Distributional Impacts of Carbon Capture in the US Power Sector

Ana Varela Varela, Daniel Shawhan, Christoph Funke, Maya Domeshek, Sally Robson, Steven Witkin, Dallas Burtraw, Burçin Ünel

Abstract: While some see carbon capture, utilization, and storage (CCUS) as crucial for cost-effective decarbonization, it faces opposition based on air pollution and equity concerns. To understand this cost–air pollution trade-off, we simulate the potential impacts of allowing CCUS deployment in the US power sector under plausible climate policies. We show that the existence of this trade-off critically depends on the underlying policy, which affects the type of generation CCUS could displace: under a policy that incentivizes coal generation, CCUS might improve health outcomes and reduce costs. When we disaggregate our results, we find that the air pollution ($PM_{2.5}$) effects of allowing CCUS, positive or negative, are largest for Black and low-income populations. We show that allowing CCUS can yield energy-cost savings, particularly benefiting lower-income communities. Our sensitivity analyses highlight the effects of uncertainties on costs and benefits. Overall, this study contributes to our understanding of broader distributional consequences of allowing CCUS.

JEL Codes: D63, H23, I14, Q2, Q47, Q52, Q58

Keywords: carbon capture, utilization, and storage, environmental justice, energy justice, electric power, incidence, air pollution

CURBING CARBON DIOXIDE (CO_2) EMISSIONS to address climate change and protecting historically overburdened communities from the disproportionate impacts of

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energy generation are two policy goals that can come into conflict. Examples from California (Fowlie et al. 2020) or France (Douenne and Fabre 2022) show that backlash from potential distributional impacts of climate policy might cause these policies to fail.

The deployment of carbon capture, utilization, and storage (CCUS) technology is igniting similar policy debates around equity in the United States. The climate provisions of the Inflation Reduction Act of 2022 (IRA) provide billions of dollars of subsidies to CCUS.[1] Yet, members of the White House Environmental Justice Advisory Committee declined to join a federal working group focused on the equitable implementation of CCUS, with one member stating "we are in fighting mode, not in guardrail mode." One official from the Department of Energy (DOE) responded that "it is going to happen, so the question is how do we design programs that are equitable" (*Inside EPA* 2022). To date, the distributional implications of the deployment of CCUS have gathered little focus in the literature despite their policy relevance. This study starts to address this critical gap.

CCUS technology traps CO_2 before it is discharged into the atmosphere. After CO_2 is captured, it is either stored deep underground in stable geological formations (such as depleted oil reservoirs) or used as an input in other industrial or manufacturing processes (Gonzales et al. 2020). For fossil-fuel-fired power plants, CCUS enables continued generation even under a policy environment that restricts greenhouse gas emissions, effectively decoupling fossil-fuel generation and CO_2 emissions.

But, even if CO_2 is captured, combustion exhausts could still contain other harmful emissions, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), fine particulate matter

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senior fellow at Resources for the Future (Burtraw@rff.org). Burçin Ünel is the executive director of the Institute for Policy Integrity at New York University School of Law (burcin.unel@nyu.edu). We are grateful to the editor, three anonymous reviewers, Karen Palmer, and Billy Pizer for their insightful comments. We also thank the participants of seminars at the Environmental Defense Fund, Resources for the Future, the London School of Economics, the University of Amsterdam, the twenty-seventh annual conference of the European Association of Environmental and Resource Economists, and the National Bureau of Economic Research workshop on the Distributional Consequences of New Energy Technologies for their helpful feedback. This study uses the Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST), currently developed and used by authors Robson and Shawhan, and Ethan Russell. Other contributors to E4ST so far include Steven Witkin, Christoph Funke, Paul Picciano, Biao Mao, John T. Taber, Di Shi, Ray D. Zimmerman, William D. Schulze, Carlos Murillo-Sanchez, Daniel Tylavsky, Jubo Yan, Charles Marquet, Yujia Zhu, Doug Mitarotonda, Yingying Qi, Nan Li, Zamiyad Dar, Andrew Kindle, Robert J. Thomas, and Richard E. Schuler. We also thank Gurobi Optimization for the use of the excellent Gurobi solver software and Energy Visuals, Inc., for the uniquely detailed Transmission Atlas and FirstRate power grid data used in this study. Authors Shawhan, Funke, Robson, and Witkin thank the Alfred P. Sloan Foundation for funding.

1. While the estimates vary based on sources, the Treasury Department estimates that the cost of these subsidies will be about $30 billion over 2023–33 (US DOT 2023).

($PM_{2.5}$), and ammonia (NH_3) (Koornneef et al. 2010; Clean Air Task Force 2023; Waxman et al. 2024). The potential for worse air quality is especially problematic for energy and environmental justice goals given that minority and lower-income communities have historically been and currently are more exposed to local pollution in the United States (Banzhaf et al. 2019; Hsiang et al. 2019; Hausman and Stolper 2021; Currie et al. 2023; Cain et al. 2024).

Beyond health, CCUS deployment might also cause disparate financial effects. Compared to other, costlier decarbonization approaches, it could enable more stable energy prices, benefiting disadvantaged communities who have higher energy burdens and energy insecurity risk. Widespread CCUS deployment can also affect households' finances through changes in government revenue and spending due to tax credits for CCUS and clean electricity that can be passed through to households in the form of taxes. In addition, changes in the energy mix can affect utility profits and, hence, the capital income accruing to households. To the extent that households have different energy and tax burdens, changes in finances caused by CCUS deployment can have distributional effects. Consequently, given its potential impact on household finances and air pollution, the overall welfare effects of large-scale CCUS deployment, including the effects on disadvantaged communities, are uncertain.

This study seeks to shed light on the existence and magnitude of the potential financial and air-pollution trade-offs caused by the deployment of CCUS in the US power sector. Specifically, we look at the effects of retrofitting existing coal power plants with postcombustion carbon capture and deploying new fossil gas plants with carbon capture in 2035, the Biden-Harris administration's target year for CO_2 emissions-free power sector (White House 2023). We consider two policy scenarios: (1) Current Policies scenario, which continues state and federal policies that exist as of December 2022, and (2) Cap scenario, which continues the same policies but also adds a more ambitious and binding national CO_2 emissions cap for the electricity sector.[2] To isolate the impacts of CCUS, we run our models with and without allowing CCUS as a technology option under each policy scenario.

We answer two related research questions. First, given a policy, where could CCUS potentially be deployed and what energy generation would it displace in 2035? Second, how does CCUS deployment change pollution exposure and household finances for different demographic groups? Our goal is to build on existing electricity market modeling to identify the potential distributional consequences of an emerging technology. Given the forward-looking nature of our analysis and its reliance on modeling assumptions,

2. We focus on a cap instead of a carbon tax because it is in effect in parts of the United States and is more politically feasible at a national level than a carbon tax. Moreaux et al. (2024) theorize CCUS deployment also within a carbon budget, consistent with the Paris Agreement's imposed ceiling.

our main contributions identify the direction of the potential impacts and their relative magnitudes, rather than overall magnitudes.

To answer these questions, we use three well-established models to (1) forecast the location and extent of CCUS deployment in the power sector, (2) translate the resulting emissions into health outcomes, and (3) evaluate how changes in energy prices, capital income, and government revenues are passed through to different demographic groups. This framework combines power-sector and reduced-complexity air pollution models that have high spatial resolution, allowing us to shed light on the localized impacts of CCUS. As some recent papers show, a spatially detailed analysis can reveal inequities that remain hidden in coarser analyses (Grainger and Ruangmas 2018; Goodkind et al. 2019; Deryugina et al. 2021). Thus, a granular setup like ours is critical to evaluate which parts of the population are being more positively or negatively affected by CCUS deployment.

Our analysis provides several insights on the aggregate and distributional impacts of the deployment of CCUS in the power sector. First, our results highlight a nuance that is missing from the current CCUS policy debates: both the aggregate and the distributional impacts of CCUS should be analyzed and understood in the context of a given policy environment. The type and location of its deployment depend on the underlying policy. Policy incentives also strongly influence what generation is displaced by CCUS and, consequently, emissions outcomes. While there are papers that document the extent of total CCUS deployment theoretically (Moreaux et al. 2024) or model it in the United States under existing policies (Bistline et al. 2024), we provide, to the best of our knowledge, the first analysis of the potential spatial impacts of CCUS under existing and potential new policies.

Specifically, we show that any trade-off between pollution and household finances depends on whether the generation CCUS could displace is cleaner than CCUS itself. The more the underlying climate policy incentivizes the continued operation of coal plants in the absence of CCUS, the greater the probability that CCUS will improve both household energy-cost savings and public health outcomes rather than causing a trade-off. If there is room for CCUS to cost-effectively reduce generation from uncontrolled coal plants or sufficiently reduce their non-greenhouse-gas emissions, CCUS can improve public health outcomes while also decreasing energy expenditures. But, if the underlying policy would eliminate almost all coal generation even without CCUS as an option, allowing CCUS is more likely to worsen the burden of local air pollution. In this setting, CCUS might displace nonemitting generation. In other words, the incremental effects of CCUS and its trade-offs in part depend on the underlying policy and what generation CCUS is displacing.[3]

3. Allowing CCUS could also provide incentives to other generation sources. For example, in the presence of a CO_2 emissions cap, allowing CCUS could increase coal-fueled generation

Second, we evaluate a comprehensive array of financial and pollution-related impacts for households. This is one notable difference from concurrent work from Waxman et al. (2024), who focus on pollution impacts.[4] Our scope allows us to make a distinct contribution to our understanding of the impacts of CCUS deployment on broader energy and environmental justice outcomes. We find that CCUS lowers the cost of energy generation, which results in energy-cost savings for both residential and nonresidential electricity users, provided that enough of the savings are passed through to consumers, as our model predicts they would be. Even under the Cap scenario—in which public health outcomes worsen with CCUS deployment—energy-cost savings alone are larger than monetized impacts of increased mortality due to higher pollution concentrations.[5] In some cases, CCUS also results in higher electricity producer profits. CCUS also changes the household tax burden due to government spending on renewable and CCUS tax credits. However, whether CCUS is net beneficial in the aggregate depends on the relative magnitudes of these changes under each policy scenario.

Third, the impacts of CCUS deployment are not evenly distributed across demographic groups. We find that CCUS would predominantly be deployed in the South and Midwest census regions. Because Black populations tend to live in regions we identify with a large potential deployment of CCUS (notably the South) and, within a given region, are more likely to live near power plants (Thind et al. 2019), we find that Black populations experience larger health impacts compared to the overall population and to Hispanic and non-Hispanic White populations in particular.[6] Specifically, the health outcomes of Black populations are more positively affected by CCUS deployment under Current Policies, and more negatively affected by CCUS under the Cap scenario. These results contribute directly to the expanding literature on environmental justice that focuses on documenting mechanisms for inequitable exposure to pollution (see reviews by Banzhaf et al. [2019] and Cain et al. [2024]).

However, beyond pollution-related health impacts, those with lower income levels benefit relatively more from changes in income and expenditures resulting from CCUS

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without CCUS. Therefore, displacement can be negative and the emission effects of total displacement are net emission effects.

4. Beyond the outcomes of focus, our work differs from Waxman et al. in two other significant aspects. First, while they focus on regional CCUS deployment in the Gulf Region, we assess a nationwide deployment in the United States, enabling us to model the power sector's responses under various policies. Second, we exclusively analyze the power sector, whereas Waxman et al. also consider industrial emitters.

5. These monetized health impacts only account for mortality induced by changes in primary and secondary $PM_{2.5}$ due to changes in emissions in SO_2, NO_x, and NH_3. We do not consider impacts of other pollutants (like O_3), morbidity effects (impacts of pollution on asthma incidence or hospitalizations), or direct impacts of SO_2, NO_x, and NH_3 other than through $PM_{2.5}$ formation.

6. Mortality impacts are monetized and measured as a share of group total income.

deployment in both policy scenarios. This variation exists largely because the energy-cost savings for these groups equal a larger proportion of their total income. In addition, they are less affected by the increased taxes necessary for the CCUS subsidies and the reduced profits of electricity generation companies because they have lower income tax rates and less ownership of generation companies. By highlighting heterogeneities that might arise in the distribution of financial impacts associated with the deployment of CCUS, our study makes a distinct contribution to the literature on the intersection of energy and environmental justice that explores unequal energy access (Doremus et al. 2022; Rubin and Auffhammer 2023).

