U.S. decarbonization impacts on air quality and environmental justice

Ciaran L Gallagher1,∗ and Tracey Holloway1,2

1 Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin—Madison, Madison, WI 53705, United States of America
2 Department of Atmospheric and Oceanic Sciences, University of Wisconsin—Madison, Madison, WI 53705, United States of America

∗ Author to whom any correspondence should be addressed.

E-mail: clgallagher@wisc.edu

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Abstract

As policy organizations consider strategies to mitigate climate change, decarbonization initiatives can also reduce health-impacting air pollutants and may affect the associated racial disparities of adverse effects. With the U.S. Environmental Protection Agency CO-Benefits Risk Assessment Health Impacts Screening Tool (COBRA), we compare three decarbonization scenarios and their impacts at the regional and county scales. COBRA calculates changes in county-level ambient fine particulate matter (PM$_{2.5}$), and associated mortality impacts, for each decarbonization scenario. We compare these patterns with demographic data to evaluate the relative exposure reduction benefit across race and ethnicity. Carbon-free electricity would reduce national average ambient PM$_{2.5}$ concentrations by 0.21 µg m$^{-3}$, compared with a 0.19 µg m$^{-3}$ reduction associated with carbon-free industrial activity, and a 0.08 µg m$^{-3}$ reduction associated with carbon-free light duty vehicle (LDV) transportation. Decarbonization strategies also vary in terms of the racial groups most benefitting from each scenario, due to regional and urban/rural patterns in emission sources and population demographics. Black populations are the only group to experience relative exposure reduction benefits compared to the total population in every scenario, with industrial decarbonization yielding 23% greater reductions in ambient PM$_{2.5}$ concentrations for Black populations than for the total U.S. population. The largest relative reduction in PM$_{2.5}$ exposure was found for Asian populations in the carbon-free LDV transportation scenario (53%). The magnitudes of total air quality improvements by scenario vary across regions of the U.S., and generally do not align with the decarbonization policy that achieves the largest equity goal. Only the transportation decarbonization scenario meets the criteria of the Justice40 Initiative nationwide, fulfilling the 2021 commitment by U.S. President Biden that federal investments in clean energy are designed to allocate at least 40% of benefits to disadvantaged communities.

1. Introduction

Fossil fuel combustion emits the vast majority of greenhouse gases (GHGs) in the United States, in addition to fine particulate matter (PM$_{2.5}$), nitrogen oxides (NO$_x$), sulfur dioxide (SO$_2$), and other pollutants. Since the same sources emit a combination of GHGs and health-damaging pollutants, climate mitigation policies present opportunities to achieve both air quality and public health goals (Gallagher and Holloway 2020).

Of the pollutants regulated by the Environmental Protection Agency (EPA) under the National Ambient Air Pollution Standards, PM$_{2.5}$ exerts the greatest health burden. PM$_{2.5}$ has well-established connections to respiratory and cardiovascular diseases (Brunekreef and Holgate 2002, Brook et al 2010). Premature mortality from PM$_{2.5}$ exposure...
from the fossil fuel sector has been estimated at 8.7 million premature deaths globally (Vohra et al. 2021), and half of the deaths from PM$_{2.5}$ pollution in the U.S. can be attributed to fossil fuel combustion (Thakrar et al. 2020).

Studies have shown that the health impacts of fossil fuel combustion in U.S. are unequally borne by vulnerable populations, especially communities of color (Tessum et al. 2019, 2021, Third et al. 2019). Sources of these pollutants are disproportionately located near residents of color, including power plants (Faber and Krieg 2002, Mikati et al. 2018, Richmond-Bryant et al. 2020), high volume roads (Rowangould 2013), and industrial facilities (Fisher et al. 2006, Mohai et al. 2009a, Lersch and Hart 2014). People of color are unequally exposed to higher ambient PM$_{2.5}$ concentrations from most anthropogenic emissions sources, with the largest disparities in exposure from industry, light-duty gasoline vehicles, and heavy-duty diesel vehicles (Tessum et al. 2021).

Counties with the highest ambient PM$_{2.5}$ concentrations tend to have larger proportions of Black populations (Miranda et al. 2011) and Black populations have been found to have nearly 10% greater exposure to ambient PM$_{2.5}$ pollution than White populations (Bell and Ebisu 2012). As such, air pollution represents a major concern for distributive environmental justice (EJ), meaning the equal distribution of environmental harms across populations (Williams and Doyon 2019). Here we evaluate how potential low-carbon policies might impact health across the U.S., with a focus on racial disparities.

