BEYOND HEALTH CO-BENEFITS: AIR QUALITY-RELATED EQUITY IMPLICATIONS OF US DECARBONIZATION POLICY

by

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Abstract

Emissions of greenhouse gases (GHG) that contribute to climate change are often associated with emissions of air pollutants that react to form fine particulate matter ($PM_{2.5}$), which is a significant cause of premature mortality and disproportionally harms people of color and low-income populations in the U.S. Ambitious climate policy to decarbonize the economy may be an appealing pathway to concurrently reduce air pollution and improve health, and a growing body of literature has established the significant health benefits from policies aimed to reduce GHG emissions. However, uncertainty remains about how different U.S. decarbonization strategies might affect air pollution-related health disparities.

This thesis explores the extent to which near-term federal carbon pricing can reduce racial/ethnic disparities in air pollution exposure, as well as pathways to reduce these disparities more generally. The main policy instrument evaluated here is an economy-wide cap-and-trade program that reduces carbon dioxide (CO_2) emissions by 50% in 2030. The analysis leverages modeled energy-economic scenarios to estimate emissions reductions under the policy and applies an air quality model to evaluate $PM_{2.5}$-related equity outcomes. In 2030, we estimate that the policy drives national emission reductions of sulfur dioxide (49%) and nitrogen oxides (16%), with smaller changes in other $PM_{2.5}$-related pollutants, relative to a baseline with no federal carbon policy. The policy reduces average $PM_{2.5}$ exposure for all racial/ethnic groups that we evaluate, with the greatest benefit for Black and non-Hispanic white populations primarily due to changes in the electricity sector. However, despite reductions in average $PM_{2.5}$ exposures, disparities remain under the policy, and the relative gap in exposure between non-Hispanic white people and people of color slightly widens on average. Sensitivity analysis evaluating alternative distributions of emissions that are consistent with total CO_2 reductions under the policy have limited impact on the results. We conclude that near-term federal carbon pricing can reduce air pollution exposure overall but has minimal impact on disparities, emphasizing the need for complementary policy to fulfill goals of mitigating environmental injustices.

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Chapter 1: Introduction

Emissions of greenhouse gases (GHG) that contribute to climate change are often associated with emissions of air pollutants that lead to the formation of fine particulate matter ($PM_{2.5}$), which causes upwards of ~200,000 premature deaths in the U.S. and disproportionally harms people of color and low-income populations (Burnett et al., 2018; Tessum et al., 2021). A growing body of literature has demonstrated how policies aiming to reduce GHG emissions, such as carbon pricing, can concurrently reduce air pollution and improve public health (Gallagher and Holloway, 2020). Therefore, implementing ambitious climate policy that decarbonizes the economy may be an appealing pathway to address air pollution concerns. However, uncertainty remains about how different U.S. decarbonization strategies might affect disparities in air pollution exposure. Addressing this question will be important to the Biden-Harris Administration's stated goals of addressing both climate change and environmental injustices in the U.S. For example, the Justice40 Initiative aims to ensure that disadvantaged communities receive at least 40% of benefits, including health benefits from reduced air pollution, resulting from certain climate and clean energy related federal investments (The White House, 2021). This thesis explores (1) the extent to which near-term federal carbon pricing can reduce racial/ethnic air pollution disparities, (2) if emissions distributions different than those under the carbon policy can better mitigate disparities while still achieving the same total CO_2 reductions, and (3) what gaps should be addressed by additional intervention (beyond market-based decarbonization policy) to address environmental injustices more directly.

Air pollution is a leading cause of premature mortality worldwide, predominately from exposure to ambient $PM_{2.5}$, which are aerosols – particles suspended in gas – that are less than 2.5 micrometers in diameter. $PM_{2.5}$ can deeply penetrate the lung and blood stream, leading to both fatal and nonfatal cardiovascular and respiratory illness (WHO, 2021a). $PM_{2.5}$ is both directly emitted (primary $PM_{2.5}$) and formed in the atmosphere through reactions among precursor gases (secondary $PM_{2.5}$), including sulfur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3) and volatile organic compounds (VOC). In 2015, one study attributed 4.2 million premature deaths to $PM_{2.5}$, ranking it as the 5th highest mortality risk factor and causing 58% of air pollution related mortality (Cohen et al., 2017). In the same study, indoor air pollution caused 2.8 million deaths (39%) and ozone caused 0.25 million (3%). In the U.S., despite improved air quality over the past half century, $PM_{2.5}$ is still responsible for substantial health damages and policies to reduce both primary $PM_{2.5}$ and precursor emissions are therefore critical to improving air quality and public health.

Significant disparities in air pollution exposure have been well documented in the U.S., disproportionately harming people of color and low-income populations for decades and persisting despite improvements in air quality (Colmer et al., 2020; Jbaily et al., 2022; Liu et al., 2021). Disparities by race/ethnicity are greater than disparities by income and exist across all income groups (Liu et al., 2021; Tessum et al., 2021). Tessum et al. (2019) show that racial/ethnic disparities also remain when accounting for group contributions to pollution (based on consumption): in 2014, Black and Hispanic people were estimated to be exposed to 56% and 63% more $PM_{2.5}$ than they were responsible for; in contrast, non-Hispanic white people experienced 17% less. Furthermore, Tessum et al. (2021) demonstrate the systemic nature of these disparities, showing that most sources of $PM_{2.5}$ disproportionately harm people of color (defined here as everyone except non-Hispanic white people), Black, Hispanic and Asian populations, including emissions from industry, light-duty gasoline vehicles, construction, and heavy-duty diesel vehicles; in contrast, coal-fired electricity generation and agriculture are the only sectors disproportionately harming non-Hispanic white people. These disparities in part reflect systematic environmental racism, including long-lasting consequences of discriminatory practices such as redlining in the 1930s where racially-biased mortgage appraisals favored white people and resulting in people of color living in more polluted neighborhoods (Lane et al., 2022). These inequitable health burdens extend beyond direct harm from $PM_{2.5}$ exposure, including more recently where higher exposure to $PM_{2.5}$ was linked to higher death rates from COVID-19, especially among people of color (Dey and Dominici, 2021). The urgency is high to identify and target systemic causes of already well-established air pollution inequities to achieve environmental justice goals (Levy, 2021; Van Horne et al., 2022).

Many studies have evaluated health benefits of climate and clean energy policies (sometimes referred to as "co-benefits"[1]), often conducting benefit-cost analyses (BCA) – where total

[1] The term "health co-benefits" is commonly used to describe benefits that arise from reducing emissions of pollutants other than CO_2 that are not directly targeted by the policy. However, it may imply that the benefits are secondary to climate benefits from reduced CO_2 emissions, even though the health benefits can be significant and, when monetized, can even exceed the climate benefits (Gallagher and Holloway, 2020). Therefore, we simply use the language "health benefits."

monetized health and climate benefits are compared to total policy costs. Here, health impact assessments can estimate air quality-related health benefits. The first step involves estimating concentrations of, and population exposure to, $PM_{2.5}$. Next, epidemiologically derived concentration-response functions (CRF) are applied to associate changes in exposure to health impacts, such as mortality and morbidity outcomes. Finally, the health outcomes can be monetized, such as by applying a value of statistical life (VSL) for the case of premature mortality. Gallagher and Holloway (2020) review 26 such studies demonstrating these health benefits of climate policy, including numerous finding that health benefits can often exceed the estimated climate benefits as well as implementation costs of the policy alone (e.g., Dimanchev et al., 2019; Thompson et al., 2016). Sergi et al. (2020) further demonstrate how simultaneously penalizing both climate and health emission damages from electricity generation yields greater net benefits than penalizing only climate damages. The BCA framework can therefore be a valuable tool to estimate total net benefits of a policy to society, weigh trade-offs among policy options, and recognize health benefits from improved air quality due to climate policy. However, this approach ignores distributional impacts, and while studies have evaluated distributional effects of climate policy on economic welfare by household income group (e.g., García-Muros et al., 2022; Rausch and Mowers, 2014; Williams et al., 2015), far fewer have evaluated effects on air pollution-related disparities.

Despite well-established health benefits of climate policy, some environmental justice (EJ) proponents have argued that market-based carbon policies will not address air pollution disparities, leading to efforts such as in California and Washington to adopt distinct and explicit EJ provisions as complements to carbon pricing (Roberts, 2021). While the impact of carbon emissions is the same regardless of the location of emissions (because carbon becomes well mixed in the atmosphere), the local nature of air pollution such as $PM_{2.5}$ means that changes in air pollution-related health burdens due to policy can be distributed unequally throughout society. Emissions markets do not guarantee reduced air pollution exposure in disadvantaged communities, and in theory have the potential to exacerbate local air quality. For example, a CO_2 cap-and-trade program sets a total limit on emissions and incentivizes emission reductions from the cheapest- or easiest-to-abate sources to achieve the specified emissions limit. Communities affected by sources with lower marginal abatement costs will typically benefit more, and therefore equity outcomes depend on the characteristics of these communities (Burtraw et al., 2005; Hernandez-Cortes and Meng, 2020). Furthermore, reductions in one location may result in increased emissions outside of the policy coverage ("leakage") that could increase exposures (Thompson et al., 2016). More generally, while relatively lower-cost carbon reduction opportunities in the near term primarily exist in the electricity sector (Yuan et al., 2022), where emissions from coal generation disproportionately harm Black and white populations (Tessum et al., 2021; Thind et al., 2019), harder-to-decarbonize sources contribute significantly to pollution disparities (Tessum et al., 2021). Therefore, while polices such as CO_2 cap-and-trade may deliver significant health benefits, they may not adequately address inequity issues particularly in the near term, and these inequities may persist unless they are targeted directly.

