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LETTER

Near term carbon tax policy in the US Economy: limits to deep decarbonization

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Abstract

This paper explores carbon dioxide (CO_2) tax policies from 2015 to 2030 in the United States economy using an energy system least-cost optimization model. We report limited near-term decarbonization opportunities outside of the electricity sector, which results in substantial CO_2 tax revenue through 2030. Second, because the social cost of carbon is uncertain, we find asymmetric deadweight loss from implementing mistakenly high or low CO_2 taxes, providing efficiency-based support for the precautionary principle. Third, despite CO_2 reductions occurring mainly in the electric sector, the abatement estimated herein is consistent with the US nationally determined contributions established under the Paris Agreement.

1. Introduction

In 2016, nearly all the world's countries ratified the Paris Agreement, which aims to limit the global temperature increase to less than 2° Celsius above pre-industrial temperatures (United Nations 2015). In order to prevent warming greater than 2° Celsius, global greenhouse gas emissions will likely need to decrease by roughly 25% below 2010 levels by 2030 and reach near-zero by 2070 (IPCC 2018). In 2014, China emitted 30% of global carbon dioxide (CO_2), followed by the United States (US), at 15% (US EPA 2014). As one of the largest emitters of greenhouse gases globally, the emission trajectory of the US will play a central role in whether the Paris Agreement's temperature targets are met.

In this paper, we explore economy-wide CO_2 tax policies in the US. The analysis uses the Integrated MARKAL-EFOM System (TIMES) energy optimization model to simulate energy use by sector, fuel type and technology, system costs, and pollution emissions under two carbon tax policies from 2010 to 2030 (Lenox 2019). The analysis includes CO_2 emissions as well as emissions of local air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter ($PM_{2.5}$). We focus on near-term policies through 2030 because the characterization of energy system technologies in the model is likely most valid over this time period. Further, with dynamic incentives for research and development of low carbon technologies in the presence of binding CO_2 policy, current characterizations of low-carbon technologies beyond 2030 is speculative at best. In pursuit of allocatively efficient policies, the paper implements emissions taxes based on recent estimates of the Social Cost of Carbon (SCC). However, since the 'true' SCC is unknown, we also examine the inefficiencies associated with carbon tax mistakes; that is, scenarios in which the carbon tax rate departs from the SCC estimate. We hypothesize that non-linearities in the marginal abatement cost curve for CO_2 will yield asymmetric inefficiencies which may be useful in guiding CO_2 tax policy.

We use the TIMES model even though other economy-wide models are available. The impetus for this choice is the detailed technology characterization of the energy system in seven sectors, and myriad sub-sectors,

specified in TIMES. This detail facilitates an analysis of responses by different sub-sectors to the carbon tax policies that we explore herein. For example, in response to the carbon tax scenarios, the TIMES model estimates changes in the fuel mix in the electric generation sector by geographic region, as well as responses within the vehicle fleet. Our joint analysis of CO_2 and local air pollution emissions is also enabled by the use of TIMES. The shortcomings of our approach center on two areas: the inability to estimate tax incidence and intersectoral spillovers, which would be enabled by computable general equilibrium models (Babatunde *et al* 2017).

Prior research has estimated CO_2 tax revenue and emissions reductions in the US. Brown *et al* (2017) quantified tax revenue from varying CO_2 taxes in the year 2045 and found a maximum reduction of 36% in CO_2 emissions compared to a business-as-usual (BAU) scenario in 2045. Metcalf (2008) found that a $15 per ton CO_2 tax lead to significant revenue and 8% CO_2 emissions reductions in 2015. Other work, such as Carbone *et al* (2013), estimated potential CO_2 tax revenue from a $20, $30, and $50 per ton CO_2 tax, and a resulting 13% to 24% reduction in CO_2 emissions by 2025 compared to BAU. Across the literature, there is substantial variation in estimated co-benefits from CO_2 policies. Air pollution reduction co-benefits may vary due to differences in time horizons, air pollutant species included in the analysis, choice of discount rate, and valuation of damage per ton of pollution abated. Saari *et al* (2015) found that a 10% reduction of CO_2 emissions in 2030 compared to 2006 levels lead to an estimated $3 billion to $21 billion reduction in damages from $PM_{2.5}$ emissions. Thompson *et al* (2014) modeled a 10% CO_2 reduction by 2030 relative to 2006 levels and found that cumulative median ozone and $PM_{2.5}$ damages decreased between $110 billion to $385 billion depending on the policy ($220 to $770 in co-benefits per ton of CO_2 abated). Balbus *et al* (2014) found $PM_{2.5}$ damage reduction benefits ranging from $36 to $179 per ton of CO_2. Nemet *et al* (2010) surveyed the co-benefits literature and found that co-benefits for developed countries across 22 estimates ranged from $2 to $116 per ton of CO_2 abated. In our analysis, we find co-benefits to range from $314 to $316 per ton of CO_2 abated using AP3 damage values for SO_2, NO_x, and $PM_{2.5}$ emissions.
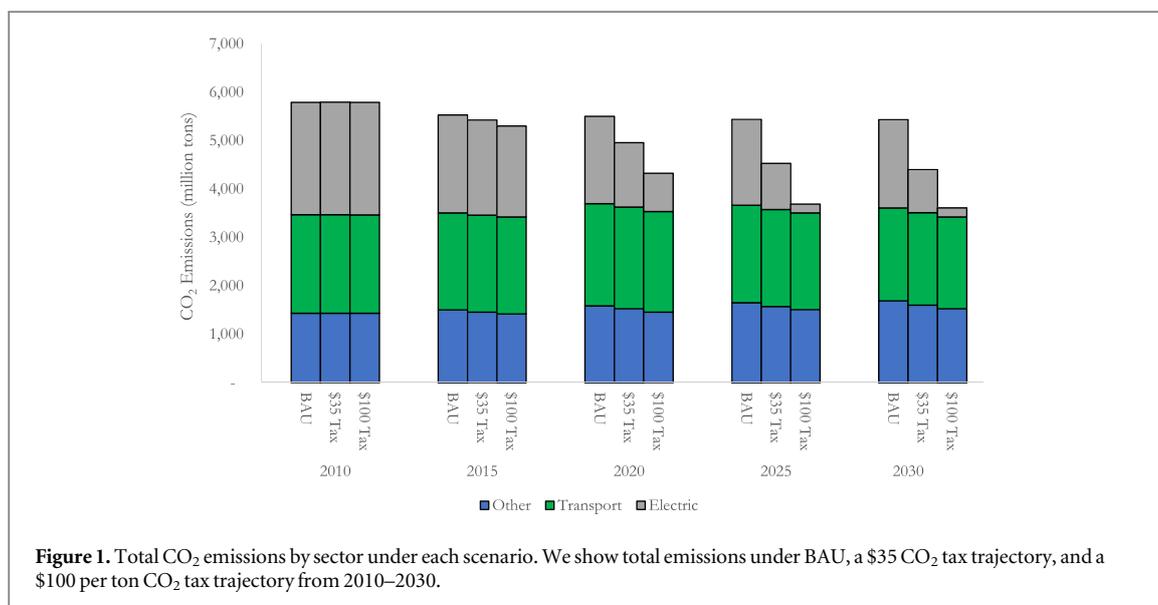
The remainder of this paper is structured as follows: section 2 discusses the datasets and models used herein. Section 3 presents our primary results. Section 4 concludes.