While climate mitigation policies can reduce harmful air pollutants, the actual distribution of public health benefits has the potential to affect EJ issues. GHGs and health-relevant pollutants behave differently in the atmosphere (Jacob 1999). While most GHGs are long-lived in the atmosphere (e.g. 10+ years for methane and 100+ years for carbon dioxide), health-relevant pollutants have shorter lifetimes (hours to days). Due to this shorter lifetime, health-relevant pollutants are highest near the point of release, and energy transitions exert their primary health impact on local communities via air quality (Smith et al. 2013). The characterization of exposed communities and potential air quality co-benefits can inform policies to mitigate climate change; to reduce ambient air pollutant concentrations; and to alleviate the racial and economic disparity in air pollution exposure and health impacts. In 2021 U.S. President Joe Biden signed an executive order to require that 40% of the benefits of federal climate and clean energy investments go to EJ communities (U.S. Exec. Order No. 14008 2021). Known as Justice40, this initiative represents the first-ever federal quantitative goal relevant to EJ, and encompasses the air quality and health co-benefits of energy system change. Evaluating Justice40 and related efforts to design climate mitigation strategies that increase racial equity requires accounting for air quality co-benefits and their EJ dimensions.

Although analyses of air quality co-benefits from climate policies are growing (Gallagher and Holloway, 2020), fewer studies include associated equity implications (Boyce and Pastor 2013, Anderson et al. 2018, Cushing et al. 2018). An analysis of the first three years of California’s cap-and-trade system found that average annual health-relevant air pollutant emissions actually increased in communities of color (Cushing et al. 2018). A separate analysis of California’s cap-and-trade program observed only a marginal reduction in health-impacting air pollutants and suggested that EJ and air quality goals would be more efficiently achieved separately (Anderson et al. 2018). Boyce and Pastor (2013) conclude that decarbonization policies could have a beneficial EJ impact, although it is dependent on policy design.

To investigate the EJ potential of nationwide complete sector decarbonization, we quantify and compare air quality co-benefits of 100% carbon-free scenarios. As policy endpoints, these scenarios can quantify the upper bounds of air quality improvement from the modeled sectors, while providing a conceptual framework to inform the development of specific technology and policy scenarios. We use the U.S. EPA CO-Benefits Risk Assessment (COBRA) Health Impacts Screening Tool, a reduced-form model (RFM) calculating annual average ambient PM$_{2.5}$ with county-level resolution. We present an overview of our analysis methods; evaluate COBRA by comparing the model baseline with ground-level air quality monitor data and model evaluation metrics with other air quality models; quantify air quality co-benefits of three decarbonization scenarios; evaluate the population-weighted exposure differences of the co-benefits by race and ethnicity to assess the EJ dimensions of these scenarios; and investigate the regional trends and urban/rural differences in air quality and equity impacts.

2. Methods

Air quality models are able to provide information on pollution exposure across wide areas, even in the absence of air pollution monitors. Two broad categories of air quality models are widely used to estimate chemical and meteorological processes controlling air pollution abundance: chemical transport models (CTMs) and RFMs. CTMs simulate time-varying atmospheric chemistry and meteorological transport, and they may be used to evaluate how emissions changes impact ambient concentrations of air pollutants at varying spatial and temporal scales. However, the required expertise, computing power, and runtime of CTMs limit their utility for policy assessment (Gardner-Frollick et al. 2022). In contrast, RFMs simplify chemical and meteorological processes, often based on CTM output, typically providing annual
average values for a narrower range of pollutants. Annual average PM$_{2.5}$ is the most common air quality parameter provided by RFMs, as PM$_{2.5}$ accounts for the majority of premature mortality, the most significant health damage. In addition, the multiple sources and chemical pathways creating PM$_{2.5}$ requires some form of spatial model, even for qualitative evaluation. As such, RFMs are increasingly used to quantify air quality and health implications of policy and technology scenarios. They have been used for EJ analyses (Bravo et al. 2016, Thind et al. 2019, Tessum et al. 2021, Gardner-Frolick et al. 2022), calculating PM$_{2.5}$ exposure of different demographic groups from various sectors and sources.

We use the U.S. EPA COBRA Health Impacts Screening Tool v4.0 (U.S. Environmental Protection Agency 2014) for this national EJ assessment. COBRA is an RFM developed by EPA to support state-level decision-making (U.S. Environmental Protection Agency 2014). While the county-scale of COBRA limits urban-scale analysis, the resolution may be compared with county-scale demographic data, consistent with previous nationwide EJ research (Miranda et al. 2011, Rowangould 2013, Clark et al. 2014). COBRA has been used to quantify air quality co-benefits in research applications at various scales and policy evaluations: (a) two individual wind farms (McCubbin and Sovacool 2013); (b) nationwide deployment of wind and solar energy (Millstein et al. 2017); (c) Clean Air Act power plant rules (Thomson et al. 2018); (d) coal-fired power plant emissions control scenarios (J Levy et al. 2007); (e) state-level Renewable Portfolio Standards (Barbose et al. 2016); (f) nationwide violated vehicle emissions standards (Hou et al. 2016); (g) deep decarbonization of U.S. energy systems (Mailloux et al. 2022). COBRA has also previously been used to investigate PM$_{2.5}$ exposure to socially vulnerable populations from prescribed fire smoke, which includes race/ethnicity, socioeconomic status, and other demographics (Afrin and Garcia-Menendez 2021).