Finally, while our analysis focuses on the direction of the impacts rather than precise magnitudes, it nonetheless highlights the importance of considering multiple dimensions of uncertainty. Existing research already highlights the vast uncertainty about the costs and the quantity of CCUS deployment (Bistline et al. 2024). Our results show that understanding the uncertainties related to both the technology itself—such as its cost and emission rates—and its effects—such as the mortality rates for a given exposure—is vital to informing related policy discussions. While we find that our aggregate results are mostly directionally robust for a given policy, whether uncertainties lead to qualitative changes in the results critically depends on the underlying policy. In other words, the effects of CCUS deployment are not as certain as current arguments might suggest.

Overall, our results speak to the growing strands of the literature that evaluate the distributional impacts of environmental policies (Borenstein and Davis 2016; Deryugina et al. 2019; Levinson 2019; Reguant 2019; Hernandez-Cortes and Meng 2023; Shang 2023) and of emerging clean technologies (Holland et al. 2019). Our study relates to Dauwalter and Harris (2023), who run simulations to determine the costs and benefits of solar capacity and resulting marginal electricity generation associated with different policy objectives. While focusing on a different technology and employing distinct methodologies, our study shares the objective of highlighting that the distributional impacts of a new technology deployment must be understood in a given policy environment.

We acknowledge that our framework for energy and environmental justice is still narrow.[7] Our models lack the ability to address several other concerns associated with CCUS, such as harms associated with continued fossil-fuel extraction, the permanence

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7. The EPA defines environmental justice as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. This goal will be achieved when everyone enjoys: the same degree of protection from environmental and health hazards, and equal access to the decision-making process to have a healthy environment in which to live, learn, and work" (US EPA 2023a). For an interdisciplinary introduction to environmental justice studies, see Holifield et al. (2020). On the other hand, the DOE defines energy justice as "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system" (US DOE 2022).

of CO_2 storage, the potential for earthquakes and groundwater issues near CO_2 injection sites, or leakage in the CO_2 pipeline network that might be harmful to human health or climate goals (Campbell 2022). Our study also does not speak to procedural justice aspects of CCUS deployment or how CCUS might influence the capacity of communities to prosper. Likewise, we do not address how individual communities may be affected by CCUS. The impacts of CCUS deployment on these aspects of energy and environmental justice are also key questions that should be explored in further research.

The rest of this paper is organized as follows. Section 1 describes the policy scenarios we will evaluate using the methodology and data described in section 2. Aggregate results are presented in section 3, while section 4 discusses modeling assumptions, uncertainty, and sensitivity of the results. Section 5 describes the distributional impacts of CCUS. Section 6 discusses policy implications and concludes.

1. POLICY SCENARIOS

The trade-offs CCUS brings are likely to depend on the climate and clean energy policies in place. These policies will influence the generation mix, as they affect the incentives for entry and exit of both fossil-fuel-fired and nonemitting energy resources, as well as coal- and fossil-gas-fueled CCUS deployment. As a result, the policies in effect will influence the emissions and locations of generation with CCUS and the type, emissions, and locations of generation displaced by generation with CCUS.

To ensure that our analysis can provide broad insights, we consider two policy scenarios for our target year of 2035: (1) Current Policies and (2) Cap, which we describe in detail below. As our goal is to understand the incremental impacts of CCUS, we run each scenario with and without CCUS as a technology option. For the cases without CCUS, we remove CCUS as an available option in our power system model.

1.1. Current Policies

Our first policy scenario includes major state and federal policies that exist as of December 2022, the time of our analysis. As the IRA was already in effect at this time, it is included in our baseline scenario.[8] We account for the IRA's subsidies for zero-emission generation, including solar, wind, geothermal, and hydropower generation, in a detailed manner, including higher subsidies for generation in "energy communities" as defined in the IRA.[9] We also include the IRA subsidies for nuclear generation and energy storage.

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8. Note that our intention is not to analyze the impact of the IRA but rather to understand the implications of CCUS deployment under a plausible policy environment.

9. The IRA defines energy communities as brownfield sites, areas with high unemployment rates, and/or areas that have experienced a recent coal mine or coal-fired electric generating unit closure.

Starting in 2025, these subsidies will become technology neutral and be available to all facilities with net-zero greenhouse gas emissions. The IRA directs these subsidies to continue until the latter part of 2032 or when US electricity sector CO_2 emissions are equal to or below 25% of 2022 levels (US Congress 2022). Based on earlier studies on the impacts of the IRA, we assume that the emissions thresholds will not be met by 2035 and these subsidies will apply to all generators built between the present and our modeled year of 2035 (Bistline et al. 2023).

Importantly, the IRA also extends and expands the 45Q tax credit, which grants each captured metric ton of carbon dioxide a tax credit of $85 or $60, depending on whether it is stored in saline aquifers or sold for enhanced oil recovery (EOR), respectively. Facilities that start construction by as late as 2033 will be eligible to receive 45Q for 12 years when they start operating, provided they meet minimum capture requirements. Because any capacity that comes online by 2035 would almost certainly have started construction by the end of 2032, we assume that all CCUS in our modeling qualify for these subsidies.

Our modeling also includes state policies. For states with a renewable portfolio or clean energy standards as of August 2022, we assume that those policies remain in effect through at least 2035. If their requirements in current law plateau or end before 2035, we assume that they continue upward at the rate of increase in their last three years of increase if no alternate energy legislation has been announced to replace the policies. All legislative or executive state goals announced by August 2022 are also included.

This scenario gives us an indication of how CCUS might affect our outcomes of interest if there are no major policy changes at the federal level.

1.2. CO_2 Emissions Cap

To illustrate how much of a difference the policy setting can make, we also estimate the effects of allowing CCUS in the presence of a binding CO_2 emissions cap, introduced as an additional policy to the Current Policies scenario. Such a policy prices CO_2 emissions explicitly, which is an emissions reduction approach generally favored by economists (Stiglitz and Stern 2017). While a national emissions cap has not proved to be politically viable to date in the United States, successful cap-and-trade programs exist both regionally (the Regional Greenhouse Gas Initiative and California's AB32) and in other parts of the world (e.g., the European Union, Korea, and China).

For this scenario, we add an emissions cap to the Current Policies scenario of 500 million short tons of CO_2 equivalent emissions (CO_2e) of CO_2 and methane emissions attributable to the electricity generation sector in the contiguous United States.[10] This level represents approximately a 72% reduction from the sector's emissions in

10. To calculate CO_2e, we count each ton of methane as equal to 13.5 tons of CO_2, which is the estimated ratio of net present values of damage from methane and CO_2 in Rennert et al. (2022) and Prest et al. (2023).

2022 (US EIA 2023) and would be binding even with widespread CCUS deployment in 2035.[11] We assume that allowances are auctioned by the government and the proceeds go to the government for general spending or to reduce taxes proportional to the average household tax rate differentiated by income quintile. This policy is likely to reduce the air quality benefits of power generation with CCUS by causing generation with CCUS to displace mostly nonemitting generation, giving us a policy scenario that is likely to increase the potential for trade-offs.

2. METHODOLOGY AND DATA

To evaluate the pollution and household finance trade-offs CCUS deployment in the power sector causes, we need to accomplish four goals. First, we must understand how much CCUS is deployed in 2035 under each policy scenario and what energy generation CCUS displaces compared to the alternative case with the same policy scenario but without CCUS. Second, we must evaluate how CCUS affects energy prices, producer prices, and government revenue, and how these impacts change household financial impacts for different demographic groups. Third, we must translate any changes in local pollutant emissions into health impacts at a sufficiently detailed spatial level to evaluate the impacts on different demographic groups. Finally, we must aggregate these impacts to evaluate potential trade-offs, both for the population overall and for specific demographic groups.

We use a four-step methodology—represented in figure 1—to achieve these four goals. The four steps are described in detail below.

2.1. Power Sector Modeling

We use the Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST), a detailed long-run power-sector model, to simulate power sector outcomes, including entry, exit, hourly operation, profits, and emissions nodal hourly wholesale electricity prices; and government spending and revenue (Shawhan et al. 2014). E4ST is a linear program with millions of optimization variables and constraints that represent the decisions of market participants and system operators. Like a system operator and competitive market, it solves for the cost-minimizing levels of generation during 16 representative days of the year. These days are weighted to represent the joint frequency distributions of electricity demand, wind, and sun across a typical year, as well as the times of greatest generation scarcity in each region of the United States and Canada.[12] E4ST uses a detailed representation of the transmission system that has approximately 5,000 nodes and 20,000 transmission branches, and greater geographical detail

11. The shadow price on the cap is $51.42 per short ton (2020$) with no CCUS and $14.83 per short ton (2020$) with CCUS.

12. While using 16 representative days is not as realistic as using all of the days of a past year, it is necessary to keep the model solvable in a reasonable amount of time despite its high spatial detail.

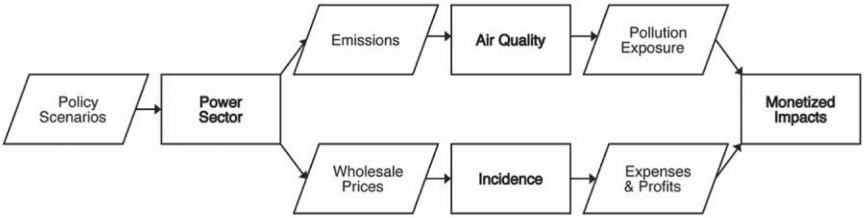

Figure 1. Schematic of the four-step methodology, including inputs and outputs of each step

than the other models included in Bistline et al. (2024). The power flows are based on an industry-standard linear approximation of the laws of physics. The model also uses detailed data about existing and buildable generators, including hourly, location-specific wind and sun resource for wind and solar generators. (See app. A for more details; apps. A–J are available online.)

In the simulations with CCUS, we allow for retrofitting of existing coal power plants with postcombustion carbon capture devices and construction of new fossil gas units with CCUS among the power plant entry options that investors can choose to build in the model.[13] We assume that new CCUS can be built only at model nodes in the United States where there was at least 100 megawatts (MW) of fossil gas generation capacity in 2016. We prohibit building of CCUS in states that, at the time we began our modeling, had policies likely to prevent the type of CCUS our model was predicting in preliminary simulations: New York, North Carolina, and Colorado.[14]

The least expensive sequestration opportunities involve enhanced oil recovery (EOR). We assume that EOR results in net CO_2 emissions of 28% of the captured CO_2, taking into account upstream and downstream effects (IEA 2015, 33) and that saline sequestration results in 0% leakage. Because coal facilities have higher CO_2 emissions, and therefore more CO_2 to be captured, retrofit coal CCUS facilities receive higher tax credits per megawatt-hour (MWh) than fossil gas CCUS. On average, retrofit coal CCUS facilities receive \$126.37 or \$89.21 per MWh for saline storage or EOR, respectively. In comparison, fossil gas CCUS facilities receive \$35.80 or \$25.27 per MWh for saline storage or EOR respectively, based on current subsidies per ton of CO_2 injected.

Table 1 shows the average cost and performance metrics we use in our main analysis for CO_2-capturing power plants and how they compare to the costs of other power plants in our simulations with CCUS under Current Policies. The average cost and performance

13. Because of the high cost of new coal plants both with and without CCUS, we assume that no new coal plants will be constructed in the United States or Canada. Likewise, following EPA's assumption in its Integrated Planning Model, we assume that retrofitting fossil gas plants with CCUS is not viable.

14. We assume that policies that require 100% nonemitting generation, or soon will, are likely to prevent generation with CCUS.