Research evaluating air pollution equity impacts of climate policy has primarily consisted of retrospective, econometric analyses of California's existing emissions markets, finding limited but mixed effects on equity outcomes and often concluding that specific EJ measures beyond climate policy will be important in addressing disparities. For example, Cushing et al. (2018) estimate that California's GHG cap-and-trade program that was implemented in 2013 exacerbated inequities, finding that over half of covered facilities increased emissions (with total emissions remaining under the cap) and that areas within 2.5 miles of facilities with increased emissions had higher shares of people of color and low-income people than areas with decreased emissions. In contrast, Anderson et al. (2018) find limited equity impacts of the same program by comparing changes in emissions and disadvantaged counties. While the prior two studies only used locations of emissions changes and community demographics, Hernandez-Cortez and Meng (2020) use an atmospheric dispersion model (HYSPLIT) to track transport of pollutants (but not secondary $PM_{2.5}$ formation), as well as a reduced-form model (InMAP) with secondary $PM_{2.5}$ formation; they find that while disparities had been increasing before the program, the program reduced disparities but did not eliminate them. Moving beyond California, Qiu (2021) evaluates, among other things, how wind power driven by state renewable energy requirements affected disparities in air pollution exposure in 2014. The study estimates which unit specific emissions were displaced (i.e., that would have occurred without the policies) and applies a state-of-the-art chemical transport model (CTM) to understand how population exposures to $PM_{2.5}$ and O_3 changed as a result. On average, the study finds that air quality changes due to policy-induced wind energy deployment vary little by income group, benefit Black and white people more and Hispanic people less the total population on average, and deliver less than 40% of the total benefits to low-income and minority communities (the overall Justice40 target); there is, however, significant variation across state.

Fewer studies have considered equity impacts of future decarbonization scenarios. Li et al. (2022), again focusing on California, apply an energy-economic optimization model and a CTM to evaluate low carbon energy scenarios in 2050, finding that reducing GHG emissions by 80% relative to 1990 levels could reduce racial/ethnic $PM_{2.5}$ disparities by up to 20% (Li et al., 2022). However, with disparities remaining in 2050 under ambitious GHG reductions, addressing disparities especially in the near-term clearly requires additional action. The report by Diana et al. (2021) explores the impact of integrating air quality and equity goals into electric sector decarbonization efforts, by cost-minimizing electricity generation under several hypothetical scenarios in 2018 to meet electricity demand in 26 regions and applying a county-level reduced-form integrated assessment model (APEEP) to link facility emissions to pollution damages. The "carbon alone" scenario assumes CO_2 emissions reductions of 20%, which are primarily achieved by shifting from coal to natural gas generation and worsen disparities for some communities. In contrast, a scenario that additionally reduces air pollution damages by 50% for racial/ethnic groups is achievable in the modeling at only 5% higher cost. However, this study appears to lack important modeling features relevant for addressing equity impacts of decarbonization, such as generation investment, realistic wind and solar profiles, more granular transmission constraints, and existing environmental policies. Lastly, the report in Burtraw et al. (2022) evaluates distributional air quality impacts of reducing U.S. GHG emissions and energy-related CO_2 emissions by 51% and 35%, respectively, by 2030 (relative to 2005 levels). They use an economy-wide energy system model (NEMS) with 25 regions and a county-level reduced-form air pollution model (EASIUR), finding among other things that total premature mortalities are reduced for each racial/ethnic group and income class. However, changes in total air pollution disparities are not addressed and the analysis relies on emissions downscaling methods without exploring uncertainty in sub-regional distributions of emissions changes that could lead to different equity outcomes.

Prior literature has therefore provided important insight to the question of efficiency-equity tradeoffs in market-based climate policy, and with mixed but limited outcomes for equity, suggest that these policies are inadequate to address disparities. However, much of the literature has focused on California, which is not likely to be representative of the rest of the county due to factors such as different existing energy mixes (e.g., little existing coal generation) and differing spatial distributions of pollution sources and disadvantaged communities. Numerous studies have applied econometric tools to compare community demographics in locations with emissions changes, either using facility proximity metrics or air dispersion models, with only few considering secondary $PM_{2.5}$ formation and exposure. While several studies have explored air quality-related equity implications of decarbonization scenarios, a crucial question remains regarding how U.S. climate policy might affect air pollution-related disparities.

Here, we[2] evaluate the air quality-related equity implications of a potential national CO_2 cap-and-trade program that could reduce economy-wide emissions by 50% below 2005 levels by 2030 (approximately in line with 2030 Paris Agreement goals). The analysis leverages modeled energy-economic scenarios to estimate policy-induced emissions reductions and applies an air quality model to evaluate $PM_{2.5}$-related equity outcomes including impacts of disparities in exposure. We provide ranges of outcomes given modeling uncertainty. I discuss policy implications, including gaps that must be addressed by complementary policy to address environmental injustices more directly.

Specifically, I aim to address the following research questions:

1. To what extent can near-term economy-wide carbon pricing reduce racial/ethnic disparities in air pollution exposure?
2. Can emissions distributions different than those under the carbon policy better mitigate air quality disparities while still achieving the same total CO_2 emissions reductions?
3. What gaps should be addressed by additional intervention (beyond market-based decarbonization policy) to address environmental injustices more directly?

This thesis is organized as follows: chapter 2 provides detailed methods, describing the modeled future energy-economic scenarios that we analyze, the emissions inventory development, and air quality modeling to estimate $PM_{2.5}$ exposure and disparities. Chapter 3 provides results, and chapter 4 discusses the role of climate policy in mitigating air pollution related inequities, and more generally, pathways to cleaner and more equitable air.

[2] This thesis draws from work which I led in collaboration with coauthors and forms the basis for a paper in preparation: Picciano et al. (2022). Beyond Health Co-Benefits: Air Quality-Related Equity Implications of U.S. Decarbonization Policy. Manuscript in preparation.

Chapter 2: Methods

This chapter describes in detail the methods we use to evaluate potential impacts of U.S. climate policy on air quality-related equity outcomes. The analysis leverages energy-economic modeling of two future scenarios for 2030, provided by and described in Yuan et al. (2022): (1) a national CO_2 cap-and-trade program that requires a 50% reduction in U.S. economy-wide CO_2 emissions relative to 2005 levels by 2030, and (2) a baseline scenario without the program. Yuan et al. (2022) evaluate the impact of these scenarios, and others, on energy sector activity, CO_2 emissions, household welfare, and total net benefits accounting for climate and air quality-related health benefits as well as economic welfare costs of the policy[3]. The carbon policy scenario in this thesis is relevant to evaluating equity concerns because it reflects the magnitude of CO_2 emissions reductions desired by the U.S. across the entire economy, and the largest emissions reductions come from the electricity sector – a relatively easier- and cheaper-to-abate sector where decarbonization efforts have largely been prioritized in the U.S. thus far.

The methods follow a multi-step process. First, we describe the energy-economic modeling of the baseline and carbon pricing scenarios that produce the energy sector activity that we leverage for this thesis (section 2.1). We then estimate future levels of emissions, using the energy modeling outcomes to scale historical U.S. emissions of CO_2, primary $PM_{2.5}$ and precursor gases that form secondary $PM_{2.5}$ in the atmosphere – SO_2, NO_X, NH_3 and VOCs; without specific information regarding how non-CO_2 emission rates will change over time, non-CO_2 emission factors are fixed at 2017 levels (section 2.2). Using these emissions, we then apply a reduced-form air quality model to estimate annual $PM_{2.5}$ concentrations and population exposures at a fine spatial scale and evaluate disparity metrics across racial/ethnic groups (section 2.3). Finally, we address uncertainty in the estimated emissions reductions under the policy as different distributions of CO_2 emissions could lead to different equity outcomes. Specifically, we produce alternative emissions distributions that are consistent with CO_2 emissions reductions in the energy modeling but provide an upper and lower range for equity outcomes for each racial/ethnic group (section 2.4). Each step is described in greater detail below.

[3] As a co-author in Yuan et al.(2022), I helped estimate that the climate and air quality-related health benefits of the policy outweigh costs (described briefly in section 2.1); however, for clarity in this thesis, the energy-economic analysis was conducted by other team members

2.1. Energy-Economic Scenarios

Yuan et al. (2022) deploy an economy-wide, energy-economic modeling tool (USREP-ReEDS) to evaluate the impact of potential CO_2 pricing policies on energy sector activity, CO_2 emissions, household welfare, and total net benefits. MIT's U.S. Regional Energy Policy (USREP) model is a computable general equilibrium model of the U.S. economy (Yuan et al., 2019), and in these simulations its electricity sector representation has been replaced by the Regional Energy Deployment System (ReEDS), a capacity expansion model of the U.S. electricity sector developed by the U.S. National Renewable Energy Laboratory (NREL) (Cohen et al., 2019). Relevant to air pollution projections in this paper, USREP represents states via 30 regions (including 18 individual states), while ReEDS spans 134 electricity balancing regions (with additional geographic representation of wind and solar resources across 356 regions).

First a baseline scenario without the potential carbon policy is constructed, where results are calibrated to the Energy Information Administration's Annual Energy Outlook 2020 reference case and in addition, reflect NREL's Annual Technology Baseline 2019 Mid-Range electricity technology costs and performance characteristics, updated state clean energy policies, and a COVID-19 pandemic adjustment. Then, the policy scenario is constructed on top of the baseline assumptions by modeling a national CO_2 cap-and-trade program that covers energy and industry-related CO_2 emissions and allows national trading of emissions allowances but without offsets or banking or borrowing across years. The program evaluated in this thesis assumes that CO_2 emission allowances are distributed to states on a per-capita basis and that the state revenue raised from allowance sales are rebated to households. Note that while other choices of allowance allocation schemes evaluated in Yuan et al. (2022) affected economic welfare outcomes, they have negligible impact on emissions outcomes and therefore are not analyzed here. Therefore, we compare two scenarios in 2030 under Mid-Range assumptions: (1) a baseline scenario ("Baseline (2030)" and (2) a CO_2 cap-and-trade scenario ("Cap 50% (2030)"). The energy-economic modeling assumptions are described in greater detail in Yuan et al. (2022).