2. Methods

This paper uses a bottom-up energy system optimization model (TIMES) to explore carbon taxes in the US energy system (Lenox 2019). The optimization algorithm in TIMES minimizes costs including, fixed, investment, and operations and maintenance costs to meet exogenous energy demand in each sector of the economy (Lenox 2019). The model also includes a market clearing condition that requires all energy and commodity demand to be met in each year. For this work, we use the EPAUS9rT (EPA TIMES 9-region) database version 16.1.3 (Lenox 2019). Sectors in EPAUS9rT include commercial, electricity production, industrial, refinery, residential, resource supply (upstream), and transportation. Each sector in EPAUS9rT includes a roster of energy technologies with detailed cost information, pollutant-specific emissions rates, and efficiencies. End-use demand in each of these sectors is specified by projections in the 2016 EIA Annual Energy Outlook from 2010–2050 (EIA 2016). The EPAUS9rT database includes energy system constraints, including limits to local air pollutants through the inclusion of the CSAPR and MATS rules, renewable portfolio standards in the electric sector, and CAFE standards in the transportation sector (NHTSA 1975, US EPA 2011b, 2011a, US EIA 2012).

We focus on the US energy system from 2010 to 2030. The benchmark is a BAU scenario that simulates how technology and emissions evolve in the absence of new policies limiting CO_2 emissions. In two additional scenarios, we implement a $35 and $100 per ton CO_2 tax trajectory on the energy system starting in 2015 and lasting through 2030. These tax trajectories are derived from the US federal government's interagency working group on the social cost of carbon (USFWGSCC) report and represent lower and upper bounds on the estimated SCC (USFWG 2016). All monetary values in this analysis are reported in 2005$ unless otherwise noted. The tax rate in the $35 tax scenario increases from $34 per metric ton of CO_2 in 2015 to $47 in 2030. Similarly, in the $100 tax scenario, the tax rate ranges from $99 to $143 per metric ton of CO_2 from 2015 to 2030 (USFWG 2016). These rising tax rate trajectories occur because as CO_2 concentrations in the atmosphere increase over time, the marginal damage from the emission of one ton of CO_2 is expected to increase. Lastly, we calibrated the BAU specification of TIMES version 16.1.3 to align with observed patterns in the energy systems between 2010 and 2020. For example, the uncalibrated BAU simulations included significant growth in electric vehicles between the 2010 and 2015 simulation years that were inconsistent with observed trajectories (electric vehicles comprised only 1% of new 2017 US light-duty vehicle sales (US DOE 2019). As a result, we added a constraint in the model to limit the share of vehicle miles travelled (VMT) by electric vehicles to near-zero until 2020. We then maintained the calibrated parameters used in the BAU scenario in the simulations with carbon taxes.

The TIMES model also simulates the emissions of SO_2, NO_x, and $PM_{2.5}$ associated with energy production. To monetize the co-benefits associated with reductions in these emissions, we use the AP3 model to calculate the

Figure 1. Total CO_2 emissions by sector under each scenario. We show total emissions under BAU, a \$35 CO_2 tax trajectory, and a \$100 per ton CO_2 tax trajectory from 2010–2030.

average national damage caused by one ton of emissions from SO_2, NO_x, and $PM_{2.5}$ in the US (Muller 2019, Tschofen *et al* 2019). As a sensitivity analysis, we also use the EASIUR and InMAP models to estimate the national aggregated damage from local air pollutant emissions (Heo *et al* 2016, Tessum *et al* 2017). Marginal damages from local air pollutant emissions increase over time, reflecting projected increases in population and per capita GDP. Figure A2 in the appendix summarizes the marginal damage rates by year and species. We then calculate the total national damages as the product of the TIMES criteria pollutant emission estimates and the marginal damages. We apply a 5% discount rate to all future costs and benefits in this analysis.
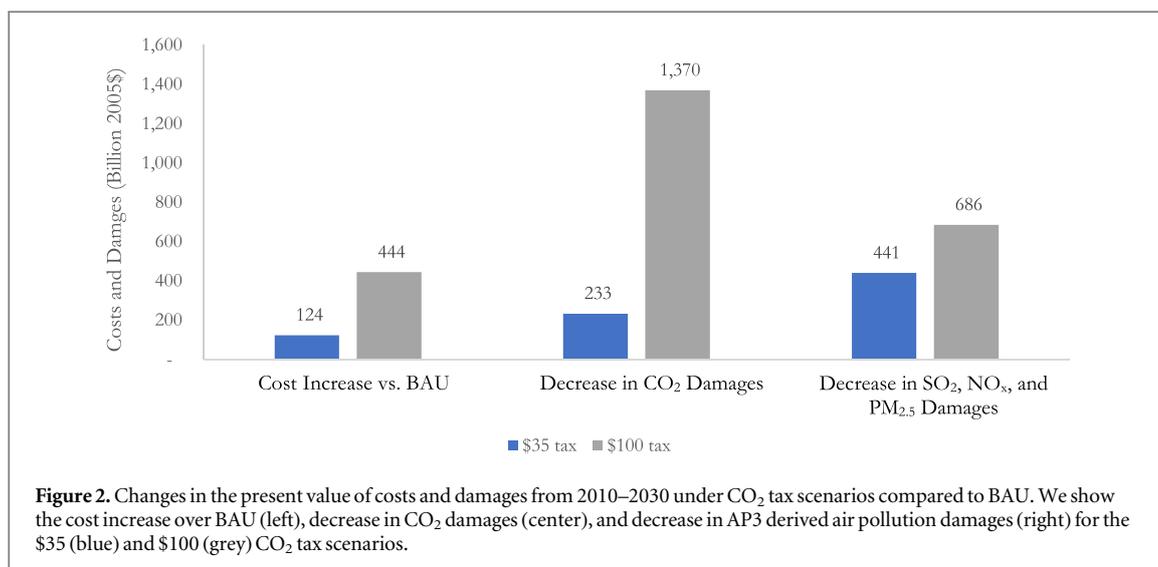
3. Results

This section of the analysis presents simulation results in three areas. Section 3.1 covers emission reductions, system costs, and CO_2 and local air pollution reduction benefits. Section 3.2 encompasses tax revenue and section 3.3 explores the efficiency implications of miscalibrations of the CO_2 taxes.

3.1. Emissions, costs, and benefits

Modeled CO_2 emissions from the US energy system total 5.8 billion tons in 2010.[1] From this level, CO_2 emissions are estimated to decrease by 24% and 38% in 2030, under the \$35 and \$100 tax scenarios, respectively (see figure 1). The two biggest sources of modeled emissions in 2010 are the electric sector (2.3 billion tons of CO_2 emissions) and the transportation sector (2 billion tons of CO_2). Figure 1 shows that CO_2 abatement is remarkably concentrated in the electricity generation sector. For example, under the \$100 CO_2 tax, 2030 electric sector emissions decrease by 92% compared to 2010 levels, while transportation sector emissions fall by only 7% in 2030 relative to 2010 levels.

The asymmetric CO_2 abatement in these sectors manifests because the electric sector has a number of carbon-reducing technology options, including carbon capture and sequestration, fuel switching from coal to gas, nuclear power, and renewable options such as wind and solar. The transportation sector does not decarbonize to the same extent because the only near-term, cost-effective low-carbon technologies available are light-duty electric vehicles. While the EPAUS9rT database includes cost and performance characteristics for hydrogen, compressed natural gas, and biofuels for medium and heavy-duty transport, such technologies are not cost-effective by 2030, even in the presence of CO_2 taxes. If the CO_2 taxes modeled in this analysis were enacted, strong dynamic incentives for vehicle manufacturers to develop low-carbon technologies would exist. However, given the nascent state of electrification for medium and heavy-duty vehicles, the technology characterization for these vehicles available in the EPAUS9rT database is reasonable for near-term analysis like the one in this paper. The upshot is that the medium and heavy-duty transportation sectors do not respond to the CO_2 taxes in our scenarios and thus generate substantial tax revenue. The remaining sectors in the economy have essentially no near-term low carbon technologies, and thus, like medium and heavy-duty vehicles, are significant sources of CO_2 tax revenue, not abatement.

