuel producers. CBO's price sensitivity for carbon dioxide emissions is a measure of those effects on net and not an explicit accounting of each.

Under CBO's framework, emissions from each sector are a function of the price of embedded CO_2. The rate at which sectoral emissions respond to changes in the price of CO_2—after accounting for changes in economic activity that could result from the implementation of an emissions tax or a cap-and-trade program—is measured by a price sensitivity: the percentage by which emissions (measured per unit of economic activity) change from a 1 percent increase in the price of embedded CO_2. Price sensitivities are negative (less than zero): An increase in the price of embedded CO_2—reflective of a tax or an increase in the real prices of fossil fuels paid in a sector—reduces sectoral emissions, all else being equal. Price sensitivities also depend on time: Because the number of options available to reduce emissions broadly grows over time (both as technological progress increases the cost-effectiveness of existing options and as new options are developed), emissions are generally more responsive to changes in the price of embedded CO_2 in the longer term than they are in the shorter term.

Thus, sectoral price sensitivities, $\eta^s(t)$ for date t, are shown by:

$$\eta^s(t) = \left(\frac{\ln\left(\frac{E^s_{\text{policy}}(t)}{\text{GDP}_{\text{policy}}(t)}\right) - \ln\left(\frac{E^s_{\text{baseline}}(t)}{\text{GDP}_{\text{baseline}}(t)}\right)}{\ln\left(\frac{P^s_{\text{baseline}}(t) + T(t)}{P^s_{\text{baseline}}(t)}\right)} \right)$$

where $P^s_{\text{baseline}}(t)$ is the price of embedded CO_2 in sector s in the baseline, $T(t)$ is the tax per metric ton of CO_2, $E^s_{\text{policy}}(t)$ and $E^s_{\text{baseline}}(t)$ are total CO_2 emissions from the combustion of

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15 See Energy Information Administration, *Annual Energy Outlook 2020* (January 2020), www.eia.gov/outlooks/archive/aeo20/; and Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.

fossil fuels in sector s in the policy case and in the baseline, and $\mathrm{GDP}(t)$ is economywide real gross domestic product (GDP) in the two cases. By using economywide GDP, CBO implicitly projects an economic response that is proportionately the same in all sectors. Accounting for changes in real GDP has little effect on price sensitivities because the percentage changes in overall real GDP are expected to be small relative to the percentage changes in the sectoral prices of CO_2 in many cases.

Ignoring the negative sign (in absolute terms, in other words), large price sensitivities indicate that emissions within a sector are very responsive to changes in the price of embedded CO_2. Because power producers can dispatch power from natural gas plants in place of coal-fired generation with comparative ease (and natural gas releases about half as much CO_2 when burned), price sensitivities in the electric power sector are generally larger than in other sectors. In the transportation sector, by contrast, price sensitivities are small, because that sector depends heavily on petroleum and has fewer cost-effective options to switch to other fuels.

CBO's analysis of the findings of EMF-32 and the 2020 AEO supports the assertion that emissions respond more sensitively to an emissions tax in the electric power sector than in either the transportation or the composite sectors. Across all simulated policies, the average price sensitivity in the electric power sector in the first year after the emissions tax is introduced is about four times higher than for transportation. Specifically, the first-year price sensitivity for the electric power sector averages about -1.8—meaning that an emissions tax that increased the price of CO_2 by 10 percent would lower emissions of CO_2 relative to GDP by about 18 percent—whereas the average price sensitivity for transportation is about -0.5, so a 10 percent increase in the price of CO_2 would reduce emissions relative to GDP by about 5 percent. The studies' findings also generally conclude that emissions are least responsive in the composite sector. For all policies examined, the average price sensitivity in the first year of the policy is about -0.2 for the composite sector, which means that a 10 percent increase in the price of CO_2 would reduce emissions in that sector by about 2 percent relative to GDP.

Long-run price sensitivities are generally larger than short-run price sensitivities, all else being equal. Short-run emissions reductions in transportation and in the composite sector would primarily stem from less driving and reduced industrial activity. Long-term reductions would be influenced more by investments in new capital—higher fuel economy standards and more alternatively fueled vehicles (such as electric vehicles), enhanced industrial processes, or commercial and residential building and appliance upgrades. Time is required for new investments to have a measurable effect on emissions, though, and the findings of the EMF-32 and 2020 AEO policy simulations broadly support that expectation (see Figure 3).

Reductions in emissions from a policy need not be larger in later years than in initial years, although specific timelines would depend on the policy and on the availability and cost of alternative technologies. Some models that CBO examined found instances in which price sensitivities in later years were smaller (in absolute terms) than in the first few years of the modeled policy. That outcome primarily occurred in the electric power sector: Some of the models found immediate and large reductions in emissions in that sector when an emissions tax was imposed; reductions in later years were incrementally smaller. Price sensitivities in future years might also be smaller depending on the costs of reducing emissions. In the electric power sector, for instance, low-cost options to reduce emissions would be readily available early on, but subsequent decreases (from utility-scale carbon capture and storage, for example) would be much more costly and, therefore, probably more limited.

Calculated price sensitivities vary among models, reflecting differences in models' structures and assumptions. Structurally, the models differ in the sets of industries they include or in the intermediate goods used in the production of other goods. The models also differ in their assumptions about the substitutability of inputs into production, the transferability of productive capital among industries, and the cost of technologies to reduce emissions.

The largest variability in the results of the models surveyed occurs during later years in the electric power sector (that is, 20 years to 30 years after carbon was first taxed). Most findings suggested price sensitivities of between 2 and 3 (in absolute terms), but a few results implied price sensitivities of 10 or more. Such high responsiveness—a large decrease in emissions from a comparatively small change in the price of embedded CO_2—stems from models that expect that advanced low-emissions technologies (carbon capture and storage or other advanced technologies) could be available at a low enough cost that they would be widely adopted (and thus capable of reducing emissions in that sector considerably). One model projected that emissions in the electric power sector might even turn negative, if bioenergy production (which removes CO_2 from the atmosphere) could be coupled with carbon capture and storage (which sequesters those emissions underground) and deployed widely.[16]

How CBO Econometrically Estimated Price Sensitivities of Energy-Related Emissions of Carbon Dioxide

To estimate overall price sensitivities—that is, to aggregate the findings of the emissions tax simulations into a representative price sensitivity measure for each sector—CBO used econometric methods to evaluate the relationship between the price of embedded CO_2 and the amount of emissions predicted by emissions tax simulations in EMF-32 and the 2020 AEO. Each model predicted a level of CO_2 emissions in response to a tax on those emissions and the resulting effect on fuel prices. Although predictions differ because of alternative modeling structures and assumptions, the results are directionally consistent: The imposition of a tax on CO_2 consistently reduces emissions. The relationship between the price of embedded CO_2, which

[16]A price sensitivity stemming from a greater-than-100-percent reduction in emissions is undefined. In such cases, CBO set those price sensitivities equal to the largest value found in any of the policy simulations the agency examined (that is, the most negative value found), roughly -17. That occurred in a small number of instances.

includes any emissions taxes present, and the resulting level of emissions forms the basis of CBO's price sensitivity estimate. CBO's current econometric estimation differs from its last update of sectoral price sensitivities in three broad ways: the functional forms, the independent variables used, and the refinements to more accurately adjust for differences between near-term and longer-term price responsiveness.

CBO's Base Estimate of Price Sensitivities. For each energy-consuming sector, CBO regressed the level of emissions against the price of embedded CO_2, the time elapsed since the tax policy was announced, and real GDP. (The data are all expressed in logarithms, so the fitted regression coefficients—the models' parameters that the regression is designed to estimate—are directly interpretable as price sensitivities.) Those regression equations also included, among the regressors, a set of indicator variables describing characteristics of the models and policies.[17] CBO controlled for models' characteristics to account for the effects of differences in models' assumptions and structure, independent from the effects of the emissions taxes themselves. Because economic activity and emissions may be affected, the other policy characteristics that CBO controlled for relate to how revenues from the emissions tax are recycled back into the economy under each policy. (Revenues in EMF-32 are returned either in lump-sum rebates to consumers or reductions in taxes on either labor or capital. EIA's 2020 AEO analysis considers only lump-sum rebates.)

CBO's general regression equation is expressed as:

$$\begin{aligned}\ln\left(E_p^s(t)\right) = {}& \alpha^s + \beta_1^s \cdot \ln\left(P_p^s(t)\right) + \beta_2^s \cdot \left(\ln(P_p^s(t))\right)^2 + \beta_3^s \cdot \ln(t) \\ & + \beta_4^s \cdot (\ln(t))^2 + \beta_5^s \cdot \ln\left(P_p^s(t)\right) \cdot \ln(t) + \beta_6^s \cdot \ln(\text{GDP}(t)) \\ & + (\text{model effects}) + (\text{policy effects})\end{aligned}$$

The dependent variable $E_p^s(t)$ is the year-t emissions in sector s, under tax policy p (including the no-tax baseline case), where the policy was announced in year 0. Analogously, the regressor $P_p^s(t)$ is the price of embedded CO_2 in sector s under policy p in period t. Squared terms in $\ln(t)$ and in $\ln(P)$ capture any nonlinear effects of those variables on CO_2 emissions. Finally, the interaction term $\ln\left(P_p^s(t)\right) \cdot \ln(t)$ captures any interdependence between its two constituent terms—that is, any change over time in the effect that the price of CO_2 has on emissions.