In the two scenarios that we use in this thesis, Yuan et al. (2022) explain that, relative to baseline, most CO_2 reductions under the policy in 2030 come from the electricity sector (77%) by shifting power generation sources from coal and natural gas to wind, solar, and nuclear, although nonnegligible reductions come from the transportation (10%) and industrial (7%) sectors as well. The national CO_2 trading market established by the cap-and-trade program yields an allowance price of $99 per metric ton in 2030 (2018$). Furthermore, the policy has negligible impacts on economic growth, and rebating program revenue to households particularly benefits low-income Americans, although the method of allocating emission allowance to states is important. After accounting for climate and health benefits, the quantifiable benefits outweigh quantifiable costs: the policy could prevent 4,700-14,000 premature deaths in 2030 from reduced $PM_{2.5}$ pollution, yielding partial net benefits of $118-201 billion (2018$) in 2030. This thesis aims to extend beyond this BCA approach, as discussed in Chapter 1.

2.2. Emissions Inventory and Projections

Next, we describe how we develop emissions inventories for a base historical year (2017) and under the modeled Baseline and Cap 50% scenarios in 2030, including steps to make them compatible with the air quality model that we use (discussed in section 2.3).

2.2.2. Historical Emissions Inventory

We first adjust a detailed, historical inventory: the U.S. Environmental Protection Agency's (EPA) National Emission Inventory (NEI) 2017 containing annual emissions of CO_2, $PM_{2.5}$, SO_x, NO_x, NH_3, and VOC (EPA, 2021a). We use emissions spanning the continental U.S. and apply adjustments required for compatibility with the air quality model, including allocating emissions spatially to grid cells and vertically to effective stack height (ESH) layers (reflecting the height of the emission plume that rises above the physical stack height). The steps differ for point sources and area (county-level) sources.

We use the unique coordinates of each point source to assign the corresponding grid cell that each source is located in. We then calculate ESHs for each point source using stack information (height, diameter, plume velocity, and plume temperature). Specifically, we apply the Holland formula (Turner, 1972), using ambient temperature and wind speed from the air quality model's atmospheric layer that corresponds to the emission source's stack height and location, and ambient pressure that we calculate as a function of sea level temperature and real stack height[4]. If a source's

[4] https://www.mide.com/air-pressure-at-altitude-calculator

stack height data is missing, we use the ESH layer of the nearest source within the same NEI Tier 2 category.

Area sources are county-level and often overlap with multiple grid cells. Therefore, we distribute area source emissions to grid cells using distributions in the NEI 2014 spatial modeling data prepared for use in Tessum et al. (2019). These NEI 2014 distributions reflect spatial surrogates, which are unique to specific emission types (e.g., population for dry cleaning emissions and interstate highways for motor vehicle emissions), that are used in development of EPA emissions modeling platforms (EPA, 2022). Here, we distribute state-level NEI 2017 emissions to grid cells based on the state-grid distribution for the corresponding NEI Tier 3[5] emissions in the 2014 dataset. We then assign all area sources the ground level ESH. Lastly, following Tessum et al. (2019), biogenic and wildfire emissions are from 2005 and held constant.

The resulting inventory contains U.S. emissions of CO_2, $PM_{2.5}$, SO_x, NO_x, NH_3, and VOC with 5,495 unique EPA Source Classification Codes (SCC). In contrast to older NEI versions, the NEI 2017 includes CO_2 emissions for many point sources from the EPA's Greenhouse Gas Reporting Program (GHGRP) as well as for transportation area sources (calculated from EPA's MOVES model). While the GHGRP does not include all sources of emissions, it includes emissions from large facilities and in total covers approximately 85-90% of all U.S. GHG emissions (EPA, 2021b). In processing the inventory for this analysis, we retain the CO_2 emissions.

2.2.3. Emissions Scaling Methodology

We then develop emissions inventories for the two future scenarios. Without specific information regarding how non-CO_2 emissions or their emissions rates will change over time, we scale 2017 emissions to 2030 based on projected outcomes modeled with USREP-ReEDS, assuming that non-CO_2 emission factors are fixed at 2017 levels. The scaling approach largely follows methods outlined by Dimanchev et al. (2019). All emissions – except power sector CO_2, SO_2, and NO_X pollutants from coal and gas fuel sources – are scaled within 29 USREP regions (Alaska is excluded) and using 20 USREP variables matched to NEI SCCs, producing 545 unique scaling combinations nationally (35 region-variable combinations have zero data). The scaling factor is calculated as the regional USREP value in 2030 divided by the value in 2017 (interpolated from

[5] In select cases where there is not a Tier 3 match, 2014 Tier 2 or Tier 1 distributions are used to allocate these remaining 2017 emissions.

2015 and 2020 results). Then, the scaling factor is applied uniformly to emissions of each pollutant (including CO_2) within the region and emissions scaling category. The method differs from Dimanchev et al. (2019) for the electricity sector, where we scale coal and gas power plant emissions for CO_2, SO_2 and NO_X to match ReEDS emissions for 134 balancing areas. CO_2 emissions are then adjusted by USREP region by broader sectors (electricity, transportation, industrial, and residential) to match CO_2 emissions output by USREP, reflecting modeled efficiency improvements over time.

2.3. $PM_{2.5}$ Modeling, Population Exposure, and Disparity Metric

We estimate annual average concentrations of $PM_{2.5}$ for each scenario using the Intervention Model for Air Pollution (InMAP), specifically the InMAP Source Receptor Matrix (ISRM) as described in and provided by Goodkind et al. (2019). InMAP a reduced complexity air quality model (RCM) that reflects atmospheric chemistry and transport of particulate air pollution (Tessum et al., 2017). The model takes a set of emissions data (primary $PM_{2.5}$, SO_X, NO_X, NH_3, and VOC), among other inputs, and predicts annual average concentrations of total $PM_{2.5}$ and its components: primary $PM_{2.5}$, particulate sulfate (pSO_4), particulate nitrate (pNO_3), particulate ammonium (pNH_4), and secondary organic aerosols (SOA). InMAP provides relatively higher spatial granularity than other RCMs or CTMs, while reducing the temporal resolution to annual scale (among other simplifications) to avoid computational requirements from more complex CTMs. Because health impacts from $PM_{2.5}$ are dominated by long-term exposure, annual-scale is suitable for this analysis (Tessum et al., 2017). InMAP has been used and validated in numerous peer-reviewed analyses of air quality and equity impacts of emissions (Goodkind et al., 2019; Tessum et al., 2021, 2019; Thakrar et al., 2020). RCMs, including InMAP, have been evaluated against each other and more sophisticated CTMs in Gilmore et al. (2019).

Given emissions inputs of primary $PM_{2.5}$, SO_x, NO_x, NH_3, and VOC, the ISRM provides the change in respective particulate concentrations (described above) in a "receptor" grid cell caused by a 1 unit increase in emissions of each pollutant in a "source" grid cell. The sum of particulate concentrations of primary $PM_{2.5}$, pSO_4, pNO_3, pNH_4, and SOA equals total $PM_{2.5}$ in each grid cell. The ISRM spatially consists of 52,411 grid cells with resolutions ranging from 1x1 km (in the most population-dense areas) to 48x48 km (in the least population-dense areas), and vertically distinguishes between three ESH layers: "ground" 0-57 m, "low" 57-379 m, and "high" > 379 m.

Emissions inputs – allocated to ISRM grid cells and ESH layers - are multiplied by the respective pollutant source-receptor matrix to produce concentrations of final $PM_{2.5}$ in each of the grid cell.

To employ the ISRM with our emissions input data, we create a shapefile of the ISRM grid using grid cell bounding box coordinates and the spatial projection provided by Goodkind et al. (2019). A benefit of using the ISRM is that it enables the attribution of emission sources to $PM_{2.5}$ concentrations in given locations, a useful feature for informing policy decisions and interventions to mitigate air pollution damages.

The ISRM includes block-group level population data by race/ethnicity from the 5-Year 2012 American Community Survey (ACS) that have been allocated to grid cells. Following Tessum et al. (2021), we evaluate outcomes for several racial/ethnic groups: Asian, Black, Hispanic, people of color (POC), and non-Hispanic white groups. Here, Hispanic spans all races; Asian, Black, and white groups are non-Hispanic and correspond only to the specific race; and POC is everyone except non-Hispanic white people. The sum of POC and white populations therefore equals the total population. Using total population projections from UVA (2018), we scale population data to 2030 by applying state level growth rates for the total population to all populations in grid cells whose spatial centroids correspond to a given state. This dataset therefore allows us to estimate $PM_{2.5}$ exposure for each racial/ethnic group. We calculate a relative disparity metric at the national and state levels as the percentage difference between the average exposure for each group and the average exposure for the total population.

2.4. Uncertainty Analysis

Different distributions of emissions are possible while still achieving total CO_2 reductions required by the policy and maintaining consistency with activity occurring in the energy-economic model simulations. In this analysis there is uncertainty in the estimated emissions reductions under the policy in part because we scale detailed NEI emissions uniformly at the USREP-ReEDS region and variable level – i.e., a top-down scaling approach. Emission sources would realistically not scale uniformly, and as a result could yield differing localized air pollution and equity impacts. To address this spatial uncertainty of estimated emissions reductions under the policy, we use the ISRM to produce alternative emissions distributions that are consistent with CO_2 emissions reductions in the energy-sector modeling but bound equity outcomes for each racial/ethnic group. Specifically, within each scaling region/variable set, we optimize point source emissions changes under the carbon policy to estimate upper and lower bounds on mortality by race/ethnicity, keeping total changes in CO_2 consistent with the primary scaling methods described in 2.2.3. This redistribution of emissions is applied to the policy case, but not the to the baseline case which remains the same. This approach aims to evaluate the robustness of the projected $PM_{2.5}$ exposures to inform environmental justice conclusions for each race/ethnicity group.