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[1] The EPA reported that energy-related CO_2 emissions were 5.5 billion tons in 2010 (US EPA 2019).

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Figure 2. Changes in the present value of costs and damages from 2010–2030 under CO_2 tax scenarios compared to BAU. We show the cost increase over BAU (left), decrease in CO_2 damages (center), and decrease in AP3 derived air pollution damages (right) for the $35 (blue) and $100 (grey) CO_2 tax scenarios.

After model calibration, electric vehicles meet 25% of light-duty VMT by 2030 in the BAU scenario. The fact that electric vehicles make up a substantial portion of light-duty VMT in the BAU scenario implies that these vehicles become a cost-effective alternative to internal combustion vehicles in meeting transportation demand in TIMES, even without carbon taxes. A CO_2 tax of $35 and $100 per ton is estimated to increase the price of gasoline by approximately $0.35 and $1 per gallon, respectively (Hafstead and Picciano 2017). However, under a $35 tax scenario and a $100 tax scenario, 2030 electric vehicle VMT do not increase significantly compared to BAU, reaching 25% and 26% of light-duty VMT, respectively. Similar electric vehicle penetration rates across scenarios manifest because light-duty vehicles are durable goods with slow turnover rates. Extended model simulations, not reported herein, show that electric vehicle penetration in 2050 is much higher under the CO_2 tax scenarios than under BAU. Thus, the combination of turnover, technological, and production constraints limit near-term deployment of light-duty electric vehicles. This contributes significantly to our finding of limited near-term CO_2 reductions in the transportation sector.
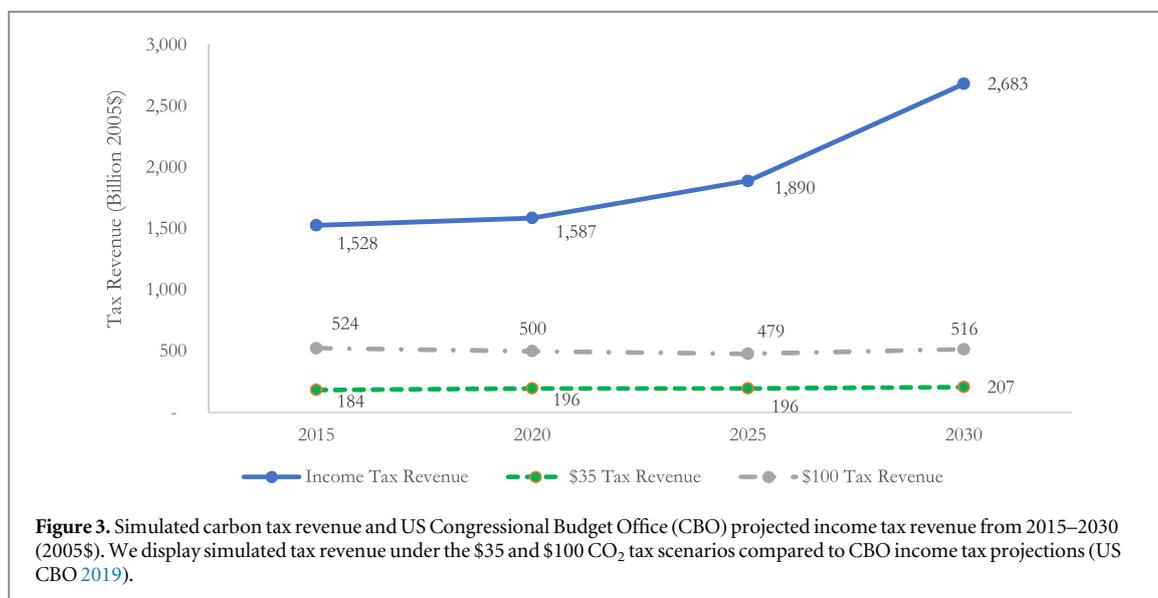
The $35 and $100 tax policies increase the present value of cumulative costs to meet energy demand through 2030 by $124 billion and $444 billion ($164 billion and $586 billion in 2019$), respectively. In figure 2, we show the increase in cumulative system costs under carbon tax scenarios, the decrease in CO_2 damages, and the decrease in air pollution damages compared to the BAU scenario for both CO_2 taxes. While there is a substantial increase in cost to meet energy demand under the CO_2 taxes, the estimated benefit-cost ratios are 1.9 and 3.1 for the $35 and $100 CO_2 tax policies, respectively.

It is important to note that results obtained for the CO_2 tax rates implemented herein are derived using two assumed SCC estimates (USFWG 2016). Thus, the modeling of each tax policy essentially assumes two possible states of the world: a low SCC state and a high SCC state. Reductions in CO_2 damage stemming from the tax policies are calculated as the reduction in emissions multiplied by the SCC, by year. This approach to damage estimation is important to consider when interpreting the benefit-cost ratios above.

Importantly, as carbon taxes spur decarbonization of the energy system, emissions of SO_2, NO_x, and $PM_{2.5}$ also fall. The pollution reductions resulting from the carbon tax policies increase cumulative present value benefits by roughly $441 and $686 billion ($582 billion and $905 billion in 2019$) between 2010 to 2030 in the $35 and $100 CO_2 tax scenarios, respectively. Including co-benefits from LAP reductions raises the benefit-cost ratios of CO_2 tax policies to about 5-to-1. Air pollution reduction co-benefits using EASIUR and InMAP-derived damage values, range from $345-$495 billion and $321-$478 billion under the $35 and $100 CO_2 tax scenarios, respectively.
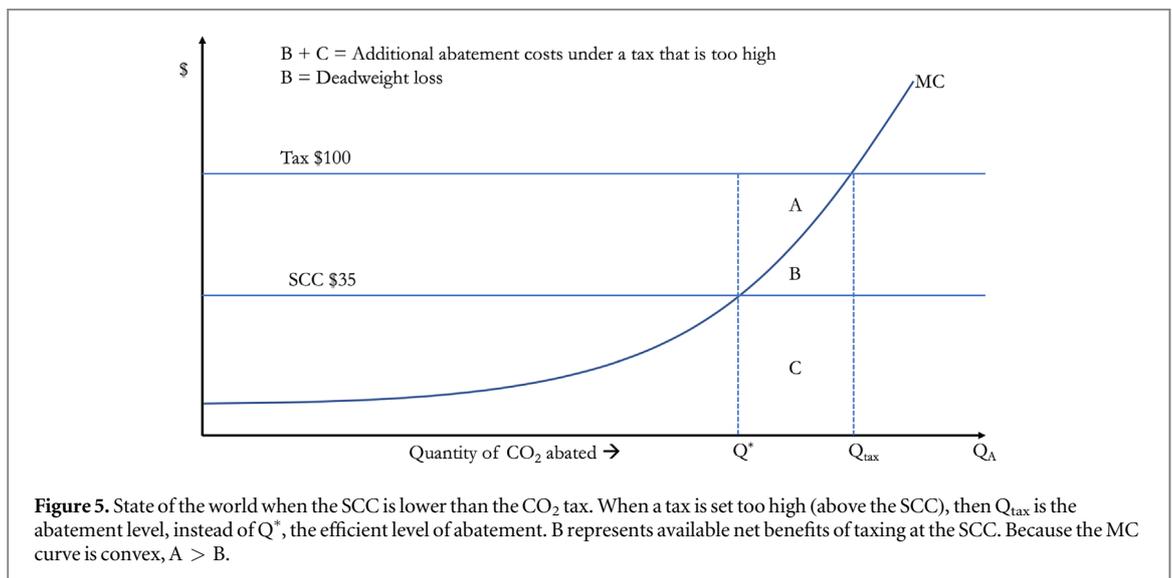
3.2. CO_2 tax revenue