Under a log specification, the sectoral price sensitivities are—in addition to the sectoral prices of CO_2 and the time since the tax policy was announced—simple functions of the estimated sectoral

[17] Indicator variables (also referred to as dummy variables) are variables that take on values of either zero or one to denote the presence of subgroups in the data. Indicator variables isolate the effects that are specific to the subgroups—specific models or revenue recycling options, in the current context—and not to the overall responsiveness of emissions to a carbon tax.

coefficients: the log of the price of embedded CO_2 (β_1^s), the squared log of the price of embedded CO_2 (β_2^s), and the interaction term (β_5^s) between the price of embedded CO_2 and the number of years since the announcement of the policy. Specifically:

$$\eta^s(t) = \beta_1^s + 2\beta_2^s \cdot \ln(P_p^s(t)) + \beta_5^s \cdot \ln(t)$$

Because longer-term price sensitivities are typically larger (in absolute terms) than shorter-term price sensitivities, all else being equal, CBO expects that $\beta_5^s < 0$ so that, over time, price sensitivities grow more negative and the response of emissions to a tax increases.[18]

In estimating the price sensitivities, CBO made two further adjustments to that procedure. The first adjustment controls for differences in the number of "observations" that each of the simulations considered. (Some models covered fewer time periods or fewer policy scenarios.) Except in two cases, CBO weighted the results of the models so that each contributed equally to the analysis: Models contributing fewer observations were weighted more heavily in proportion. The two exceptions are the findings of EIA's National Energy Modeling Systems (NEMS) in EMF-32 and those of the 2020 AEO. Because they both came from the same EIA model, just at different points in time (2017 and 2020), CBO weighted those results less heavily, effectively treating them as a single set of observations.[19]

An emissions tax would impose a larger change to the price of embedded CO_2 than a single price sensitivity is meant to reflect, so CBO made a second adjustment to account for how the responsiveness of emissions depends on the size of the tax. CBO's econometric estimation measures the sensitivity of emissions to small changes in the price of embedded CO_2. To account for the larger change inherent in each tax policy, CBO predicted the emissions response by averaging two price sensitivity estimates: one evaluated at the baseline price of CO_2 and the other evaluated at the policy price of CO_2 (that is, the price of CO_2 including the emissions tax). That average measures the "arc" price sensitivity—the predicted response to a significant change in the price of CO_2—rather than the instantaneous "point" price sensitivity from a mathematically small change in the price of CO_2.

[18] CBO's estimation of coefficients controls for the effects on overall economic activity present in the EMF-32 and AEO 2020 simulations, although CBO's price sensitivity equations do not explicitly reference policy effects on real GDP. Such effects are exceedingly small relative to changes in the sectoral emissions and costs of carbon stemming from a carbon tax and would have a minor effect on price sensitivity estimates. For example, in the AEO 2020 simulations, the carbon price sensitivity in the electric power sector in the case of a $26 per MT CO_2 emissions tax ($25 per MT CO_2 in 2019 dollars) increasing in inflation-adjusted terms by 5 percent per year would average -2.71 over the first 10 years of the policy if the change in real GDP was accounted for but -2.73 if GDP effects were ignored.

[19] Because the AEO 2020 simulations had about three times the observations that the NEMS simulations had in EMF-32, about 75 percent of the weight between the two analyses was placed on AEO 2020.

Results of CBO's 2020 Base Estimate. CBO's most recent update concludes that the electric power sector's emissions of CO_2 have become considerably more responsive to changes in the price of embedded CO_2, emissions in the transportation sector have become less responsive, and those in the composite sector have remained about as responsive as CBO previously estimated (see the lines marked "2010 Estimate" and "2020 Base Estimate" in Figure 4). Those changes result both from developments in energy markets since 2010 and from methodological differences in CBO's estimations, although the relative importance of those factors in CBO's sensitivity update is clearest for the electric power sector.

Market Factors. In CBO's view, market factors have made CO_2 emissions in the electric power sector more responsive to price changes over the past decade. Lower-carbon, natural gas-fired generation has become more competitive with coal-fired generation than it was a decade ago, owing to lower prices for natural gas and lower costs for new generating capacity.[20] At the same time, the cost of renewable generating capacity, particularly wind power, has fallen substantially, and supply has increased significantly. A tax on emissions would probably spur additional growth in renewable capacity.

In the transportation sector, by contrast, the relative contribution of market factors to changes in the estimated price sensitivities is less clear. On the one hand, certain market developments are consistent with CBO's directional findings. For example, the imposition of more stringent fuel economy standards for vehicles between 2010 (the time of CBO's last update) and 2016 (the time of the EMF-32 study) could have led manufacturers to use many of the available technologies, leaving fewer opportunities for further emissions reductions and lowering the responsiveness of CO_2 emissions within the transportation sector.[21]

On the other hand, certain factors point to the opposite effect. Growing electrification of the vehicle fleet, for example, probably increases the sensitivity of transportation-related CO_2 emissions to an emissions tax as opportunities for low-carbon fuel switching become available in

[20] The nearly fivefold increase in natural gas produced from shale resources (shale gas) since 2010 was a major reason that natural gas prices fell and helped natural gas-fired generation become more competitive with coal-fired generation. In its most recent long-term outlook, EIA projects that U.S. shale gas production—and total natural gas production, more broadly—will continue to grow in the coming decades and keep prices low in historical terms. EIA has also estimated that the costs of building gas-fired generation have fallen significantly relative to coal-fired generation: Measured on an equivalent per-unit-of-generating-capacity basis, the cost of gas-fired capacity fell by about 75 percent since 2010, compared with a decline of about 50 percent for coal-fired generation. That trend, coupled with EIA's expectation that the prices of natural gas will remain low in future years, suggests that gas-fired capacity should continue to remain cost-competitive with coal-fired generation over the next several decades. See Energy Information Administration, *Annual Energy Outlook 2021* (January 2021), www.eia.gov/outlooks/aeo/, and Energy Information Administration, *Annual Energy Outlook 2010* (May 2010), www.eia.gov/outlooks/archive/aeo10/index.html.

[21] In addition to the studies in EMF-32, CBO's 2020 price sensitivity update includes results from the more recent AEO 2020. But because AEO 2020 is a small portion of the overall analysis, it contributes to CBO's findings to a smaller extent than the EMF-32 studies collectively do.

a sector historically dependent on a single fuel. Indeed, greater sales of electric vehicles raised electricity use in transportation above previous projections. According to EIA, electricity use in transportation in 2019 (before the 2019–2020 coronavirus pandemic) was about 50 percent higher than the agency projected for that year in its 2016 outlook, the benchmark projection for the EMF-32 study.[22] But although growing electrification in recent years has probably increased the sensitivity of transportation emissions to a potential tax, that effect has probably been small because of the slow turnover of the vehicle stock and the comparatively small role that electricity still plays in the sector.[23] However, depending on the pace of future electrification, later assessments would probably find more responsiveness of CO_2 emissions in transportation than the responsiveness found in the EMF-32 and AEO 2020 studies.

For the composite sector, CBO's conclusion that emissions in that sector have remained about as sensitive to a potential tax as previously estimated—particularly in the years immediately following the imposition of a tax—is consistent with recent market trends. In particular, the stock of capital in the composite sector (residential housing, commercial buildings, and industrial equipment and machinery) is both large and long lived, so efficiency improvements from new technologies take time to take hold. Indeed, even with efficiency enhancements since 2010, emissions of carbon dioxide in the composite sector are little changed.

Methodological Considerations. CBO's 2020 update of the price sensitivity estimates is based on a sampling of models that all measure the same set of emissions tax policies, and from a consistent baseline. By contrast, CBO's 2010 estimates were based on a survey of the estimated energy, environmental, and economic effects of a set of different cap-and-trade proposals, and those were not all calibrated to match the same baseline conditions. Those earlier proposals also varied in stringency and in the industries or sectors they targeted, among other factors.

CBO's current methodology of estimating sectoral price sensitivities differs from that used in the 2010 update. The process in 2020 involved first fitting a model to the simulation data to estimate the effects of a policy change on emissions, then estimating sectoral price sensitivities from the resulting fitted coefficients. The process in 2010, by contrast, involved estimating the price sensitivities directly from an econometric specification of the relationship between a set of measures constructed from the data, rather than from observable quantities of emissions and the price of CO_2. The two methods differ not only in their central functional relationships, but also in the independent variables, interaction terms, and higher-order terms they include. Although each approach was designed to measure the same effects, CBO's approach in 2020 directly reflects

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[22] See Energy Information Administration, *Monthly Energy Review* (August 2021), www.eia.gov/totalenergy/data/monthly/, and *Annual Energy Outlook 2016* (September 2016), www.eia.gov/outlooks/archive/aeo16/.

[23] Electricity accounted for less than 1 percent of total energy used in transportation in 2020. See Energy Information Administration, *Monthly Energy Review* (September 2021), www.eia.gov/totalenergy/data/monthly/.

the theoretical relationships between CO_2 emissions and the price of embedded CO_2 and other independent variables. Because the two approaches are not identical, they would not produce estimates that were entirely consistent with each other even if they were based on a common set of baseline observations.

Adjusted Estimation for Near-Term Price Sensitivities. Although CBO's base estimate indicates that sectoral emissions of CO_2 become more sensitive to changes in the embedded price of CO_2 over time—stated differently, that emissions become progressively more responsive to emissions taxes in future years—the sectoral price sensitivity estimates are not much greater in later years than in initial years. In CBO's judgment, the base estimate overstates actual price sensitivity in those initial years, particularly in the electric power sector.

