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Meeting U.S. greenhouse gas emissions goals with the international air pollution provision of the clean air act

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Abstract

We explore economic, distributional and health consequences of U.S. greenhouse gas emissions objectives that could be achieved using Section 115 of the Clean Air Act (international air pollution), which has only recently received detailed legal analysis as a potential U.S. climate policy tool. Under it a national emissions target could be allocated among the states. This illustrative analysis considers 45% and 50% reductions of energy and industry-related CO_2 emissions by 2030, below 2005 levels, via a model rule. Different approaches (based on legal precedent) for the interstate allocation are considered, along with alternative rates of technology improvement. The detail needed to analyze this approach is provided by MIT's U.S. Regional Energy Policy model (30 individual states and multi-state regions), with its electricity sector replaced by the U.S. National Renewable Energy Laboratory's Renewable Energy Development System (ReEDS). Air quality benefits are estimated using modeling tools developed by academic researchers and the U.S. Environmental Protection Agency. Three-quarters of emissions reductions in 2030 come in the electric sector, while reductions elsewhere illustrate the efficiency advantage of a multi-sector policy. With all states participating in allowance trading, the resulting national emissions price is lower than in older assessments. The difference is due to lower growth expectations, recent state policies, falling costs of low carbon technologies, and an improved representation of electric system flexibility by the ReEDS model. Even ignoring climate and air quality benefits, economic welfare grows at near the baseline rate for all regions regardless of the interstate allocation approach. When states distribute allowance revenue to residents on an equal per-capita basis, the policy is welfare improving to the lowest income quintile in all regions. Aggregation of control costs, the mortality effects of reduced particulates, and the value of avoided climate damages yields positive national net benefits in all cases.

1. Introduction

To make its contribution to the Paris Agreement goals of keeping global warming 'well below' 2 °C and 'pursuing efforts' to hold to 1.5 °C, the U.S. set its new nationally determined contribution (NDC) to achieve economy-wide reductions in greenhouse gas (GHG) emissions of 50%–52% below 2005 levels in 2030. Though states, cities, and many in the private sector are taking action on their emissions, federal leadership is needed, and pending congressional legislation seems unlikely to meet the 2030 target. Additional executive action under the Clean Air Act could provide a way forward. Here, we examine the possible use of Section 115 of the Act, which would allocate a national target among the states and, with trading, yield a national emissions price.

Section 115 (42 U.S. Code § 7415) on International Air Pollution has been part of the Clean Air Act since 1965, and it offers an opportunity to assign emissions targets to the states, covering all sectors and sources (Burger 2020)[5]. When Section 115 is triggered, the U.S. Environmental Protection Agency (EPA) may require each U.S. state to develop an implementation plan through the same process used for the National Ambient Air Quality Standards (NAAQS), which provides flexibility for states to adopt a range of policy tools (e.g. fees, permits, auctions) that can build upon their existing efforts. For example, under Section 115 the EPA could set a target for total U.S. GHG emissions (or more likely focus on fossil-fuel derived CO_2 as in our example) and allocate the required reductions to the states in some manner[6]. EPA could issue a model rule to provide states with a uniform allowance trading framework, but states would be free to adopt other approaches to meet their assigned targets if they chose. Each state would also maintain discretion about how to distribute the allowances, or revenue from allowance auctions (see section 2.1 for more detail).

For this illustrative analysis, we assume the program is implemented as a cap and trade program with auctioned allowances, and that revenue is returned to the states and distributed to residents on an equal per-capita basis. Such a program is sometimes referred to as a cap and dividend program. The analysis explores 45% or 50% reductions in CO_2 emissions below the 2005 level in the U.S. by 2030, the higher level being very close to the 50%–52% target announced by the Biden-Harris Administration for all GHGs. Welfare costs and distributional effects are evaluated at the state/regional level, and a partial net national benefits assessment is conducted, reflecting the value of avoided premature mortalities due to reduced particulate air pollution and the value of avoided climate damage based on the social cost of carbon.

Potential U.S. climate policies that involve carbon pricing, either through a cap and trade system or carbon taxes, have been widely explored, typically using models of the national economy that include some detail on energy demand and supply. Novel methodological contributions of this paper include (1) specific analysis of Section 115 as a policy tool, (2) inclusion of regional detail (30 individual states and multi-state regions) in MIT's U.S. Regional Energy Policy (USREP) model, (3) inclusion of electricity sector detail of the Renewable Energy Development System (ReEDS) model developed by the U.S. National Renewable Energy Laboratory, and (4) quantification of air quality benefits using EPA and other modeling tools—all as combined in an overall policy analysis.

An additional and important contribution of the analysis is to attempt to capture how the energy sector has been rapidly changing in ways likely to lower the cost of emissions reductions. Reasons include (1) substantial declines in expected emissions growth in the U.S., which is widely seen as flat or declining slightly even in the absence of new policies to reduce emissions—especially when recent state and federal policies are taken into account, (2) lower costs for natural gas, solar and wind electricity, and of electric vehicles (NREL [U.S. National Renewable Energy Laboratory] 2019, Bloomberg New Energy Finance 2020, NREL [U.S. National Renewable Energy Laboratory] 2020, EIA [U.S. Energy Information Administration] 2020a, Xiao *et al* 2021), which reduces the cost of shifting away from coal generation and from internal combustion engines in light duty vehicles, and (3) better representation by the ReEDS model of the possible contribution of intermittent renewables. These factors obviously interact to reduce projected emissions and the costs of further reductions with new policy.

We provide a partial assessment of the monetary benefits of this illustrative implementation of Section 115, for comparison with the costs. To do this we use an estimate of the social cost of carbon set by the U.S. federal government. Additional health benefits of reduced particulate matter-related mortalities are calculated using a reduced-form air quality model and regulatory-standard methods for monetizing these benefits. Additionally, we evaluate the distributional effects of the mitigation policy among regions and income groups, another important consideration in any policy. Overall, this analysis combines updated estimates of costs, state policies, and economic outlooks to conduct a fairly complete integrated assessment of a novel policy that could be implemented to meet U.S. climate goals.

While we focus on implementation under Section 115 of the Clean Air Act, aspects of the analysis could be illustrative of other carbon pricing programs that might be adopted under new legislation. For example, the overall cost of the policy, its implications for regional and sectoral reductions, and the benefits of the policy would be broadly similar if the same national emissions targets were achieved with legislative carbon pricing. However, there are distinguishing aspects of Section 115 implementation: under the Clean Air Act, it is up to individual states to implement policies that achieve their assigned targets, and

[5] The legislative history of the Act indicates that climate concerns were on policymakers' radar when the provision was enacted (Barnett 2020), but it is a heretofore rarely used part of the Act yet to be tested in the courts (Richardson 2017).

[6] In this paper, we generally use the term 'allocate' to refer to the division of emissions reductions to the states by EPA. Because we imagine implementation through a model rule, this is equivalent to the distribution of allowances in this manner (see section 2.5). There is then a second phase of allocation when states distribute their share of allowances. For this analysis we assume this is exclusively by per capita rebates, both for simplicity and so that we can focus on how allocation of emissions reduction obligations by EPA influences regional impacts.

the revenue from allowance auctions flows to the states (rather than to the federal government as might occur in a national cap and trade system). Thus, the allocation of targets among states has implications for how much potential revenue each state will gain from the sale of allowances, and therefore on the net effect of the policy on residents of different states (and the resulting political economy). It also does not likely allow the federal government to retain allowance revenue to ensure revenue neutrality (revenue equaling expenditure). Finally, while some models of carbon pricing either ignore or presume elimination of preexisting state and federal climate programs, Section 115 would explicitly allow states to build on those efforts. So, while some aspects of the results would be applicable to any carbon pricing program of similar design, some of the more detailed results are dependent on specific implementation features of Section 115.

Section 2 provides an overview of the methods used, including features of implementation under existing authority in the U.S. Clean Air Act; section 3 describes the results; and section 4 discusses their implications.

2. Methods

2.1. Implementation under existing federal authority

Several legal scholars have examined Section 115 and concluded it is a viable option that can be implemented by the Executive Branch without further legislative action (e.g. Burger 2020). It thus offers an administration the option to cover most GHG emissions and meet domestic goals and international commitments. Any major climate regulation will nonetheless be challenged in the courts and attacked by critics in Congress, industry, and the general public. An administration weighing the legal, policy, and political risks against the benefits of such a program can use modeled estimates of the potential economic and policy impacts in such a decision.

There are potential advantages to this policy, which could impose an incentive for emissions reduction that is common across CO_2 emitting energy and industrial sectors. Previously, the Obama Administration launched a Climate Action Plan whose centerpiece was action under the Clean Air Act. It applied Section 202(a), which grants the EPA the authority to regulate emissions from new motor vehicles, and Section 111, which does the same for new and existing stationary sources (used to set standards for power plants, landfills, and oil and gas operations). This sectoral approach can make it difficult to address key sources of emissions, such as vehicles already on the road. Also, the constraints within each section of the statute (e.g. the directive to use the 'Best System of Emissions Reduction' under Section 111) can limit potential reductions. Further, the sector-by-sector approach not only reduces the speed of reductions, by requiring multiple time-consuming rulemakings, but can also miss potential economic efficiencies by limiting the ability to seek the lowest-cost emission reductions regardless of source or location. Also important, it opens the potential for leakage[7] to under- or uncontrolled sectors. Absent further action, one prediction of baseline emissions in 2030 is that total U.S. GHG emissions might be 20%–26% below 2005 levels. (Pitt *et al* 2021). Conventional regulatory policies could further reduce emissions. But because of constraints on these measures, the failure to address all emission sources, the possibility of leakage and rebound[8] effects, and risk of court challenge, reductions could fall short of their estimated performance. This makes an examination of all possible policy tools worthwhile.