This analysis finds that, between 2010 and 2030, CO_2 taxes levied on the US energy system yield a large and enduring source of revenue. Because CO_2 emissions constitute an externality, abatement of CO_2 relative to the BAU levels bolsters economy-wide allocative efficiency. In contrast, other taxes (the income tax, for example) impose considerable distortions on the US economy in order to generate revenue (Ballard *et al* 2016). Implementation of carbon taxes represents an opportunity for the US economy to transition from a distortionary tax system to one that corrects large-scale market failure.

Figure 3. Simulated carbon tax revenue and US Congressional Budget Office (CBO) projected income tax revenue from 2015–2030 (2005$). We display simulated tax revenue under the $35 and $100 CO_2 tax scenarios compared to CBO income tax projections (US CBO 2019).

The proceeds from a $35 CO_2 tax increase over time from $184 billion to $207 billion ($243 billion to $273 billion in 2019$) per year between 2015 and 2030, while those from a $100 CO_2 tax range between $479 billion to $524 billion per year ($635 billion to $695 billion in 2019$)(see figure 3). While this substantial source of revenue is positive news from the perspective of federal fiscal policy, if low-carbon technologies do not become available to other sectors beyond electricity generation and light-duty vehicles in the future, it is possible that persistent emission levels could ultimately prohibit attainment of longer-term CO_2 targets established in the Paris Agreement. If low-carbon technologies do become viable in the future and the SCC does not rise rapidly, then CO_2 tax revenue would potentially fall as the energy system decarbonizes.

The $35 and $100 carbon tax revenues projected herein comprise between approximately 8%-34% of federal income tax depending on the year and tax scenario (US CBO 2019). For instance, as displayed in figure 3, 2015 federal income tax revenue totaled $1.5 trillion (2005$) and revenue from a $35 carbon tax would have totaled $184 million (2005$), or 12% of revenue. As this is a large share of total income tax revenue, it is also helpful to consider progressively designed tax offsets to alleviate income inequality. According to the Pew Research Center, individuals earning less than $50,000 per year comprised 61.4% of all filed tax returns, but accounted for only 5.4% of all paid income tax revenue (Desilver 2017). The revenue from the $35 carbon tax, therefore, is more than sufficient to fully replace income taxes levied on the bottom 61.4% of taxpayers. Another potentially useful application of carbon tax revenue is repairing infrastructure. In 2014, total spending from the federal Highway Trust Fund and governments at the state and local levels to build, operate, and maintain highways totaled $135 billion (2005$)(Shirley 2015). This expenditure is less than the projected revenue from the $35 carbon tax in 2015. Lastly, $111 billion (2005$) was allocated to US defense and non-defense research and development in 2018 (AAAS 2019). Revenue from the $35 carbon tax could potentially double federal funding for research and development in the US or be allocated to decarbonization and climate adaptation research.

As we examine tax revenue by sector, it is important to note that the demand for electricity generation as well as VMT increases exogenously between 2010 and 2030 in our simulations. As illustrated in figure A8, tax revenue is generated from various sectors across the economy under a CO_2 tax. Under the $35 tax, revenue is predominantly derived from the transportation and electric sectors. Under the $35 CO_2 tax trajectory, electric sector carbon tax revenue declines from $66 billion (36%) in 2015 to $42 billion (20%) in 2030, while transportation's share grows from $68 billion (37%) to $90 billion (43%) over the same time horizon. In the $100 carbon tax scenario, tax revenue from the electric sector falls from $186 billion (35%) in 2015 to $26 billion (5%) in 2030 as the revenue share from transportation increases from $198 billion (38%) in 2015 to $271 billion (53%) in 2030. While there is net decarbonization by 2030 across the energy system, transportation sector CO_2 emissions fall by only 6% or 7% in the $35 and $100 CO_2 tax scenarios, respectively. The transportation sector's share of CO_2 emissions and tax revenue increases because of the low penetration rate of light-duty electric vehicles (roughly 25% of light-duty VMT are electric by 2030 across both carbon tax scenarios), growth in VMT, and limited options to decarbonize medium and heavy-duty vehicles. Given the dynamic incentives presented by either CO_2 tax, it is likely that the transportation sector would continue to decarbonize as more vehicles and vehicle types switch from internal combustion engines to electric-based technologies.

Figure 4. State of the world when the SCC is higher than the CO_2 tax. When a tax is set too low (below the SCC), then Q_{tax} is the abatement level, instead of Q^*, the efficient level of abatement. A represents available net benefits of taxing at the SCC. Because the MC curve is convex, $A > B$.

Figure 5. State of the world when the SCC is lower than the CO_2 tax. When a tax is set too high (above the SCC), then Q_{tax} is the abatement level, instead of Q^*, the efficient level of abatement. B represents available net benefits of taxing at the SCC. Because the MC curve is convex, $A > B$.

3.3. Miscalibration of the CO_2 taxes

While the USFWGSCC reported a range for the estimated SCC, the 'true' SCC value remains unknown. Accordingly, in our final empirical exercise, we evaluate the efficiency implications of setting the wrong carbon tax rate. To explore this question, we evaluate the net benefits of the $35 carbon tax, assuming that the 'true' SCC is $100 and then repeat this exercise for the $100 tax assuming that the 'true' SCC is $35.

Deadweight loss occurs when there are inefficiencies in an economy, such as pollution externalities. In the context of CO_2, externalities are fully internalized when the $ per ton damage from emissions are included in the cost to produce energy. The absence of corrective taxation, or taxes calibrated to a value other than the $ per ton damage, will result in deadweight loss. Therefore, both tax 'mistakes' generate deadweight loss. We demonstrate the conceptual difference between the two tax calibration mistakes in figures 4 and 5. In figure 4, we illustrate a state of the world in which a CO_2 tax is set below the SCC and deadweight loss is represented by the area labeled 'A'. In figure 5, we illustrate a state of the world in which a CO_2 tax is set above the SCC, and the deadweight loss is represented by the area labeled 'B'. Because the marginal cost curve is convex, area 'A' (the deadweight loss) in figure 4 is greater than area 'B' (the deadweight loss) in figure 5.

Table A1 reports that if the true SCC is $100 per ton, but emissions are taxed at only $35 per ton, the resulting net present value of deadweight loss is $353 billion ($466 billion in 2019$). However, if the true SCC is $35, and emissions are taxed at $100 per ton, the net present value of deadweight loss is only $94 billion ($124 billion 2019$). The difference in the efficiency implications of these two symmetric miscalibrations of the CO_2 tax stems from the convexity of the marginal abatement cost curve. If the marginal cost curve is linear, the deadweight loss would be

equal since, in the present simulations, the error in the tax rates are the same. The factor of three difference in deadweight loss we report suggests a highly non-linear marginal cost curve.