One reason is timing. In EMF-32—which accounts for 10 of the 11 studies that CBO evaluated—the emissions tax does not take effect until about four years after the tax policy is announced.[24] That interval provides markets time to adjust to a new tax. Although CBO controlled for the time between the announcement of the emissions tax policy and the date of its implementation in its econometric specification, the time trend on which its estimates are based reflects mostly medium- and long-term responses because almost all studies CBO surveyed cover only those periods. Only the AEO simulated short-term emissions responses: The 2020 study modeled an emissions tax that started in 2021. Each sector had initial price sensitivities close to zero (indicating less responsiveness by emissions; see the left-most set of price sensitivity observations in Figure 3) that continued to grow to their long-term trends. But those observations are a small subset of all findings, so they do not contribute greatly to the estimated initial response, which is far more influenced by the much larger number of responses for the medium- and long-run cases.

Another reason that the initial responsiveness of emissions in the electric power sector may be overstated by CBO's estimates is that most of that initial response reflects the switch from using coal to using natural gas to produce electricity. Potential for further switching remains, but its effect is likely to be smaller because of developments in energy markets since 2016, when the EMF-32 analyses were conducted.

For instance, in its 2016 energy outlook, EIA projected that in 2020 about 1,400 terawatt-hours (TWh) of electricity would be produced from coal-fired generation and about 1,200 TWh of electricity would be produced from gas-fired plants. But initial estimates of actual 2020

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[24] The EMF-32 studies calibrated their baselines to the 2016 AEO, so all of them examined a policy that would implement a carbon tax in 2020. See James R. McFarland and others, "Overview of the EMF 32 Study on U.S. Carbon Tax Scenarios," *Climate Change Economics*, vol. 9, no. 1 (2018), www.worldscientific.com/doi/10.1142/S201000781840002X; and Energy Information Administration, *Annual Energy Outlook 2016* (September 2016), www.eia.gov/outlooks/archive/aeo16/.

generation suggest only about 775 TWh for coal, versus 1,650 TWh for natural gas.[25] Although EIA expects that gap to narrow somewhat in 2021 because of pandemic-related reasons, the agency projects that more power will be produced using natural gas than coal over the coming years (see the top panel of Figure 5). Even without a tax on carbon, considerable fuel switching has already occurred since 2016, in part because the unexpectedly high growth of natural gas produced from shale lowered prices of natural gas and allowed natural-gas-fired generation to be cost competitive with coal-fired generation. Accordingly, fuel switching has altered the distribution of emissions in the electric power sector: Previously expected to remain large, the gap between total emissions from coal-fired generation and those from gas-fired generation has narrowed considerably since 2016, and that narrowing is projected to persist (see the bottom panel of Figure 5).

To account for the possibility of greater-than-estimated differences in initial price sensitivities, CBO adjusted its regression specification. Rather than fitting one set of coefficients to the entire span of data, CBO fit a "spline" function that features two sets of coefficients, one for the initial nine years after a policy announcement, and the other for later years. (CBO experimented with other splits but found that that specification best fit the data—ensuring that the initial trends present in the models would be reflected in this adjusted analysis.)[26] CBO used different combinations of explanatory variables and time components for each sector, based on a goodness-of-fit criteria and reflecting CBO's judgment about the differences between near- and long-term price sensitivities.

The effect of introducing spline factors to control for separate time periods is most pronounced in the electric power sector. In that sector, fitting a spline function to the data yields initial-year price sensitivity estimates that are smaller (less negative) but that increase (in absolute terms) more rapidly in the first few years of a policy (see the line marked "2020 Update With Spline" in Figure 4). Under that specification, the estimated price sensitivities in some years are greater (more negative) than in the 2020 base estimate. The price sensitivity plot exhibits a kink at the spline "knot" in year 9, after which price sensitivities increase slightly and then level out (similar to the base regression). The estimates from the spline specification imply that the responsiveness of emissions in the electric power sector would be lower (and sectoral tax revenues would be higher) in the first half of a 10-year budget period than the base ("nonspline") specification predicts, but they would be higher (with lower tax revenues) during the second half of that period.

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[25] See Energy Information Administration, *Annual Energy Outlook 2016* (September 2016), www.eia.gov/outlooks/archive/aeo16/, and *Annual Energy Outlook 2021* (February 2021), www.eia.gov/outlooks/aeo/.

[26] The EMF-32 models simulate five-year intervals, so the first two observations in those models occur in years four and nine. AEO 2020 provided annual projections.

The effects of fitting a spline function are more muted in the other two sectors. The transportation sector exhibits very little change under the spline estimation, mostly because the price sensitivities in the base estimate do not exhibit a strong time trend. The changes in the initial-year price sensitivities in the composite sector are like those in the electric power sector, although more modest. CBO used a spline specification for the transportation and the composite sectors—even though the effects were small—to maintain consistency with the approach it used for the electric power sector.

Effects of the Price Sensitivity Update on Carbon Dioxide Emissions and Projected Tax Revenues

Because emissions of CO_2 in the electric power sector have become more responsive to prices since 2010, an emissions tax would lower emissions in that sector by a proportionately larger amount now than under CBO's previous estimates, all else being equal. Even with the updated price sensitivities, though, the projected effect on total emissions would be relatively modest (see Figure 6). Using the 2020 update of sectoral price sensitivities, CBO and the staff of the Joint Committee on Taxation evaluated the revenue effects of an illustrative emissions tax that starts at $25 per MT and grows at an inflation-adjusted rate of 5 percent per year.[27] The projected reduction in greenhouse gas emissions (essentially all of which would be CO_2) would be about twice as large in this update as they would have been under CBO's prior estimates; nonetheless, 92 percent of emissions subject to the tax would remain in the first year, and 83 percent would remain in the 10th year. (Emissions that would be subject to the tax in 2021, the first year of the potential policy, are the estimated 4.8 billion metric tons of CO_2 emissions from the burning of fossil fuels to produce energy and the 0.4 billion metric tons of other CO_2 and greenhouse gas emissions from large industrial facilities.)

In part, the modest effect on overall emissions is because the emissions reductions would be primarily confined to the electric power sector (see Figure 7). The changes in the transportation and composite sectors would be comparatively small. Each sector accounts for about one-third of all energy-related emissions of carbon dioxide, so about two-thirds of CO_2 emissions would be little changed under a tax.

The relatively small reductions in the transportation and composite sectors are primarily because price sensitivities in those sectors are much lower (in absolute terms) than in the electric power sector, so emissions would not respond greatly to an emissions tax. But a related reason is that the price of embedded CO_2 in the transportation sector is more than twice as high as in the other sectors, so an emissions tax would have a relatively small effect on the price of emissions in

[27] Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.

transportation. Transportation is highly dependent on a single fossil fuel, petroleum, the final price of which is greater than other fossil fuels per unit of energy. That is not only because of the cost of the crude oil itself, but also because of the cost of refining it into the array of usable petroleum products.

The effects on revenues from the price sensitivity update would also be modest (see Figure 8). In the 2020 examination of the illustrative tax, CBO concluded that calendar year gross revenues from that tax—revenues received before accounting for any offsetting reductions in tax collections elsewhere in the economy—would total about $1.5 trillion (in current dollars, which are not adjusted to remove the effects of inflation) over 10 years.[28] The same policy, examined using the prior price sensitivity estimates, would generate about $1.6 trillion in gross revenues, an average difference of 7 percent (or $11 billion, in current dollars) a year.[29]

Despite the modest differences overall, the effect of the price sensitivity update in the electric power sector is noteworthy. Reductions of energy-related CO_2 emissions in the first year of the modeled tax policy would be about three times greater with the revised price sensitivities, declining to about twice as large by the 10th year (see the top panel of Figure 9). Nearly all the difference in gross revenue estimates stemming from the price sensitivity update is because of lower revenues from the electric power sector (see Table 2). Before the update, estimated gross tax receipts in the electric power sector under the modeled emissions tax would have totaled about $37 billion in 2021, growing to about $51 billion by 2030 (see the bottom panel of Figure 9). Estimates determined using the updated price sensitivities consistently hover around $32 billion to $35 billion, however. Although those estimated revenues remain significant, the updated price sensitivities reduce projected revenues from the electric power sector by about $110 billion over the 10-year period. (All of those amounts are in current dollars.)

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[28] Net revenues over the 10-year period, which account for offsetting reductions in tax revenues elsewhere, would be about $1 trillion, in CBO's and JCT's joint estimation.

[29] In its cost estimates, CBO reports fiscal year totals (October through September). This paper reports calendar year totals so that revenues received are consistent with annual emissions.

Appendix: How CBO Calculates Sectoral Prices of Embedded Carbon Dioxide

An emissions tax or an allowance price from a cap-and-trade program would raise the price of fossil fuels, propel the switch to lower-carbon fuels, and spur an overall reduction in emissions. The price of embedded carbon dioxide is an average that measures the implicit price of emissions in a sector. Because that average would be affected by the imposition of a tax or an allowance price, the relationship between emissions and the price of embedded CO_2 in the models that the Congressional Budget Office surveyed for this analysis forms the basis of the agency's estimation of the sensitivity of CO_2 emissions to a tax (or allowance price).