Section 115 can be triggered when the EPA '… has reason to believe that any air pollutant or pollutants emitted in the United States cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare in a foreign country' (endangerment), and that the other country 'has given the U.S. states essentially the same rights with respect to the prevention or control of air pollution occurring in that country as is given that country' (reciprocity). The EPA then may require each U.S. state to develop an implementation plan through the same process used for implementing the NAAQS, which provides flexibility to adopt a range of policy tools (e.g. fees, permits, auctions) that can build upon existing efforts in those states.

For example, under Section 115 the EPA could set a target for total U.S. GHG emissions (or more likely focus on fossil-fuel derived CO_2 as in our example) and allocate the required reductions to the states in some manner. The EPA could issue a model rule to provide states with a uniform allowance trading framework, but leave states free to adopt other approaches to meet their assigned targets. Each state would also maintain discretion about how to distribute the allowances, or revenue from allowance auctions.

The U.S. Supreme Court has offered deference to the EPA in determining how to distribute emission reduction obligations among the states. In its ruling on *EPA vs. EME Homer City*, the Court laid out three approaches by which such an allocation could be made (Barnett and Teitz 2020). One would

[7] 'Leakage' occurs when a policy that incompletely covers all emissions contributes to an increase in emissions elsewhere. For example, a policy reducing emissions in the electricity sector could reduce demand for fossil fuels, lowering their prices and spurring an increase in their use and emissions from other (under-regulated) sectors.

[8] A 'rebound' effect occurs when increasing efficiency of energy use (such as in a vehicle) lowers the cost of operations and creates an incentive to use more (drive more miles), partially undercutting the benefits of higher efficiency.

allocate emissions to equalize marginal compliance costs across the states (as the EPA did in the cross-state air pollution rule). A second would allocate in proportion to a baseline emissions level, and a third would be on a per-capita basis. Other allocations, or combinations of approaches, are possible, but we use these three approaches to illustrate how the EPA's allocation choices might be used to balance regional considerations. Importantly, both state and federal policies that remain in place would help reduce additional actions needed to meet each state's target.

For the purposes of modeling implementation and economic efficiency, we have assumed that the EPA will issue a model rule that involves trading, consistent with 42 U.S.C. § 7410(a)(2)(A) which calls for state plans to 'include enforceable emission limitations and other control measures, means, or techniques (including economic incentives such as fees, marketable permits, and auctions of emissions rights)'. This would allow the system to function as a cap and trade system, nested within the 115 framework, and is analogous to the cross-state air pollution rule and NOx SIP Call (EPA [U.S. Environmental Protection Agency] 2009), where the EPA's model rule was universally adopted by relevant states.

2.2. The combined USREP-ReEDS model

We explore the path to U.S. emissions goals under Clean Air Act Section 115 using the U.S. Regional Energy Policy (USREP) model, which is a multi-region, multi-sector, multi-household recursive-dynamic computable general equilibrium model of the U.S. economy with myopic foresight (Yuan *et al* 2019). To better capture the behavior of renewable generation sources, which will be important contributors to emissions reduction, the electric sector of USREP is replaced by the Renewable Energy Deployment System (ReEDS) model (Brown *et al* 2020), which provides needed detail on technology characteristics and regional structure of the U.S. electric system. Details of the USREP and ReEDS models and their integration are described in supplementary material A (available online at stacks.iop.org/ERL/17/054019/mmedia). The analysis considers a reduction in national CO_2 emissions of 45% and 50% below the 2005 level by 2030, which spans a range of near-term emissions reductions that are consistent with a straight-line path to the 2050 net zero emissions goal laid out by the Biden-Harris Administration (as well as being close to the goal for 2030). A recent IPCC Special Report identified a 40%–60% cut in global CO_2 emissions below 2010 levels by 2030 was needed to remain below 1.5 °C of warming (IPCC 2018).

2.3. Policy and economic assumptions

Baseline assumptions about technology, economics, and policy are critical to the results of any implementation of Section 115. Technology costs (e.g. of wind turbines, solar PV, and electric vehicles) continue to fall, state policies on emissions have advanced, and the COVID-19 pandemic, even as the nation gradually recovers, will likely have lasting effects. Our analysis begins by creating an AEO reference scenario calibrated to the 2020 Annual Energy Outlook (EIA [U.S. Energy Information Administration] 2020) and to recent state economic activity (BEA [U.S. Bureau of Economic Analysis] 2020). We then further adjust the AEO reference to construct two alternative baselines, a mid-range baseline and a low-cost baseline, taking into account more recent economic and policy developments. For both baselines we include an adjustment, admittedly highly uncertain, to economic and emissions growth by reducing the labor force employment rate, based on estimates of the initial labor force impact of COVID-19 with gradual recovery through 2030 as discussed in detail in Reilly *et al* (2021). We also capture newer state policies not reflected in the AEO 2020 baseline (supplementary material B). Our focus is on results through 2030 and is also the target date of the new U.S. NDC under the Paris Agreement.

The two alternative baselines differ in technology costs and energy efficiency improvements, including the possible effect of additional policy measures by states and the federal government. The mid-range baseline includes NREL [U.S. National Renewable Energy Laboratory] (2019) mid-range technology cost assumptions (NREL [U.S. National Renewable Energy Laboratory] 2019), historical rates of energy efficiency improvements, and electric vehicle (EV) costs that remain a premium over internal combustion engine (ICE) vehicles through 2030. The low-cost baseline incorporates NREL [U.S. National Renewable Energy Laboratory] (2019) low technology cost assumptions, assumes EV cost parity with ICE's after 2025, and incorporates energy efficiency improvement rates in all states that match California's achievement in recent decades. Some observers point to the fact that projections of renewable energy costs often prove to be far too pessimistic, with actual costs falling well below the estimates within a few years from when the estimate was made, although supply chain disruption has led to recent increases (Bloomberg 2021). On the other hand, assuming efficiency gains like those in California across all states is a fairly optimistic assumption, so we believe these two cases are useful points of reference, assuming a policy is implemented as we describe it. Readers no doubt will have their own opinions as to which is more likely. Government revenue neutrality is maintained at baseline levels in all policy scenarios through adjustment of personal income tax rates. A summary of these features of the AEO reference, the two baselines, and steps in scenario construction is provided in table 1. Illustrative analysis of the impact of other assumptions (e.g. natural gas prices) on

Table 1. Reference, baseline and policy scenarios.

Scenario label	Scenario description
AEO reference	• Regional economic growth calibrated to BEA GSP (BEA [U.S. Bureau of Economic Analysis] 2020) for the historical years, future U.S. economic growth calibrated to AEO 2020 reference projection, and regional electricity load grows at the same rate as AEO 2020 electricity supply • NREL's ATB 2019 Mid-Range Electricity technology cost and performance assumption • ReEDS reference case assumption on RPS, CES and wind/solar carve out by state • AEO 2020 CAFE standards for Light Duty Vehicles, with LDV costs based on a review by Ghandi and Paltsev (2019).
Mid-range baseline	• Electricity technology cost and performance assumptions as in the Reference, including NREL [U.S. National Renewable Energy Laboratory] 2019 'Mid-Range' ATB cost and performance assumptions • COVID-19 pandemic effect implemented as an impact on the labor force • Regional abatement policies including policy updates in RPS/CES and wind/solar carve outs and in the Regional Greenhouse Gas Initiative (see supplementary material B).
Low-cost baseline	• Regional policy updates and COVID-19 impacts as in the mid-range baseline • Uses NREL [U.S. National Renewable Energy Laboratory] 2019 'Low' ATB cost and performance assumptions • Assumes 3% per year annual energy efficiency improvement in all states/regions similar to CA's annual rate in recent decades. • Assumes electric vehicle cost parity with ICE vehicle cost after 2025 (i.e. in the 2030 time step). The ICCT (Lutsey and Nicholas 2019) and Bloomberg New Energy Finance (2020) project parity by the mid-2020's.
Policy scenarios	• A national cap on fossil-fuel derived CO_2 is set relative to the 2005 emissions • The national cap starts in 2025 with a 30% reduction target, and achieves overall 45% or 50% reductions below the 2005 level by 2030 • Banking and borrowing of allowances are not allowed • No emissions offsets are available • Regional emissions control measures and targets in the baseline remain in place • State shares of emissions reductions generated based on three allocation rules, equal per-capita, equal marginal cost, or equal percentage cut from base year • State allowance revenue derived from auctioning of allowances is distributed on a per-capita-basis to each state's residents.

responses to carbon prices can be found in Creason *et al* (2018) and Huntington *et al* (2020).

We also note here that our model does not capture policy-induced innovation, which is very hard to quantify, although early work suggests that it can exert significant downward pressure on carbon prices (Fried 2018, Eugster 2021).