Table 1. Typical Cost and Performance Assumptions for Power Plants for the Year 2035

Generation Type	Total Cost to Build (mln $/MW)	Annual Fixed Costs ($/MW)	Variable Costs ($/MWh)	Heat Rate (MMBtu/MWh)	Capital Recovery Factor (%/Year)	Levelized Cost of Energy ($/MWh)
New fossil gas combined cycle	.89	28,000	27.37	6.36	6.8%	39.31
New fossil gas with CCUS	1.37	58,971	31.41	6.88	6.8%	51.96
Existing coal	NA	57,953	26.41	10.12	N/A	Varies
Coal CCUS retrofit incremental costs	1.67	45,260	10.34	4.29	6.8%	Varies
Solar	.75	14,721	0	N/A	6.8%	37.47
Wind	.94	37,489	0	N/A	6.8%	38.75
Offshore wind	2.72	81,471	0	N/A	6.8%	76.28
Four-hour battery	.83	20,980	83.18	N/A	6.8%	158.92
New nuclear	7.35	145,960	2.84	10.44	6.8%	83.27

Note. This table shows average costs. Costs of retrofits vary by capacity, heat rate, and region of the retrofitted plant. Appendix B shows the functions used to determine the cost and performance of coal retrofits. This table includes only the costs of capturing, compressing, and transporting or storing CO_2. The coal CCUS retrofit costs row includes only the cost of installing the postcombustion CCUS system and the associated changes in variable and fixed costs. The incremental heat rate for coal CCUS is relative to the average of 10.12 MMBtu/MWh in the non-CCUS coal row. The heat rate penalty is larger for retrofitted coal than for new fossil gas because the coal units are less energy efficient, emit more CO_2 per unit of energy, and also have less efficient CO_2 capture systems. The levelized cost of energy of fossil gas and coal units assumes a capacity factor of 85%. In reality, the capacity factor is determined endogenously in our modeling. For a table showing the costs of all buildable technologies modeled, see app. A. Capital recovery factor is the percentage of the up-front capital cost that must be recovered in 2035. A 6.8% capital recovery factor is consistent with an economic lifetime of 30 years and a real weighted average cost of capital of 5.44% per year. In the investor decision about adding CCUS capacity, we adjust the 45Q subsidy downward to the discounted average value of the 12-year subsidy spread over the economic lifetime of the CCUS capacity. Battery variable cost is calculated as the cost to charge based on the average wholesale price of electricity.

of CCUS depend on the underlying generating units, which vary by the policy scenario, as the underlying policy affects retirements and regions where the generators are built.

We assume a 90% capture rate for all CCUS, consistent with the CO_2 capture cost assumption sources we have used. For coal CCUS, we compute unit-specific retrofit costs and heat rate penalties using data in US EPA (2021b) after reducing the costs by 22% to account for assumed cost reductions between 2019 and 2035 (Vimmerstedt et al. 2022). The heat rate penalties cause retrofitted units to have higher fuel costs and lower generation capacity. Our central cost and performance assumptions for fossil gas CCUS units come from an expert elicitation, using values for the 50th percentile of the costs (Shawhan et al. 2021). The average short tons captured per MWh of net generation are 1.35 for coal CCUS (varying considerably among generators) and 0.38 tons per MWh for fossil gas CCUS.

For other new generators, we use the moderate development path estimates from NREL's Annual Technology Baseline 2022 (Vimmerstedt et al. 2022). More detail on generator costs is given in appendixes A and B.

For transportation costs, we use a US national CO_2 transport and sequestration cost model from EPA's Integrated Planning Model (US EPA 2021b). Each state has a supply step function for CO_2 sequestration, and the petroleum-producing states have steps representing EOR. This functional form makes the cost of sequestration increase with scale. There is a per-ton transportation cost within each state and between each pair of states. E4ST solves for optimal CO_2 transport and sequestration. In each CO_2-capturing state, there is a uniform clearing price for CO_2 transportation and sequestration together.

We calculate location-specific retail electricity prices using nodal locational marginal prices, policy compliance costs, and state-specific distribution fees. We calculate the distribution fees on a state-by-state basis to match actual retail prices during a historical calibration year. The costs of state policies, such as renewable energy portfolio standards, are distributed evenly over all electricity sold in the corresponding states.

We input the results from E4ST simulations into the incidence and air pollution models, both of which are described below. The incidence model uses results on state-level residential and nonresidential electricity consumer savings, national changes in government spending, and national changes in electricity producer surplus. The air pollution model uses generation unit-level data as inputs, including emissions, annual generation, and generator characteristics.

2.2. Household Financial Incidence

To evaluate how the energy-cost effects and government taxation effects are passed through to households in different regions with different demographic characteristics, we use the Resources for the Future (RFF) Incidence Model (Williams et al. 2014, 2015; Gordon et al. 2015). The model uses data from the Consumer Expenditure Survey, CEX (US BLS 2022), and the American Communities Survey (ACS) to create shares of total national income and spending (including electricity expenditures) belonging to households of different racial/ethnic groups and income quintiles (defined by per capita income) by census region.

The Incidence Model distributes the changes in residential electricity expenditures based on each household's share of total residential electricity expenditures.[15] We

15. The Incidence Model uses expenditure changes rather than consumer surplus changes because the E4ST model assumes fixed electricity consumption. Changes in expenditure reflect the pass-through to consumers of changes in investment and operational costs.

assume that the structure of electricity rates across households remains the same in all scenarios, although actual household impacts would likely be affected by utility rate structures that vary across states, utilities, and sometimes consumption and income groups. Nonresidential electricity expenditure changes from E4ST are distributed to households proportional to the household-type market basket of expenditures on all other goods and services. This distribution represents the way that electricity expenditure changes in the commercial, industrial, and transportation sectors ultimately filter down to households.

To determine the impact of government revenue changes on households, the Incidence Model assumes a balanced budget constraint. This assumption means that any change in government spending—due to 45Q subsidies for CCUS, or production and investment tax credits for renewables and nuclear or changes in revenue collected from allowances sold under a Cap—require a corresponding change in revenue raised from households. The model distributes changes in government revenue from 45Q and the renewable and nuclear tax credits proportional to household corporate income tax burden because the IRA tax credits are funded with corporate taxes.

However, 10.2% of IRA-related tax credit revenue changes are not distributed to households to account for the portion of US capital stock that is foreign held (US Department of the Treasury 2012) and thus responsible for a portion of corporate taxes. Changes in government revenue from the carbon price are distributed to households proportional to their average tax rate. Both the average tax rate and the corporate income tax rate come from the US Treasury (US Department of the Treasury 2022) and are assigned to households according to total income differentiated by income quintile.

Allowing CCUS also affects the profits earned by generators because it affects electricity prices and generator costs. We assume that any changes in generator profits result in changes in capital income. Households of different income levels receive different proportions of their income from capital sources, with higher-income households receiving most of them. The Incidence Model shares out changes in producer profits according to each household's share of national capital income, once again excluding the 10.2% of capital that is foreign-held.[16]

2.3. Air Quality and Mortality Impacts

2.3.1. Assessment of Pollution Mortality-Related Impacts

To evaluate pollution concentrations, we use a reduced-complexity air-pollution model, InMAP[17] (Tessum et al. 2017). InMAP uses data on emissions derived from the power

16. To provide evidence of global effects, we present aggregate monetized results that include impacts for foreign-held capital in fig. 10.

17. InMAP has been used in several recent papers that evaluate health impacts of pollution, e.g., Mayfield et al. (2019), Shapiro and Walker (2020), Hernandez-Cortes et al. (2023), and ; Hernandez-Cortes and Meng (2023).

sector modeling (including quantity, location, and stack characteristics) as inputs. From these, it estimates annual-average ambient concentrations of fine particulate matter ($PM_{2.5}$), including that was directly emitted and that was formed in the atmosphere from chemical reactions of SO_2, NO_X, and NH_3.[18] One key advantage of InMAP is its high resolution in populated areas (down to a 1 km grid), which allows us to evaluate pollution concentration changes at the scale of the census block group, a geographical unit that contains between 600 and 3,000 people (US Census Bureau 2019).

We then estimate mortality impacts derived from these pollution concentrations by adopting a linear concentration-response (C-R) function, which is standard in the literature—for instance, Goodkind et al. (2019). (See app. E for a more detailed description of the methodology.) A key input for C-R functions is the parameter that determines the mortality impacts associated with a given increase in pollution for a specific demographic group. We adopt recently estimated coefficients from Di et al. (2017), which indicate that an increase in $PM_{2.5}$ concentration of 10 micrograms per cubic meter ($\mu g/m^3$) raises the mortality risk by 7.3% on average. In the main results presented below, we assume uniformity in the response of all demographic groups to a marginal change in pollution concentration, along with an average mortality rate for each county in the United States These assumptions allow us to attribute differences in mortality impacts among different demographic groups solely to changes in exposure to pollution.[19]

2.3.2. Non-CCUS Emission Rates

This subsection describes data sources and assumptions used to estimate emission rates of four pollutants (SO_2, NO_x, $PM_{2.5}$, and NH_3) of non-CCUS electricity generation. These are the electricity generation sector's main contributors to fine airborne particulate matter (US EPA 2023b). For existing generators, we use generator-specific emission rates for SO_2 and NO_X provided by the vendor S&P global/SNL (S&P Global 2023). As these data do not include direct $PM_{2.5}$ emissions, we complement these data with $PM_{2.5}$ emission rates collected under the Emissions and Generation Resource Integrated Database (eGRID), a data source from the EPA's Clean Air Markets Division (US EPA 2020).

For data on new generators without CCUS, we use SO_2 and NO_X emission rates from Sargent and Lundy (2020). For $PM_{2.5}$, we assume an emission rate per generator equal to the average rate of all generators of the same type in the EPA's eGRID, weighted by generator heat input. Given that plants of all ages are included in the

18. We do not estimate effects on or damages from ground-level ozone because the power plants in the states that represent most of the power sector's contribution to human exposure to ground-level ozone are likely to continue to be subject to an ozone-season NO_X emissions cap (Bowers 2024).

19. We relax this assumption in the appendix. Figure A.10 shows results of allowing C-R estimates and mortality rates to vary by race and ethnicity.

eGRID, we use data only from newer plants (which started generation in 2015 or after) to compute these averages. Finally, we derive NH_3 emission rates from aggregate emissions and generation data from the EPA and EIA. (See app. D for a more detailed discussion.)

2.3.3. CCUS Emission Rates

We detail below the emission rates we assume for CCUS generators. We define emission rates per unit of heat input: the emission rate specifies how much of a pollutant is generated (in units of mass) by each unit of fuel heat input used by the plant.

We apply these pollutant emission rates to the total heat input of CCUS units. As noted in section 2.1 above, we assume that CCUS plants have a heat rate penalty per unit of energy output relative to a comparable plant without CCUS, to operate the CCUS equipment. This assumption implies that even if the emissions rate per unit of heat input of a plant with CCUS remains unchanged after a retrofit, the plant emits more of that pollutant per MWh of electricity output.

Given the current lack of data from operational plants in the United States (Rochelle 2024), we develop novel estimates for the CCUS plants considered in our modeling (coal retrofits and new fossil gas with CCUS). We gather data from existing literature, DOE front-end engineering design (FEED) studies on existing and proposed CCUS plants, and consultation with experts. Table 2 summarizes the emission rate

Table 2. Emission Rates per Unit of Heat Input, for the Four Air Pollutants Considered

Emission Type	Upper Bound	Lower Bound
	Coal CCUS Retrofit	
$PM_{2.5}$	104%	30%
NO_x	100%	50%
SO_2	3%	0%
NH_3	.0155 lb/MMBtu	100%
	New Fossil Gas Plant with CCUS	
$PM_{2.5}$	100%	0%
NO_x	100%	0%
SO_2	100%	0%
NH_3	.0138 lb/MMBtu	0%

Note. For coal-generating units, emission rates (except upper-bound NH_3) are expressed as percentage of rates at the same unit before retrofit. For gas-generating units, they are expressed as a percentage of rates of a new non-CCUS combined-cycle plant. Emission rates are given per unit of heat input.

changes for the four air pollutants considered. (See app. C for a detailed discussion on sources for each emission rate.)

Given the dispersion of estimates found, we construct three different sets of CCUS emission rates: an upper-bound set in which emission rates are the highest plausible based on existing data, a lower-bound set in which emission rates are the lowest plausible, and a set that consists of the midpoints between the upper-bound and lower-bound rates. The main results presented in the paper use the midpoint set. We test the sensitivity of our results by assuming the upper-bound and lower-bound emission rates in section 4.