First, using the ISRM, we calculate marginal mortality values (total U.S. mortality caused per ton of emissions of primary $PM_{2.5}$, SO_2, NO_X, NH_3, and VOC) for emissions from each grid cell by race/ethnicity, using the concentration response function from Krewski et al. (2009). By matching emissions to their respective marginal mortality values from ISRM, we can then calculate the mortality across each race/ethnicity caused by each source and pollutant. Emissions that are eligible to vary are point sources that (1) have CO_2 emissions; (2) cause $PM_{2.5}$-related mortality; and (3) are non-zero in the 2030 baseline. Within each of the USREP-ReEDS region[6] and scaling variable pairs and for each race/ethnicity group, the scaling factors for emissions sources are optimized to produce a range of mortality outcomes, subject to several constraints: (1) emissions of any pollutant cannot be less than 0 (lower bound); (2) emissions of any pollutant cannot double the higher of the value in the 2017 inventory or 2030 baseline (upper bound); (3) total CO_2 emissions within a region and scaling set remain constant. (The optimization is conducted using R version 3.6.3 and package *lpSolveAPI*.) The result are sets of emissions that capture a range of mortality outcomes for each race/ethnicity to provide upper and lower bounds. Emissions are input to the ISRM to yield a range of exposures and disparities. The optimization formulation is presented below for a representative region and scaling variable set and race/ethnicity group.

Maximize or minimize:

$$objective\ function = \sum_i S_i TM_i$$

where:

- i = unique index of eligible emissions sources

[6] The USREP region is used except for power sector coal and gas emissions, where the ReEDS region is used instead.

- $TM_{i,r}$ = total mortality (for a given race/ethnicity group) caused by emissions at source *i*, where emissions are the higher of emissions at source *i* for each pollutant in 2017 or 2030 baseline.
- S_i = scaling factor (decision variable) applied to emissions all pollutants at source *i*, allowed to range between 0 and 2. In other words, while in the uniform scaling method S_i is uniform across all emission sources within a region and scaling variable set, here S_i is unique to each emissions source *i* as determined by the optimization.

Subject to:

1. Total CO_2 emission within a region and scaling variable set equal values calculated using the uniform scaling method.

$$\sum_i S_i CO2_i = \sum_i CO2_i$$

2. Emissions of any pollutant cannot be less than 0 (lower bound) and cannot double the higher of the level in the 2017 inventory or 2030 baseline (upper bound).

$$0 \leq S_i \leq 2$$

Chapter 3: Results

Results are presented in two parts. Section 3.1 presents our main estimate of impacts of the carbon policy in 2030 ("Cap 50% (2030)") relative to baseline results in 2030 ("Baseline (2030)") and 2017 ("Hist. (2017)"). Section 3.2 then presents an uncertainty analysis addressing how different distributions of CO_2 emissions reductions might lead to different equity outcomes. Specifically, the uncertainty analysis includes alternative emissions distributions that are consistent with policy-driven CO_2 emissions reductions in the energy-sector modeling but provide an upper and lower range for equity outcomes for each racial/ethnic group. The uncertainty analysis also includes illustrative emissions distribution scenarios beyond modeled energy-sector outcomes that aim to better mitigate $PM_{2.5}$ disparities while still achieving total CO_2 reductions consistent with the policy.

3.1. Impacts of Carbon Policy

National emissions by sector in 2017, Baseline (2030) and Cap 50% (2030) are shown in Figure 3. In the energy-economic modeling presented in Yuan et al. (2022), CO_2 emission reductions relative to baseline in 2030 are driven the most by the electricity sector (77%), followed by transportation (10%), industry (7%), and residential and commercial sectors (6%). The changes vary regionally, with the greatest absolute CO_2 reductions in Texas followed by the Alabama-Georgia-Tennessee region, and the greatest reductions relative to baseline in Idaho-Wyoming and West Virginia. In contrast, states such as California and New York that already have ambitious emission reduction targets in the baseline experience few addition reductions under the policy. The regions and sectors with changes in CO_2 emissions also experience changes in non-CO_2 emissions. Relative to Baseline (2030), total emissions of SO_X and NO_X are reduced under the policy by 49% and 16%, respectively. This outcome is driven primarily by changes in electricity sector (93% and 87% reductions), particularly a near-elimination of coal-fired generation, but reductions in other fuel combustion sources as well. Smaller reductions are seen in other pollutants in other sectors: 7% (primary $PM_{2.5}$), 1% (NH_3) and 5% (VOC). Note that the latter three pollutants increase in total from 2017 to 2030, as well as some sectors across all pollutants. Relative to Baseline (2030), state level total emissions decrease for each pollutant and state except where growth in the agriculture sector increases related emissions of NH_3. Significant reductions from Texas through the Mid-Atlantic region largely reflect a transition towards cleaner electricity generation.

Figure 3. National emissions (Billion MT for CO_2 and Million MT for non-CO_2 pollutants) by pollutant and sector in 2017, Baseline (2030) and Cap 50% (2030). Percentage changes from the 2017 and 2030 Baselines are displayed.

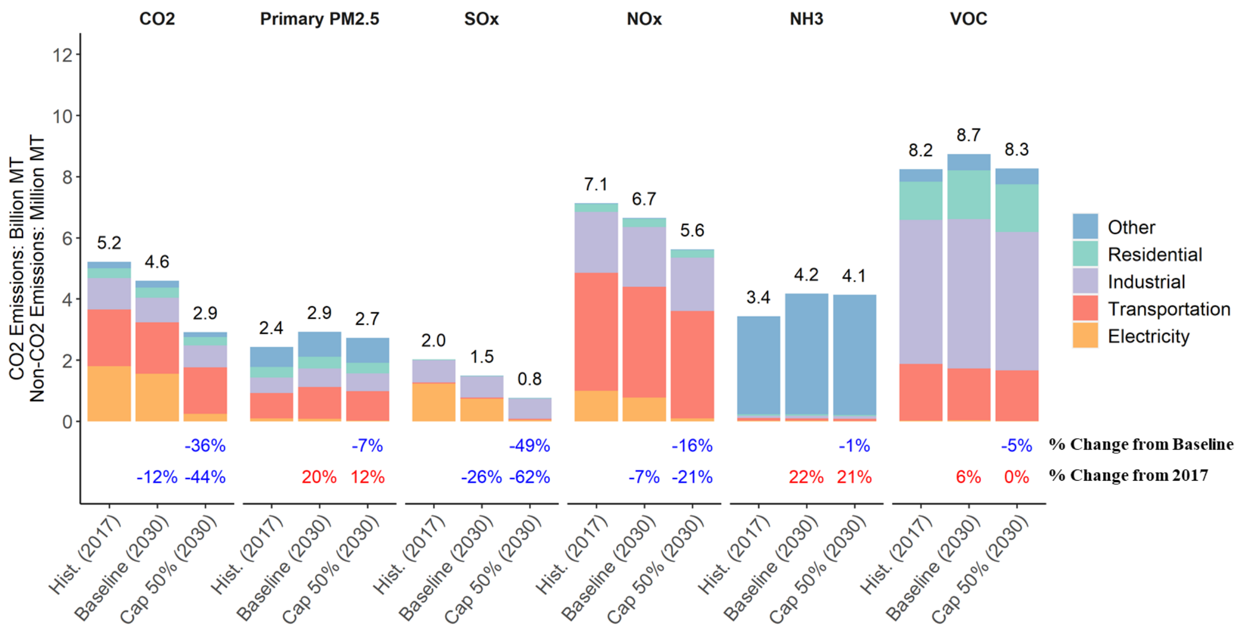


Figure 4 shows $PM_{2.5}$ concentrations (reflecting primary and secondary $PM_{2.5}$) for Cap 50% (2030) (panel a), changes from 2017 and Baseline (2030) (panels b-c), and contributions by sector to changes from Baseline (2030) (panels g-i). Relative to Baseline (2030), the policy drives a reduction in total population-weighted average concentration by 0.37 $\mu g/m^3$, with decreases in nearly every grid cell (>99.8%) and with changes ranging from -1.97 to 0.44 $\mu g/m^3$. Reductions are greatest from Texas through the Mid-Atlantic region, driven largely by coal electricity emissions (d) followed by industrial emissions (g). Coal electricity emissions account for nearly half of the reduction in total average exposure (-0.16 $\mu g/m^3$), with remaining reductions from transportation (-0.06 $\mu g/m^3$), residential (-0.06 $\mu g/m^3$), industrial (-0.05 $\mu g/m^3$), non-coal electricity (-0.02 $\mu g/m^3$), and food and agriculture (-0.01 $\mu g/m^3$). Note that the average population-weighted concentration does increase relative to 2017, with increases and decreases varying across the country (c).

Figure 4. Row 1 (a-c): Annual average $PM_{2.5}$ concentrations ($\mu g/m^3$) under Cap 50% (2030) and changes from Baseline (2030) and Baseline (2017). Rows 2-3 (d-i): Change in concentrations under Cap 50% (2030) relative to Baseline (2030), by six sectors. National population-weighted averages are listed under each respective title.