Released in 2020, COBRA v4.0 includes baseline emissions for every county in the contiguous U.S. for the years 2016, 2023, and 2028 with corresponding projected population and incidence data (see SI for details on the 2023 baseline). The emissions data is projected by EPA using the 2016v1 Air Emissions Modeling Platform and incorporates federal and state measures including but not limited to the Mercury and Air Toxics Rule, the Cross-State Air Pollution Rule Update, and fuel economy standards.

Atmospheric chemistry and transport in COBRA is simulated with a source-receptor matrix based on Climatology Regional Dispersion Model, a Gaussian dispersion model (U.S. Environmental Protection Agency 1995). COBRA quantifies changes to annual average ambient PM$_{2.5}$ concentrations, including both primary (emitted) PM$_{2.5}$ and secondary (chemically produced) PM$_{2.5}$ (including secondary organic aerosols, SOA) due to emissions of NO$_x$ (input in the model as NO$_2$), SO$_2$, volatile organic compounds (VOCs), and ammonia (NH$_3$). The simplified structure of COBRA likely introduces errors in the complex gas to aerosol chemistry of SOA formation (Pandis et al. 1992, Hildebrandt et al. 2009, Srivastava et al. 2022). Because emissions, chemistry, and meteorology all affect PM$_{2.5}$ concentrations, emissions data alone cannot be used to estimate PM$_{2.5}$ exposure and equity impacts of emission reductions on air quality.

Based on calculated annual PM$_{2.5}$ exposure at the county level, COBRA quantifies the health impacts with a linear model informed by nearly 30 peer-reviewed epidemiologic studies (U.S. Environmental Protection Agency 2014). Avoided mortality is based on health impact functions from Krewski et al. (2009) (low estimate) and Lepeule et al. (2012) (high estimate). To monetize avoided mortality, COBRA applies the value of a statistical life (VSL) based on the mean VSL from 26 studies with a 3% discount rate (U.S. Environmental Protection Agency 2014). We use COBRA’s prepopulated VSL for 2023 of $9.7 million (2017$). We mapped the COBRA output of air quality changes with ArcGIS 10.8 (ESRI 2020).

We evaluated COBRA against 2016 and 2019 ambient PM$_{2.5}$ concentrations from the U.S. EPA air quality system (AQS) monitors (U.S. Environmental Protection Agency 2020). Only monitors with the parameter name ‘PM$_{2.5}$—Local conditions’ and sample duration of ‘24 h’ or ‘24 h block averages’ were included in analysis. Counties with no monitors were removed from analysis and readings from monitors in counties with multiple monitors were averaged; this resulted in $n = 604$ counties for year 2016 and $n = 617$ counties for year 2019. Annual county-level monitor data was then compared with COBRA output.

Three nationwide decarbonization scenarios, each assuming a complete and instantaneous elimination of fossil fuel combustion (No-FF) within each sector, were simulated in COBRA by applying a 100% reduction in baseline PM$_{2.5}$, SO$_2$, NO$_x$, NH$_3$, and VOC emissions for (a) industrial fuel combustion (No-FF Industry); (b) electric utility fuel combustion (No-FF Electricity); and (c) light duty gasoline, diesel, and ethanol E-85 highway vehicles (No-FF LDV). The first two scenarios represent the entirety of a COBRA Tier 1 emissions category. The light duty vehicle (LDV) transportation scenario is a subset of the Highway Vehicles Tier 1 category and accounts for 54%–91% of county-level on-road transportation emissions. Each sector is treated independently, a simplification that is not realistic but highlights the differentiated impacts of these emission sources on U.S. populations. This approach of evaluating the
policy endpoints of complete decarbonization scenarios provides a conceptual framework to inform the development of specific technology and policy scenarios. Given the linear structure of COBRA, results here may be scaled to estimate impacts and equity of less aggressive changes, additive changes at the national scale, and/or provide a point of comparison for COBRA users evaluating regional, state, or local emission changes.

Demographic and socioeconomic data were obtained from the National Historical Geographic Information System, which hosts decennial Census and yearly American Community Survey (ASC) data (Manson et al. 2020). County-level 2015–2019 ASC five-year estimates of race/ethnicity were the focus of this study, as race/ethnicity have been found to determine air quality outcomes more significantly than poverty or educational attainment (Mohai et al. 2009b, Miranda et al. 2011, Mikati et al. 2018, Thind et al. 2019). Race and ethnicity groups are mutually exclusive and include Hispanic or Latino and non-Hispanic African American or Black, Asian, American Indian or Native Hawaiian, and White. We define ‘communities of color’ as the total population minus the non-Hispanic White population, a metric used in previous EJ research (Cushing et al. 2018, Tessum et al. 2021), to include all individuals that identify as Hispanic/Latino, Black, Asian, Native Hawaiian/American Indian, Pacific Islander, some other race, or two or more races. The Hispanic/Latino ethnicity alone accounts for almost half of the communities of color grouping.