As reflected in table 2, retrofitting coal plants with CCUS can have the largest impact on the emissions rates of SO_2 and NH_3. CCUS requires almost complete removal of SO_2 from exhausts (EEA 2020). Even in our pessimistic set of emission rate assumptions, SO_2 emission rates per unit of heat input are only 3% of pre-retrofit rates. In contrast, adding CCUS can increase emissions of NH_3 depending on the capture technology, although the amount of NH_3 emitted is highly controllable (Purswani and Shawhan 2023). At best, we assume that adding CCUS leaves NH_3 per unit of heat input unchanged. Emission rates for NO_x and $PM_{2.5}$ have a wider range of possible changes. Existing projects have demonstrated both a small increase in $PM_{2.5}$ emissions as well as a decrease to 30% of pre-retrofit rates (Purswani and Shawhan 2023). Existing projects show a range of NO_x reductions between zero and 50% (Purswani and Shawhan 2023).

New fossil gas with CCUS could have the same $PM_{2.5}$, NO_X, and SO_2 emission rates per unit of heat input as fossil-gas-fueled generating units without CCUS, or it could have only trace emissions of local air pollutants, approximated as zero in our assumptions, depending on the CCUS technology (Iyengar et al. 2022). For NH_3, we assume that the emission rate per unit of heat input might increase by a factor of almost five, although that seems pessimistic relative to recently planned CCUS projects in the United States (Purswani and Shawhan 2023).

2.4. Monetized Impacts

Finally, we group the estimated financial and health effects on US households into four broad categories: (1) effects of residential and nonresidential electricity cost savings on household expenditures; (2) profits earned by generators; (3) changes in tax payments resulting from changes in government spending on subsidies for CCUS, renewables, and nuclear, and from changes in revenue from selling the national power sector emissions allowances when there is a national CO_2 emissions cap; and (4) averted pollution-related mortality, monetized using the value of a statistical life (VSL).[20]

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20. We adopt EPA's VSL value of $7.4 million in 2006 USD (US EPA 2014) and adjust it for inflation to 2020 USD and for changes in real income until the year 2035, yielding a VSL equal to $12.1 million. For this step, we use EPA's estimates for inflation and real income US EPA (2023b).

3. AGGREGATE US RESULTS

In this section, we present the effects for all US households together. We summarize the effect on the energy generation mix under the two policy scenarios considered, as well as the impacts on pollution-related mortality and household finance. This section concludes by presenting the aggregate monetized effects of CCUS deployment on US households considering all impacts measured. The future amount of generation with CO_2 capture is subject to uncertainty over a wide range (Bistline et al. 2024), so the signs of the effects and the magnitudes of effects relative to each other are the results of greatest interest.

3.1. Changes in the Generation Mix

The impacts of CCUS fundamentally depend on what its characteristics are, where it is built, which generation it displaces, and how it operates. In this subsection, we address these factors using E4ST.

3.1.1. Generation Mix without CCUS

While the IRA provides subsidies for various nonemitting resources, it does not penalize emissions. In contrast, a CO_2 emissions cap imposes a cost on coal and fossil gas units based on their emissions intensity. As coal units need to buy more than twice the emissions allowances per MWh as gas units do, more coal generation remains online under Current Policies than under the Cap scenario. Figure 2*A* shows the generation mix in the year 2035 under both policy scenarios when CCUS is not allowed ("Without CCUS" bars).

Without the cap, more of the fossil-fuel generation and emissions come from coal, and the cap leads to more solar and wind when there is no CCUS allowed. Hence, in the simulations without CCUS, the Current Policies scenario leads to more local pollution given that coal generation leads to more SO_2 and NO_x emissions than fossil gas. This difference in the outcomes without CCUS turns out to be a key driver of its impacts and distributional implications.

3.1.2. Impacts of CCUS Deployment on Generation Mix

When we allow CCUS as an option, the differences between the policy outcomes are attributable to the interaction between the technology and the underlying policy (fig. 2*A*, "With CCUS" columns).[21] Under Current Policies, our modeling projects that there will be 719 terawatt-hours (TWh) of generation from 97 gigawatts (GW) of coal with CCUS and 166 TWh of generation from 24 GW of gas with CCUS. This projection falls within the range of CCUS deployment reported by Bistline et al. (2024).[22] Under the Cap scenario, the modeling projects 723 TWh of generation from 98 GW of coal with CCUS

21. Table A.5 summarizes the annual average capacity factor by technology and scenario.

22. Bistline et al. (2024) model the IRA's effect on the power sector using 11 "state-of-the-art" models of the energy and power sector systems, with different structure, inputs, spatial, and temporal resolutions.

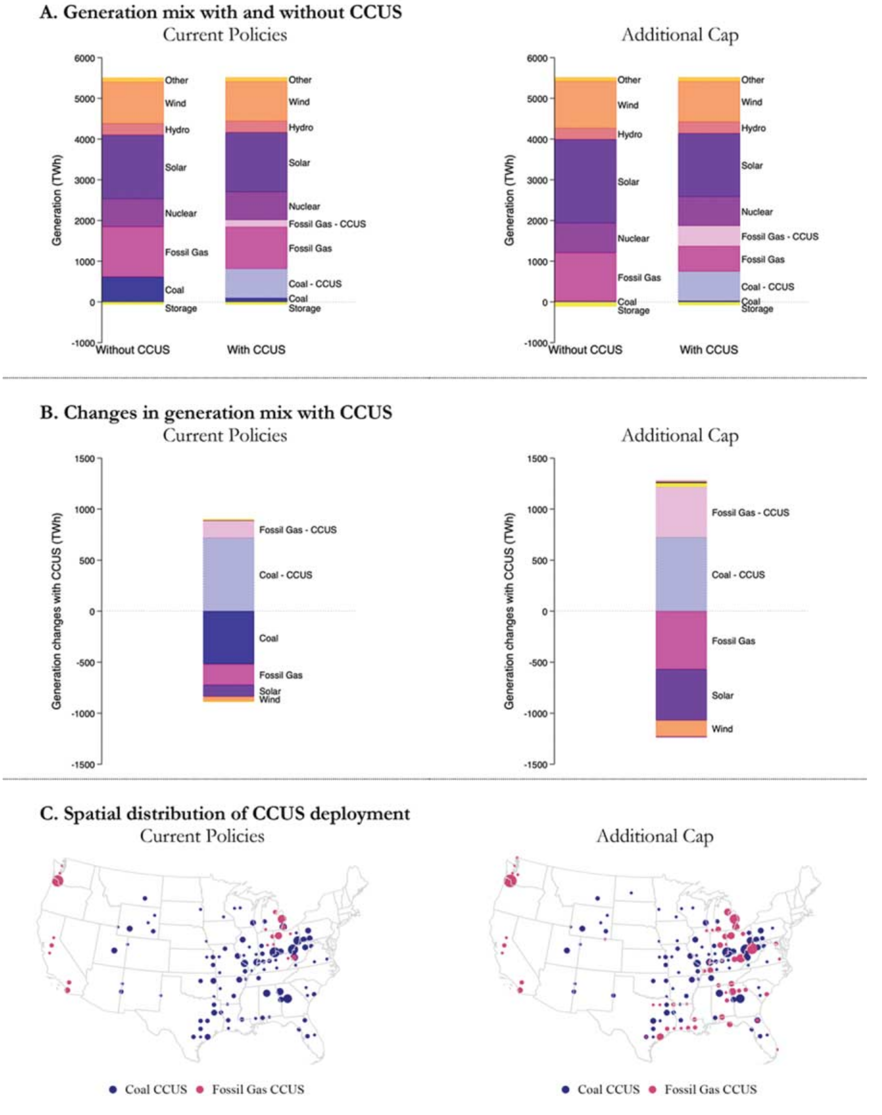

Figure 2. Generation mix. In all panels, output for the Current Policies scenario is shown on the left and for the Cap scenario on the right. Panel *A* shows generation sources both when carbon capture, utilization, and storage (CCUS) is not allowed and when it is. Panel *B* shows changes when CCUS is allowed. Positive values represent generation increases with CCUS, whereas negative values indicate that it decreases. Panel *C* maps the spatial distribution of CCUS generation. TWh = terawatt-hour.

and 495 TWh of generation from 75 GW of gas with CCUS. The Cap causes a larger ratio of gas CCUS to coal CCUS by imposing a price on CO_2 emissions. Gas CCUS has a lower CO_2 emission rate. In both policy settings, the opportunities to use captured CO_2 for EOR are fully taken, accounting for approximately 138 million tons of CO_2. The rest of the captured CO_2, 895 million tons with Current Policies or 1,025 million tons with an additional CO_2 Cap, is sequestered in saline aquifers.

Figure 2*B* shows that, under Current Policies, about 60% of the generation that CCUS displaces is coal-fueled generation, and the rest is fossil gas, solar, and wind. Under the Cap, the displaced generation consists almost entirely of fossil gas, solar, and wind. This difference has important implications for the air quality impacts of CCUS, as discussed in later sections.

It is also important to note that the CCUS deployment is not uniformly distributed across the country. It is concentrated in the South and Midwest of the United States (fig. 2*C*). These are therefore the regions of the United States that are likely to see the largest impacts of CCUS deployment. There is relatively little CCUS deployment in the West and most parts of the Northeast census regions. Again, this key difference turns out to be a driver of the distributional implications, as explained in section 5.

3.2. Pollution-Related Mortality

Under Current Policies, CCUS deployment leads to an average decrease in pollution exposure. This decrease is brought about by large drops in SO_2 emissions, given that generation from CCUS-retrofit coal is nearly SO_2 free. Emissions for the other three pollutants increase, particularly for NH_3, emissions of which are almost 40 times higher with CCUS (fig. 3*A*). As far as the formation of secondary $PM_{2.5}$ is concerned, under current policies, increases in emissions of NO_x, primary $PM_{2.5}$,, and NH_3 are dominated by drops in SO_2, leading to overall lower levels of combined primary and secondary $PM_{2.5}$ exposure.

Spatially, the reductions in secondary $PM_{2.5}$ exposure are concentrated in a belt spanning from the Texas-Louisiana border to Pennsylvania, covering large parts of the lower Midwest and upper South census regions (fig. 3*B*). As detailed above, this geographical area corresponds to the deployment of CCUS generation (fig. 2*C*) and is, therefore, a region in which CCUS generation replaces standalone coal generation. Even outside of this belt, the majority of the United States also experiences reductions in $PM_{2.5}$ exposure, albeit smaller. However, some areas in the upper Midwest and West census regions bear increases in $PM_{2.5}$ exposure (notably, the states of California, Nevada, North Dakota, and Minnesota). As noted above, these regional discrepancies in pollution exposure with CCUS are key to explaining some of the distributional impacts described in section 5.