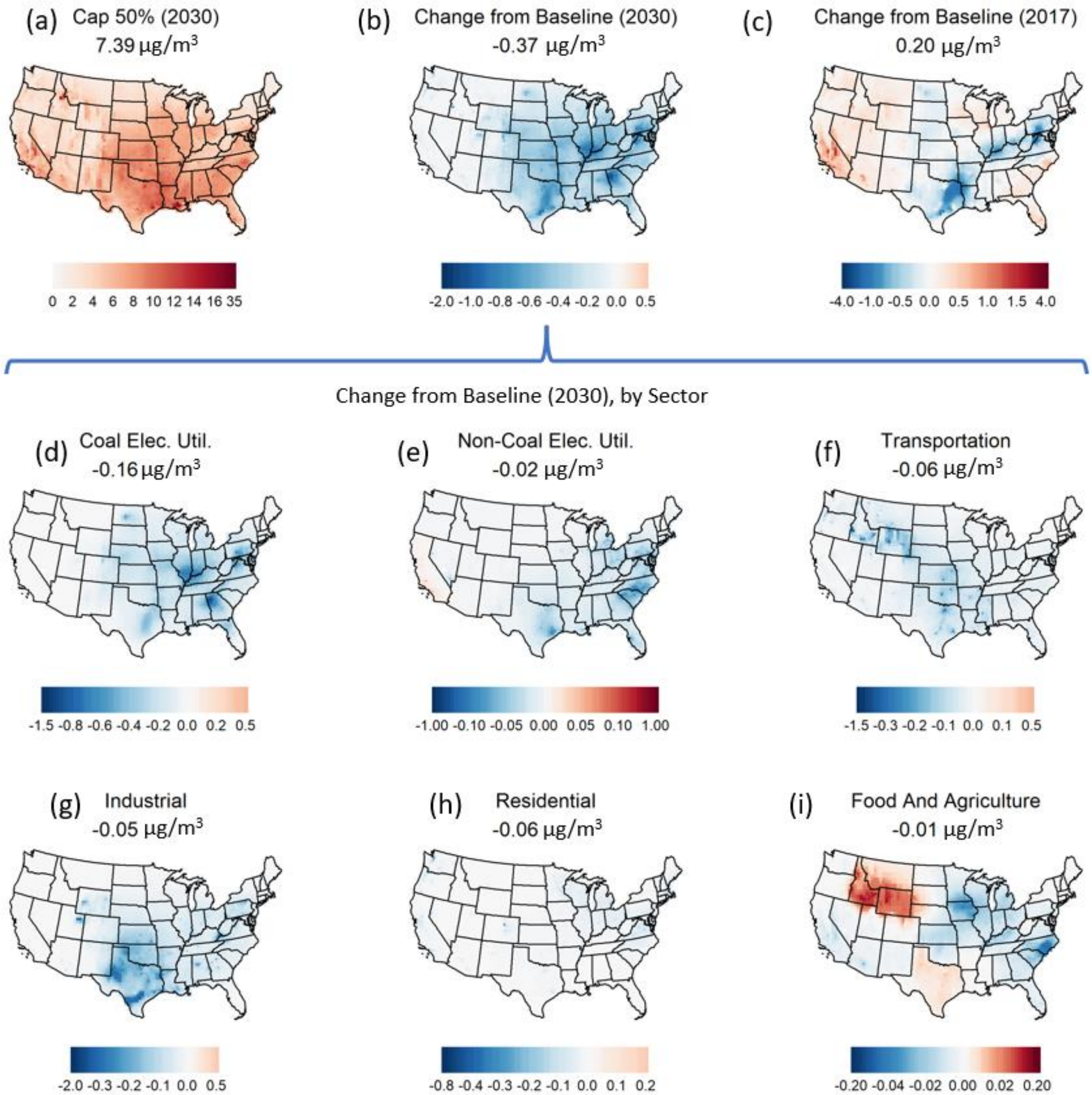


Figure 5 shows average $PM_{2.5}$ exposures and disparities for each race/ethnicity in 2017, Baseline (2030) and Cap 50% (2030). The disparity is the percentage difference between the exposure for a given group and the total population (TotalPop). In 2017 relative to average exposure for the total population, people of color (POC), Black, Asian, and Hispanic populations experience higher exposures (disparities) by 12.1%, 18.4%, 7.8% and 11.3% respectively. In contrast, non-Hispanic white populations experience lower than average exposures by 6.9%. Relative to 2017, the average exposure increases for each group in the Baseline (2030) and Cap 50% (2030) scenarios but is lower in Cap 50% (2030) compared to Baseline (2030) for each group. In other words, the carbon policy reduces average exposures for every group relative to a scenario with no carbon price. However, relative to 2017, disparities for Asian, Hispanic, and people of color on average increase in Baseline (2030) and even more in Cap 50% (2030), despite the reduction in magnitude of exposure. In contrast, disparities for Black people and white people decrease on average.

In 2030 under Cap 50% relative to Baseline, average exposures decrease for all racial/ethnic groups, with the greatest reductions for Black (0.44 $\mu g/m^3$) and white populations (0.37 $\mu g/m^3$), which aligns with prior research that coal-fired electricity generation disproportionately harms Black and white communities. These reductions in exposure are greater than the reductions for the total population on average (0.36 $\mu g/m^3$), thus reducing the relative disparity for Black people (from 17.9% to 17.8%) and decreasing the already negative disparity for white people even more on average (from -7.3% to -7.7%). In contrast, reductions in exposure Asian (0.33 $\mu g/m^3$), Hispanic (0.32 $\mu g/m^3$), and people of color (0.36 $\mu g/m^3$) are less than for the total population. As a result, the relative disparities increase for Asian (9.1% to 10.1%), Hispanic (12.2% to 13.3%) and people of color (12.5% to 13.1%), and the disparity gap between these groups and white people widens slightly. While each group on average does benefit from the carbon policy with lower average exposures, the change is small and disparities persist (or even increase), revealing that the policy is not effective at reducing these disparities.

Figure 5. Population-weighted average $PM_{2.5}$ exposure and disparity by race/ethnicity in 2017, Baseline (2030) and Cap 50% (2030). Disparity is calculated as the relative difference between $PM_{2.5}$ exposure for the given group and the total population.

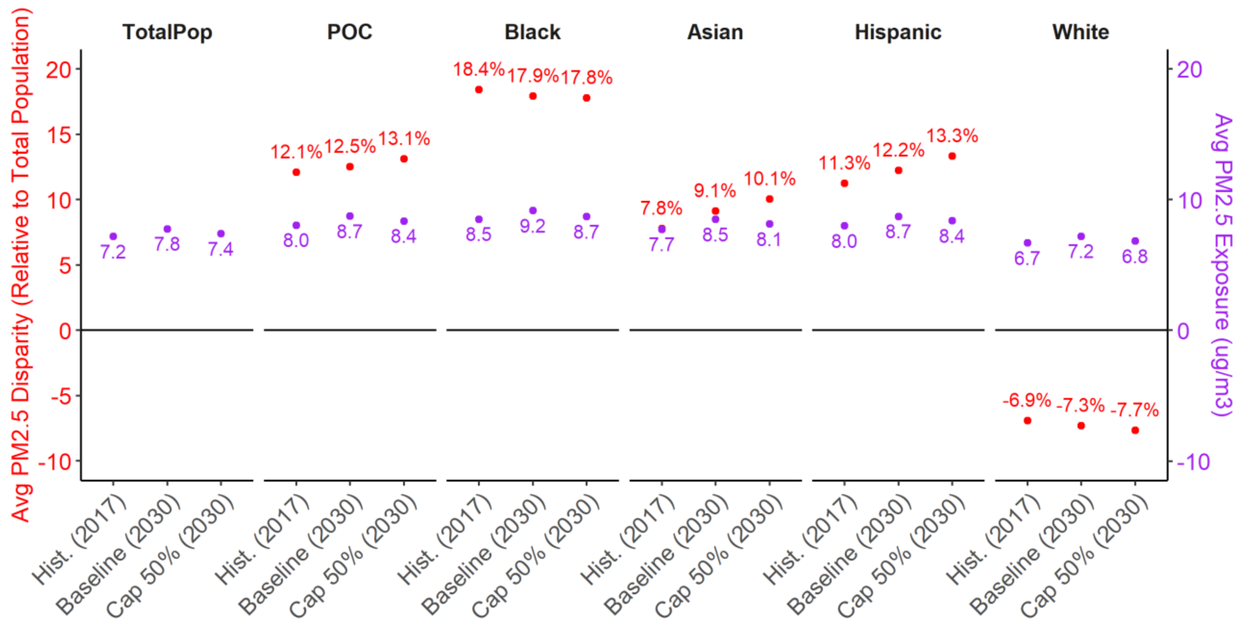
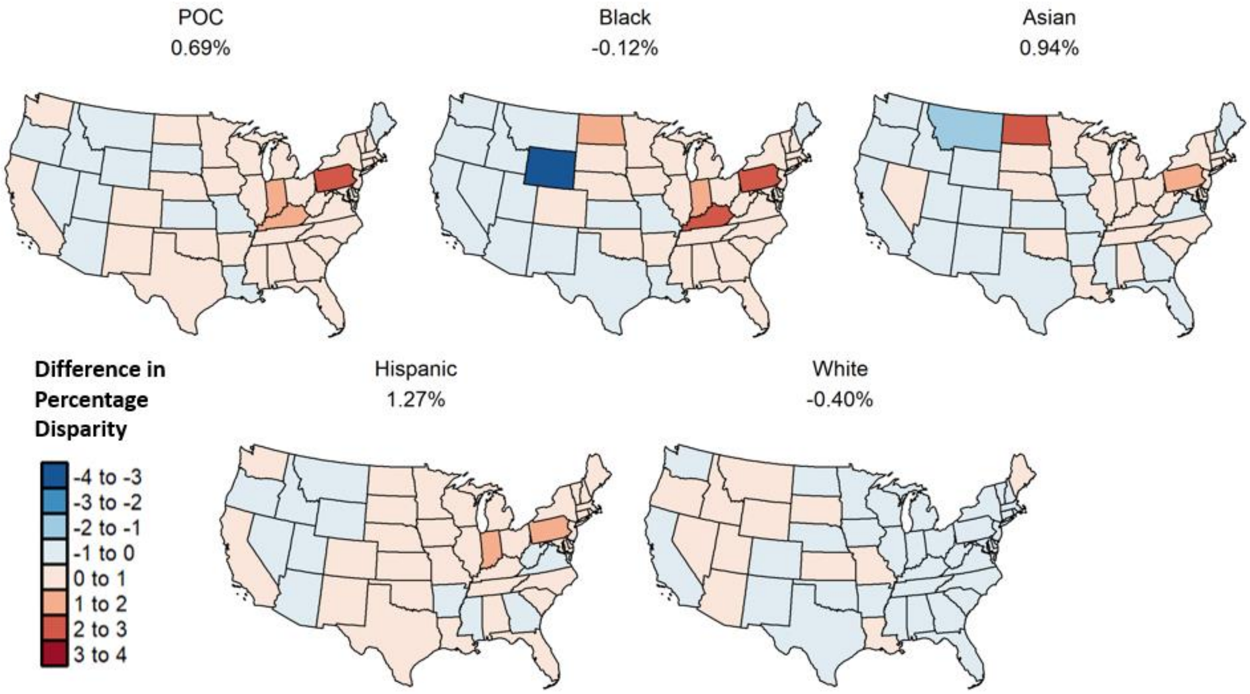


Figure 6 shows the change in disparities by state between Cap 50% (2030) and Baseline (2030), showing a significant variation of impacts regionally. Review of spatial distributions of changes in population-concentrations by racial/ethnic groups reveal that benefits to Black populations primarily occur in the Southeast while benefits to Hispanic populations primarily occur in south-central U.S. such as in Texas.