This exercise makes a compelling, efficiency-based argument for pursuing the precautionary principle. As the prior literature has effectively argued, the SCC is deeply uncertain (Weitzman 2009). This uncertainty poses significant challenges to policymakers charged with calibration of a carbon tax. In such a context, the results of our simulation suggest that it is more efficient to err by overtaxing CO_2 than by implementing too lenient a tax. Our results suggest the efficiency gain from invoking the precautionary principle is on the order of a factor of three.

4. Conclusion

In this paper, we use a state-of-the-art energy system optimization model replete with rich technological characterizations of the US energy system to explore two near term carbon taxes. It is important to note that TIMES focuses on the energy system and does not include all carbon emitting sectors. For example, the agriculture sector was responsible for 9% of US greenhouse gas emissions in 2017 (US EPA 2020) and it is not included in the TIMES model. Our work has three central findings. First, we find that the opportunities for near-term deep decarbonization in the energy systems included in the TIMES model are limited to the electric generation sector. As such, the other sectors subject to carbon taxation produce substantial carbon tax revenue, amounting to between 8% and 34% of income tax revenue. Provided the carbon taxes persist, we project that directed technical change will enhance abatement in other sectors thus reducing future revenue.

Second, acknowledging the uncertainty associated with the true social cost of carbon, we explore the efficiency consequences of an erroneous CO_2 tax. Our simulations probe symmetric tax calibration mistakes. We find that it is four-times more costly to under-tax CO_2 than it is to over-tax CO_2, making the case for invoking the precautionary principle on efficiency grounds.

Our work has immediate policy relevance. Extant resistance to carbon taxation should be mitigated by the large potential offsets of existing distortionary taxes such as the income tax. In addition, the findings herein point clearly to the preference for aggressive carbon taxation in the presence of uncertainty in the SCC and convex marginal costs. The reductions in CO_2 emissions projected herein would put the US on track to meet the nationally determined contributions established under the Paris Agreement. However, our results also suggest that there is a need for cost-effective low carbon technology innovation that would allow decarbonization beyond the electricity generation sector. It is possible that the dynamic incentives from the imposition of environmental taxation could spur such technological developments. Future work should evaluate the spill-over effects of environmental taxation on technology innovation.

Acknowledgments

Data availability

Input data and simulation results for this work is available at http://doi.org/10.5281/zenodo.3716416.

Appendix

Methods
In this paper, we use the TIMES model, which is a bottom-up energy system optimization model. The model uses as input a database built by the US Environmental Protection Agency (EPA) entitled EPAUS9rT (EPA TIMES 9-region) and includes the commercial, electric, industrial, refinery, residential, resource supply (upstream), and transportation sectors for the US economy. The EPAUS9rT database is populated using data from the US EIA Annual Energy Outlook. The TIMES model uses linear optimization and a specified set of end-use demands in order to model US energy use, costs, and emissions of CO_2, SO_2, NO_x, and $PM_{2.5}$ from the energy system between 2010–2050.

Figure A1. Annual CO_2 tax rate values for the \$35 and \$100 CO_2 tax scenarios. The \$35 tax ranges from \$34 to \$47 per ton of CO_2 and the \$100 tax ranges from \$99 to \$143 per ton of CO_2 between 2015–2030.
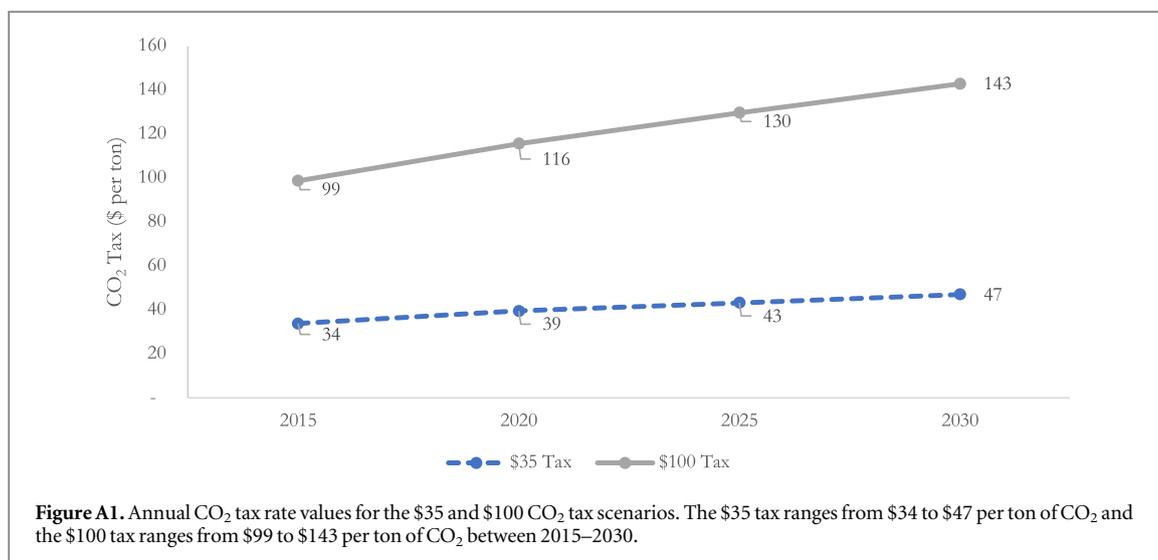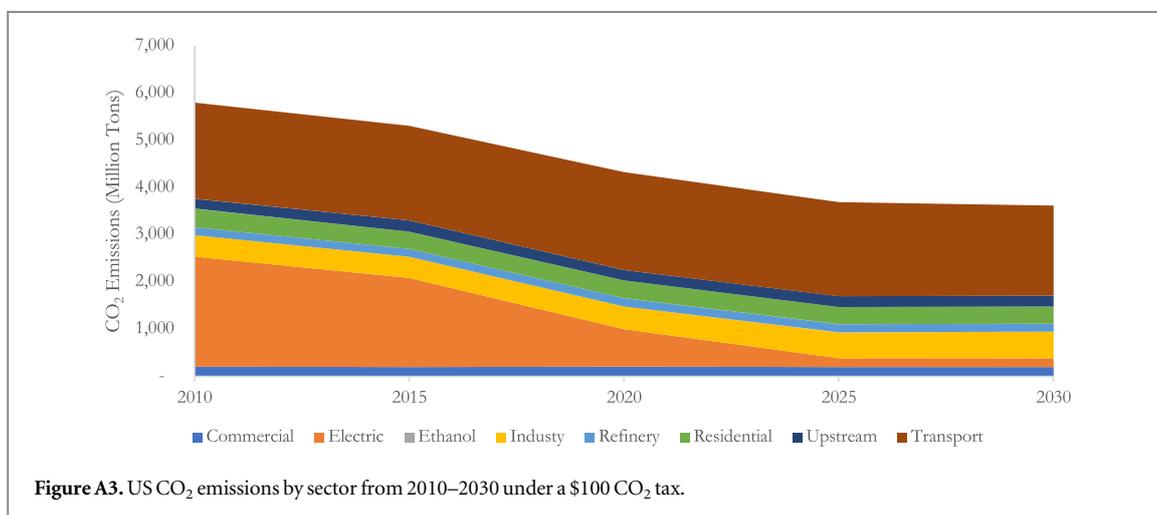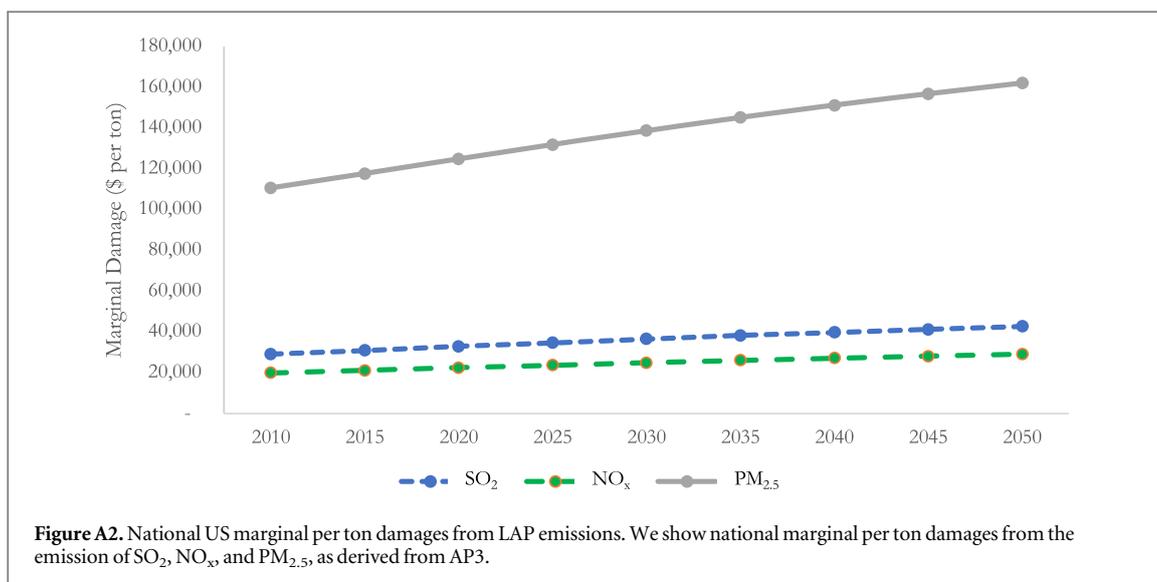
Table A1. CO_2 tax policy and the implications of picking the 'wrong' tax and SCC combination. The first column displays the tax, the second column displays the SCC, the third column displays the cost increase to the energy system under the tax, the fourth column shows the CO_2 reduction benefits compared to BAU using the SCC in second column, and the fifth column displays the net benefits under each tax and SCC combination.