Fossil fuels release different amounts of CO_2 when burned—natural gas releases about 25 percent less CO_2 than oil and about half as much as coal.[1] The price of embedded CO_2 is a method of standardizing expenditures on fossil fuel use and emissions and thus facilitating their comparison. To calculate that price, total spending on fossil fuel energy used in a sector is divided by the emissions attributable to that sector when the fossil fuels are burned. The resulting measure is the "price" of emissions: the average number of dollars spent by consumers and businesses to emit one metric ton of CO_2 from fossil fuel combustion. A tax on CO_2 would raise the individual prices of fossil fuels and, therefore, the price of embedded CO_2. Thus, greater spending on fuels would be necessary in the absence of changes in the amount and types of fossil fuel purchased. Those potential higher outlays would incentivize business and consumers to make choices that would reduce emissions.

For 2020, CBO calculated that the price of embedded CO_2 in the electric power sector in the Energy Information Administration's 2020 *Annual Energy Outlook* reference case was $136 per metric ton, meaning that final users spent an average of $136 on electricity produced from fossil fuels for each metric ton of CO_2 released by that production. Similarly, the prices of embedded CO_2 for the transportation sector and the composite sector (which is a combination of the residential, commercial, and industrial sectors) were $310 per metric ton and $102 per MT, respectively. Under CBO's methodology, an illustrative $25 per MT tax on CO_2 would increase the price of embedded CO_2 in those three sectors to $161 (electric power), $335 (transportation), and $127 (composite). Coupled with an estimate of the price sensitivity of emissions, increases in the prices of embedded CO_2 would generate estimates of how much emissions of CO_2 would decline because of the tax.

[1] Energy Information Administration, "Carbon Dioxide Emissions Coefficients" (February 2016), www.eia.gov/environment/emissions/co2_vol_mass.php.

Example Calculations of Prices for Carbon Dioxide, by Sector

The following sections provide examples of the calculation of the price of embedded CO_2 for each sector for a common year in EIA's 2020 AEO reference case.

Electric Power Sector

The first step in computing the price of embedded CO_2 is to calculate total spending on fossil fuels in the production of electricity. For the electric power sector for 2020, CBO estimates that total fossil fuel spending—measured in terms of the retail rates that customers pay for electricity produced from those fossil fuels—was $223 billion in the reference case. That amount reflects purchases of coal, natural gas, and petroleum by utilities, priced according to the higher rates customers (final users) pay for electricity. Specifically, EIA projected that customers would purchase 12.7 quadrillion British thermal units (Q Btu) of electricity in 2020 at an average price of about $31 per million Btus (M Btu), totaling about $390 billion. Coal, natural gas, and petroleum were expected to account for about 57 percent of all energy inputs (21.0 B Btu out of 36.8 Q Btu), so the value to customers of those fossil fuels in terms of prices they paid for electricity would be 57 percent of $390 billion, or $223 billion.

- **Coal.** U.S. businesses and households in 2020 were projected to pay about $98 billion for the coal used to produce electricity, CBO estimates. According to EIA, about 25 percent of all fuel inputs into electricity production would be coal (9.2 Q Btu out of 36.8 Q Btu). Thus, 25 percent of the $390 billion of electricity expected to be purchased ($98 billion) would be attributable to the coal used in electricity production.
- **Natural Gas.** EIA projected that 11.6 Q Btu of natural gas would be used to produce electricity in 2020, accounting for 32 percent of all fuel inputs. Accordingly, customers would be expected to pay $123 billion for electricity produced by natural gas–fired power plants (32 percent of $390 billion).
- **Petroleum.** Little oil is used to produce electricity. According to EIA, about 0.2 Q Btu, or roughly 0.5 percent of all fuels used in production, was projected to come from oil. CBO estimates that consumers would have paid about $2 billion in 2020 for power produced from oil (0.5 percent of $390 billion).

The next step in computing the price of embedded CO_2 is to divide those estimates of spending by the CO_2 emissions from fuels used in the sector. EIA projected that emissions in the electric power sector would total 1,504 million metric tons (MMT) in 2020: Coal would account for 875 MMT, natural gas for 616 MMT, and oil for 13 MMT. Thus, the price of embedded CO_2 for coal used in the electric power sector would be $112 per MT: a $98 billion final value to customers for coal used divided by 875 MMT of emissions. Put another way, for each metric ton of CO_2 emitted from burning coal to produce electricity, customers were expected to have paid an average of $112 in 2020 for coal-fired power. On the basis of EIA's projection, CBO calculated that the 2020 price of embedded CO_2 for natural gas in the electric power sector was $200 per MT CO_2, and for petroleum, $140 per MT CO_2.

The final step in computing the price is to use individual fossil fuel price estimates to calculate the average price of embedded CO_2 for the sector. For the electric power sector in 2020, CBO estimates that the price of embedded CO_2 would be $136 per MT CO_2, the harmonic mean of prices of embedded CO_2 for each fuel and the emissions from burning them:

$$\$136 \text{ per MT} = \left(\frac{1{,}504 \text{ MMT}}{\frac{875 \text{ MMT}}{\$112} + \frac{616 \text{ MMT}}{\$200} + \frac{13 \text{ MMT}}{\$140}} \right)$$

Transportation Sector

The price of embedded CO_2 was calculated in a similar way for the transportation sector. The main distinction is that petroleum-based fuels account for nearly all (98 percent) of fossil fuel energy used in that sector, and coal is not used in any meaningful way. Based on information available from EIA, CBO calculated that about $567 billion was expected to have been spent for fossil fuel energy in the transportation sector in 2020, and an estimated 1,830 MMT of CO_2 emissions were expected to have been released in the sector from that combustion.[2] Accordingly, consumers and businesses were projected to have spent about $310 on energy for each metric ton of CO_2 released ($567 billion divided by 1,830 MMT CO_2)—almost all of that through purchases of petroleum-based fuels.

Composite Sector

Direct emissions in the residential and commercial sectors—emissions from nonelectrical sources only—primarily reflect the use of oil and natural gas for space heating.[3] In the industrial sector, more than half of direct emissions result from combustion for heat and power for industrial processes.[4]

CBO computed individual fossil fuel emissions and the end-use value of purchases of fossil fuels as the residuals after accounting for the electric power and transportation sectors. For example, natural gas emissions were projected to total 1,683 MMT in 2020, with 621 MMT from the

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[2] Energy Information Administration, *Annual Energy Outlook 2020* (January 2020), www.eia.gov/outlooks/archive/aeo20/.

[3] Ibid.

[4] Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2018*, EPA 430-R-20-002, Table 10-2 (April 2020), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018.

electric power and transportation sectors.[5] Thus, projected natural gas emissions in the composite sector would be 1,062 MMT. Similarly, EIA projected that natural gas use would total 32.2 Q Btu in 2020. Of that, 1.1 Q Btu would be used as industrial feedstocks for the manufacturing of chemicals, fertilizers, and other products, so 31.1 Q Btu of natural gas would be burned among all sectors. (Feedstocks are not burned and release no CO_2.) Thus, 19.4 Q Btu of natural gas would be used in the composite sector, calculated as the difference between the 31.1 Q Btu burned in total and the 11.7 Q Btu of natural gas that would be used in the other two sectors.[6]

On the basis of EIA's projection, CBO estimated that the average 2020 end-use price for the natural gas used in the composite sector was $5.3 per M Btu. That estimate reflects the volume-weighted harmonic mean of the final prices for natural gas used in the residential and commercial sectors and for heat and power in the industrial sector. EIA does not provide price information for other industrial uses of natural gas (that used during natural gas production itself or at processing plants, for instance, or natural gas used for liquefaction), but CBO's approach implicitly assumes that the prices of those industrial uses would be the same as the overall average price of natural gas in the sector.

In CBO's estimation, total end-use spending on natural gas in the composite sector was $103 billion in 2020 (the product of the 19.4 Q Btu of natural gas burned and the $5.3 per M Btu average projected price paid by final users). The price of embedded CO_2 for natural gas in the composite sector was $97 per MT CO_2, the ratio of the $103 billion expected to be spent for natural gas and the 1,061 MMT of emissions from its combustion. Similarly, the prices of embedded CO_2 for coal and oil in the composite sector were $33 per MT CO_2 and $235 per MT CO_2. The overall price of embedded CO_2 in the composite sector—calculated using the harmonic mean—was about $102 per MT CO_2.

Procedure for Estimating Incomplete and Missing Values

The models that CBO relied on for its price sensitivity update of CO_2 emissions—most of which came from the Energy Modeling Forum's EMF-32 study—did not report the same set of simulation findings as EIA did in its 2020 energy outlook. When price or quantity findings were incomplete or absent, CBO estimated those values using relationships present in the EIA's 2016

[5] Energy Information Administration, *Annual Energy Outlook 2020* (January 2020), www.eia.gov/outlooks/archive/aeo20/.

[6] Natural gas use in the composite sector can also be calculated directly. According to EIA's projections, natural gas use in 2020 would consist of 5.1 Q Btu for residential, 3.6 Q Btu for commercial, 6.6 Q Btu for industrial heat and power, 1.3 Q Btu for refining heat and power, 2.0 Q Btu for lease and plant fuel, 0.2 Q Btu for liquefying natural gas for export, and 0.7 Q Btu for powering pipelines.

energy outlook (the analysis to which the EMF studies calibrated their baseline cases).[7] For example, to calculate the quantities of fossil fuels used to produce electricity for EMF models that did not provide projections of those quantities, CBO used the simulation results from those models of the electricity produced by different fossil fuel generators coupled with representative heat rates computed from EIA's 2016 reference case.[8] Similarly, energy prices in the EMF-32 studies were generally provided on only an aggregate basis. The prices of fuels on a sectoral basis—the average price of petroleum used in transportation or the price of natural gas paid by electricity producers—were based on relationships between sectoral and marketwide commodity-level prices as in EIA's 2016 reference case.