Figure 6. State-level percentage point changes is disparity under Cap 50% (2030) relative to Baseline (2030). Changes in national relative disparity are provided under each population name.



3.2. Addressing Uncertainty: Ranges of Emissions and Equity Outcomes

Next, we check if spatial uncertainty in the estimated emissions reductions under the policy could lead to different equity outcomes. Specifically, we evaluate alternative emissions distributions that are consistent with CO_2 emissions reductions in the energy-sector modeling but provide an upper and lower range for equity outcomes for each racial/ethnic group. Figure 7 shows the changes in disparity and exposure by group between Cap 50% (2030) and Baseline (2030). For all groups except Black people, the narrative remains the same, with small ranges of uncertainty produced. For Black people, the change in disparity range does cross zero, suggesting that depending on how emissions change, the disparity can either increase or decrease, although the magnitudes of changes are small.

Figure 7. Ranges in the change in $PM_{2.5}$ exposures and disparities by race/ethnicity between Cap 50% (2030) and Baseline (2030).

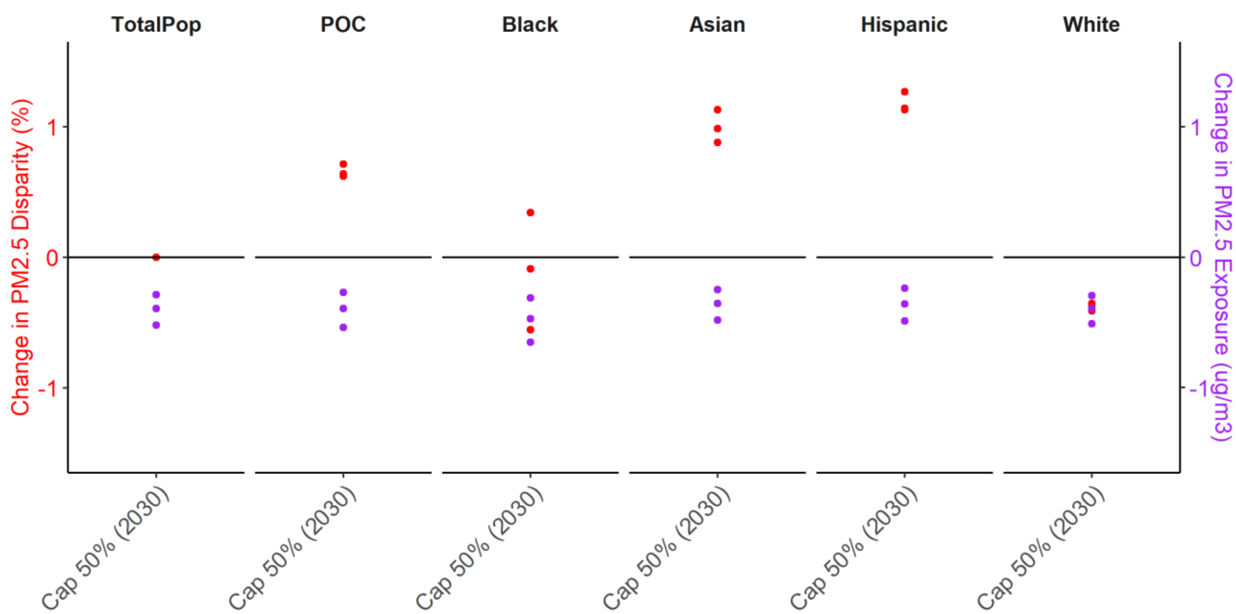
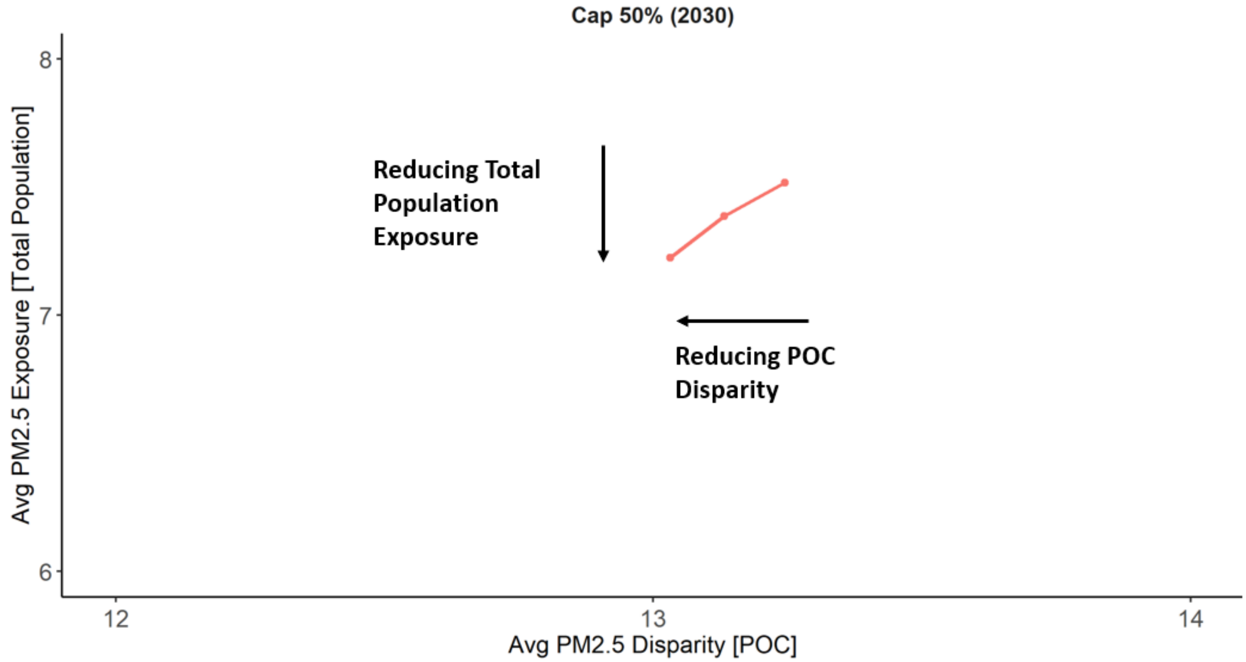


Figure 8 explores how decreasing disparities for POC affects the average exposure for the total population. It shows that reducing POC disparity also reduces exposure to total population, a small win-win.

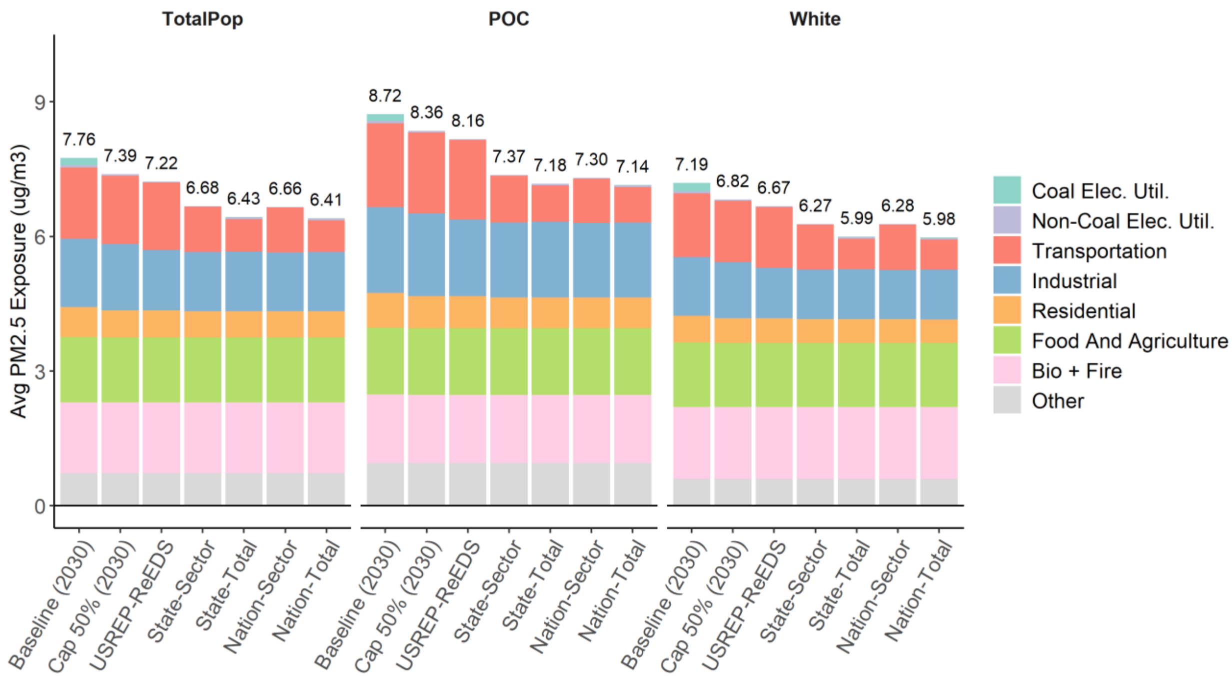
Figure 8. Average exposure for the total population (y-axis) versus average disparity for people of color (x-axis).



The framework demonstrated here can provide a valuable check on robustness of results and can be expanded to explore if emissions distributions that are different than those under the carbon policy better mitigate air quality disparities while still achieving the same total CO_2 emissions reductions.