2.4. Benefits estimation

We estimate partial national net benefits under these scenario assumptions as the sum of the benefits of a reduced contribution to climate change and the health benefits (reflecting mortality but not morbidity) from reduced fine particulate matter ($PM_{2.5}$) air pollution, less the direct welfare costs of mitigation. Climate benefits are estimated using a 2030 social cost of carbon (SCC) of $86.35 per metric ton, drawn from the interim results of the U.S. Government's Interagency Working Group (IWG [Interagency Working Group on Social Cost of Greenhouse Gases] 2016, OMB 2021) for a 2.5% discount rate adjusted to the 2018 dollars used in the welfare analysis. The IWG included estimates for a range of discount rates and evaluated uncertainty in climate damages and so it includes a wide range for the SCC. The value we use is intended to be illustrative of the climate benefits (see supplementary material F for a sensitivity analysis with a 3% discount rate SCC). There are conceptual, practical, and empirical challenges with the social cost of carbon, discussed at length, with recommendations on how to improve these estimates, in the National Academy of Science review (NASEM [U.S. National Academies of Science, Engineering and Medicine] 2017). The IWG is expected to release updated estimates of the SCC in 2022, and notes in its most recent report that current estimates 'likely underestimate societal damages from GHG emissions'.

Future emissions of primary $PM_{2.5}$, sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds are projected by scaling detailed National Emissions Inventory (NEI) data[9] (EPA [U.S. Environmental Protection Agency] 2020) based on regional

[9] We start with the NEI 2014 inventory prepared for InMAP in Tessum *et al* (2017), and adjust it to match aggregate emissions in the NEI 2017 at the state and NEI tier-2 level, in order to reflect recent emission changes.

USREP-ReEDS outcomes, using methods described in Dimanchev *et al* (2019). Concentrations of final $PM_{2.5}$ are estimated using the Intervention Model for Air Pollution (InMAP), a reduced-form air quality model that simulates atmospheric chemistry and transport of pollutants (Tessum *et al* 2017). InMAP produces final $PM_{2.5}$ concentrations in a spatial grid of 46 998 grid cells with resolution varying between 1 km by 1 km (in more population-dense areas) to 288 km by 288 km (in less population-dense areas). Using these gridded concentrations, we estimate county average concentrations that are spatially compatible with population and mortality incidence rate data described below. Specifically, using the spatial centroids of InMAP grid cells and U.S. counties, we calculate for each county the inverse-distance-weighted average of concentrations using the closest grid cell in each of the four quadrants surrounding the given county. This method therefore assigns a higher weight to concentrations closer to the county.

County level population and all-cause mortality incidence rates are from the EPA's COBRA model for the year 2025 (EPA [U.S. Environmental Protection Agency] 2018a). Population is scaled to 2030 at the state level using state level projections from UVA (2018), which is consistent with USREP population assumptions. All-cause mortality incidence rates are scaled to 2030 at the county level using all-cause mortality incidence projections in the EPA's BenMAP model (EPA [U.S. Environmental Protection Agency] 2018b). We then apply two concentration response functions reflecting associations between changes in exposure of $PM_{2.5}$ and premature mortality found in the literature: a 'high' association (Lepeule *et al* 2012) and 'low' association (Krewski *et al* 2009), yielding high and low net benefits.

Health benefits are monetized by multiplying the reduced number of premature mortalities by EPA's value of a statistical life (i.e. reduction in mortality risk) of $10.4 million for 2030 (in 2018 dollars), which was calculated by extrapolating EPA estimates for 2023 and 2028 (EPA [U.S. Environmental Protection Agency] 2018a) to account for per-capita income growth. The air pollution health benefits only include the continental U.S., and only reflect changes in premature mortality (i.e. not morbidity), which have been estimated to account for approximately 95% (Jaramillo and Muller 2016) to 99% (EPA [U.S. Environmental Protection Agency] 2018a) of total monetized $PM_{2.5}$ related health damages. Among other potential benefits not considered are avoided tropospheric ozone effects on health, air pollution effects on agroecosystems, and potential broader benefits of reduced fossil fuel mining, handling, and use (Epstein *et al* 2011, Alvarez *et al* 2012, Lemly and Skorupa 2012, Lutz *et al* 2013, Lemly 2015, Jha and Muller 2017).

2.5. Emissions reduction, allowance allocation and revenue distribution

For purposes of modeling, we assume the cap and trade program starts in 2025, with a focus on results in 2030. The model solves every 5 years. In an actual implementation it is likely that the cap would be gradually tightened over the intervening years. The allowances allocated in any year are assumed to be fully used in that year (if the cap is binding). That is, there is no banking or borrowing. The Biden-Harris Administration has a long-term (2050) goal of net zero emissions, but with our focus on 2030 we do not run our model beyond that year, in part because the EPA would be highly likely to revisit any regulatory program of this scope and potential impact (leading to significant uncertainty about how firms would bank or borrow), and because technical challenges with projections that far in the future (Barron *et al* 2018) make banking or borrowing behavior even more speculative. Additionally, this implementation without banking or borrowing gives a clear picture of a policy that precisely hits the already ambitious near-term targets. Given the recursive dynamic structure of the model and assumption of no banking or borrowing, the results for 2025 and 2030 are invariant to assumptions of the stringency of the cap in later years.

In reality, expectations of market participants about the post-2030 period (e.g. policy stringency, technological advance, future fuel prices) could affect near-term outcomes, especially if banking and/or borrowing were allowed. For example, expecting much more stringent policies could lead to greater investment in very low carbon technologies in the near-term to avoid later loss of value of higher carbon assets. Technological pessimism in hard-to-reduce sectors could lead to greater near-term control and banking of allowances for later years, whereas with optimism about future low carbon technologies, market participants might borrow from future allowance allocations if such borrowing were allowed.

As modeled, there is a single market for allowances in each year, and a single price for that year. As under Section 115 the reduction requirements are assigned to states, each state could auction allowances (distribute them freely, or meet targets with other measures), or more likely the EPA could offer to set up allowance auctions on behalf of the states. As with existing cap and trade systems, such as that in Europe, prices in trades among market participants would vary daily and hourly in response to varying expectations of the ease or difficulty of achieving targeted reductions, regardless of how allowances were distributed or auctioned. We do not capture these market dynamics.

Following the Supreme Court guidance in *EPA vs. EME Homer City*, we analyze three approaches to distributing national emissions targets among the states. Note that because we assume a model rule that caps emissions, the allocation of allowances (i.e. as budgets) to states defines the emissions they are allowed before trading.

- Equal marginal cost. The allocation is determined so that, if each state were to auction its allowances only within the state, the auction price would be identical across states, creating no opportunities for allowance arbitrage across regions. While it is possible to achieve this result exactly in the model simulation, an actual allocation would only approximate this outcome. States with less expensive reductions receive tighter targets.
- Equal percentage cut from base year emissions. Allowances are allocated to each state so that, if there were no trading, the response in each state would be an equal percentage (i.e. proportional) cut in emissions from its 2005 level.
- Equal per-capita. Allowances are allocated to states in proportion to population.

To explore the distributional consequences of each approach, we assume each state will distribute the allowance revenue (untaxed) to its residents on a per-capita basis, though states have other options (see, e.g. Hafstead 2020).

We impose revenue neutrality to assure that welfare accounting fully reflects policy costs. This is done by imposing a change in the personal income tax rates at the federal level. The adjustment of the personal income tax rates has an income effect on household consumption and welfare which further affects economic activities and the associated emissions. We have not analyzed a scenario without revenue neutrality imposed, meeting this condition through other means, or the impact of benefits on tax revenues.

3. Analysis results

3.1. Emissions prices, reduction levels, sectoral contributions, and allowance trade

Baseline emissions changes in the mid-range and low-cost baselines are shown in table 2.

We assume the same emissions reduction target of 30% below the 2005 base year in 2025 for both the 45% and 50% reduction scenarios, resulting in identical national allowance prices of \$14 per ton CO_2 for the mid-range baseline and \$7 per ton for the low-cost baseline (table 3)[10]. These 2025 prices are consistent with the U.S. Energy Information Administration's Annual Energy Outlook 2020, which projected that an \$18 carbon price puts the emissions covered in the model 28% below 2005 levels by 2025, largely by retiring marginally economic coal units. The prices diverge in 2030, at levels roughly comparable to other recent studies for the mid-range baseline (Barron et al 2018, Larsen et al 2018, Kaufman et al 2019, 2020, EIA [U.S. Energy Information Administration] 2020b) (see supplementary material G).

Table 2. Baseline CO_2 emissions changes.

Baseline	Reduction below 2005 levels 2025	2030
Mid-range	18.5%	21.1%
Low-cost	23.0%	30.7%

Table 3. Emission price (\$ 2018).

Baseline	% Reduction from 2005 in 2030	Allowance price (\$/tCO_2) 2025	2030
Mid-range	45%	\$14	\$68
	50%	\$14	\$99
Low-cost	45%	\$7	\$20
	50%	\$7	\$35

Textbook discussions of cap and trade systems point out that their value is that they yield the lowest cost reductions for any given target regardless of the allocation of allowances (Montgomery 1972, Hahn and Stavins 2011). From this principle, we might expect no difference in allowances prices or emissions among states across the allocation approaches. The independence of abatement and allowance allocations is, however, a partial equilibrium result. In general equilibrium, the allocation of revenue/allowances will have an income effect. Different distributions of revenue will produce differences in income among consumers, and their differing consumption patterns will have an effect on the quantity of different goods demanded, and thus an effect on emissions and which sectors and regions offer the lowest cost abatement. The income effects are very small, so their effect on abatement, emissions, and the carbon price also is very small. In fact, we find the variation in carbon prices among the three allocation approaches to be less than \$1/tCO_2, and similarly negligible differences in emissions among states and sectors. Thus, we report results only for the equal marginal cost allocation.