To evaluate the racial equity dimensions of modeled decarbonization scenarios, we compared population-weighted average concentrations (PWCs), as a proxy for exposure for total population and each racial/ethnic group. For PM$_{2.5}$ we calculated PWC with the following equation:

$$\text{PWC} = \frac{\sum_{i=1}^{n} (P_i \times C_i)}{\sum_{i=1}^{n} P_i}$$

where $P$ is the population total and $C$ is the reduction of ambient PM$_{2.5}$ concentrations. Exposure difference between each racial/ethnic group and the total population was calculated as follows:

$$\text{Exposure Difference} = \frac{(\text{PWC}_{\text{racial/ethnic group}} - \text{PWC}_{\text{total population}})}{\text{PWC}_{\text{total population}}}$$

where each PWC (total population and each racial/ethnic group) was calculated on a county scale. The percent difference is reported as the relative reduction benefit (RRB) for each county. A similar methodology calculating ‘relative exposure disparity’ was used by (Tessum et al. 2021) to investigate the racial inequities of PM$_{2.5}$ pollution exposure. We calculated the exposure differences across each scenario and by urban and rural counties, based on the U.S. Census definition of ‘urbanized area’ (>50,000 people) for the urban designation and ‘rural’ (<2500 people) for the rural designation (U.S. Census Bureau 2010).

For each scenario, we calculate the percent of monetized health benefits (high estimate) that accrue in majority-minority counties, meaning population is >50% people of color. This calculation approximates the relevance of our decarbonization scenarios for President Biden’s Justice40 Initiative. The White House EJ Advisory Council recommended including majority-minority communities in their formal guidance on what constitute a ‘disadvantaged community,’ the term used in official documentation of Justice40 (WHEJAC 2021). We use the monetized health benefit because the Justice40 Initiative specifies that it is 40% of the benefit of federal investments that should flow to EJ communities (U.S. Exec. Order No. 14008 2021).

3. Results and discussion

3.1. Model evaluation

COBRA baseline PM$_{2.5}$ concentrations were statistically compared with AQS ground monitor data using root mean square error, mean error, normalized mean error, mean bias, normalized mean bias, and $R^2$ correlation (table S1). We find a strong spatial correlation between annual average PM$_{2.5}$ calculated by COBRA and monitored data for the same year: $R^2 = 0.75$ for 2016, $R^2 = 0.83$ for 2019. This comparison is only possibly for counties that have a monitoring system ($n = 604$ for 2016 and $n = 617$ for 2019). There is little difference in the $R^2$ value (<1%) across the three COBRA baselines (2016, 2023, and 2028) and the AQS data for both 2016 and 2019.

It should be noted that COBRA was developed with calibration factors that stem from monitor data, specifically 2016 EPA Federal Reference Method and EPA/National Park Service Visibility Interagency Monitoring of Protected Visual Environments data (U.S. Environmental Protection Agency 2014). Because COBRA was adjusted based on monitored data, the high level of agreement observed does not necessarily speak to model skill in capturing physical and chemical atmospheric processes.

Studies that quantify air quality co-benefits using multiple methods have found the COBRA model’s high and low monetary public health benefit estimates to be the same magnitude as those of other RFMs (Barbose et al. 2016, Wiser et al. 2016). COBRA has also been found to reproduce air quality concentrations similar to a more advanced dispersion model (Levy et al. 2003).

PWCs from COBRA have also been found to be similar to InMAP, another RFM with finer spatial
resolution previously used for EJ air quality analyses (Tessum et al. 2019, 2021, Thind et al. 2019). Tessum et al. 2017) reported that both COBRA and InMAP found similar spatial patterns in concentrations and were well correlated with WRF-Chem, an advanced CTM. COBRA’s R² (squared Pearson correlation coefficient) were reported to be 0.96 for area-weighted concentrations and 0.95 for population-weighted concentrations across 11 emissions scenarios compared with WRF-Chem. Additionally, the mean fractional bias (MFB) and mean fractional error (MFE) for area-weighed concentrations were 12% and 25% respectively; the MFB and MFE for population-weighted concentrations were −26% and 26%. (Tessum et al. 2017). The calculated MFB and MFE for COBRA against WRF-Chem meet PM model bias performance goals ±30% (MFB) and ±50% (MFE) and model performance criteria ±60% (MFB) and ±75% (Boylan and Russell 2006). Collectively, these results suggest that COBRA would be expected to capture the distributional impacts of emission changes on PM₂.₅ and related health outcomes at a level of skill comparable to other RFMs.