To that end, figure 9 explores illustrative emissions distribution scenarios beyond modeled energy-sector outcomes that aim to better mitigate $PM_{2.5}$ disparities while still achieving total CO_2 reductions consistent with the policy. It shows the result of minimizing POC mortality while keeping CO_2 constant for respective emissions group combinations: “USREP-ReEDS” (consistent with results above), “state-sector”, “state-total”, “national-sector”, “national-total.” These are also shown in comparison to the main impacts estimated for the Baseline and Cap 50% in section 3.1. It shows that you can further reducing POC exposures beyond what was achieved under the carbon policy, while still meeting the same CO_2 emissions reductions. As expected, the “National-Total” scenario results in the greatest reduction in POC exposure. Like figure 8, the results also show that prioritizing reductions in exposure for people of color also reduces exposure for white people and the total population on average. However, the magnitude of reductions tapers off and appear limited, perhaps by the amount of total CO_2 reductions applied here as well as slightly limited CO_2 coverage in the emissions inventory.

Figure 9. Average $PM_{2.5}$ exposure under alternative, CO_2-consistent distributions that minimize POC mortality: i.e., POC mortality is minimized while keeping CO_2 constant for respective emissions groups.



Chapter 4: Discussion and Policy Implications

This thesis aims to contribute insightful research at the intersection of decarbonization policy, air pollution, and environmental justice. As emissions of GHGs are associated with emissions that contribute to $PM_{2.5}$ exposure, ambitious climate policy to decarbonize the economy could be an appealing pathway to concurrently reduce air pollution. Much prior research has demonstrated the health benefits of reduced air pollution resulting from climate and clean energy policy, often providing total net benefits to society. Some research has explored air pollution related equity impacts of market-based climate policy, but typically have either focus on existing markets in California, have not modeled secondary $PM_{2.5}$ formation, have not considered disparities or have not addressed uncertainty in the modeling. As the Biden-Harris Administration works to address stated goals of mitigating both climate change and environmental injustices in the U.S., this thesis explores a critical question: how might federal decarbonization strategies affect disparities in $PM_{2.5}$ exposure? We find that while the carbon policy improves air quality and health over all, it does not sufficiently address disparities in air pollution exposure, emphasizing the need for alternative, environmental justice-specific intervention.

In this chapter, I explore the prospects for federal market-based decarbonization policy, including the future role for such policy in the U.S. and implications for air pollution related health and equity outcomes (section 4.1). Then, I consider alternative policy pathways to combat persisting $PM_{2.5}$ related health and equity issues (section 4.2). Lastly, I present areas for future research (section 4.3)

4.1. Prospects for Federal Market-Based Decarbonization Policy

In 2021, the U.S. re-entered the Paris Agreement, pledging to reduce national GHG emissions by 50-52% below 2005 levels by 2030. This goal aligns with a pathway to net-zero GHG emissions by 2050, a global goal intended prevent warming greater than 1.5-2 degrees Celsius above pre-industrial levels that would cause the worst impacts of climate change (IPCC, 2018). At the same time, the Biden-Harris Administration also aims to direct 40% of certain climate investments to disadvantaged communities to mitigate environmental injustices including from air pollution (The White House, 2021). Despite these signals of intended climate and environmental justice action, the U.S. currently lacks a comprehensive federal action plan. To understand the prospects for U.S.

Congress to implement such policy, it is important to reflect on past efforts to pass similar policy and expected impacts for outcomes related to the Administrations goals.

In 2010, new climate legislation introduced in Congress – the Waxman-Markey bill that included an economy-wide carbon cap-and-trade program - passed the U.S. House but failed to pass in the Senate. This failure reflects difficulty for reaching bipartisan support on climate policy, and therefore some argue that regulation under existing authority provides a better route. Specifically, the EPA has authority under the Clean Air Act (CAA) – extensive federal legislation mandating the EPA to regulate harmful air pollution – to implement GHG regulating policy, although this has been subject to substantial legal battle. In particular, the 2007 landmark Supreme Court case *Massachusetts vs EPA* ruled that the EPA has authority to regulate GHGs from stationary and mobile sources as air pollutants. This ruling, combined with the 2009 Endangerment Finding ruling that that determined GHGs are a danger to human health and welfare, form a basis for climate policy authority under the CAA[7].

In 2015, the Obama Administration implemented the Clean Power Plan (CPP) rule, mandating the EPA and states to decrease CO_2 emissions from the U.S. power sector by 32% below 2005 levels by 2030. The regulatory authority cited was the Section 111(d) of the CAA, which applies to designated sources. However, legal challenges followed, and the CPP was eventually stayed and then replaced by the Trump Administration's Affordable Clean Energy (ACE) rule, which required efficiency (heat rate) improvements at existing coal-fired power plants[8]. The ACE rule also faced challenge in court, and by 2020 was been rejected by the DC Circuit Court of Appeals, which ruled that the EPA had used too narrow of an interpretation of the CAA. This ruling was timely for the Biden-Harris Administration, which was presented with a clean slate to pursue new applications of the CAA (Farah, 2021).

Legal scholars in Burger et al. (2020) argue that one possible path lies with Section 115 of the CAA, which is the international air pollution provision. Section 115 is triggered when two conditions are satisfied: (1) air pollution "endangers" other nations; and (2) other nations take reciprocal action to reduce their emissions. The Intergovernmental Panel on Climate Change (IPCC) demonstrates substantial scientific evidence of the detrimental impact of GHGs on the

[7] http://outsideinradio.org/shows/massvepa
[8] http://outsideinradio.org/shows/massvepa

environment, climate, and health, supporting the first condition. With the Paris Agreement, the U.S. and other nations have joined an international agreement to reduce emissions, which could satisfy the second condition regarding reciprocity. However, Section 115 has rarely been used since its implementation in 1965 and uncertainty remains. For example, it is unclear if GHGs can be regulated as air pollutants in this context (Burger et al., 2020). Therefore, while the prospects for carbon pricing and climate action more generally at the federal level are therefore quite uncertain, the Biden-Harris Administration is actively seeking to implement ambitious federal policy and understanding impacts related to the Administration's climate and environmental justice goals in highly important.

Literature has well-established that there are significant health benefits from policies aimed to reduce GHG emissions. Yuan et al. (2022) add additional evidence of this outcome when evaluating federal economy-wide carbon pricing programs that could meet the Biden-Harris Administrations climate goals, estimating impacts of the policies on energy sector activity, CO_2 emissions, household welfare, and net benefits reflecting reduced $PM_{2.5}$-related premature mortality. As modeled and discussed in Yuan et al. (2022), 77% of the reductions in CO_2 relative to baseline in 2030 come from the electricity. In Yuan et al. (2022), we estimate that the policy could prevent 4,700-14,000 premature deaths in 2030 from reduced $PM_{2.5}$ pollution and yield partial net benefits of $118-201 billion in 2030 when accounting for climate and health benefits as well as economic welfare costs of the policy. However, achieving both climate and environmental justice goals in the U.S. requires moving beyond this traditional benefit-cost analysis framework.

In this thesis, we showed that the CO_2 cap-and-trade program nearly eliminates coal-fired electricity pollution and reduces total U.S. SO_2 and NO_X emissions by 49% and 16% respectively, with much smaller changes in other pollutants – primary $PM_{2.5}$, NH_3 and VOCs – that contribute to total $PM_{2.5}$. When considering the net effect of emissions changes on total $PM_{2.5}$, we found that the policy reduced $PM_{2.5}$ exposure for each race/ethnicity evaluated. Black people and white people experienced the greatest average reduction in exposure, respectively, exceeding the average for the total population. Hispanic and Asian people also experienced reduced exposure on average but less than the total population. We identified that electricity sector emissions drove about half of the reductions in total population exposure. There are also regional differences, with the largest reductions occurring in parts of Texas, the Midwest and Mid-Atlantic regions. Relative to 2017, $PM_{2.5}$ exposure increased in parts of the U.S. in both the baseline and policy case in 2030.

Despite reductions in $PM_{2.5}$ under the policy relative to baseline, there is less effect on relative disparities in exposure, calculated as the relative difference between each racial/ethnic group and the total population. Black, Hispanic, and Asian people continued to experience disparities, while white people experienced less exposure than the total population on average. While the disparity for Black people reduced slightly under the policy, the disparity for Asian, Hispanic, and people of color increased slightly, widening the disparity gap relative to white people. The reason that only Black people and white people experience reductions in disparities are because their exposure is reduced by more than the total population on average. This outcome occurs because the carbon policy eliminated nearly all coal-fired electricity, which as explained earlier has been shown to disproportionately harm only Black and white people more than average (e.g., as shown by Tessum et al. (2021)). Considering uncertainty in emissions distributions under the policy has little effect on the result, showing the potential for the disparity for Black people to slightly increase rather than decrease, but otherwise not qualitatively changing the findings. We do show that efforts to prioritize reductions for people of color do benefit the entire population, including white people, on average. Furthermore, exploring scenarios beyond carbon pricing illustrates opportunities to further reduce exposure and mitigate disparities while achieving the same CO_2 reduction goals. However, extent of air pollution mitigation is limited due to the magnitude of the CO_2 reductions desired by 2030. We conclude that while market-based decarbonization policy can yield air pollution and health benefits for all, it is an insufficient tool to adequately address air pollution disparities in the near term – a finding that is also consistent with prior literature, as discussed previously.

4.2. Alternative Pathways to Cleaner and More Equitable Air

Given the limited capability for market-based decarbonization policy to directly address air pollution disparities, it is necessary to consider alternative pathways to achieving cleaner and more equitable air quality the U.S. First, this section explores authority under the CAA to directly regulate $PM_{2.5}$ concentrations via tighter NAAQS. Next, it explores the role of complementing or expanding climate policy with environmental justice specific provisions. While the CAA directly regulates air pollution including $PM_{2.5}$ and can set air quality thresholds through uniform national standards, the path towards tighter standards may be long and complex and sparse air pollution monitoring networks greatly limit effectiveness. While climate policy is on the forefront of the Biden-Harris Administration's agenda, the specific policy design will greatly impact the efficacy in improving air quality and related inequities.