Allowance prices under the low-cost baseline are one-half the mid-range 2025 levels and are about one-third the 2030 prices. In the remaining sections, we focus on the mid-range baseline. Results for the low-cost baseline are provided in supplementary material C.

State emission reductions are shown in figure 1. First considering the 45% target (light blue bars), the reductions in emissions vary widely. West Virginia (WV) experiences the greatest reduction (80%) and Texas (TX) the least (24%). Projected 2030 baseline emissions are indicated by pink crossbars in the

[10] We tested the sensitivity of 2030 results to plausible variation in the 2025 target and found the effect to be insignificant.

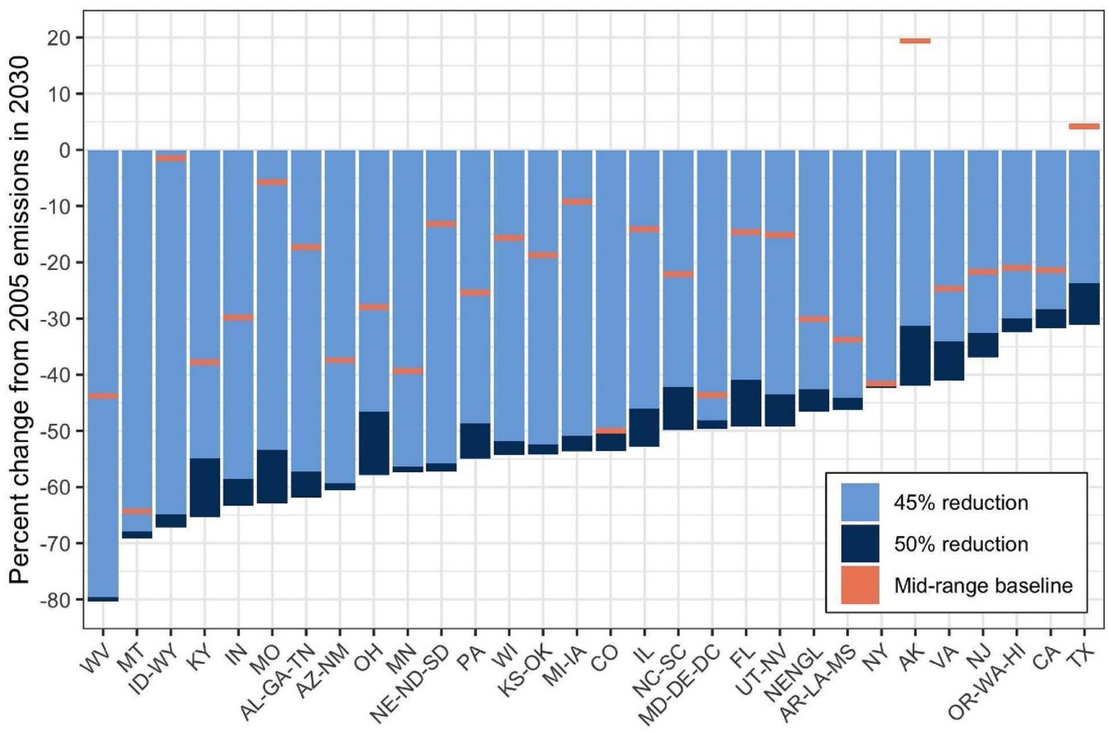

Figure 1. Percent reduction in 2030 from 2005 emissions, by state/region. Percent reduction in CO_2 emissions from a 2005 base year (equal marginal cost allocation). Pink crossbars show emissions reductions in the mid-range baseline. States/regions are ordered by percent change in emissions in the 50% reduction scenario.

figure, and almost all are well below their 2005 levels. Exceptions are Alaska (AK) and Texas (TX), where projected 2030 emissions are above 2005 levels, and Idaho-Wyoming (ID-WY), where 2030 emissions are about the same as the 2005 level.

The response to the carbon price (the amount of light blue bar below the pink line) is generally more similar across states, with some exceptions. States with significant state level policy, such as Colorado (CO) and New York (NY), are already at or near the federal target, but if economics were favorable, they might reduce further, resulting in net allowance sales to entities in other regions. Also, the detailed results for Montana (MT) show that its abundant wind resources are economically competitive and lead to the state nearly achieving its federal requirement in the baseline, requiring little more effort.

The further effort required to meet the 50% target (dark blue bars) varies considerably among states. The national level carbon price yields the greatest reductions in states where there are low-cost abatement options, such as, for example, shifting away from coal power generation to gas or renewables. WV and MT exhaust most of their low-cost abatement options in the 45% case, and so abate very little additionally in the 50% scenario. Other states such as Kentucky (KY), Ohio (OH), Missouri (MO), and Alaska (AK) pick up more abatement in the 50% scenario, reflecting the projected location of the next set of least cost options.

Figure 2 shows the same information as figure 1 but plots the reductions from the mid-range baseline 2030 projection rather than from the 2005 base year emissions. Shown are both tons (bars) and percentage (red dots) for the 45% reduction scenario (top panel) and the 50% reduction scenario (lower panel). The equal marginal cost allocation is used as an example; as discussed above, expected state emissions are nearly identical across the three allocation approaches, with only small differences due to income effects of variation in allowance revenue among states.

Figure 2 also shows the contributions to emissions reduction by the power, transportation, industry, commercial, and residential sectors. Consistent with earlier analysis of potential U.S. carbon prices (Barron *et al* 2018), the electric sector is the source of 77%–81% of reductions nationally and also accounts for the largest share of reductions in nearly all states[11]. However, even at the moderate emissions prices in table 3, roughly 8%–10% of national reductions come in transport, another 7% in industry, and smaller amounts in the other sectors (for a total of 19% in the 45% reduction case, or 23% in the 50% reduction case). This result illustrates the advantage, noted

[11] We note that reductions outside of the electricity sector become increasingly important after 2030. This analysis may also underestimate the availability of low-cost reductions in non-electricity sectors due to calibration to historical relationships instead of directly representing emerging low carbon technologies for those sectors.

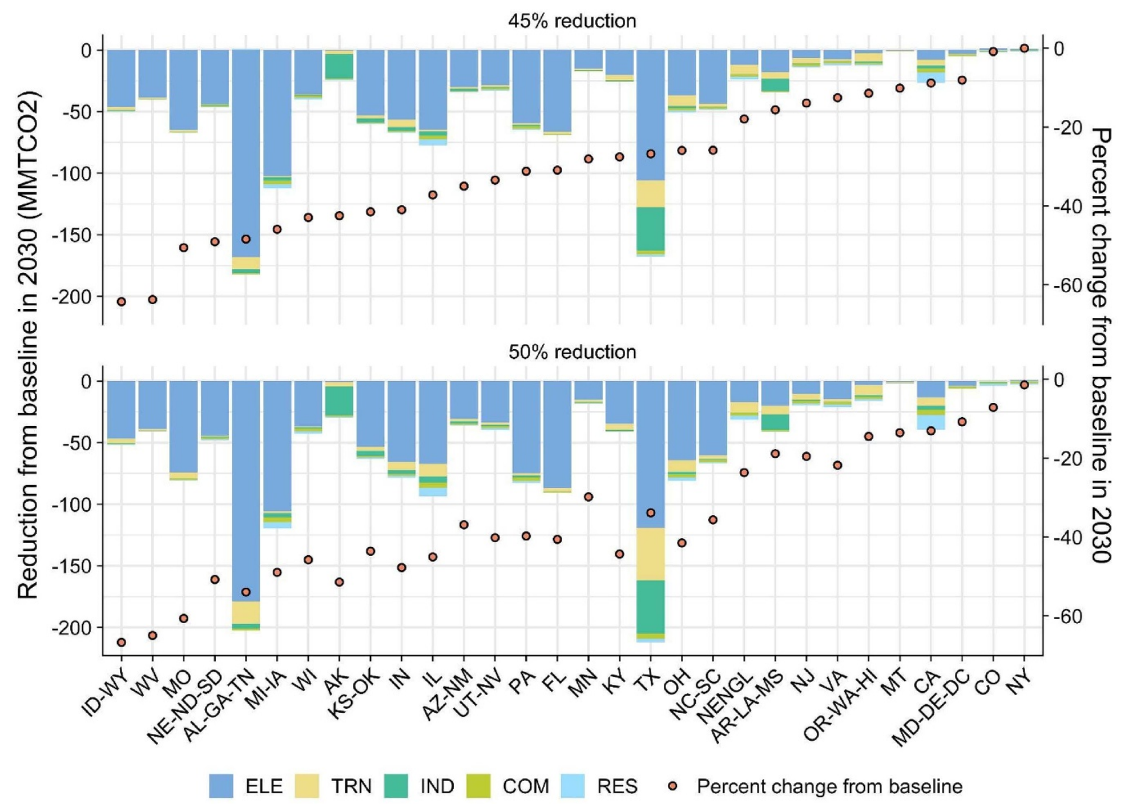

Figure 2. Percent reduction in 2030 from baseline emissions, by state/region and sector. Reductions in CO_2 by sector in 2030 relative to the mid-range baseline across states/regions under equal marginal cost allocation. Right-hand axis shows percentage reduction relative to the baseline. States/regions are ordered by percent change from baseline in the 45% reduction scenario. (ELE is the electricity sector, TRN is transportation, IND is industry, COM is the commercial sector, and RES is the residential sector.)

earlier, of avoiding a sector-by-sector approach that would naturally focus on the most attractive near-term target sector(s). The uniform incentive across sectors avoids the leakage that would be expected from a focus just on the electric sector and captures efficient reductions available elsewhere. At the same time, states may choose to adopt additional measures that could alter the balance of reductions across sectors. For example, transportation planning has often been a key part of state plans under other parts of the Clean Air Act (EPA [U.S. Environmental Protection Agency] 2022) and could help increase reductions occurring in that sector (Javid *et al* 2014).