The impact of CCUS deployment on pollution exposure has the opposite sign in the presence of a CO_2 emissions cap: most of the United States experiences increases in pollution exposure, most notably the lower Midwest–upper South belt (fig. 3*B*). In this case,

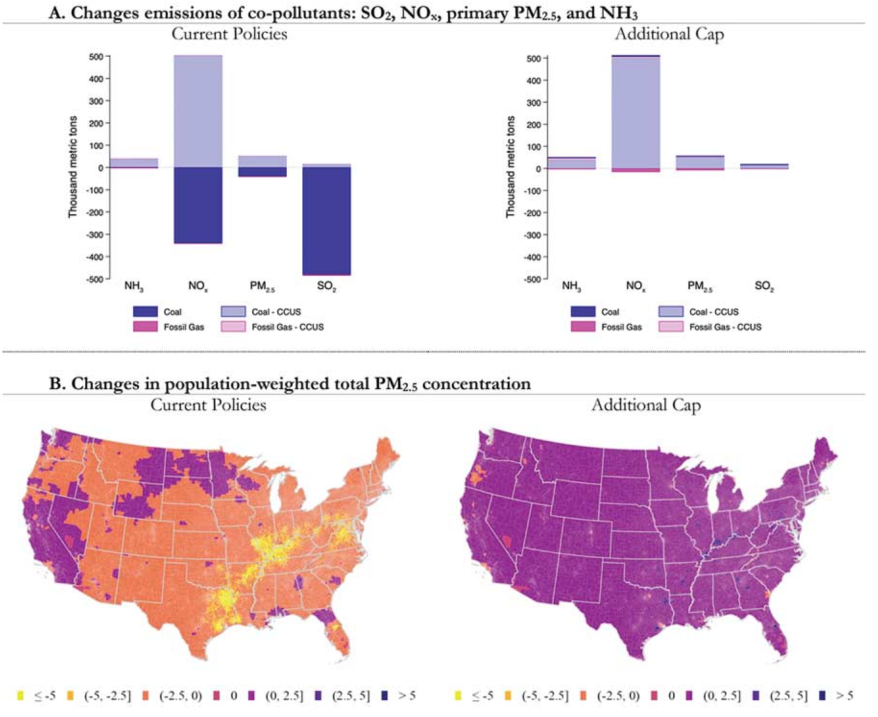

Figure 3. Local pollution changes with carbon capture, utilization, and storage (CCUS). In all panels, output for the Current Policies scenario is shown on the left, and for the Cap scenario on the right. Panel *A* shows changes in NH_3, NO_x, $PM_{2.5}$, and SO_2 emissions by generation source when CCUS is allowed. Positive values represent a net increase in emissions whereas negative values indicate a net decrease. Panel *B* maps the population-weighted concentration, measured as $P_b \cdot (a_b/\Sigma_b a_b)$, where P_b is pollution concentration in census block group b measured in $\mu g/m^3$, a_b is population count in census block b. The denominator is the aggregate US population in millions. Positive values represent increases in population-weighted total $PM_{2.5}$ concentration when CCUS is allowed, whereas negative values represent decreases. Figure A.9 shows changes in absolute (nonweighted) $PM_{2.5}$ concentration.

CCUS generation is replacing mostly fossil gas generation without CCUS and renewables (fig. 2*B*), leading to large increases in NO_x, primary $PM_{2.5}$, and NH_3 emissions.

These results highlight one of the key takeaways from this study: the sign of the health impacts caused by CCUS deployment depends on the underlying policy scenario.

3.3. Financial Incidence

Allowing CCUS as a technology option changes electricity expenditures and generator profits (understood as capital income). Under Current Policies, the availability of

CCUS decreases electricity expenditures and increases generator profits (fig. 4*A*). Allowing CCUS reduces the private costs of generation because it is, in some cases, less costly than the alternatives—partly due to government subsidies—and thus allows more choices in the optimization. Most of the savings are passed on to consumers in the form of lower prices of electricity. The higher generator profits are distributed to households proportional to their capital income.

Under the Cap scenario, adding CCUS also decreases electricity expenditures and increases generator profits (fig. 4*B*). Notably, adding CCUS under a Cap reduces electricity expenditures more than under Current Policies because CCUS both decreases the carbon price burden in electricity prices and increases the government subsidies flowing to the electricity sector.

CCUS deployment also affects government revenues and spending, which translates into a changed tax burden for consumers. First, because CCUS technologies receive the 45Q tax credit, additional operation of CCUS requires additional government spending, which needs to be recovered through taxes. Second, in cases where CCUS generation displaces renewable generation, it decreases government spending on renewables tax credits. Additionally, under a Cap, new CCUS deployment reduces government revenue from the sale of emissions allowances and hence increases the tax burden under a balanced-budget assumption. In other words, the availability of CCUS under either policy increases government expenditures (or decreases revenue under the Cap) and would have to be recovered through additional taxes. These additional tax burdens are larger than the energy-cost savings under both scenarios.

3.4. Overall Monetized Impacts

Overall, these results show that the deployment of CCUS does not necessarily result in a health-energy-cost savings trade-off (fig. 4). While this trade-off is present in the case of a Cap—in which CCUS deployment leads to higher pollution exposure and hence mortality, as well as cheaper electricity—CCUS leads to both lower pollution-related mortality and lower energy costs under Current Policies. The generation that CCUS replaces is behind these differences: replacing mostly coal in the case of Current Policies and mostly renewables and non-CCUS fossil gas in the case of a Cap.

Whether enabling CCUS as a feasible option leads to positive aggregate impacts under a policy scenario depends on the relative magnitudes of these effects. The energy-cost savings under a Cap are not high enough to offset the negative impact on mortality and government revenue, leading to a net negative aggregate impact under this policy scenario. However, there are positive net benefits under Current Policies, despite the additional tax expenditures, highlighting the importance of considering the underlying policy scenario in analysis. Section 4 examines the key assumptions of our modeling and the sensitivity of our results to plausible combinations of key modeling parameters.

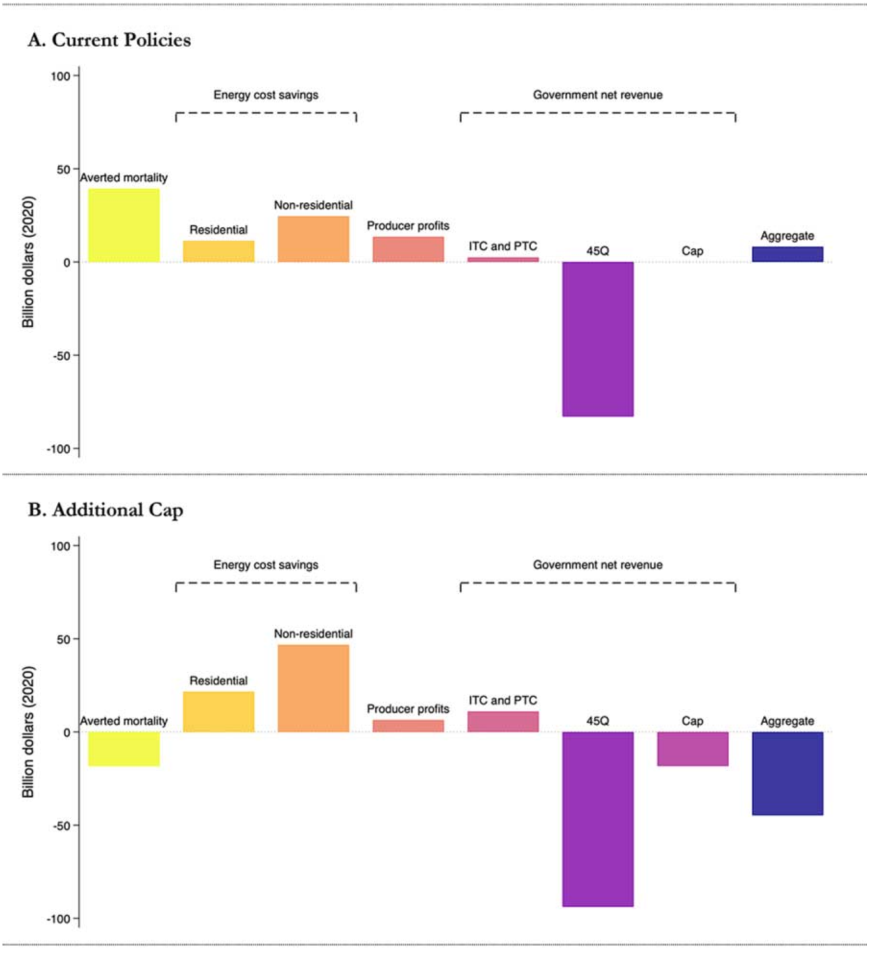

Figure 4. Monetized health and financial impacts of carbon capture, utilization, and storage (CCUS) on US households. The figures show the monetized impacts of allowing CCUS on US households. Positive values represent net benefits relative to the case when CCUS is not allowed, while negative values are net costs. Panel *A* shows the output for the Current Policies scenario and panel *B* for the Cap scenario. The seven left-most bars summarize impacts due to (1) averted pollution-related mortality; (2) household savings given estimated impacts on residential electricity expenditures; (3) household savings given estimated impacts on nonresidential electricity expenditures, distributed to households proportional to their share of spending on nonelectricity goods; (4) generator capital income; (5) tax incidence for households from the government investment and production tax credits; (6) tax incidence for households from the government 45Q credits for CCUS; and (7) tax incidence for households from government sale of national CO_2 emissions allowances. Positive values in the fifth, sixth, and seventh columns represent tax reductions, negative are increases in tax burden. The right-most bar (the eighth column) aggregates all categories. Note that the impacts of carbon emissions reductions are not included (see fig. 10).

4. UNCERTAINTY: KEY ASSUMPTIONS AND SENSITIVITY ANALYSES

In this section, we first discuss some key assumptions underlying our modeling. Given that future CCUS deployment can be estimated only with uncertainty—for example, Bistline et al. (2024)—it is important to evaluate how different assumptions could impact the main conclusions of our analyses. We then show a sensitivity analysis for different combinations of some key modeling parameters such as cost and emissions rate assumptions for CCUS.

We acknowledge that an exhaustive review of all potential sources of uncertainty—in terms of policy environment, electricity markets, technological innovation, future electricity consumption, and so forth—is unfeasible. Nonetheless, this section underscores a key issue discussed throughout the paper: the health-financial trade-off resulting from CCUS deployment cannot be analyzed in isolation. Rather, it is essential to consider various dimensions of uncertainty.

4.1. Key Assumptions

4.1.1. Non-CCUS Technology Costs

The amount of CCUS deployment and related impacts depends on the relative future costs of different technologies. Section 2.1 details the projections for the costs of building, retrofitting, and operating generators, but these projections—both in absolute terms and relative to one another—are highly uncertain. While we consider a low-cost and a high-cost CCUS scenario in section 4.2, investigating the full range of potential CCUS deployment that could result from a wide range of relative technology costs is beyond the scope of this study.

As the difference in the generation mix in the baseline without CCUS is a main driver of whether a potential trade-off between health and energy-cost savings exists, comparing our two policy scenarios also gives us insights into the effects of non-CCUS technology costs and allows us to elaborate on the robustness of our results to these costs. For example, changes in technology costs that lead to a cleaner baseline without CCUS (e.g., cheaper nonemitting generation or costlier fossil-fueled generation) would lead to a cleaner baseline without CCUS, creating more room for a trade-off.

If nonemitting generation technologies were costlier than in our input assumptions, then we would expect to see more emitting resources in no-CCUS cases. Thus, we expect that CCUS adoption and the cost savings and emissions reductions per MWh of generation with CCUS would all be larger. However, if gas- and coal-fueled generation without CCUS were both more costly, CCUS generation and the cost savings per MWh of CCUS generation would likely be larger and the emission reductions smaller. As our main contribution is the direction of change, rather than the overall magnitude, we can infer the effects of uncertain technology costs from our two policy scenarios.

4.1.2. CCUS Deployment

While our CCUS deployment results fall within the ranges of CCUS in the multimodel paper by Bistline et al. (2024), they might be above what is realistically achievable by 2035 if there are frictions to the speed with which CCUS can be deployed, that is, if fast deployment of CCUS has some added costs. In such a case, the emissions reductions per MWh of CCUS generation would likely increase, at least slightly, relative to our current results because of an increased amount of non-CCUS coal and gas generation for CCUS to displace. The sign of the effect on cost savings per MWh of CCUS generation in this case would depend on how the average resource cost changed. Moreover, in our modeling, the cost of adding CCUS to a coal generation unit is affected by the unit's heat rate and capacity but not by the presence of a SO_2 scrubber. In reality, the presence of a scrubber could in some cases reduce the cost of adding CCUS if it is, or can be modified to be, effective enough not to need replacement with more effective scrubbing.

4.1.3. Elasticity of Demand

For ease of interpretation, the simulations for this study had price-responsive electricity consumption only at times and locations where the price reached $5,000 per MWh. As the frequency of such outcomes is low, the consumption in our modeling is less price responsive than in reality (Feehan 2018; Deryugina et al. 2020). Consequently, our analysis omits the additional emissions that would result from the consumption response to lower electricity prices. However, we estimate that a price elasticity of -0.5 would change the health benefit of allowing CCUS by only approximately $0.4 billion (1%) in the Current Policies scenario[23] and $0.3 billion (2%) in the Cap[24] scenario.