4.2.1. Prospects for $PM_{2.5}$ Standards under the Clean Air Act

While air pollution continues to cause significant health burdens in the U.S., it is important to acknowledge the role of policy in improving air pollution over recent decades. For example, since 1990, the CAA was estimated to prevent 230,000 deaths by 2020 due to reduced $PM_{2.5}$ levels (EPA, 2011). In the same study, considering additional benefits from reduced infant mortality, ozone-related mortality, chronic bronchitis, heart disease, asthma exacerbation, emergency room visits, and lost school and workdays, total estimated monetary benefits of $2 billion dwarfed the estimated compliance costs of $85 million by greater than a factor of 30. These health improvements are due numerous CAA provisions, among which are National Ambient Air Quality Standards (NAAQS) – uniform concentration limits for six "criteria" air pollutants including $PM_{2.5}$ – and the 1990 Acid Rain program regulating SO_2 emissions, a precursor to $PM_{2.5}$ emitted primarily from coal-fired power plants.

One pathway to mitigate air quality and disparities could be to tighten NAAQS limits under the CAA. The CAA was primarily established in 1970, although provisions existed as early as 1963, and significant amendments were made in 1977 and 1990. The CAA first and foremost mandates that the EPA, in conjunction with states, regulate air pollution harmful to public health and welfare. One prominent feature includes the NAAQS for six "criteria" air pollutants: carbon monoxide, lead, nitrogen dioxide, ozone, sulfur dioxide, and particulate matter ($PM_{2.5}$, PM_{10}). Both $PM_{2.5}$ and several key precursor emissions are therefore regulated by NAAQS, which in part have driven reductions in $PM_{2.5}$ concentrations overtime.

NAAQS can include both primary and secondary standards for ambient air quality concentrations. Primary standards protect health with an adequate margin of safety (without economic or technological consideration), while a secondary standard protects public welfare (e.g., extreme weather, climate). While economic and technological feasibility may be considered by states, neither must be considered in setting emission limitations to meet NAAQS. Specifically, three standards exist for $PM_{2.5}$, which have tightened over time but have not changed since 2013 (EPA, 2021c).

1. Primary: maximum annual mean concentration (averaged over 3 years) of 12 μg/m^3
2. Secondary: maximum annual mean concentration (averaged over 3 years) of 15 μg/m^3
3. Primary and secondary: maximum 24-hour 98^{th} percentile concentration (averaged over 3 years) of 35 μg/m^3

NAAQS specify a uniform requirement across all the U.S. thereby setting a minimum level of air quality that should be shared by all. Currie at al. (2020) show that $PM_{2.5}$ exposure and Black-white disparities decreased from 2000-2015 – where they attribute 60% of reductions to the NAAQS. However, clearly disparities in exposure persist and have not sufficiently been addressed by current regulation under the Clean Air Act. Some areas either out of compliance (i.e., in nonattainment) or overly compliant, leaving room for disproportionate exposure among communities (Miranda et al., 2011). One issue is that EPA maintains a relatively sparse network of monitors throughout the U.S. that measure concentrations of ambient $PM_{2.5}$ (Fowlie et al., 2020). With such data, historical population exposures can be estimated, for example based on the monitor of nearest proximity to a residence. This assumption can be problematic, however, if individuals experience different air quality than the nearest monitor, which can be the case if one's residence is not very close to a monitor or environmental conditions cause different concentrations within a relatively small spatial radius. With this network it can be very easy to miss high concentrations in disadvantaged communities.

Nevertheless, and particularly if the monitoring network were improved, a tighter NAAQS standard could be beneficial. In 2021, the World Health Organization (WHO) updated its older 2005 air pollution guidelines based on greater scientific understanding of health burdens caused by air pollution, including lowering $PM_{2.5}$ thresholds for annual average (5 μg/m^3) and daily average (15 μg/m^3) (WHO, 2021b, 2021a). At the end of 2020 in the U.S., the EPA under the Trump Administration conducted its review of the current $PM_{2.5}$ NAAQS and issued a final ruling to maintain the existing standard for the next five years. This decision was made despite recommendations from EPA staff scientists to reduce the annual standard to between 8 and 10 μm/m^3, estimating that a standard of 9 μm/m^3 would prevent 12,150 deaths (a 27% reduction from deaths associated with the current standard) (Davenport, 2020). These scientists previously were on a panel that advised EPA's Clean Air Act Scientific Advisory Committee (CASAC), but the panel had been disbanded under the Trump Administration. Administrator Wheeler disregarded the recommendation due to insufficient evidence on the health effects of $PM_{2.5}$ and an indecisive recommendation by CASAC (Eilperin et al., 2020). The Biden-Harris Administration may still be able to update the standard sooner than five years, although the process through which new standards are proposed, implemented, and finally achieved can be lengthy.

4.2.2. Prospects for Joint Climate and Environmental Justice Policy

While climate policy may deliver significant health benefits, this thesis, and other research, shows that such policies aiming to reduce carbon emissions alone do not address air pollution inequities. Environmental justice concerns have arisen in state level climate policy particularly in California and are playing a role shaping new climate policy in Washington State (Roberts, 2021). As noted earlier, key disparities arise from harder-to-decarbonize sectors such as industry and heavy-duty diesel transportation (Tessum et al., 2021). An economy-wide carbon price will enable the lowest-cost carbon reduction methods, which in the near term primarily occur in the electricity sector (Yuan et al., 2022) which only contributes a relatively small fraction to population exposure. Therefore, additional intervention is clearly needed to mitigate disparities especially in the near term. Some argue that constructing climate policy using tools of standards, investments, and justice – instead of markets – may be more effective at achieving equity goals (Roberts, 2020). Furthermore, environmental justice efforts that are community-driven and based on community-needs will be are necessary to address context-specific and unique circumstances, as described in a coherent framework presented by Van Horne et al. (2022).

The findings in this analysis suggest that recent efforts in states such as California and Washington to adopt distinct and explicit EJ provisions as complements to carbon pricing are necessary steps to address EJ goals. For example, EJ concerns regarding CA's cap-and-trade program (AB 32) led to the adoption of AB 617, or the Community Air Protection Program, in 2017. AB 617 aims to increase pollution monitoring to identify hotspots, better address the hotspots, and advance participatory justice with greater community involvement in the regulatory process (Fowlie et al., 2020). Similarly, Washington State legislature passed in 2021 the Climate Commitment Act (Senate Bill 5126), establishing an economy-wide cap-and-invest program (beginning 2023) with

GHG emission reduction targets leading to net-zero emissions by 2050 while at the same time centering EJ goals. Specifically, beyond the carbon policy, the CCA integrates the Health Environment for All (HEAL) Act, or Senate Bill 5141, requiring environmental justice action, including: expanding the coverage of air pollution monitoring by 2023, directing at least 35% of investments to communities disproportionately harmed by air pollution, directing at least 10% of investments for Tribal projects, and requiring EJ reviews ever two years with evaluations of criteria pollutant emissions standards (Tempest et al., 2021). Washington State also has sector-specific policies such as for transportation, industry, and buildings (Roberts, 2021). Through these policy measures as blueprints, California and Washington State provide leading examples going forward of ambitious action to jointly address climate change, air quality, and environmental injustices.

4.3. Future Work

This analysis provides valuable insight and frameworks for evaluating equity implications of decarbonization, setting the stage for future analysis in this area. Here, we outline research ideas building on this analysis.

First, additional equity metrics could be considered beyond the relative disparity metric used here. For example, rather than comparing weighted-average population exposures, exposures in disadvantaged communities could be compared, where communities could be identified using screening tools developed at the federal or state levels. In using screening tools, however, it is also important to critically evaluate methods for how disadvantaged communities are identified. For example, the Climate and Economic Justice Screening Tool (CEJST) developed for the Justice40 Initiative so far does not include race due to concern over possible legal challenges, despite the strong tie between race/ethnicity and air pollution disparities (Friedman, 2022). Lastly, differences between maximum and minimum exposures could be calculated to ensure that averages do communities with low exposure do not obscure communities with high exposure.

Second, methods to appropriate estimate premature mortality by race/ethnicity could be considered, using up-to-date concentration response functions. This analysis presents exposures by race/ethnicity only, following methods in Tessum et al. (2019) which states that "health impacts of air pollution depend on biological and environmental factors that are independent of ambient $PM_{2.5}$ concentration and differ among demographic groups." Recent epidemiological literature presents mortality relative risk estimates by race/ethnicity (Di et al., 2017), and applying such functions, along with mortality incidence rates for the respective groups, could be compared to more functions for the total population. In fact, Spiller at al. (2021) apply these racial/ethnic specific CRFs and mortality incidence rates, finding that they result in 150% higher mortality for Black adults than when applying traditionally-used CRFs that largely reflect urban white populations.

Third, the optimization framework developed in this analysis demonstrates how linearized air pollution impacts can be leveraged to explore what alternative distributions of emissions can better mitigate air quality disparities while still achieving climate goals. This analysis provides several illustrative examples, but this space could be further explored. For example, if climate legislation is passed, it will be value to understand how complementary policy can best target remaining gaps in disparities. Efforts to shift research focus from descriptive analysis towards actionable solutions for addressing systemic air pollution disparities is of utmost importance.

Carefully crafted policy interventions to reduce both direct $PM_{2.5}$ and precursor emissions will be critical to improving air quality and public health equitably in the U.S. This thesis analyzes and discusses a number of potential pathways worth considering. While the Clean Air Act authorizes direct regulation of $PM_{2.5}$ levels nationally, the potential of tighter standards in the near-term may be low and sparse monitoring networks greatly limit the effectiveness of the standards. Another possible path includes climate policy aimed to reduce GHG emissions, which could lead to air quality benefits. Climate policy focused on the electricity sector or economy-wide policies pricing carbon will largely reduce emissions in the electricity sector in the near term as these emissions are among the lowest to abate. While reducing output from coal-fired power plants and their emissions of sulfur dioxide will greatly improve health, other harder-to-abate sectors such as industry contribute significantly to health impacts and air pollution disparities with particularly high impacts on disadvantaged communities. While policies requiring net zero emissions by 2050 would eventually require abatement from these sectors, near-term reductions are less likely. Targeted air quality mitigation efforts, such as increased monitoring, greater participation in regulatory processes by disadvantaged groups, and sector-specific policy provisions particularly for emission sources contributing to inequities are important to consider. Through these policy approaches, the U.S. can continue progress towards a cleaner, healthier, and more just future.

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