States with significant energy-intensive and fossil energy production such as TX, AK, and Arkansas-Louisiana-Mississippi (AR-LA-MS) show the greatest reduction in emissions from industry, in part because fossil fuel industries (such as refineries) shrink, lowering emissions from them. AK and MT have very little or no reduction from the power sector relative to the baseline. In AK, the power sector accounts for less than 10% of emissions, so even a substantial reduction in the power sector would not contribute much to the state's overall reduction. As noted earlier, MT has shifted largely to wind power in the baseline, so no additional power sector reductions are available. Similar to MT, in CA and the RGGI member states—New England (NENGL) and New Jersey (NJ)—the electric sector achieves a large share of reductions in the baseline, leading non-electric sectors to play a bigger role in the overall reduction.

Notably, we are considering only CO_2 emissions from industry and energy, so possible contributions from reductions in CO_2 emissions from land clearing or increases in land carbon uptake are not considered here, nor is the role of non-CO_2 GHGs. While these sources and potential sinks are included in U.S. international commitments, efforts to reduce these emissions or enhance sinks could take various forms. For land use, the current U.S. NDC contemplates a range of measures aimed at changing agricultural and land use practices. We note that trading systems have not directly included land use and have limited the use of such reductions as offsets out of concern that design and/or enforcement issues in a credit system could severely undermine the integrity of the cap and trade system (Reilly and Mercier 2021). The EPA could also choose to include some other GHGs in the 115 program (as California does for some sources under AB32's cap and trade system), or it could rely on a mix of subsidies or other regulations to reduce those emissions. For example, the current U.S. NDC includes updated regulations for methane from oil and gas and includes the new, dedicated trading system under the American Innovation and Manufacturing (AIM) Act for hydrofluorocarbon (HFC) reductions (EPA [U.S.

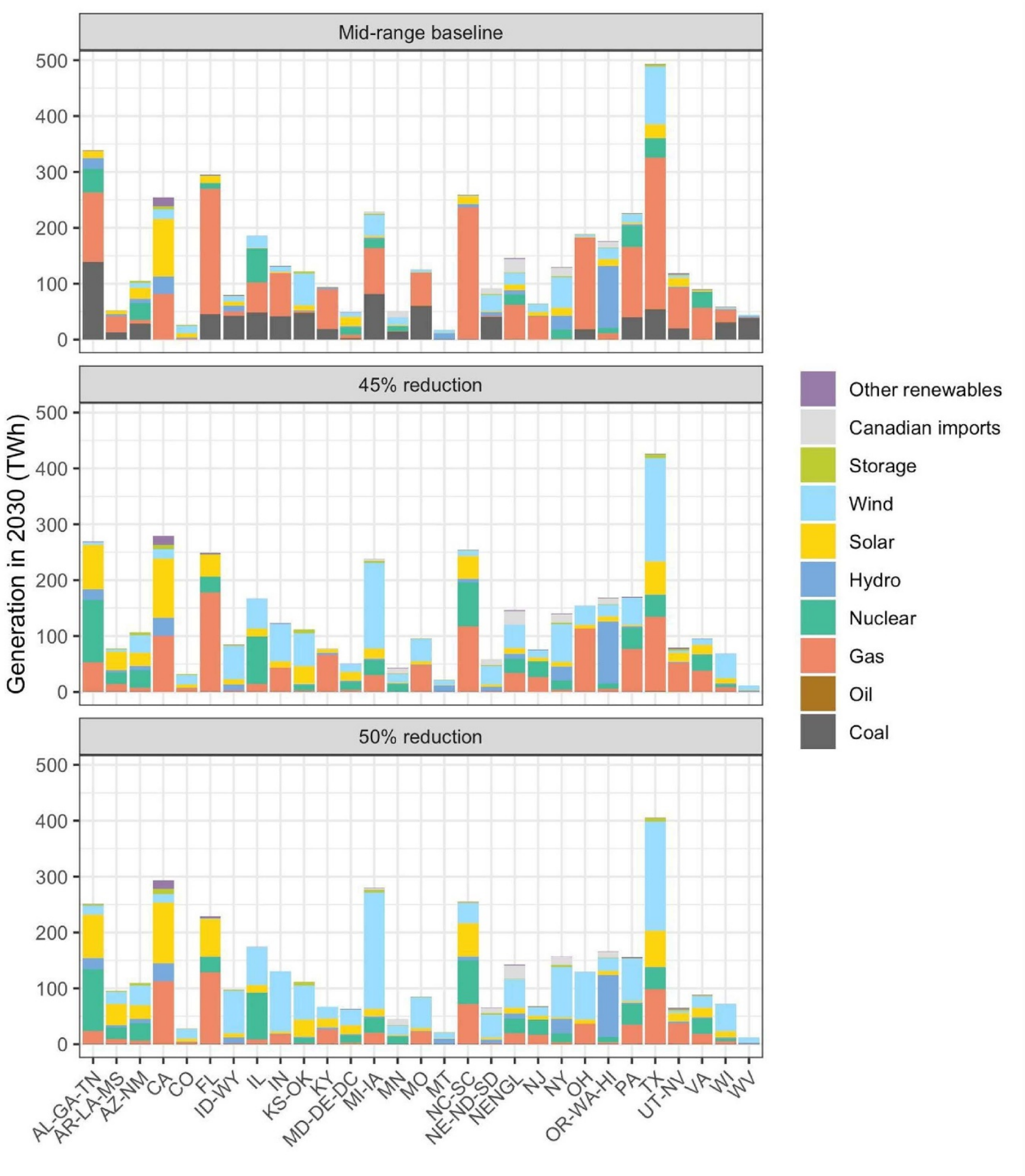

Figure 3. Sources of electricity generation in the power sector by state/region, mid-range baseline. Generation by state/region for the 45% and 50% reductions are under equal marginal cost allocation. States/regions are ordered alphabetically.

Environmental Protection Agency] 2021, U.S. NDC [The United States of America Nationally Determined Contribution] 2021).

If these various sources are not included in the cap and trade system, and addressed instead through other means, then they would only have very indirect effects on the results presented here. For example, if subsidies or control measures on agricultural sources of methane or nitrous oxide led to changes in agricultural prices, a different level of agricultural production might result, with consequences for CO_2 emissions from energy use in agriculture. But this addition would have only a very small influence on the emissions price. We have not evaluated the inclusion of offsets in a Section 115 program, which some legal scholars believe the EPA may have authority to do (Schwartz 2020), but this would likely further reduce carbon prices in 2030. An administration using Section 115 would need to adjust the stringency of the program to account for their projected ability to reduce GHGs outside the program in order to hit any given all-GHG target (for example by increasing reductions in fossil CO_2 emissions if land use emissions are projected to increase and/or non-CO_2 GHG emissions are harder to reduce).

Within the electric sector (figure 3), both wind and solar generation increase significantly compared with present levels. With cross-state trade and trade in carbon allowances, states without large low-cost wind and solar resources have options of importing lower carbon electricity, buying allowances, or some combination of imports and allowances rather than necessarily producing all the low carbon electricity needed within the state. Solar resource advantaged states, who also have heavy air conditioning demand in the summer when solar energy is abundant, invest more heavily in this solution (e.g. states in the southwest and south). Other states with large wind resources (central and plains) generate more power from wind. Matching supply over the course of seasons and peaks of demand can lead to a more even combination of both (TX, KS-OK).

Consistent with several recent studies (Abhyankar *et al* 2021, Bistline *et al* 2021, Hultman *et al* 2021), conventional coal-fired electricity generation retires as uneconomic in all states under both the 45% and 50% reduction scenarios[12]. The biggest difference between the two reduction scenarios is much less generation from gas in the 50% reduction scenario in IN, KY, OH, PA, and VA, but even in that case there remains room for a significant component of gas generation. (See supplementary material D for the percentage share of electricity generation by energy source) Various studies have shown that gas generation can play an important role in keeping costs low with intermittent renewables because its capital cost is relatively low and it can be ramped up to meet demand when other sources are not available. For example, a recent NREL study showed costs of abatement in the electric sector rising rapidly to several hundred dollars per ton of carbon abated when renewable contributions rise above 80% (NREL [U.S. National Renewable Energy Laboratory] 2021).

The expansion of renewable generation comes along with an increase in capacity investment. In 2030, overall power project investment rises by about $50 billion in the mid-range 50% reduction scenario compared to the mid-range baseline. Going forward past 2030 and anticipating deeper cuts, either the contribution of emissions reductions from other sectors will need to ramp up with investment support for technology breakthrough and deployment, or gas use in the power sector will need to decline further. If cost-effective reductions are not available in other sectors and electricity storage remains expensive, marginal costs of reductions may ramp up rapidly with deeper cuts, as in the NREL analysis cited above.

An additional interesting result is the expected pattern of trade among states in allowances. Figure 4 reports the difference between the implicit number of allowances a state would receive (given its allocated reduction amount) and emissions in the state after abatement (i.e. the number of allowances that would need to be turned in by state entities to cover remaining emissions) under the mid-range 50% reduction case.