[7] Energy Information Administration, *Annual Energy Outlook 2016* (September 2016), www.eia.gov/outlooks/archive/aeo16/.

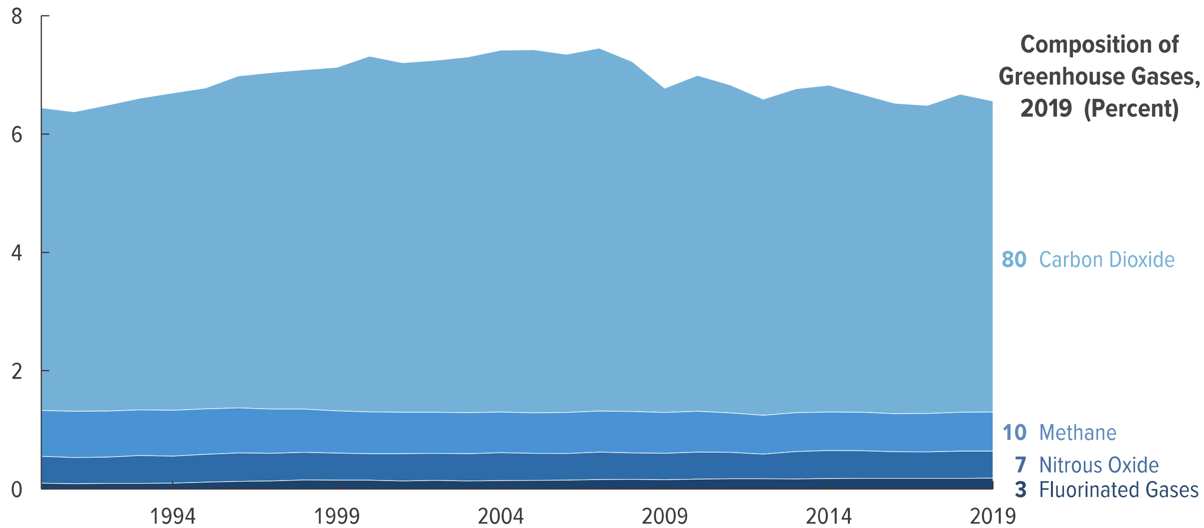
[8] A heat rate measures the amount of energy necessary to produce a unit of electricity for different types of generators.

Figures

Figure 1.

Total U.S. Greenhouse Gas Emissions, 1990 to 2019

Billions of Metric Tons of Carbon Dioxide Equivalent



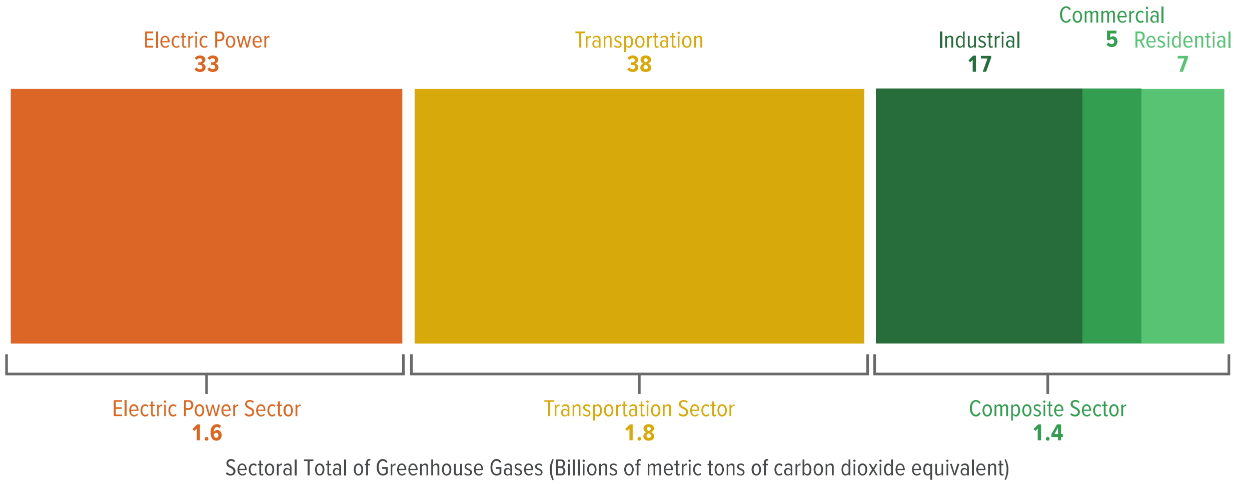
Data source: Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990– 2019*, EPA 430-R-21-005 (April 2021), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

Greenhouse gases differ in their contribution to warming per physical unit of gas, and, for simplicity, they are often measured in terms of metric tons of carbon dioxide equivalent—quantities of emissions that, over a period of years (usually a century), contribute to the greenhouse effect by as much as a metric ton of carbon dioxide. In 2019, forests and soils absorbed about 800 million metric tons of carbon dioxide equivalent, on net, offsetting about 12 percent of total emissions. The absorption by forests and soils has declined by 13 percent since 1990, when forests and soils absorbed about 900 million metric tons of carbon dioxide equivalent, on net, offsetting about 14 percent of total emissions at the time.

Figure 2.

Distribution of Energy-Related Emissions of Carbon Dioxide in the United States, by Sector, 2019

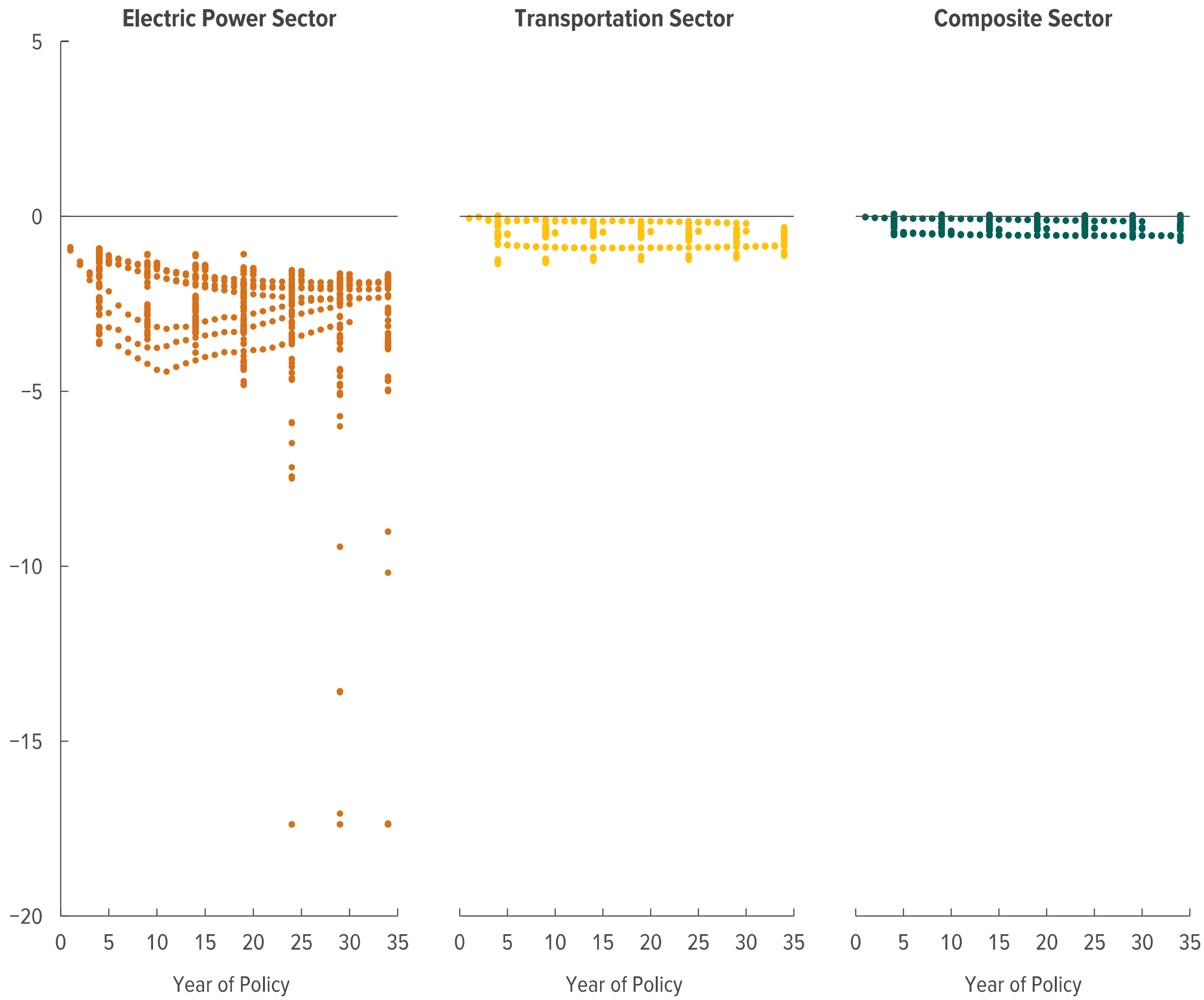
Percent



Data source: Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019*, EPA 430-R-21-005 (April 2021), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

Figure 3.