3.2. Air quality and health impacts

The three modeled decarbonization scenarios reduce emissions of PM₂.₅, SO₂, and NOₓ with much smaller impacts on NH₃ and VOCs. Figure 1 shows the contribution of LDV highway vehicles and fuel combustion for industry and electricity for each of these three major emissions as well as anthropogenic primary PM₂.₅ and CO₂ relative to other sources not evaluated here (e.g. waste disposal and recycling, off-highway vehicles, and natural resources).

Primary PM₂.₅ emissions were decreased by 1%–3.5% from the baseline in the three scenarios (figure 1). The decreases in primary PM₂.₅ emissions may be overestimated (up to 20%) as emissions from break and tire wear are included in COBRA, and these emissions will still occur with EVs, potentially at higher rates (Padoan and Amato 2018, Timmers and Achten 2018). ‘Miscellaneous’ sources make up most primary PM₂.₅ emissions, including prescribed burning (12%), forest wildfires (12%), agricultural crops (15%), and fugitive dust from unpaved roads (21%). Our three scenarios reduce a quarter of total U.S. anthropogenic primary PM₂.₅ emissions, with industrial fuel combustion comprising the largest reduction.

As SO₂ emissions are primarily associated with coal burning in the electricity sector, the no-FF electricity scenario would eliminate almost half of the nation’s SO₂ emissions (46%) while industrial fuel combustion would eliminate 16% of the baseline’s SO₂ emissions (figure 1). Additional emissions from non-combustion industrial processes (e.g. chemical manufacturing, metals processing), which are not reduced in our scenarios, contribute nearly a quarter of the baseline’s SO₂ emissions.

Emissions of NOₓ were decreased by about 10% in every scenario (figure 1). Other major sources of NOₓ include off-highway vehicles (21%), and heavy-duty highway vehicles (9%), other fuel combustion (8%), and natural resources (12%). Across our scenarios, NH₃ emissions were reduced by 4% and VOC emissions by <2% in total (figure S1). Hazardous air pollutants (HAPs) associated with these sectors were not explicitly included in our analysis, but many HAPs are also VOCs (e.g. benzene) which were included.

In comparison, our decarbonization scenarios would eliminate nearly half of U.S. CO₂ emissions, with No-FF Industry responsible for 8%, No-FF Electricity for 20%, and No-FF LDV for 19% of the
nation’s anthropogenically-emitted CO₂ (figure 1, U.S. Environmental Protection Agency 2021).

All decarbonization scenarios yield reductions in ambient PM$_{2.5}$ concentrations in all contiguous U.S. counties (figure 2). Carbon-free electricity would reduce national average ambient PM$_{2.5}$ concentrations by 0.21 μg m$^{-3}$, compared with a 0.19 μg m$^{-3}$ reduction associated with carbon-free industrial activity, and a 0.08 μg m$^{-3}$ reduction associated with carbon-free light duty vehicle (LDV) transportation.

Counties vary widely in their response to modeled scenarios, ranging from minimum PM$_{2.5}$ reduction of 0.01–0.03 μg m$^{-3}$ in the least impacted counties to 2.15 μg m$^{-3}$ in the most impacted county for carbon-free electricity, 1.41 μg m$^{-3}$ in the most impacted county for carbon-free industry, and 0.72 μg m$^{-3}$ in the most impacted county for LDVs.

The regional patterns of air quality improvement differ in each modeled decarbonization scenario (figures 2(a)–(c)). No-FF Industry produces the largest air pollution reductions in the Southeast, along the Great Lakes, as well as in Pennsylvania, California, and New York (figure 2(a)). No-FF Electricity would have the greatest reduction in ambient PM$_{2.5}$ concentrations in the Midwestern U.S, especially Ohio, Illinois, Indiana, Michigan, and Pennsylvania (figure 2(b)). Where stationary point sources of power plants and large industry centralize emissions, vehicle emissions are widespread, such that county maximum and national average reductions from No-FF LDV are half or less of the same metrics for the other two scenarios. Benefits of carbon-free LDVs are highest in urban areas where vehicle ownership and population densities are highest (figure 2(c)). California counties would see an average of four times greater ambient PM$_{2.5}$ concentration reductions from than the nationwide average, with some of the largest counties in California seeing reductions up to ten times greater.

The location of ambient PM$_{2.5}$ reductions has implications for who will benefit from decreased exposure to air pollution. Black people are highly represented in the South, where 58% of the nation’s Black population resides, and in urban areas in the North (figure 2(d)). Hispanic populations are concentrated in the southwest, especially California, Arizona, New Mexico, and Texas. Similarly, Asians live in high numbers in California, Washington, and Texas as well as urban areas where they are collocated with other populations of color.