In figure 4 the states/regions are ordered clockwise, starting with the highest net sales under the equal percentage cut from base year allocation, and ending with the largest net purchasing state. As a result, the equal per-capita plot spirals in, showing AL-GA-TN to be the largest net seller of allowances and TX to be the largest net buyer. We plot the absolute level of net allowance sales, and so larger states (in terms of population and emissions) are likely to be larger net buyers or sellers because an allocation deviating just a few percent from remaining emissions will result in larger net absolute purchases or sales than a small state where the allocation could deviate by a larger percentage. TX is the largest net purchaser under both equal percentage cut from base year and equal per-capita allocations. CA is the second largest purchaser under the equal percentage cut from base year allocation, but is the largest net seller under equal per-capita. Other states that swing considerably among the allocation formulas are NY, NENGL, FL, IN, and KY. MN, WI, CO, and UT-NV show virtually no net trade in any of the allocations indicating that all require an almost identical reduction under both stringencies and the emissions allocation is almost exactly the level of remaining emissions.

An equal marginal cost allocation rule ensures that the number of allowances implicitly allocated to each state would equal the allowable emissions under that allocation. Of course, any model/analysis supporting the allocation would only approximate reality, leaving the likelihood that allowances required in each state would differ from those implicitly assigned. In addition, absent specific restrictions, any entity in any state could purchase allowances at initial auction, or wait to purchase them in the 'after-market' if they needed them to cover their emissions. Hence, even if the equal marginal cost allocation perfectly approximated actual abatement in each state, there is likely to be net trade among states because there is no reason to expect that entities in each state would purchase an amount at initial auction that would add up to exactly to the amount the state would need.

3.2. Economic impacts

3.2.1. Welfare

To capture the social costs and benefits of the policy, we use the welfare metric of compensating variation. The USREP model provides a measure of welfare at the state level, which is computed as state consumption, taking account of changes in leisure and reflecting both compliance costs and revenue from allowance sales. (See supplementary material E for state revenues from allowance sale under mid-range and low-cost assumptions.) It endogenously calculates direct welfare effects of mitigation policies, discussed

[12] Our model includes coal with carbon capture and storage as a technology option, but it does not deploy on this time frame.

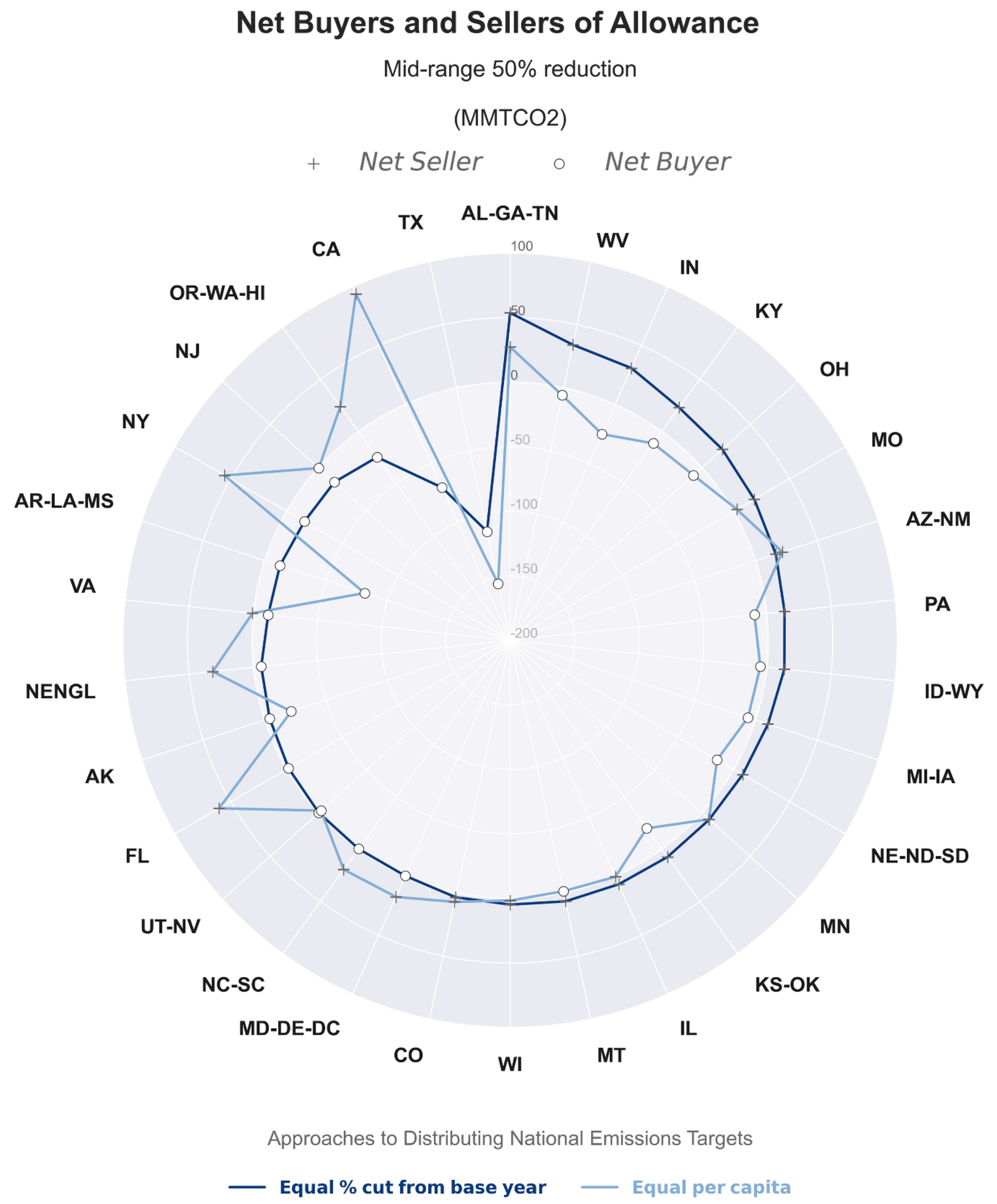

Figure 4. Net allowance sales (+) or purchases (◦) given the state allocation for the equal percentage cut from baseyear and equal per-capita allocations. The equal marginal cost allocation, not plotted, would be a perfect circle at 0.0. Shading indicates the net trade position: darker is selling, lighter is buying.

in this section. These endogenous estimates do not include benefits of improved air quality or reduced climate impacts, considered below.

At the national level, the impacts of emissions reductions on welfare are modest. Even before accounting for climate and air quality benefits, economic welfare continues to grow at almost the baseline rate in all scenarios. Achieving a 45% reduction in CO_2 delays the economy reaching its January 1, 2030 level of welfare by only 1.6 months, to mid-February. Meeting a 50% target means that welfare reaches the same level by mid-March (a 2.5 month delay).

The welfare effects differ among the states, and this effect also differs depending on the choice of allocation method (figure 5). States with high emissions in 2005 relative to population such as WV are favored under the equal percentage cut from base year. The greatest reduction in welfare growth occurs in the state most heavily dependent on energy production, Alaska (AK). Because of the significant number of allowances it would receive, West Virginia