Distribution of Price Sensitivities of Energy-Related Emissions of Carbon Dioxide in the Studies That CBO Relied On for Its Update, by Sector

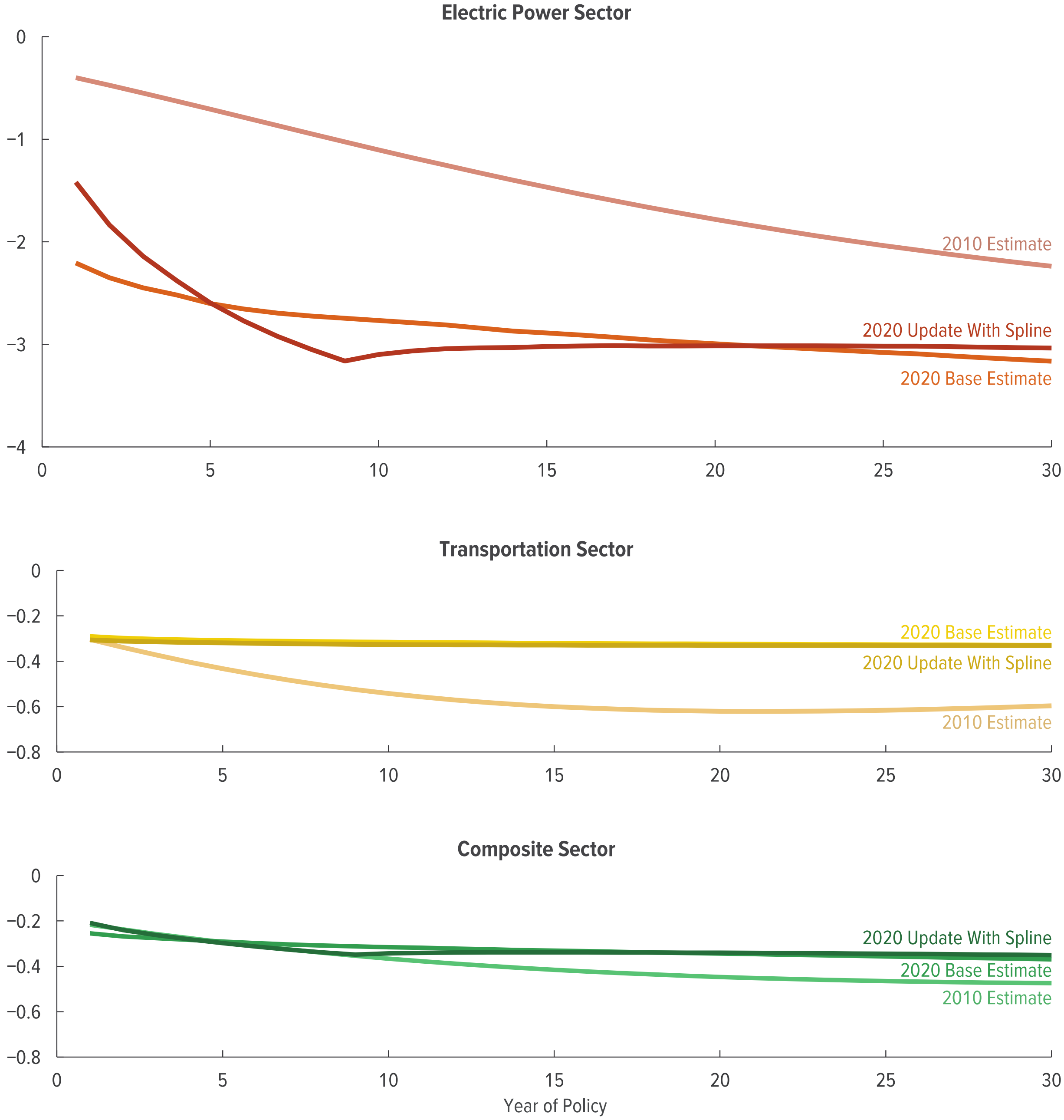


Data source: CBO's calculations of results from Energy Modeling Forum, *EMF 32: U.S. GHG and Revenue Recycling Scenarios*, https://emf.stanford.edu/projects/emf-32-us-ghg-and-revenue-recycling-scenarios, and Energy Information Administration, *Annual Energy Outlook 2020* (January 2020), www.eia.gov/outlooks/aeo/.

Results are based on simulations from modeling multiple tax policy scenarios on carbon dioxide emissions.

Figure 4.

CBO's Prior and Updated Estimates of Price Sensitivities of Energy-Related Emissions of Carbon Dioxide, by Sector

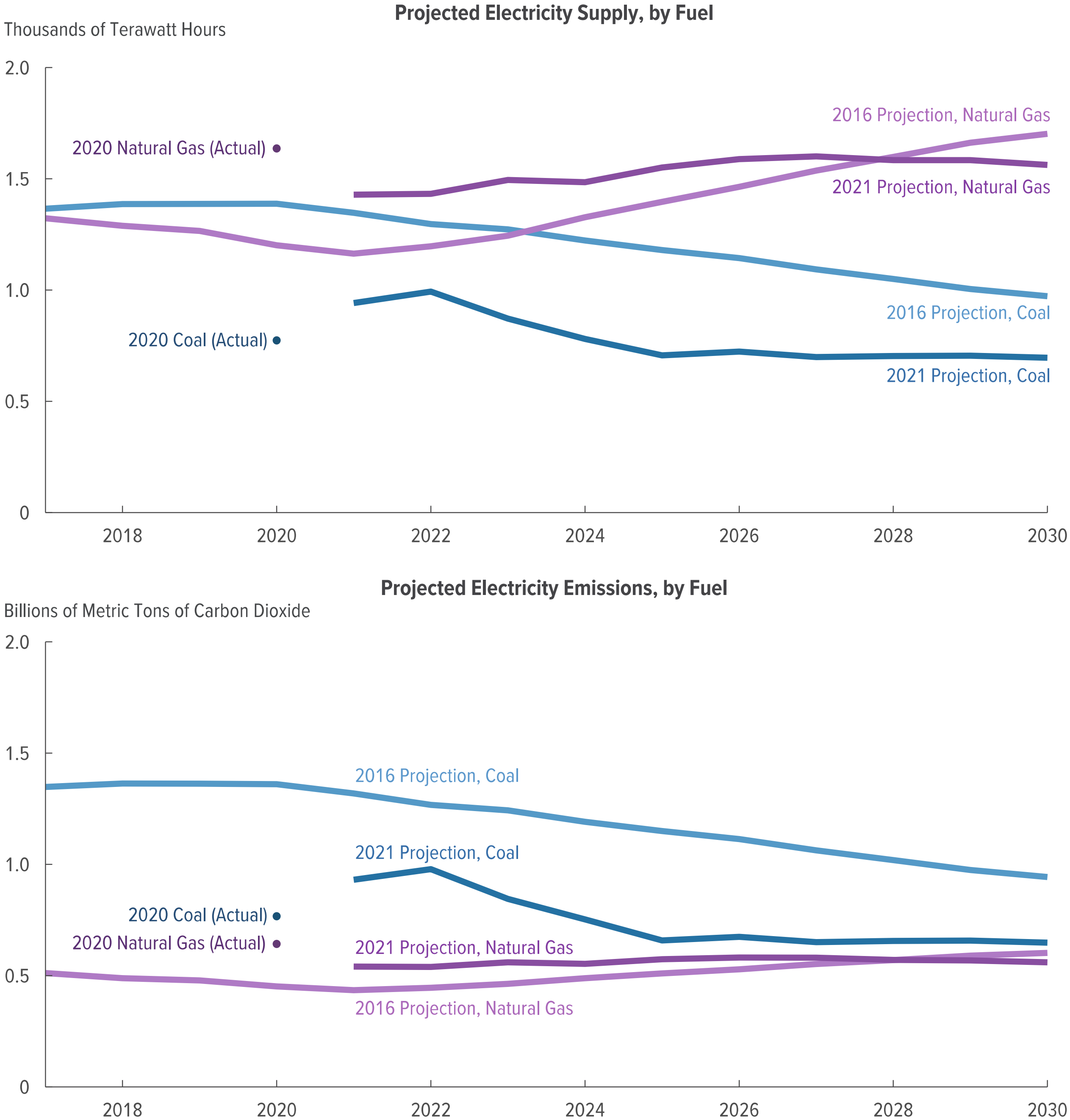


Data sources: Energy Modeling Forum, *EMF 32: U.S. GHG and Revenue Recycling Scenarios*, https://emf.stanford.edu/projects/emf-32-us-ghg-and-revenue-recycling-scenarios; Energy Information Administration, *Annual Energy Outlook 2020* (January 2020), www.eia.gov/outlooks/aeo/.

Results are based on simulations that modeled the effects of tax policy scenarios on carbon dioxide emissions. The price sensitivity estimates reflect CBO's calculation of the baseline price of embedded carbon dioxide based on EIA's 2020 AEO and the addition of a $25 tax on carbon dioxide emissions (in 2019 dollars) from burning fossil fuels when producing energy that grows at 5 percent per year in real (inflation-adjusted) terms.

Figure 5.