CO_2 Policy	Social cost of CO_2	Cost Inc. versus BAU (billion 2005\$)	CO_2 Reduction Benefits (billion 2005\$)	Net Benefits (billion 2005\$)
Tax \$100	\$100 SCC	\$444	\$1,370	\$926
Tax \$35	\$100 SCC	\$124	\$697	\$572
Difference				\$353
CO_2 Policy	Social Cost of CO_2	Cost Inc. versus BAU (billion 2005\$)	CO_2 Reduction Benefits (billion 2005\$)	Net Benefits (billion 2005\$)
Tax \$100	\$35 SCC	\$444	\$460	\$15
Tax \$35	\$35 SCC	\$124	\$234	\$109
Difference				\$94

The EPAUS9rT database contains a number of technologies for the TIMES model to choose from during optimization. Each technology has an associated investment cost, operations and maintenance cost, fuel efficiency, and emissions factors. Many of the technologies in the EPAUS9rT database have increasing fuel efficiency over time; however, endogenous learning is not included in this model, and technology cost and performance do not depend on quantity deployed. Since the EPAUS9rT database includes a limited description of future technologies, we focus on the years 2010–2030 for this analysis because the characterization of technologies is likely most accurate.

The TIMES model can be used to model different policies such as a business-as-usual (BAU) case, which includes the Cross-State Air Pollution Rule (CSAPR), Mercury and Air Toxics Standards (MATS), renewable portfolio standards (RPS), and the Corporate Average Fuel Economy Standards (CAFE). In this analysis, we run the TIMES model to produce a BAU scenario from 2010–2030 and then run the model two additional times with the CO_2 taxes outlined in figure A1, which includes CO_2 tax trajectories that we label as \$35 and \$100 taxes for simplicity (all monetary values in this analysis are reported in 2005\$ unless otherwise stated). The \$35 and \$100 CO_2 taxes follow estimates of the US federal government's intra-agency working group on the social cost of carbon report (USFWGSCC).

In addition to CO_2, TIMES also simulates the emissions of SO_2, NO_x, and $PM_{2.5}$ from the US energy system. In our analysis, the TIMES model calculates the emissions of each air pollutant species under the BAU scenario as well as under our CO_2 tax scenarios. We calculate the damage resulting from the emissions of SO_2, NO_x, and $PM_{2.5}$ under the BAU, \$35, and \$100 CO_2 tax scenarios. In order to calculate damages, we use reduced complexity models (RCMs) entitled AP3, EASIUR, and InMAP in combination with other datasets from the EPA, the US Census, and the Organization for Economic Co-operation and Development (OECD). The RCMs calculate the damage that results from the emission of one ton of a pollutant in each county throughout the US In order to calculate a national average marginal social cost by pollutant for the entire US, we use the RCM county-level damage data in combination with data from the US EPA National Emissions Inventory (NEI). The
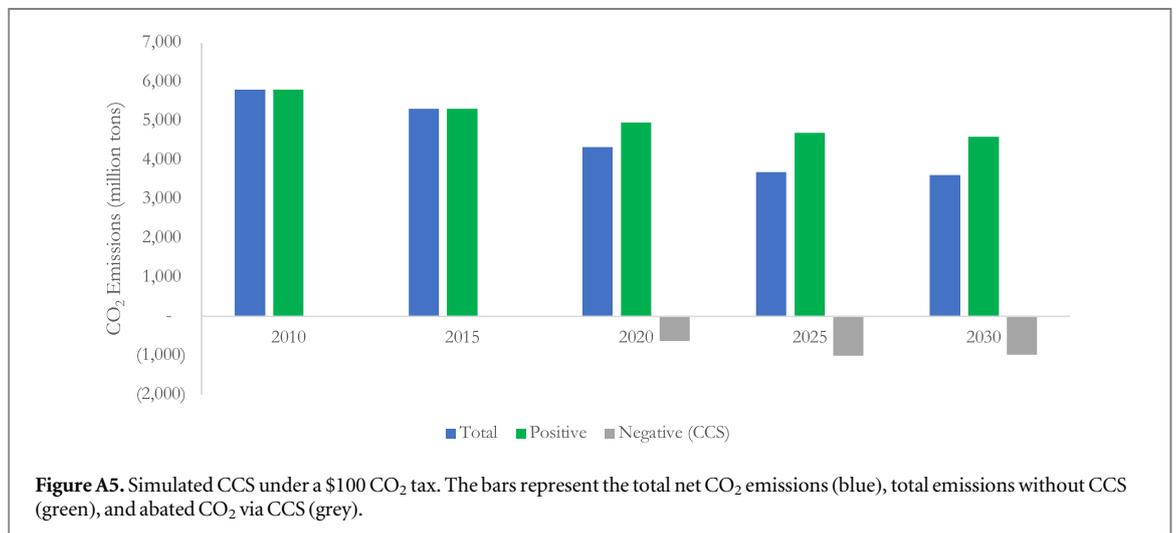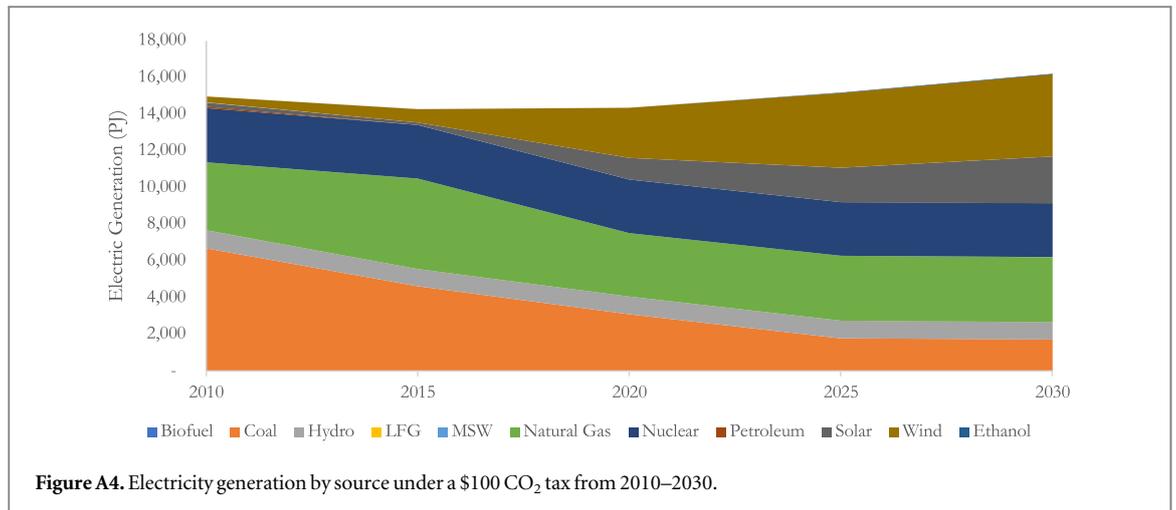
Figure A2. National US marginal per ton damages from LAP emissions. We show national marginal per ton damages from the emission of SO_2, NO_x, and $PM_{2.5}$, as derived from AP3.