4.1.4. Balanced Budget and Tax Distribution

Our aggregate results are sensitive to both the balanced budget assumption and the method of tax distribution. Changes in government revenue do not typically correspond to the changes in taxes in the year that the revenue change occurs. More often, they result in a change in debt, which may lead to a change in taxes in later years. Changes in government revenue may also affect the cost of borrowing for the government and influence government costs indirectly. Even assuming the tax changes occur in the year of government expenditure, they might not lead to changes in the taxes designed to fund the program but, rather, to changes in other taxes. In addition, some government programs (e.g., the Regional Greenhouse Gas Initiative) might not have

23. Assumes incremental generation has system-wide average emission rates and that damage-per-ton values match those in US EPA (2023b).

24. Assumes the generation share changes resulting from the additional consumption would be proportional to the generation share changes between the Current Policies CCUS scenario and Cap CCUS scenario, except no change in hydroenergy.

such a constraint. If the balanced budget assumption does not hold or taxes are distributed differently, CCUS might be strictly net beneficial regardless of changes in pollution exposure. The distribution of allowance revenue can also dramatically change the progressivity or regressivity of a policy.

4.1.5. Partial Equilibrium

Our results derive from a partial equilibrium analysis and, consequently, we do not consider general equilibrium effects in the broader economy resulting from changing generation sources or differential health and financial impacts. Likewise, we do not consider the potential learning by doing that can spread to CCUS use in other sectors of the economy, such as industrial facilities, or to processes for removing carbon dioxide directly from the atmosphere.[25] We also assume that population does not move in response to changes in energy generation types and associated pollution.[26] Addressing these questions is an important avenue for future research.

4.1.6. Year of Analysis

We evaluate effects for 2035 with a generation mix that includes between 0% and 10% coal. CCUS deployment over a longer term could result in worse health impacts due to less fossil-fueled generation that can be displaced and to better financial results because the cost savings from CCUS could become larger as CO_2 emissions reduction goals become more costly to meet.

4.2. Sensitivity Analysis

Even under the assumptions described above, our results could be sensitive to many uncertainties, such as CCUS costs and emissions rates, C-R estimates, and the VSL. Figure 5 examines the sensitivity of the aggregate monetized impact of CCUS deployment across these parameters. To test sensitivity to our cost assumptions, we construct a high- and a low-cost scenario based on expert elicitation and the literature. (See app. G for further details on cost assumptions in these scenarios; and figs. A.1–A.4 for results; figs. A.1–A.15 are available online.) For emissions rates, we use upper and lower bounds from table 2. We also allow for alternative C-R estimates from the literature, a lower value from Krewski et al. (2009) and a higher one from Lepeule

25. The IPCC (2022, 40) deems the deployment of carbon dioxide removal technologies "unavoidable" if net-zero CO_2 emissions are to be achieved.

26. Currie et al. (2023) find that movement of Black or non-Hispanic White populations to areas with different pollution levels has contributed little to relative changes in exposure between these two groups. Hernandez-Cortes et al. (2023) find a similar result when focusing only on pollution from the electricity sector. To the extent that these findings continue to hold in the future, it would alleviate the constraint of assuming an immobile population that we make in this study.

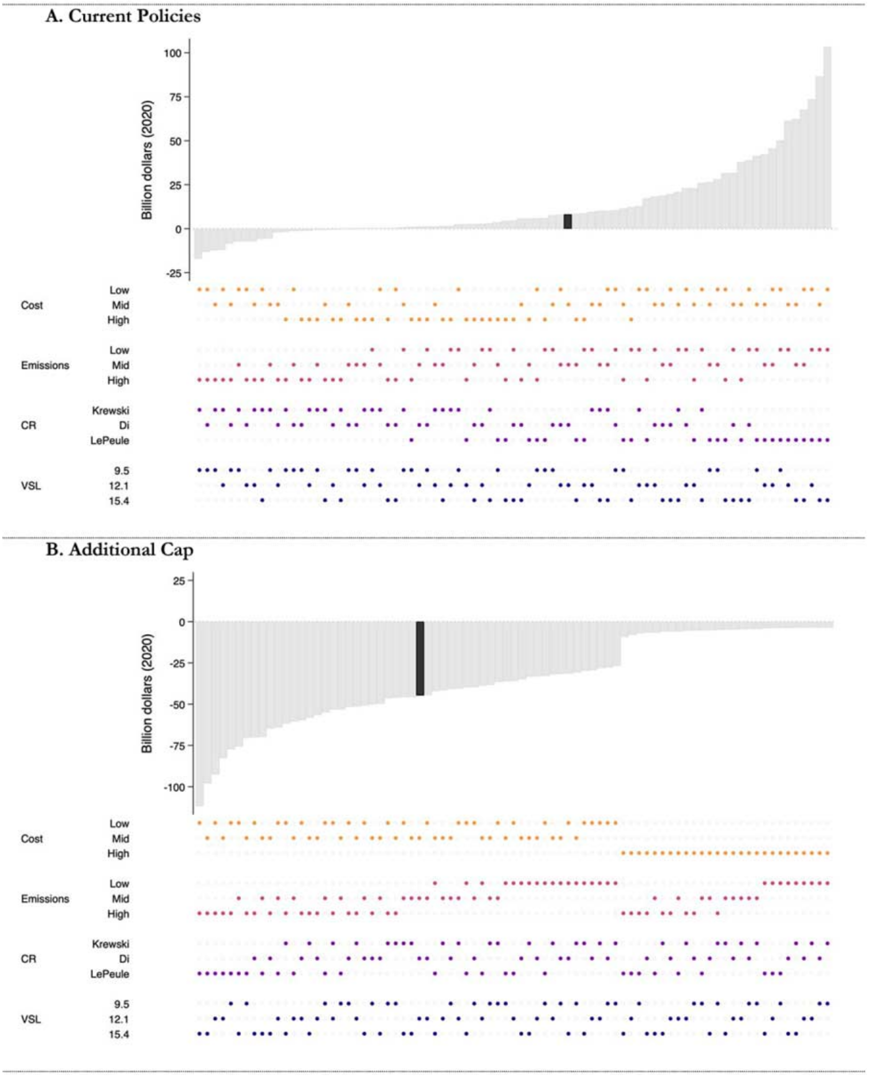

Figure 5. Sensitivity to modeling parameters of aggregate monetized impact. Figures show the aggregate monetized impacts under different modeling parameters as they relate to the emissions rates from carbon capture, utilization, and storage (CCUS) generation (Emissions), concentration-response estimators mapping changes in $PM_{2.5}$ exposure to mortality changes (CR), and assumed value of statistical life (VSL). Our central choice of parameters, presented in the main text, is highlighted in black. (Midpoint emissions rates; concentration-response estimators from Di et al. [2017], and a VSL equal to 12.1 M$). Panel *A* shows the Current Policies scenario, and panel *B* for the Cap scenario. See also Krewski et al. (2009) and Lepeule et al. (2012.

et al. (2012). (See app. E for more details.) Finally, uncertainty about the VSL can be an important contributor to our monetized estimates (US HHS 2016). We use a lower VSL (the current value of $9.5M) and a higher one ($15.4M, chosen so the interval around the adopted VSL is symmetrical).

CCUS deployment is sensitive to cost assumptions. In the high-cost scenario, we see little CCUS adoption (fig. A.1), which results in aggregate monetized impacts that are close to zero in both policy scenarios (fig. 5). In the low-cost scenario, there is a slight increase in coal CCUS and a large increase in gas CCUS at the expense of reduced fossil gas and nonemitting generation, relative to our central-cost assumptions (fig. A.1). Given the relatively small difference in emissions between these generation types, the shifts in generation lead to minor changes in averted mortality. These generation changes also yield additional energy-cost savings, which are largely offset by higher tax expenses (see app. G for more details). Therefore, aggregate monetized effects for the low and central CCUS-cost cases remain similar for a given combination of emissions rates, C-R, and VSL parameters (fig. 5).[27]

Figure 5 further shows that CCUS leads to a positive aggregate impact under Current Policies for most combinations of the parameters. The most negative aggregate outcomes stem from a set of conditions that reduce the positive averted mortality effects under this policy scenario: if CCUS is highly emitting, so the pollution reductions of substituting fossil-fuel generation by CCUS are small (low emissions rates), these reductions in pollution are translated into fewer deaths (low C-R), and we value these deaths little (low VSL).

Under the Cap, CCUS leads to a negative aggregate impact under all combinations of our sensitivity scenarios, even though the magnitude varies. The most negative aggregate outcomes come from a combination of parameters that increase the negative averted mortality effects of CCUS: if CCUS is highly emitting, so the pollution increases of substituting nonemitting generation by CCUS are large (high emissions rates), reductions in pollution are translated into more deaths (high C-R), and we value these deaths a lot (high VSL).

These sensitivity results highlight the prevalence and importance of considering uncertainty in CCUS policy decisions. The variability of magnitudes under different assumptions and policy scenarios shows that nuance is important in discussions around the distributional impacts of CCUS deployment. It is not feasible to come up with a one-size-fits-all statement or policy.

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27. Beyond aggregate effects, the impacts across individual categories (e.g., averted mortality, energy-cost savings, taxes, etc.) are largely consistent in direction across the high-, central-, and low-cost cases under the midrange assumptions for emission rates, C-R, and VSL (fig. A.2). The only exception is producer profits under a Cap, which are positive in the low- and central-cost cases but negative—albeit very close to zero—in the high-cost case.

Finally, a stakeholder might be considering the effects of just a coal CCUS or just a gas CCUS project, or costs and regulations might make the likely balance between coal CCUS and gas CCUS quite different than in our results. Therefore, we have estimated the effects of allowing only coal CCUS and only gas CCUS. Most of our aggregate impact findings above continue to hold under these scenarios. (See app. H and figs. A.5–A.8, for a more detailed discussion.)

5. DISTRIBUTIONAL IMPACTS FOR US HOUSEHOLDS

This section explores how the costs and benefits of CCUS deployment presented above are distributed along income and race/ethnicity lines.[28] We also discuss distributional impacts by census region, as these help contextualize our race and ethnicity results. Overall, this section highlights stark differences in how the financial and air-pollution effects of CCUS are distributed under each of the underlying policies studied.

5.1. Impacts by Income Quintiles

We find that the effects of CCUS deployment are heterogeneous along the income distribution. Figure 6 shows significant differences in pollution-related mortality as the percentage of group income between the top and the bottom income quintiles when CCUS is allowed.

When we look at exposure levels, we find that those with lower incomes already experience the largest health impacts.[29] This finding is consistent with the well-established fact that low-income communities tend to live closer to power plants (Thind et al. 2019). It is then expected that they would be more affected by CCUS replacing dirtier or cleaner energy generation. Consequently, lower-income populations reap relatively more benefits when CCUS leads to aggregate lower mortality under Current Policies and suffer a relatively larger burden under a Cap, when CCUS worsens pollution levels overall.

Beyond health impacts, we also find differences in how the deployment of CCUS affects the savings and revenue in different income-quintile brackets in both policy scenarios. Energy-cost savings for those with the lowest income represent a larger share of their total income, which more than offsets the relatively smaller increases in tax burden. The opposite is true for the top income quintile: energy-cost savings represent a smaller share of their income, while the tax burden increases significantly due to the larger tax shares. As a result, CCUS leads to aggregate savings for those in the lowest income quintile and aggregate losses for those in the highest income quintile under both policy scenarios.

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28. Appendix F justifies using income and race/ethnicity as dimensions along which to measure distributional impacts.

29. We estimate that the absolute value of monetized health impacts is 22% higher for those in the lowest quintile of the income distribution compared to those in the highest under Current Policies, and 56% higher under a Cap.