The No-FF Industry yields $90.5 billion annual public health benefits, which is 37% more than No-FF Electricity ($66.1 billion), despite 10% less reduction in PM$_{2.5}$ concentrations. In addition, the No-FF LDV Transportation has a 61% less reduction in PM$_{2.5}$ concentrations than No-FF Electricity, but only 34% less health benefit ($43.3 billion annually). Differences in spatial colocation of population and air pollution sources accounts for the differences in relative PM$_{2.5}$ reduction versus health benefits. No-FF Industry and No-FF LDV Transportation emissions reductions are statistically higher in urban counties relative to rural counties, while the no-FF Electricity emissions reductions are not statistically different between urban and rural designated counties (table S3). This suggests that industry and LDV transportation pollution have a greater effect on urban areas. Thus, the PM$_{2.5}$ concentration reductions in these scenarios lead to more of an exposure reduction for larger populations, elucidating the higher public health benefits.

### 3.3. Evaluation of distributive EJ

To evaluate distributive EJ, we use the metric of RRB (%) for the reduction in ambient PM$_{2.5}$ concentrations across race/ethnicity. Defined as the relative change in PWC for a specific racial/ethnic group relative to total PWC in each county, the RRB captures the colocation of racial and ethnic populations with improved air quality, which also indicates the air pollution-related health benefits for these groups. These patterns are qualitatively evident at the regional scale in figure 3, and aggregated on a national basis in figure 3. The RRB metric is based on changes to PM$_{2.5}$ concentrations, so a large positive value represents a larger benefit for that race/ethnicity compared to the total population.

In figure 3, positive RRB values denote more air quality benefit for that racial/ethnic group compared to the total population, while negative RRB values indicate less air quality benefit than average. While every scenario yields health and exposure reduction benefits for every racial group, in some cases there are disproportionate positive and negative impacts of a decarbonization scenario on a particular racial/ethnic group.

Black populations are the only racial group with disproportionate benefits from every scenario. This result also highlights the disproportionate exposure to air pollution from these sources currently affecting Black communities.

The largest RRB for Black populations was found for the No-FF Industry scenario, which would reduce PM$_{2.5}$ exposure for Black communities 23% more than the U.S. average (figure 3(a)). The largest reduction in PM$_{2.5}$ pollution from decarbonizing fuel combustion for industry occurs in the South, specifically Virginia, North Carolina, South Carolina, Tennessee, Florida, and along the Gulf Coast (figure 2(a)), corresponding to regions with larger Black populations (figure 2(d)). Rural Black populations would see an even greater relative benefit in the No-FF Industry scenario (73% RRB) compared to Black communities in urban counties (20% RRB). In fact, this discrepancy between rural and urban Black populations holds across all three scenarios (figure 3(b)).

The largest overall RRB was found for Asian populations in the No-FF LDV Transportation scenario,
Figure 2. The change in ambient PM$_{2.5}$ concentrations for (a) No-FF Industry; (b) No-FF Electricity; and (c) No-FF LDV Transportation. (d) The racial diversity of the U.S. as presented by counties where racial/ethnic minorities are highly represented. Highly represented denotes that a racial/ethnic minority group’s population is greater than the national share (Hispanic 18.7%, Black 12.1%, Asian 6.1%, and Native 5%; map adapted from a Brookings map using 2015–2019 ACS five-year estimates). Counties with two or more highly represented minorities are also indicated.

at 53% (figure 3(a)). Transportation emissions are higher along major roads (Mukherjee et al 2020) and in urban areas (table S3), corresponding with higher population density. This relates to a large RRB for Asian populations since 98% live in urban counties. The largest reductions in the No-FF LDV scenario were found in California, where more residents live closer to high volume roads than in other states (Rowangould 2013). California is home to large Asian populations (figure 2(d)), as one third of all Asians in the U.S. live in that state alone. We also find larger transportation-related reductions in ambient PM$_{2.5}$ concentrations in urban areas, including Washington, D.C.; Baltimore, MD; Philadelphia, PA; New York, NY; Atlanta, GA; Charlotte, NC; Miami, FL; Chicago, IL; Indianapolis, IN; Twin Cities, MN; Detroit, MI; Salt Lake City, UT; Denver, CO; and Seattle, WA. The collocation of Asian populations in urban areas and in California result in the largest RRB in our analysis.

No-FF LDV also results in the largest RRB for Hispanic populations and communities of color. Non-emitting LDV transportation (e.g. electric vehicles) would preferentially benefit Hispanic populations (29% more than the total population) and communities of color (22% more than the total population) (figure 3). Patterns for Hispanic populations and communities of color are similar to those for Asian populations discussed above, with high populations in California and urban areas (figure 2(d)). In the U.S., a quarter of Hispanic people and 18% of all people of color live in California. While 87% of the U.S. population lives in urban counties, 95% of Hispanics and 93% of people of color live in urban areas.