Figure A3. US CO_2 emissions by sector from 2010–2030 under a \$100 CO_2 tax.

US EPA NEI lists emissions from various sources by type and location. For the results presented in this paper, we use the NEI emissions inventory's energy-related emissions data and AP3 damage data to produce an emissions-weighted national per ton marginal social cost for SO_2, NO_x, and $PM_{2.5}$.

Over time, population in the US is forecasted to increase, which implies that the marginal damage from emissions on a per ton basis will also increase. The US Census provides population projections, and the OECD provides a GDP forecast for the US, both through 2060 (OECD 2014, US Census Bureau 2017). From the population and GDP projections, we calculated the increase in per capita GDP in the US through the end of our modeling horizon. We use this increase in population and per capita GDP over time to extrapolate the concurrent annual increase in damages per ton from SO_2, NO_x, and $PM_{2.5}$, which we illustrate in figure A2. To calculate total damage by pollutant in the US, we next multiply the total emissions of SO_2, NO_x, and $PM_{2.5}$ modeled in TIMES by the national damages outlined in figure A2.
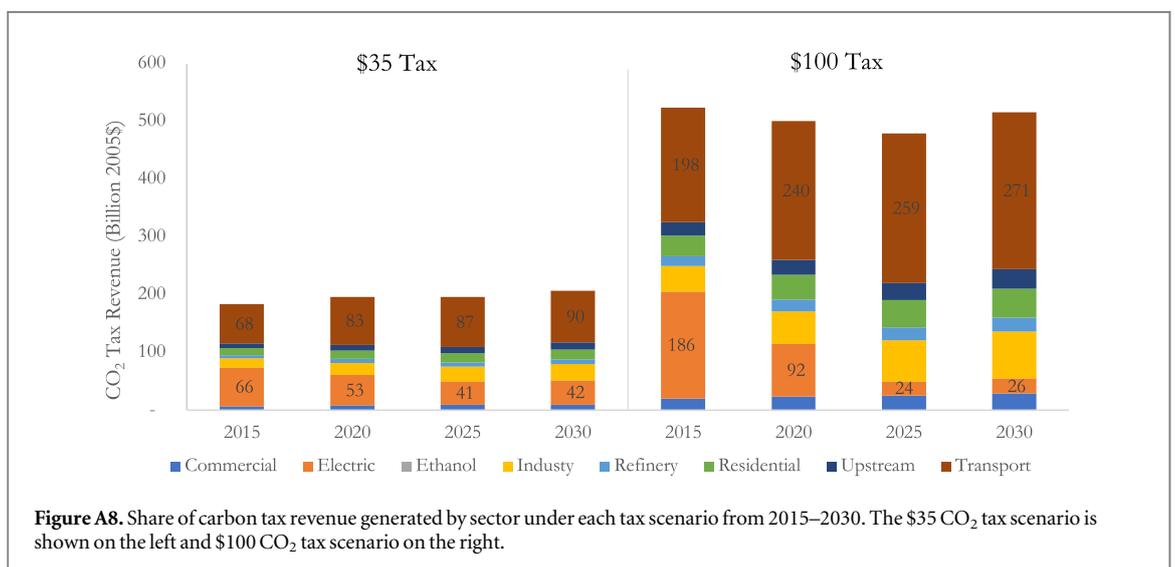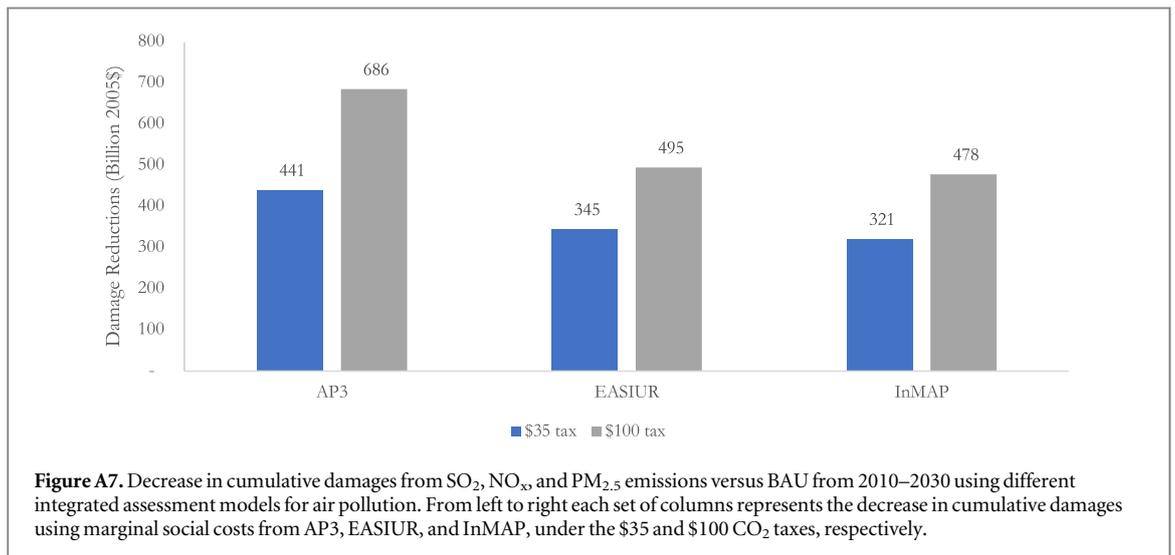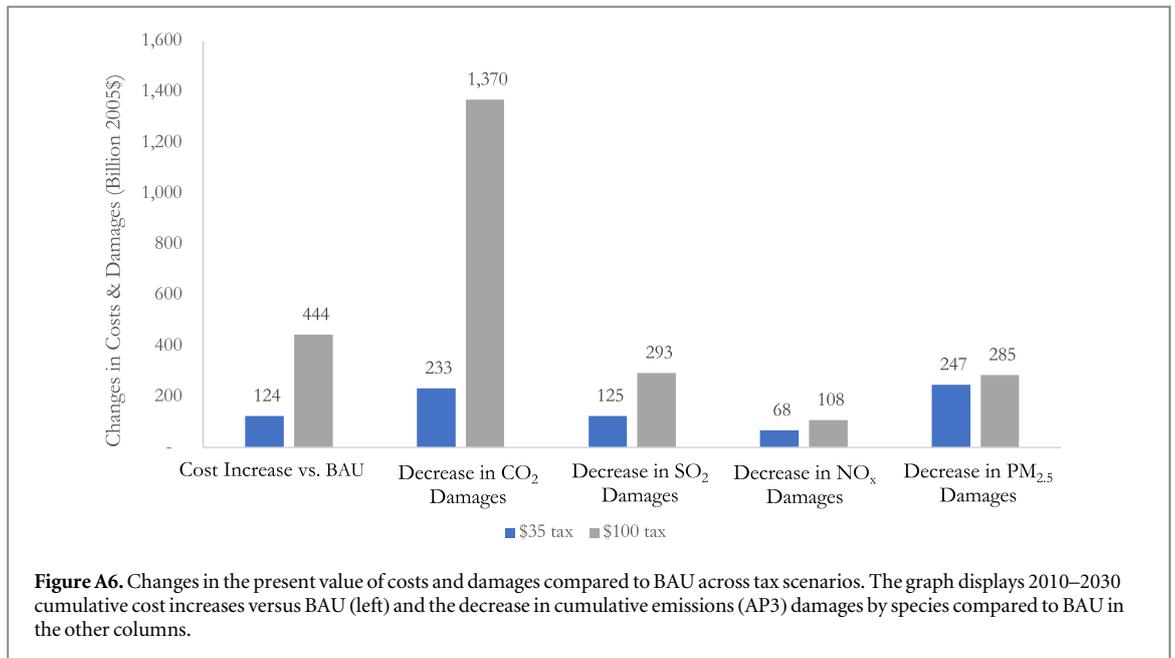
Results