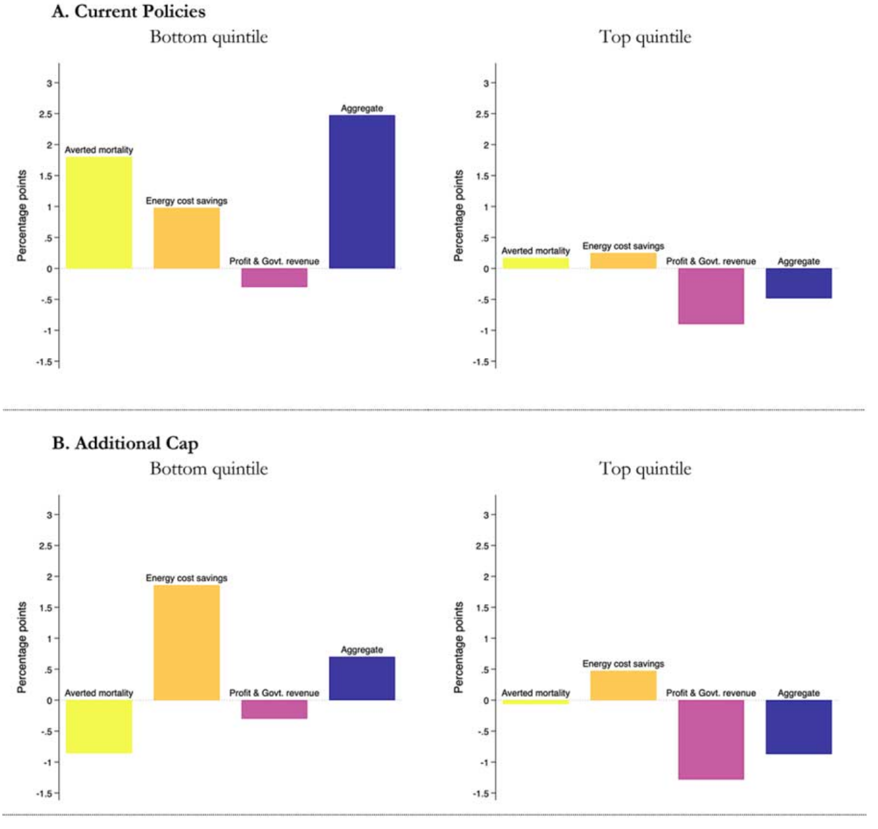

Figure 6. Income quintile (top and bottom): impacts of carbon capture, utilization, and storage (CCUS) as percentage of group total income. Figure shows monetized impacts of allowing CCUS on the populations in the bottom quintile of the income distribution (*left*) and top quintile (*right*). Positive values represent net benefits relative to the case when CCUS is not in the choice set, while negative values are net costs. Figures are expressed as a percentage of the group's total income. Panel *A* shows the output for the Current Policies scenario and panel *B* for the Cap scenario. Figure A.11 shows all distribution quintiles.

Aggregating health and financial impacts, we find that CCUS is expected to be beneficial in most cases for those in the lowest quintile: even when pollution-related mortality and the tax burden increase, as in the case of the Cap, they are more than offset by energy-cost savings. On the other hand, increases in tax burden make the deployment of CCUS negative for those with high income in both scenarios. These results highlight that CCUS deployment can be progressive, benefiting those with lower incomes relatively more.

5.2. Impacts by Region

This subsection presents the distributional impacts of CCUS deployment by US census region, as these are important to contextualize the changes by race and ethnicity.

There are salient differences across US regions with respect to pollution-related mortality of CCUS deployment (fig. 7). As described above (sec. 3 and fig. 2C), the deployment of CCUS generation is heavily concentrated in the South and Midwest regions of the United States. Therefore, these regions experience the largest air-pollution-related health impacts of CCUS deployment. The underlying policy determines the direction of this impact: positive under Current Policies (when CCUS mostly displaces coal) and negative under a Cap. On the other hand, the health impacts are comparatively small for the Northeast and, particularly, the West.

Differences across regions also arise in energy-cost savings, which are again largest for the Midwest and South, and the smallest for the West and Northeast, in both scenarios considered. This is again a consequence of the different regional deployment of CCUS. Unlike health impacts and energy-cost savings, the increase in tax burden is roughly uniform across the nation, as the changes in federal tax expenditures are distributed to everyone.

Because of these differential changes, CCUS deployment would negatively impact the Northeast and the West under both policy scenarios, as the increase in tax burden dominates the health and savings category. On the other hand, it is a net positive in aggregate for the Midwest and the South under Current Policies, and minimally net negative in the case of a Cap, where CCUS leads to higher pollution-related deaths in these two regions.

These results evidence regional trade-offs of CCUS deployment, even within a uniform national policy scenario, which are driven by the substantial regional differences in resource deployment. These regional differences drive, in part, the distributional effects by race and ethnicity, as described below.

5.3. Impacts by Race and Ethnicity

Ethnic and racial groups experience varying changes in pollution exposure (fig. 8). Individuals from all groups observe mostly reductions in exposure under the Current Policies scenario, while experiencing mostly increases in exposure with the Cap. However, changes are larger in absolute value for Black populations than for non-Hispanic White populations. Hispanic populations observe the smallest changes in exposure (in absolute value) of the three demographic groups, with a large spike around zero indicating no changes in pollution exposure.

These changes are consistent with two facts: first, Black populations tend to live in regions with a large deployment of CCUS,[30] and second, within a given region, they

30. Burtraw et al. (2022), investigating the effects of decarbonizing the US economy, also find that health impacts among racial/ethnic groups are mostly driven by regional population concentrations.

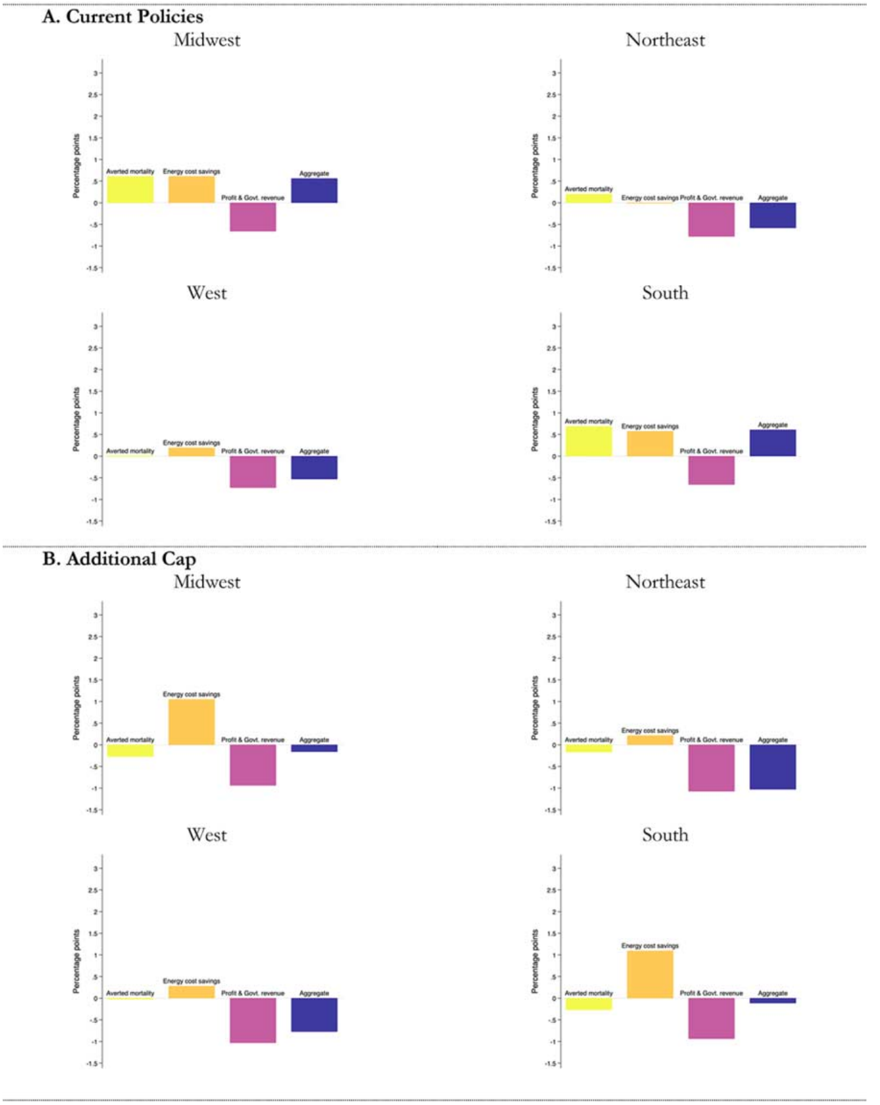

Figure 7. Monetized impacts of carbon capture, utilization, and storage (CCUS) by region as percentage of group total income. Figure shows monetized impacts of including CCUS in the choice set of generation sources for the populations in the Midwest (*top left*), Northeast (*top right*), West (*bottom left*), and South (*bottom right*). Positive values represent net benefits relative to the case when CCUS is not in the choice set, while negative values are net costs. Figures are expressed as a percentage of the group's total income. Panel *A* shows the output for the Current Policies scenario and panel *B* for the Current Policies plus a Cap scenario.

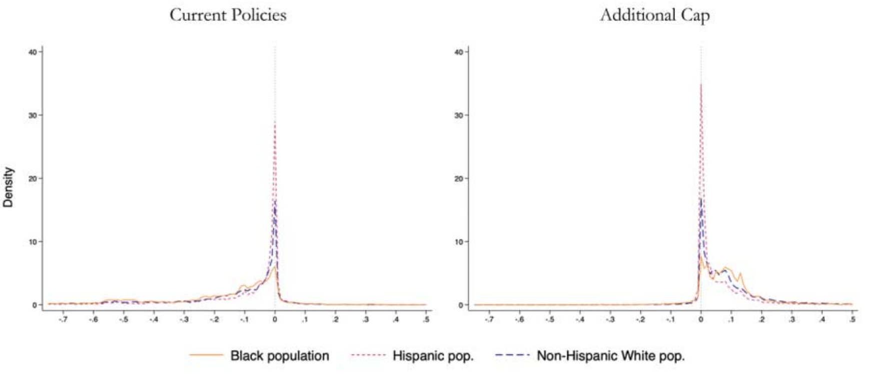

Figure 8. Race and ethnicity: changes in individual $PM_{2.5}$ exposure ($\mu g/m^3$) with carbon capture, utilization, and storage (CCUS). The figures plot kernel density curves, which estimate the distribution of changes in $PM_{2.5}$ exposure for populations within race/ethnicity groups after allowing CCUS. Positive values are increases in $PM_{2.5}$ exposure relative to the case when CCUS is not allowed, while negative values are decreases. The figure on the left shows the output for the Current Policies scenario, and the figure on the right for the Cap scenario.

are more likely to live near power plants (Thind et al. 2019). Indeed, figures A.12 and A.13 show that health impacts are larger for Black populations within each census region, the only exception being the Northeast region under a Cap. As a result, Black populations are relatively more affected by the emissions effects of CCUS deployment: positively under Current Policies, and negatively under a Cap. On the other hand, Hispanic populations are less affected, given that this group is more prevalent in the West and CCUS deployment leads to minimal changes for this region, and the fact that Hispanic populations are less likely than Black to live near power plants (Thind et al. 2019). These results evidence that the impact of CCUS deployment is not uniform across minority groups.

This differential exposure leads to distinct monetized health impacts, which are larger in absolute value for Black populations (fig. 9). This result is particularly salient for Black individuals with lower incomes (figs. A.14, A.15). The assumption underlying this result is that all groups respond similarly to changes in pollution concentration. If we consider group-specific mortality rates and concentration-response estimates, the implications for CCUS are even starker for Black populations (table A.4 and fig. A.10; tables A.1–A.5 are available online). In that case, the monetized health benefits relative to group total income for Black populations under Current Policies are seven and six times larger than for non-Hispanic White and Hispanic populations, respectively.