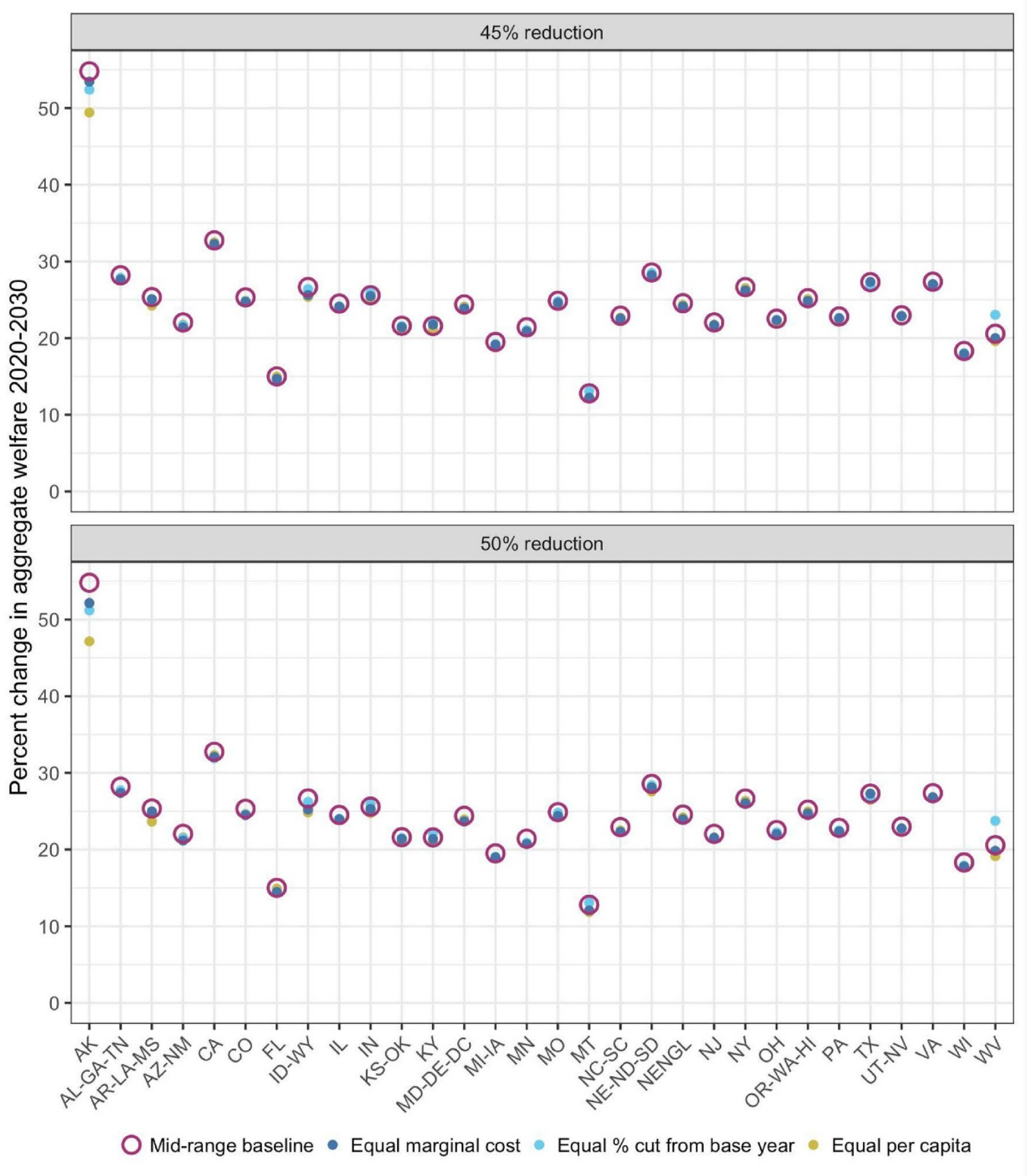

Figure 5. Percent change in aggregate welfare under equal per-capita, equal marginal cost and equal percentage cut from base year allocations. Percent change in welfare 2020–2030 in the mid-range baseline (red circles) compared to growth in the 45% reduction case under the three allocation methods. Welfare growth does not include health or climate benefits in the policy cases. States/regions are ordered alphabetically.

(WV) has a noticeable gain in welfare under the equal percentage cut from base year allocation.

3.2.2. Monetized benefits and costs

Estimated monetized net benefits, shown in table 4, are positive and significant in all the cases studied, ranging from \$94 billion (low-cost 45% reduction; low reduced mortality) to \$201 billion (mid-range 50% reduction; high reduced mortality). Mortality and climate benefits are greater in the 50% reduction than in the 45% reduction scenarios. They also are greater under the mid-range assumptions than under the low-cost baseline, because the lower baseline has lower pollution emissions to begin with. Mortality benefits from reduced $PM_{2.5}$ exceed climate benefits under the high response of mortality to $PM_{2.5}$ exposure but are less than climate benefits with the Low estimate, and $PM_{2.5}$ related mortality benefits alone offset negative welfare impacts except under the mid-range assumptions with the lower mortality response. Compared to the assumed SCC of \$86/ton CO_2, the national average health benefit per ton of CO_2 reduced ranges from \$39/ton (mid-range; low reduced mortality) to \$100/ton (low cost; high reduced mortality), as shown in table 4, although these results vary spatially. $PM_{2.5}$ related mortality

Table 4. Avoided mortality (lives), and welfare cost and benefits[a] (2018$ billion), for the Continental U.S. in 2030 relative to mid-range and low-cost baselines, for high and low concentration response functions.

	Mid-range		Low-cost	
Net benefits (high response)	45%	50%	45%	50%
Reduced adult mortality from $PM_{2.5}$	**11 852**	**14 356**	**8027**	**10 834**
Climate and health benefits	**242**	**293**	**155**	**209**
Health benefits	123	149	83	112
Climate benefits	119	144	72	97
Change in welfare (cost only)	**−60**	**−92**	**−15**	**−29**
Net benefits	**182**	**201**	**141**	**180**
Marginal health co-benefit ($/t$CO_2$)	**89**	**89**	**100**	**100**
	Mid-range		**Low-cost**	
Net benefits (low response)	**45%**	**50%**	**45%**	**50%**
Reduced adult mortality from $PM_{2.5}$	**5230**	**6334**	**3544**	**4782**
Climate and health benefits	**174**	**210**	**109**	**146**
Health benefits	54	66	37	50
Climate benefits	119	144	72	97
Change in welfare (cost only)	**−60**	**−92**	**−15**	**−29**
Net benefits	**113**	**118**	**94**	**118**
Marginal health co-benefit ($/t$CO_2$)	**39**	**39**	**44**	**44**

[a] Not all air quality or climate benefits can be monetized with current tools.

benefits were calculated at the state level and are generally greater for the eastern half of the U.S. where air quality levels are poorer due to greater coal power generation, which disappears in the policy scenarios (Yuan *et al* 2021). At the time of this analysis, state level metrics to evaluate climate benefits associated with reduced CO_2 emissions (e.g. state level social costs of carbon) are not available, and therefore we are unable to estimate aggregate state level partial net benefits reflecting changes in air pollution, climate and economic welfare. (Net benefit results using a SCC reflecting a 3% discount rate ($59/ton) is available in supplementary material F.)

The finding that monetized climate and health benefits exceed climate policy costs is consistent with prior literature, including numerous studies reviewed in Gallagher and Holloway (2020). For comparison, Dimanchev *et al* (2019) estimated that a carbon price in the Midwestern U.S. could deliver a health benefit of $224 per ton of CO_2 reduced in 2030, while Thompson *et al* (2016) estimated that a carbon price in the Northeastern U.S. could deliver a health benefit of $101 per ton of CO_2 reduced in 2030. The higher value in the former can partly be explained by dirtier emissions baseline in the Midwest than the Northeastern U.S. (e.g. due to greater coal-fired generation). Dedoussi *et al* (2019) estimates historical implied health co-benefits of CO_2 reductions, with a national average of $46/t$CO_2$ in 2011 (2018$), with state values ranging from $7 to $98, again demonstrating regional variation. The national average value was estimated to decline by 71% from 2002 to 2017, decreasing to about $26/t$CO_2$. While assumptions including policy type, stringency and coverage will of course impact magnitudes of health benefits across studies, the present findings provide further evidence of the significant net benefits of decarbonization efforts, even without accounting for significant unquantified benefits.

3.2.3. State/regional revenue

With a uniform national allowance price, the allocation method determines the distribution of funds among the states. The allowance value per capita—the amount states would distribute to each resident if they chose a simple lump sum distribution of revenue—is an identical $669 under the equal per-capita allocation, for the 45% reduction. In the equal percentage cut from base year, the range is from $356 to $2,403, with California (CA) the lowest and Alaska (AK) the highest. Under the equal marginal cost allocation, the range is $424 to $3046, with New York (NY) the lowest and AK the highest. AK has by far the highest emissions per capita, and so both the equal percentage cut from base year and equal marginal cost allocation methods produce smaller impacts than equal per-capita allocation. In general, emissions intensive states are favored by the equal percentage cut from base year and equal marginal cost allocations. West Virginia (WV) and Montana (MT) are especially favored under the equal percentage cut from base year allocation because by 2030 their emissions in the baseline have already fallen substantially (and they were emissions intensive in 2005). (More state revenue details are provided in supplementary material C.)

3.2.4. Distributional effects

An important concern of policymakers is to avoid regressive policy measures. While the price increases resulting from requiring emitters to hold allowances have the potential to be regressive because low income households spend a larger share of their income on energy, the allowance revenue provides a means to offset these regressive effects[13]. Per-capita rebates generally have the effect of making carbon pricing policies progressive, with net *improvements* in welfare to the lowest income households relative to baseline projections (Caron *et al* 2018a, 2018b, Metcalf 2019a). This is in strong contrast to cap and trade systems that freely allocate the allowances to producers. As shown by Rausch *et al* (2010, 2011a, 2011b) free allocation to producers exacerbates the distributional effects as the value of allowances become a lump sum distribution to companies, with the value ultimately going to owners/shareholders of the companies, largely higher income households. States would have the option of free allocation of their share of allowances to some producers (for example to trade exposed industries) or to use the allowances for other purposes (e.g. energy efficiency) which would alter the distributional impacts seen here.

The welfare effects by income level we report in this section do not include air pollution or climate benefits. Some studies (Hajat *et al* 2015) have found health impacts from poor air quality tend to fall on lower-income households in the U.S., which means a Section 115 policy could produce further welfare improvements for those households. This will depend on what sources of pollution are reduced, and further analysis is needed to determine if the abated pollution sources disproportionately contribute to the health problems of lower income households.

The per-capita rebates lead to modest welfare improvements for the lowest income quintile (relative to the baseline) in all 50 states under a 45% reduction (figure 6). The second income quintile also sees welfare improvements in regions representing 19–33 states with 36%–51% of the U.S. population, depending upon the allocation approach[14]. The largest reductions in welfare growth are generally in the highest income quintile, with the impact still usually less than 1%. At the national level, this translates to a delay of −1.3–9.6 months in reaching the baseline welfare level of 2030 for the highest income quintile, depending upon the region and allocation approach. Across states and regions there is, as expected, variability in the patterns of the distributional impacts.

4. Discussion

This analysis investigates a carbon allowance program, as it might be implemented under Section 115 of the Clean Air Act, designed to meet a 45% or 50% 2030 CO_2 emission reduction goal. As with many Clean Air Act programs for other pollutants, the EPA would lay out goals and guidelines, leaving implementation details to be decided by the states. Economic efficiency would be best achieved through such a trading program with broad scope, but a state could choose other policies to meet its target, such as command and control measures, if they better met individual circumstances and policy goals[15]. We note that formal implementation of Section 115 will require detailed attention to the interaction between existing state emissions trading systems and Section 115, as states would face a range of options which may include using existing programs to meet their obligations without participation in the model rule, phasing out existing programs in favor of the model rule, or some hybrid (Wentz and Snyder 2020).