The \$35 and \$100 CO_2 taxes reduce CO_2 by 24% and 38% in 2030, respectively, compared to 2010 levels. In the BAU scenario, without a CO_2 tax, emissions decrease by only 6% in 2030 compared to 2010 levels. Decreases in BAU CO_2 emissions occur primarily in the electric sector. As illustrated in figure A3, which shows emissions under a \$100 tax on CO_2, the majority of CO_2 reductions take place through the decarbonization of the electric sector, while other sectors' CO_2 emissions remain relatively constant from 2010–2030. In figure A4, we show that much of the decarbonization in the electric sector is a result of decreasing coal generation and increasing solar and wind generation. Coal and natural gas remain part of the electric system, however, much of the CO_2 emissions from these generation sources are abated via carbon capture and sequestration (CCS). In figure A5,

Figure A4. Electricity generation by source under a $100 CO_2 tax from 2010–2030.

Figure A5. Simulated CCS under a $100 CO_2 tax. The bars represent the total net CO_2 emissions (blue), total emissions without CCS (green), and abated CO_2 via CCS (grey).

the grey bars represent the amount of CO_2 that is abated via CCS from natural gas and coal power plants under a $100 CO_2 tax.

In the $35 and $100 CO_2 tax scenarios, the present value of the 2010–2030 cumulative increases in cost to the energy system is $124 and $444 billion, respectively. Compared to BAU, the reduction in cumulative present value damages from either CO_2 or LAP emissions are enough to justify both CO_2 tax policies from a cost-benefit perspective. The reduction in cumulative present value damages from CO_2, SO_2, or $PM_{2.5}$ alone, which we outline in figure A6, is enough to justify the $35 CO_2 tax policy. Furthermore, cumulative reductions in NO_x damages are approximately half the value of the cost increase to the energy system from 2010–2030 under the $35 CO_2 tax.

As outlined in table A1, selecting a tax rate other than the true social cost of carbon will produce a deadweight loss. If damages from CO_2 emissions are $100 per ton and emissions are taxed at $35 per ton, there are $353 million in net benefits available that could be gained by taxing CO_2 at $100 per ton instead. Additionally, if damages from CO_2 emissions are $35 and emissions are taxed at $100 per ton, there are $94 billion in net benefits available that could be gained by taxing CO_2 at $35 per ton instead. The deadweight loss in the state of the world in which CO_2 is taxed above the SCC is far less than in the state of the world in which CO_2 is taxed below the SCC. These results suggest that under an uncertain SCC, policymakers should consider taxes that are aligned with higher as opposed to lower estimates of the SCC. If a CO_2 tax below the SCC is implemented, there could be hundreds of billions of dollars in additional inefficiencies compared to a policy that overtaxes CO_2.

Figure A6. Changes in the present value of costs and damages compared to BAU across tax scenarios. The graph displays 2010–2030 cumulative cost increases versus BAU (left) and the decrease in cumulative emissions (AP3) damages by species compared to BAU in the other columns.

Figure A7. Decrease in cumulative damages from SO_2, NO_x, and $PM_{2.5}$ emissions versus BAU from 2010–2030 using different integrated assessment models for air pollution. From left to right each set of columns represents the decrease in cumulative damages using marginal social costs from AP3, EASIUR, and InMAP, under the $35 and $100 CO_2 taxes, respectively.

Figure A8. Share of carbon tax revenue generated by sector under each tax scenario from 2015–2030. The $35 CO_2 tax scenario is shown on the left and $100 CO_2 tax scenario on the right.

Table A2. $35 CO_2 tax scenario data. Column 1 on the left displays the year. Column 2 shows the CO_2 tax rate in each year. Column 3 shows the system cost increase above BAU in each year. Column 4 shows the CO_2 reduction benefits compared to BAU in each year. Column 5 shows the local air pollutant (LAP) reduction benefits in each year compared to BAU.

	$35 CO_2 Tax Scenario			
Year	CO_2 Tax $ per ton	Cost Inc. versus BAU Billion 2005$	CO_2 Benefits Billion 2005$	LAP Benefits Billion 2005$
2010	0			
2015	34	1.16	3.45	13.64
2020	39	10.62	21.39	37.53
2025	43	22.59	39.52	69.75
2030	47	25.61	48.62	81.61
Present value		124.34	233.49	440.52

Table A3. $100 CO_2 tax scenario data. Column 1 on the left displays the year. Column 2 shows the CO_2 tax rate in each year. Column 3 shows the system cost increase above BAU in each year. Column 4 shows the CO_2 reduction benefits compared to BAU in each year. Column 5 shows the local air pollutant (LAP) reduction benefits in each year compared to BAU.

	$100 CO_2 Tax Scenario			
Year	CO_2 Tax $ per ton	Cost Inc. versus BAU Billion 2005$	CO_2 Benefits Billion 2005$	LAP Benefits Billion 2005$
2010	0			
2015	99	7.03	22.14	29.48
2020	116	47.33	136.23	64.26
2025	130	73.26	227.30	94.09
2030	143	76.65	260.95	102.16
Present value		444.42	1370.12	685.56

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