Even given these larger reductions in health-related mortality under Current Policies when CCUS is allowed, compared to a baseline without CCUS, Black populations would still experience larger mortality impacts from $PM_{2.5}$, measured as a share

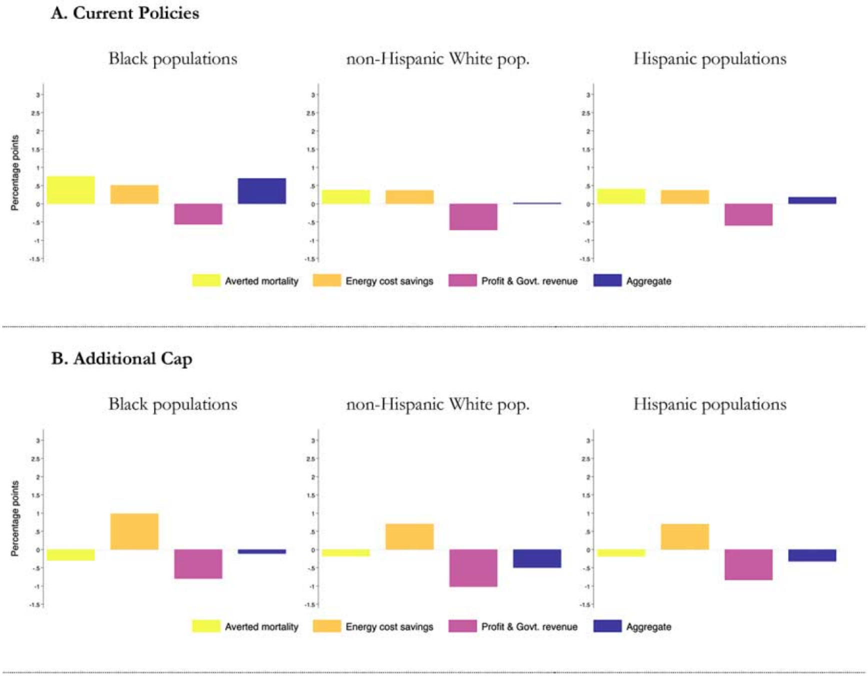

Figure 9. Race and ethnicity: impacts of carbon capture, utilization, and storage (CCUS) as percentage of group total income. Figure shows monetized impacts of allowing CCUS on populations of different race and ethnicity: Black populations (*left*), non-Hispanic White populations (*center*), and Hispanic populations of any race (*right*). Positive values represent net benefits relative to the case when CCUS is not in the choice set, while negative values are net costs. Figures are expressed as a percentage of the group's total income. Panel *A* shows the output for the Current Policies scenario and panel *B* for the Current Policies plus a Cap scenario.

of income, than both non-Hispanic White and Hispanic populations.[31] In other words, CCUS under Current Policies would alleviate some of the unequal exposure of Black populations to pollution but would not completely eliminate it.

Figure 9 also shows that the distribution of savings and revenue impacts of CCUS by race and ethnicity is not uniform. We find that Black populations, who are more likely to reside in areas with CCUS deployment, experience the largest energy-cost savings as a share of their income under both policy scenarios. The savings of Hispanic and non-Hispanic White populations are smaller and similar to each other. Due to

31. Specifically, the monetized mortality impacts as a percentage of group income under Current Polices for Black populations would be 1.4 and 2.3 times larger than for Hispanic and non-Hispanic White populations.

their higher income—especially higher capital income—and thus higher tax rates, non-Hispanic White populations bear relatively larger increases in tax burden. Indeed, non-Hispanic White and Black populations within the same income quintile face similar financial impacts under both policy scenarios in our modeling (figs. A.14, A.15).[32] The aggregate differences across these two groups in our modeling hence come from the larger share of Black populations in the lower end of the income distribution.

Overall, Black populations would gain relatively more from CCUS deployment under Current Policies and lose relatively less under the Cap. These relative differences result from larger energy-cost savings and less incremental tax burden in both policy scenarios and from a larger mortality reduction. As in the case of aggregate results, whether CCUS deployment can contribute to meeting broad distributional outcomes goals depends on the underlying policy scenarios.

5.4. Summary of Distributional Impacts of CCUS Deployment

Overall, the results presented above highlight that, under Current Policies, the deployment of CCUS might be net beneficial to lower-income and Black populations, leading to both lower air-pollution-related mortality and larger energy-cost savings for those groups, while being net detrimental to top-income quintiles or people living in the West and the Northeast. In this policy case, the deployment of CCUS will contribute to reducing the environmental burden on disadvantaged groups. However, the opposite might be true under a Cap, emphasizing how the policy environment in which CCUS is implemented can affect the progressiveness of its deployment. Finally, our distributional results are directionally robust to generation-mix changes coming from different CCUS-cost assumptions or from allowing only coal CCUS or gas CCUS, with very few exceptions (see apps. G, H for details).

6. DISCUSSION AND CONCLUSION

As distributional considerations are becoming a key issue in climate policy design, it is important to evaluate potential trade-offs new technologies could bring and how policy design could change these trade-offs. In this study, we evaluate the argument that CCUS technology could exacerbate the pollution and economic burden on historically disadvantaged communities.

Our results show that there are important trade-offs associated with the deployment of CCUS technology. The availability of CCUS can lead to overall savings in household energy expenditures under plausible policy scenarios. However, given the

32. This conclusion relies on our incidence modeling methodology that considers the average relationship between income, capital income, and taxation. If Black households owned less wealth than White households, even within an income quintile, Black households would receive a lower portion of their income from capital sources and, subsequently, still might experience differential financial impacts after controlling for income.

incentives the IRA provides, CCUS could also lead to an increased household tax burden. Importantly, whether the introduction of CCUS as a technology option leads to a higher or lower number of $PM_{2.5}$-related deaths compared to a no-CCUS alternative depends on the type of climate policy in effect because the underlying policy strongly influences the types of generation that CCUS would displace.

Our analyses show the importance of considering the underlying climate policy when evaluating a national CCUS policy. If the underlying policy is one that leaves room for CCUS to reduce CO_2 emissions, such as in the Current Policies scenario, then allowing CCUS can indeed lead to more CO_2 abatement, with accompanying reductions in copollutants. In contrast, if the underlying policy is one that leads to a cleaner baseline, such as a binding CO_2 emissions Cap that will not be adjusted in light of more CCUS, then allowing CCUS may increase copollutants. Therefore, even if CCUS could lead to some energy-cost savings, it could also increase the number of pollution-related deaths, creating the trade-off that we outlined in the introductory section. In this case, an additional policy to reduce local pollution may be necessary, as also highlighted by Fowlie et al. (2020). While we focus on a national policy, the same insight applies to state policymakers when they are thinking about CCUS siting or subsidy decisions.

In addition, as an emerging technology, the level of CCUS deployment in the near future is highly uncertain. The magnitude of CCUS deployment depends highly on specific modeling assumptions, such as its costs. Our directional results for a given policy scenario, however, are robust under most combinations of parameters. Furthermore, our two policy scenarios represent cases with and without a potential for cost-air pollution trade-off. Thus, we can discern the range of potential CCUS effects even when our modeling cannot capture important policy uncertainties, such as changes in electricity market designs.

Importantly, effects are not distributed uniformly. CCUS deployment leads to aggregate savings for the lowest income quintile, irrespective of the policy scenario considered. With respect to pollution-related mortality, our findings indicate that Black populations are the most affected by CCUS deployment, either positively or negatively. This finding is consistent with their higher likelihood of residing in regions with significant CCUS deployment and close to power plants within these regions. Hispanic populations are less affected. Considering ethnic minority groups as a single aggregate group[33] would obscure significant differences between outcomes for Black and Hispanic populations.

Given its objective of analyzing the distributional effects of CCUS in the United States, this study has focused on the impacts on different groups in the US population. Thus, in our results above, we did not include financial impacts to foreign owners of capital or the potential climate benefits, which are hard to assess at a local level, given the global nature of CO_2. However, CCUS deployment would have impacts beyond US borders. Foreign owners of US power plants would also be impacted by changes in tax revenue and capital

33. For instance, EJSCREEN, the EPA's environmental justice screening tool, classifies as "minority" all individuals except those who identified as non-Hispanic White.

profits. In addition, if CCUS were to change the level of CO_2 emissions in the United States, that would have effects outside and inside the United States that we have not included in the analysis above.

Figure 10 summarizes the monetized impacts of CCUS deployment including these two sets of global impacts. The increase in profits for non-US generator owners

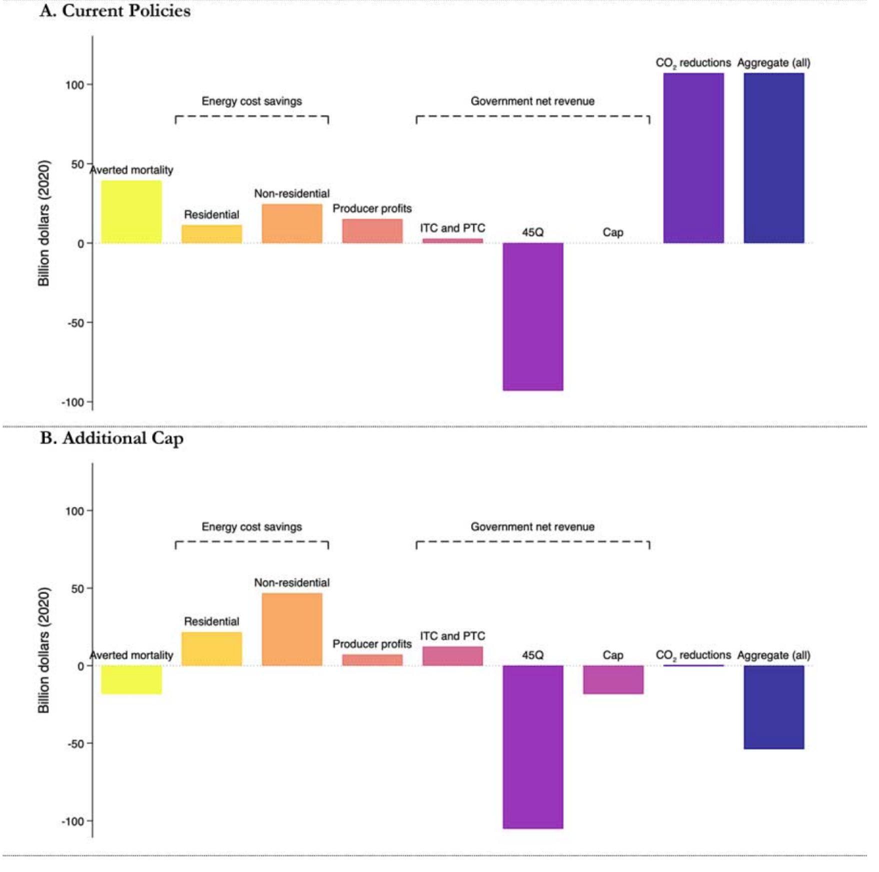

Figure 10. Monetized global health and financial impacts of carbon capture, utilization, and storage (CCUS). Monetized impacts of allowing CCUS, including the effects of changing CO_2 emissions and revenues for non-US generator owners. Panel *A* shows the output for the Current Policies scenario and panel *B* for the Current Policies plus a Cap scenario. Positive values represent net benefits relative to the case in which CCUS is not in the choice set, while negative values are net costs. The first seven left-most bars summarize the same categories of impacts as in figure 4. Producer profits, tax incidence, and 45Q includes both US and foreign owners of capital. The eighth bar shows the gains from reductions in CO_2e emissions, monetized using a social cost of carbon equal to 248$/ton of CO_2 (US EPA 2023c). Right-most bar (the ninth) aggregates all impacts.

does not offset their higher tax expenses, and this effect alone contributes to a diminished positive impact of CCUS. However, we find that CCUS leads to substantial CO_2 reductions under Current Policies, mostly because it expedites the phase-out of coal capacity that lacks CO_2 capture. Accounting for this additional benefit using the values for the social cost of carbon from the EPA[34] would increase the estimated aggregate benefits of CCUS deployment in this scenario by a factor of 13, compared to the case presented above without global benefits. In contrast, CCUS does not lead to additional CO_2 abatement in the Cap scenario because the cap is binding.

These CO_2 reductions under Current Policies would surely have distributional impacts as well. While we know that climate change has affected and will continue to affect disadvantaged communities more severely (US EPA 2021a), there are still no well-established methods to allocate climate effects to different demographic groups. Even EPA, in its most recent power sector rule, with its most sophisticated environmental justice analysis to date as of 2023, continues to discuss the distributional impacts of climate change qualitatively (US EPA 2023d). Thus, our distributional analysis does not include these climate effects.

Truly achieving net-zero emissions from the power sector means that fossil-fueled generation with CCUS that captures less than 100% of greenhouse gas emissions cannot remain operational unless accompanied by some method of CO_2 removal from the atmosphere. Whether allowing CCUS in the transition is net beneficial, and who wins and loses, depends on underlying climate policy.

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