Projections of Electricity Supply and Energy-Related Emissions of Carbon Dioxide in the Electric Power Sector, 2017 to 2030



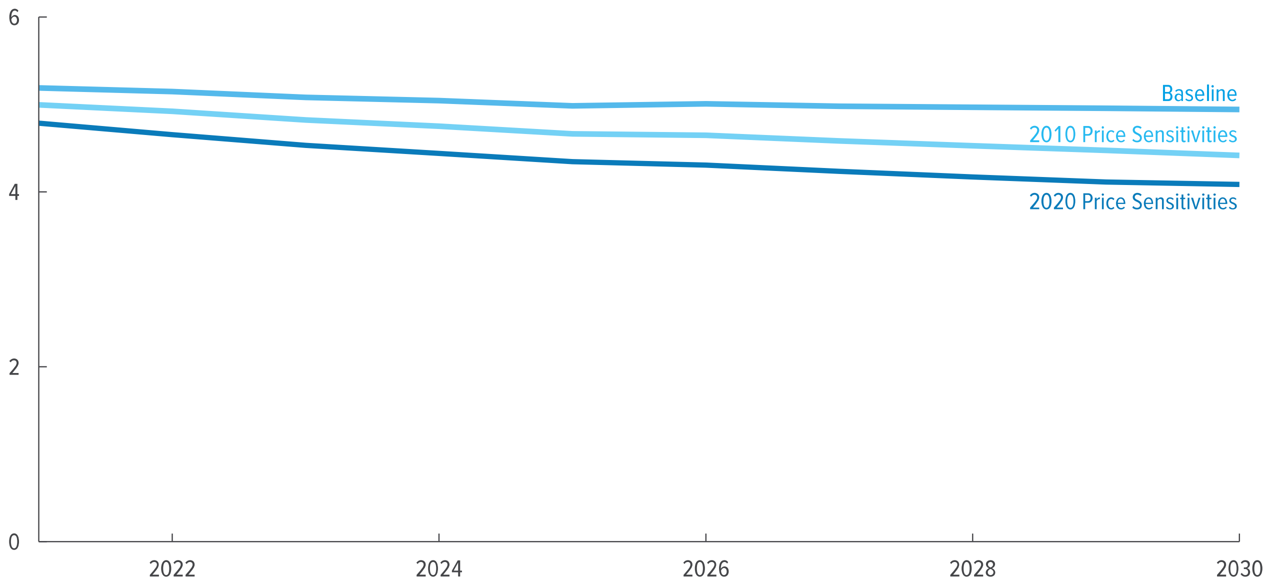
Data source: Energy Information Administration, *Annual Energy Outlook 2021* (February 2021) www.eia.gov/outlooks/aeo/, and *Annual Energy Outlook 2016* (September 2016) www.eia.gov/outlooks/archive/aeo16/.

In this figure, the points represent estimated actual values, and the lines represent EIA's projections.

Figure 6.

Effect of 2020 Price Sensitivity Update on Energy-Related Emissions of Greenhouse Gases From a Potential Tax on Those Emissions

Billions of Metric Tons of Carbon Dioxide Equivalent



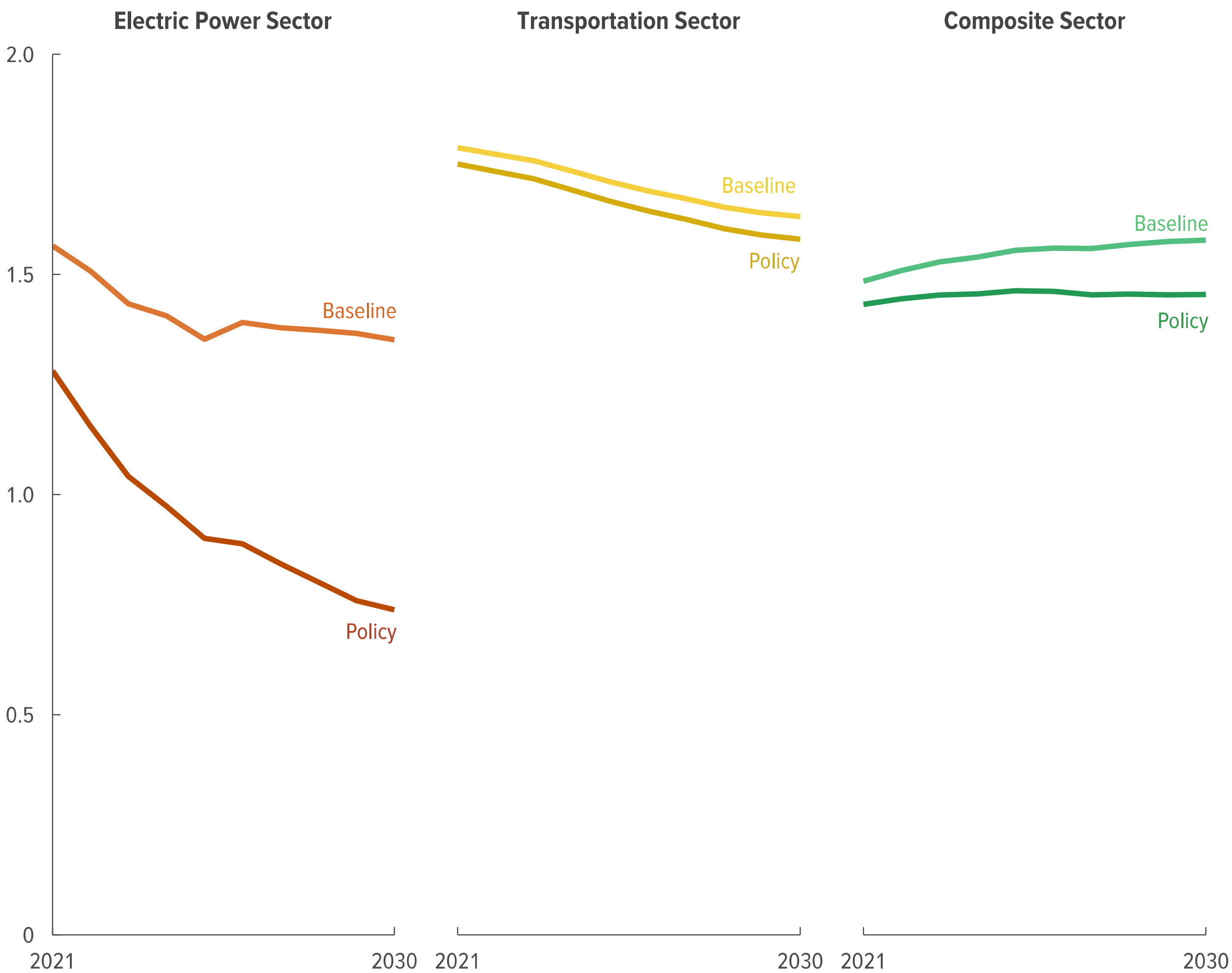
Data source: Congressional Budget Office.

These calculations are based on a tax of $25 per metric ton on most emissions of greenhouse gases in the United States (measured in carbon dioxide equivalent units) starting in 2021 and growing at a real (inflation-adjusted) rate of 5 percent per year. The emissions subject to the tax include carbon dioxide released from the burning of fossil fuels when producing energy as well as nonenergy carbon dioxide and other greenhouse gas emissions from large manufacturing facilities. For details, see Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.

Figure 7.

Effect of a Potential Tax on Energy-Related Emissions of Carbon Dioxide, by Sector

Billions of Metric Tons of Carbon Dioxide



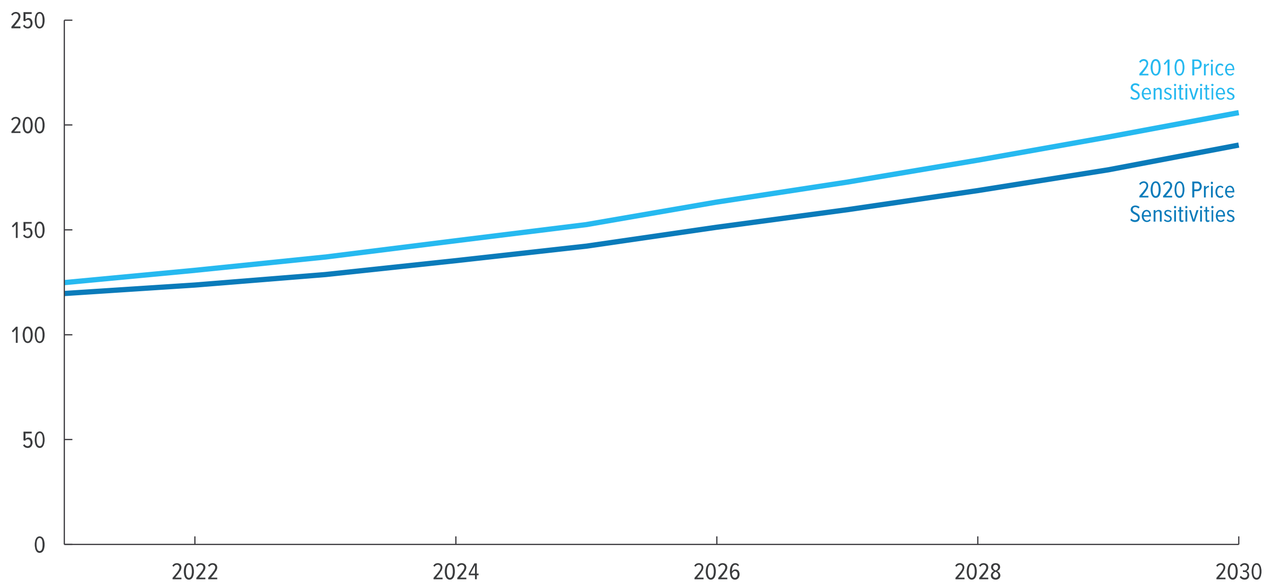
Data source: Congressional Budget Office.

These calculations are based on a tax of $25 per metric ton on most emissions of greenhouse gases in the United States (measured in carbon dioxide equivalent units) starting in 2021 and growing at a real (inflation-adjusted) rate of 5 percent per year. Energy-related emissions of carbon dioxide are those released from the burning of fuels fuel when producing energy. Those emissions account for nearly 95 percent of all greenhouse gas emissions subject to the tax. For details, see Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.