Even larger RRBs for Asian and Hispanic populations as well as communities of color would occur in urban areas (figure 3(b)), as urban areas coincide with the greatest decreases in transportation-related air pollution and large racial/ethnic populations. Urban Asian populations would experience a 43% reduced reduction benefit from No-FF LDV while Asians living in rural counties would see <1% of a reduced exposure reduction benefit. The RRB for Hispanic populations in urban counties is 24%, in contrast with only a 5% RRB for rural Hispanic populations. Similarly, urban communities of color would see an 18% RRB from decarbonized LDV transportation compared to the total population, whereas rural communities of color would only experience 5% RRB.

White populations only experience a positive RRB in the No-FF Electricity scenario (figure 3(a)). This scenario leads to air quality improvement in Pennsylvania, Ohio, Indiana, and Illinois (figure 2(b)), states in the Rust Belt with high levels of coal combustion for electricity generation. Other
Figure 3. (a) Relative reduction benefit (RRB, %) in air quality improvement, meaning the percent difference between the population-weighted change in PM$_{2.5}$ concentrations for each racial/ethnic group and the scenario average. (b) Relative reduction benefit (RRB, %) for each racial/ethnic group in urban (>50,000 people) and rural (<2,500 people) counties.

Studies have also found this region to have high co-benefits from clean electricity (Millstein et al, 2017, Abel et al, 2018, Buonocore et al, 2019, Mailloux et al, 2022). The northern half of the U.S. has a larger White population, including the states located in the Rust Belt (figure 2(d)). Power plants are often located in rural areas, which are also more predominately White. These patterns lead to modest relative benefits of no-FF electricity for White populations (4%) and less RRB for Asian (−7%) and Hispanic (−13%) populations, as well communities of color (−6%).

Spatial heterogeneity of pollution and demographics can occur at the sub-county level, with pronounced effects in urban areas. Coarser resolution, like the county-scale in COBRA, has been found to estimate lower calculated population-weighted average exposure and average exposure difference between minority and White populations (Paolella...
et al 2018). As a result, our results likely underestimate RRB differences among groups.

3.4. Regional discrepancy in pollution reduction and equity goals

Because decision-making on carbon reduction strategies often takes place at the regional, state, and local level, we considered impacts of decarbonizations over the ten U.S. EPA regions (figure 4(a)). The largest reduction across regions and scenarios would result from No-FF Electricity in Region 5, the Upper Midwest, at 0.39 $\mu g m^{-3}$. The largest reduction in the No-FF Industry scenario would occur in Region 2, comprised of New York and New Jersey, at 0.33 $\mu g m^{-3}$. The largest reduction in the No-FF LDV scenario would also occur in Region 2 at 0.18 $\mu g m^{-3}$. Although Region 9, including California, would see the largest impact from carbon-free transportation, in fact about half of the U.S. regions would see even greater reductions in PM$_{2.5}$ from non-emitting transportation than would Region 9.

Five of the ten EPA regions would have the largest reduction in air pollution concentrations from No-FF Industry scenario, including the Southeast and South Central U.S., the Pacific Northwest, as well as New England down to New York and New Jersey (figure 4(b)). Four of the ten EPA regions would have the largest air quality improvement from No-FF Electricity, including the Great Plains, the Central U.S., the Middle Western U.S., and the Mid-Atlantic states. Only Region 9, which includes California, Nevada, and Arizona, would have the largest reduced air pollution from No-FF LDV transportation.

No-FF LDV transportation accounts for the largest RRB for people of color in eight of the EPA regions (figure 4(b)). Only No-FF Industry in Regions 4 and 9 yields a larger RRB for communities of color. We find that only one EPA region accomplishes largest overall air quality improvement and RRB for communities of color with one decarbonization scenario: Region 4 in the Southeast with No-FF Industry (figure 4(b)). This shows a discrepancy between what decarbonization policies would yield the largest total reduction in air pollution and equity goals.

3.5. Justice40 Initiative

To investigate if the three decarbonization scenarios can advance the Biden Administration’s Justice40 Initiative, we calculate what percent of health benefits flow to majority-minority counties. We find that only the health benefits from decarbonized transportation would align with Justice40 Initiative across the contiguous United States, with 44% of the benefit accruing in majority-minority communities. No-FF Industry would yield 33% of health benefits in majority-minority communities, and No-FF Electricity only 24%.

All three scenarios, however, yield more than 40% of health benefits in majority-minority counties in some states (figure S2, table S4). No-FF Transportation aligns with the Justice40 Initiative the most frequent, in ten states, then No-FF Industry in eight states, and finally No-FF Electricity achieves this threshold the least, in only five states.