Our results show that, using Section 115, the emissions prices and welfare costs are substantially lower than those found in studies a decade earlier (e.g. Fawcett *et al* 2009) but in line with more recent studies (Barron *et al* 2018, Larsen *et al* 2018, Kaufman *et al* 2019, 2020, EIA [U.S. Energy Information Administration] 2020b). The difference is likely due to a combination of continuing expansion of ambitious state policies in the electricity sector, reduction in renewable energy costs, and (more modestly) the growth and emissions effects of the pandemic. The policy is also progressive. Consistent with earlier studies (Rosenberg *et al* 2018, Caron *et al* 2018b, Metcalf 2019b), equal lump sum payments to state residents generally lead to net benefits to lower income households.

When the mitigation cost is combined with the monetized health benefits of reduced particulate air pollution and climate benefits using the social costs of carbon, we find positive net benefit to the U.S. in all cases. Including air pollution-related health benefits from avoided morbidity outcomes (in addition to avoided mortality included here) or other climate damages would further increase the net benefit. Section 115 is one avenue to establishing such a

[13] Equal lump sum distribution of allowance revenue tends to be progressive because even though lower income households spend a larger share of their income on energy, their absolute level of expenditure is much less than wealthier households. In addition, our background assumption of holding total tax revenue unchanged (in real terms) maintains federal expenditures, including transfer payments, constant, essentially indexing transfer payments for any price changes. Such indexing of transfer payments also contributes to policy progressivity (Cronin *et al* 2017, Goulder *et al* 2019), although only for those who receive significant transfer payments (i.e. not necessarily the working poor).

[14] Under the 50% reduction, depending on the allocation method the lowest income quintile sees welfare improvements in 49–50 states containing 94%–100% of the US population. Welfare in the second income quintile improves in 19–27 states with 31%–46% of the U.S. population.

[15] For example, some states such as California and New York have increasingly focused on ways to combine market measures with tools to address environmental injustice.

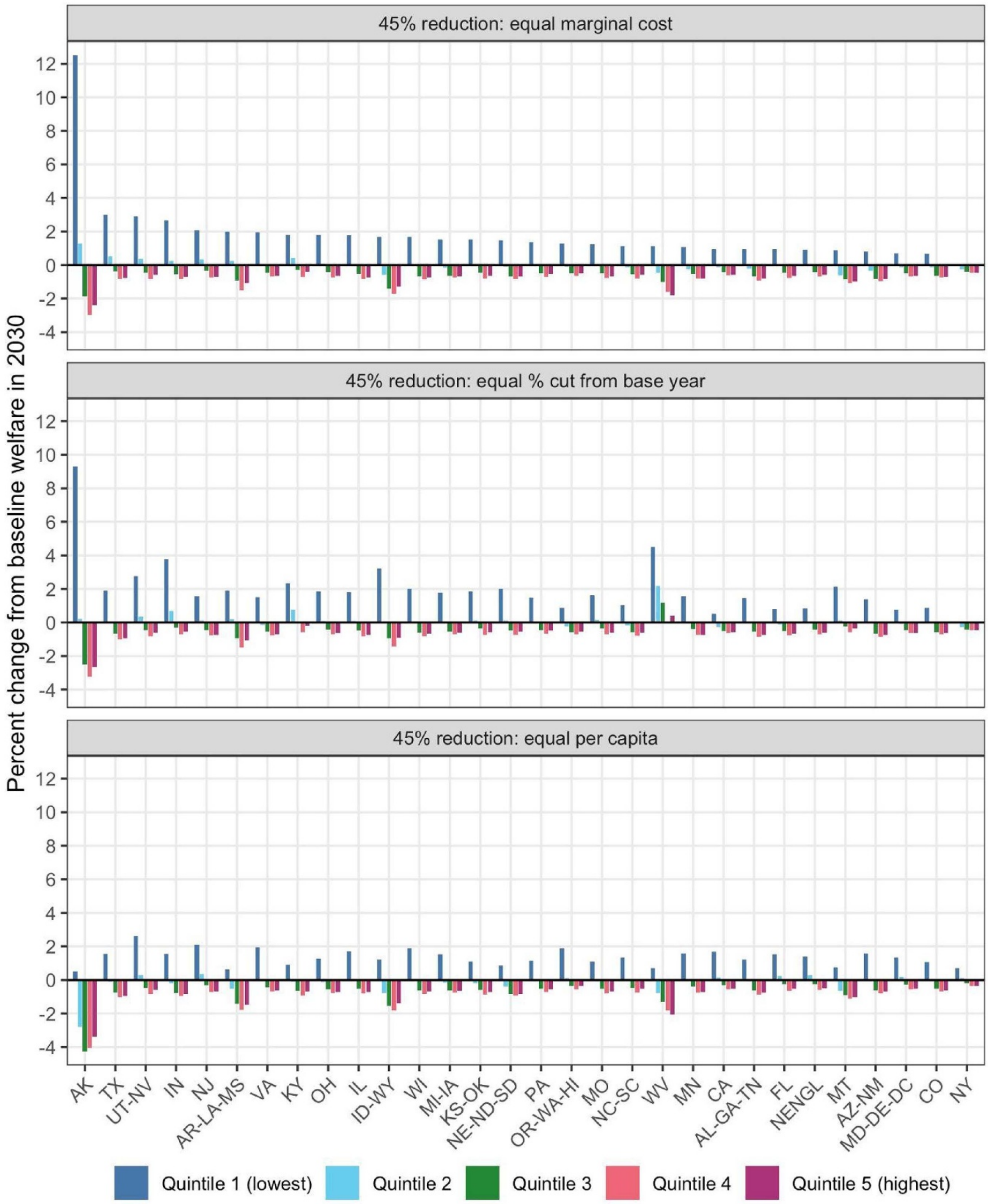

Figure 6. Distributional impact by income quintile, 45% reduction by equal marginal cost, equal percentage cut from base year, equal per-capita allocations. State/regional welfare impacts, stated as a percent change from welfare in the mid-range baseline in 2030, by national income quintile under each allocation method. Does not include air pollution or climate benefits. States/regions are ordered by percent change in quintile one welfare under the equal marginal cost allocation. Relative to 2020 (not shown in figure), all income quintiles in all states/regions see welfare increases in 2030, regardless of the allocation method.

trading program with broad scope, but the analysis presented here could be generally applicable to the establishment of a trading program under other authorities.

The disaggregation of the U.S. in the USREP-ReEDS model for this analysis, to 30 individual states and multi-state regions, yields useful insight into the potential differential effects of the policy among states and issues in its implementation. For example, because Section 115 would be implemented through a state implementation plan (SIP process), the costs, benefits and impacts attributable to the program depend on the emissions policies already put in place by a state. The analysis reveals that states such as Colorado, New York and California, which already have ambitious economy-wide programs, would need to achieve few, if any, additional reductions to comply with the program (figure 2). Technology advances, such as greater reductions in solar cost as assumed in the low-cost baseline, might enable states like Arizona and New Mexico to meet their goals with little additional effort as well (supplementary material figure C2).

The detailed representation of individual states also shows the degree to which regional disparities in welfare cost can be moderated by the allocation of allowances among the states. There are strong correlations between emissions, costs of reduction, and population among states, so the differences resulting from different allocation procedures are relatively small for most states. Still, allocation by marginal cost or reduction from base year appears better than per capita at reducing the negative outliers in per-capita impacts. The EPA could seek input on other approaches, including combinations of these three studied here, to further reduce disparities across states and regions.

The analysis results also highlight the advantages, particularly at this critical stage of federal policy formulation, of a policy that can impose a uniform price incentive across all economic sectors. Not surprisingly, the lowest cost emission reductions are in the electric sector. General recognition of this fact easily leads to a sector-by-sector approach to emissions reduction with a dominant focus on this sector—e.g. some version of the Power Plan proposed by the Obama Administration, a clean energy standard, and/or extension of existing subsidies to renewables. As shown in figure 2, even at the prices found in this analysis, a substantial fraction (19%–23%) of cost-effective reductions is available outside the electric sector. This fact highlights two advantages of a broad carbon pricing policy (perhaps with a collection of additional regulations for emissions outside CO_2 from industry and energy). First, a focus on just one or two major polluting sectors runs the risks discussed in section 2, of missing low-cost reductions in the near term, discouraging electrification, and even causing leakage of activities from electricity use into other technologies, perhaps based on natural gas. Second, and perhaps more important, a sectoral approach misses the opportunity to bring all sectors into a system providing equivalent economic incentives for emissions reduction across the economy, as would be appropriate for meeting the longer-term challenge. A path to zero emissions can be imagined in the electric sector given current technologies, but other sources, like industrial emissions and air travel, will be much more difficult to control. Something like the Section 115 implementation examined here would be a major step toward signaling that all sectors need to decarbonize. Hybrid approaches are also possible. For example, if the Congress were to enact an expanded system of subsidies and penalties directed at electricity sector emissions, many more states might find themselves already in compliance with the targets in a Section 115 program.

As we noted in the introduction, any administration considering Section 115 would have to weigh legal, policy, and political risks against the benefits of such a program. An updated analysis of the likely impacts of the policy, following an approach similar to the one conducted here, can help to illuminate economic, health and policy tradeoffs of different policy approaches.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.6391179

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Conflict of interest

The authors declared that they have no conflict of interest. For transparency, we note that A. R. B. has consulted in the past for Environmental Defense Fund and the Center for Applied Environmental Law and Policy on topics unrelated to this study.

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