Figure 8.

Effect of 2020 Price Sensitivity Update on Gross Revenues From a Potential Tax on Energy-Related Emissions of Greenhouse Gases

Billions of Current Dollars

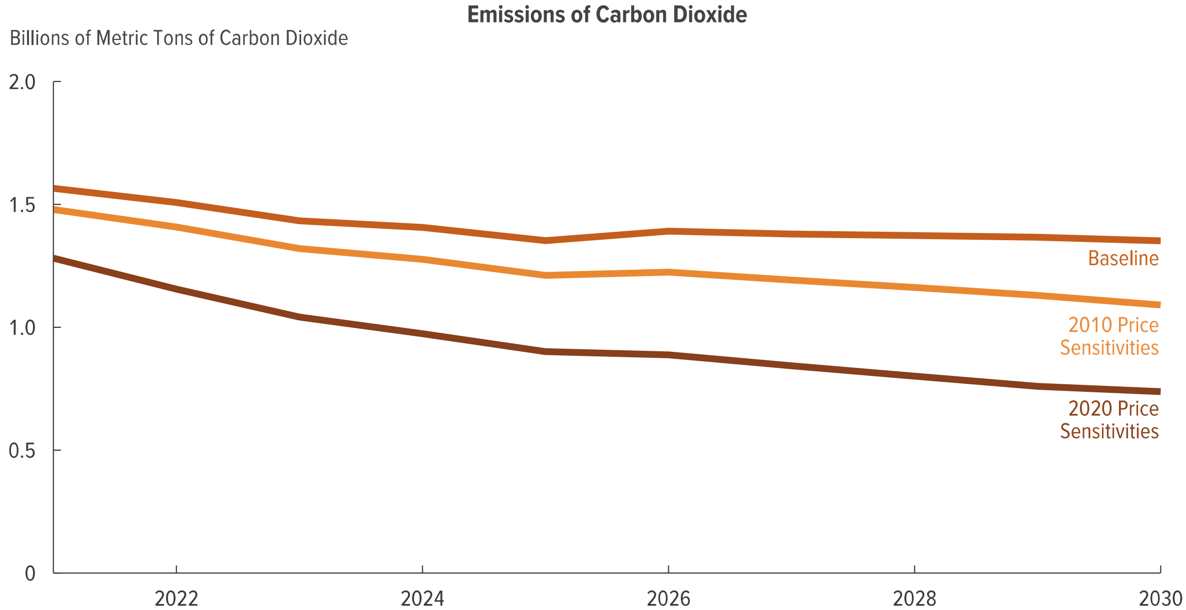


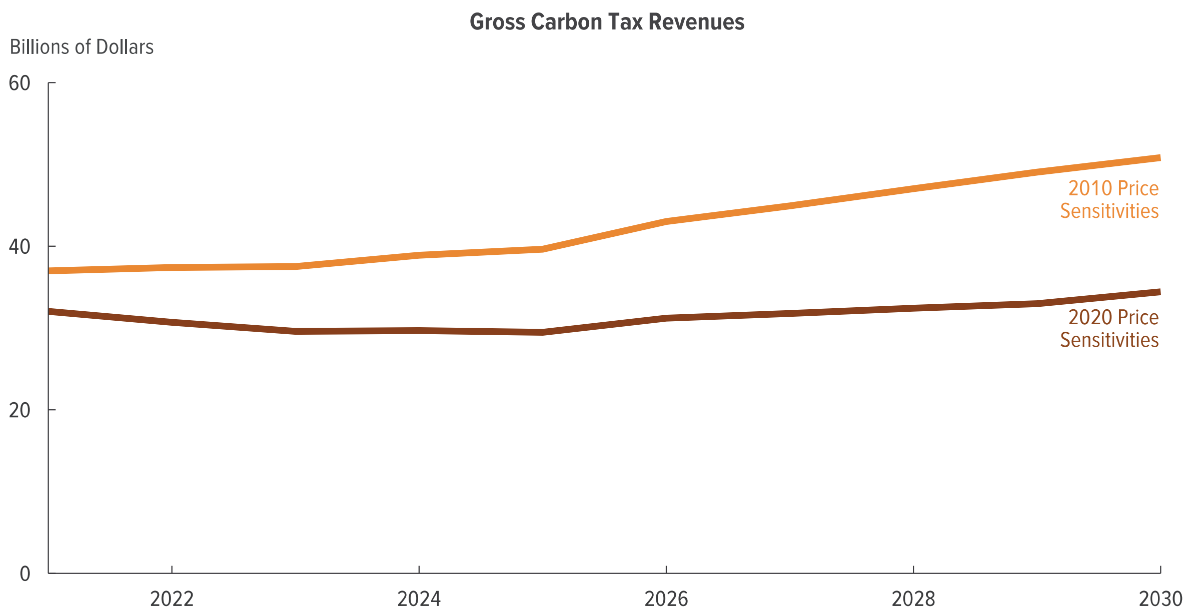
Data source: Congressional Budget Office.

These calculations are based on a tax of $25 per metric ton on most emissions of greenhouse gases in the United States (measured in carbon dioxide equivalent units) starting in 2021 and growing at a real (inflation-adjusted) rate of 5 percent per year. The emissions subject to the tax include carbon dioxide released from the burning of fossil fuels when producing energy as well as nonenergy carbon dioxide and other greenhouse gas emissions from large manufacturing facilities. See Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.

Figure 9.

Effect of 2020 Price Sensitivity Update on Energy-Related Emissions of Carbon Dioxide and Tax Revenues in the Electric Power Sector From a Potential Tax on Those Emissions





Data source: Congressional Budget Office.

These calculations are based on a tax of $25 per metric ton on most emissions of greenhouse gases in the United States (measured in carbon dioxide equivalent units) starting in 2021 and growing at a real (inflation-adjusted) rate of 5 percent per year. Energy-related emissions of carbon dioxide are those released from the burning of fossil fuels when producing energy. Those emissions account for nearly 95 percent of all greenhouse gas emissions subject to the tax. The plotted tax revenue estimates reflect calendar year gross revenues received (tax revenues received before any offsetting reductions in tax collections elsewhere in the economy). For details, see Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.

Tables

Table 1.

Models That CBO Relied On to Update Its Carbon Dioxide Price Sensitivities

Model	Study	Policy Evaluated
ADAGE-US	Woollacott, "The Economic Costs and Co-Benefits of Carbon Taxation: A General Equilibrium Assessment," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per metric ton (MT) carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
CEPE	Rausch and Yonezawa, "The Intergenerational Incidence of Green Tax Reform," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
DIEM	Ross, "Regional Implications of Carbon Taxes," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
EC-MSMR	Zhu and others, "Revenue Recycling and Cost Effective GHG Abatement: An Exploratory Analysis Using a Global Multi-sector Multi-region CGE Model," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
FARM	Sands, "U.S. Carbon Tax Scenarios and Bioenergy," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
GH-E3	Chen, Goulder, and Hafstead, "Quantifying the Determinants of Future CO_2 Emissions," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, one revenue recycling method
IGEM	Jorgensen and others, "The Welfare Consequences of Taxing Carbon," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
NEMS	Arora and others, "EMF 32 Results from NEMS: Revenue Recycling," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2040, two revenue recycling methods
NewERA	(No companion report)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
USREP-ReEDS	Caron and others, "Exploring the Impacts of a National U.S. CO_2 Tax and Revenue Recycling Options With A Coupled Electricity-Economy Model," *Climate Change Economics*, vol. 9, no. 1 (2018)	$25 and $50 per MT carbon taxes growing at 1% and 5% real, 2020-2050, three revenue recycling methods
NEMS (AEO)	Energy Information Administration, *Annual Energy Outlook 2020 With Projections to 2050* (January 2020)	$15, $25, $35 per MT carbon taxes growing at 5% real, 2021-2050, one revenue recycling method

All of the models except the last one listed are from the Energy Modeling Forum; see John Weyant, *EMF 32: US GHG and Revenue Recycling Scenarios*, https://emf.stanford.edu/projects/emf-32-us-ghg-and-revenue-recycling-scenarios, and are in 2010 dollars. The last model listed is from the Energy Information Administration's 2020 long-term outlook and is in 2019 dollars.

Table 2.

Effects of 2020 Price Sensitivity Update on Revenues From a Potential Tax on Energy-Related Emissions of Greenhouse Gases

Billions of Current Dollars

	Estimated Gross Revenues, 2021 to 2030				
	Electric Power Sector	Transportation Sector	Composite Sector	Other Gases	Total Revenues
Calculation Using 2010 Price Sensitivities	425	565	504	116	1,609
Calculation Using 2020 Price Sensitivities	314	571	504	109	1,498
Change in Estimated Gross Revenues	-111	7	0	-7	-111

Data source: Congressional Budget Office.

These results are based on a tax of $25 per metric ton on most emissions of greenhouse gases in the United States (measured in carbon dioxide equivalent units) starting in 2021 and growing at a real (inflation-adjusted) rate of 5 percent per year. The emissions subject to the tax include carbon dioxide released from the burning of fossil fuels when producing energy as well as nonenergy carbon dioxide and other greenhouse gas emissions from large manufacturing facilities. The estimates reflect calendar year gross tax revenues (tax revenues before any offsetting reductions in tax collections elsewhere in the economy). For details, see Congressional Budget Office, *Options for Reducing the Deficit: 2021 to 2030* (December 2020), p. 85, www.cbo.gov/publication/56783.