3.6. Comparison to other EJ research

Our results are consistent with studies evaluating current air pollution burdens by demographic group (table 1). While the papers included in table 1 use
### Table 1. Quantitative comparison of racial/ethnic exposure disparities to air pollution across papers with different metrics.

| Publication | Industry | Electricity | LDV transportation | Ambient PM2.5 exposure |
|-------------|----------|-------------|--------------------|------------------------|
|             | Present study | Present study | Present study | Present study |
| Method      | COBRA    | InMAP       | COBRA             | InMAP                  |
| Metric      | RBB, %    | Exposure disparity, % | RBB, % | Exposure disparity, % | RBB, % | Exposure disparity, % | Monitor data | Monitor data |
| White       | −6       | −12         | 4                 | 8                      | 5.9     | −14                 | −15          | 13.1      | —          |
| Black       | 23       | 23          | 7                 | 18                     | 6.6     | 3                   | 22           | 14.4      | 2.73       |
| Asian       | 5        | 19          | −7                | −18                    | 3.6$^a$ | 53                  | 39           | 12.7      | —          |
| Hispanic    | 4        | 24          | −13               | −38                    | 3.4$^a$ | 29                  | 27           | 13.6      | 0.83       |
| Communities of color | 9 | 20 | −6 | −13 | — | 21 | 24 | — | — |

$^a$ Indicates number is estimated from a figure.

$^b$ Odds ratios for the multivariable logistic regression modeling the probability of that demographics residing in a county with the worst 20% PM$_{2.5}$ concentrations vs a county with the best 20% PM$_{2.5}$ concentrations.
different methods and metrics to examine the racial/ethnic disparities of air pollution, the trends that emerge from those studies are consistent with the results from our analysis of the EJ impacts of decarbonization co-benefits.

First, the disparity of exposure to PM$_{2.5}$ pollution for Black populations is pervasive (Miranda et al. 2011, Bell and Ebisu 2012, Tessum et al. 2021). Tessum et al. (2021) found that Black populations are disproportionately exposed to higher air pollution from every source type (ranging from industry and power plants to agriculture and road dust). Miranda et al. (2011) found that Black populations were overrepresented in counties with the worst annual and daily PM$_{2.5}$ concentrations, as captured by AQS monitors. Bell and Ebisu (2012) separated PM$_{2.5}$ concentrations into 14 chemical components and found that Black populations were more exposed to 13 out of 14 components relative to White populations. A study of the Clean Air Act transport and mercury rules found larger ambient PM$_{2.5}$ concentration reductions in the Southern regions with higher Black populations (Thomson et al. 2018). Thind et al. (2019) found that Black populations would experience the highest average impact (mortality rate) from PM$_{2.5}$ pollution due to U.S. electricity generation overall, but more specifically in the Upper Midwest and Mid-Atlantic. In alignment with current air pollution disparity research, we find that decarbonization will disproportionately benefit Black populations, both urban and rural (figure 3).

In contrast, White populations are most affected by air pollution from electricity generation (table 1), and thus would benefit more than average from a carbon-free electricity sector (figure 3). Tessum et al. (2021) found that coal-fired electricity, along with agriculture, were the only two sectors disproportionately affecting White populations. Another analysis which evaluated the implementation of the Clean Air Act’s transport and mercury rules, two regulations aimed at coal-fired power plants, found that White and rural counties saw the largest air quality improvement after the regulations’ implementation (Thomson et al. 2018). A separate study of PM$_{2.5}$ pollution and resulting mortality from U.S. electricity generation found White populations to have a higher mortality rate from PM$_{2.5}$ exposure than the over-all population average, although it is lower than for Black populations (Thind et al. 2019). While White populations had the highest proportional burden of PM$_{2.5}$ from electricity generation in 2014, retired power plants resulted in a decrease in absolute and proportional burden for White populations by 2017 (Richmond-Bryant et al. 2020).

Our research does not consider all the pollution sources that Tessum et al. (2021) does, but the sources of PM$_{2.5}$ pollution that contribute the largest absolute exposure disparity for Black, Hispanic, and Asian populations, and people of color include the ones eliminated in our decarbonization scenarios: industry and transportation. Tessum et al. (2021) reports the largest absolute disparity for Black and Hispanic populations, as well as communities of color as a group was attributed to industrial sources, with LDV as second for Hispanics and communities of color, whereas we find that decarbonizing LDV would have more of an RRB for Hispanic populations and communities of color than decarbonizing industry. For Asian populations, LDV transportation resulted in the largest absolute disparity source and industrial sources as second largest (Tessum et al. 2021), which is consistent with our conclusion that Asian populations would see higher than average improvement in PM$_{2.5}$ concentrations. Research using satellite-derived NO$_2$ concentrations, associated with transportation emissions, found that non-White census tracts are consistently exposed to higher NO$_2$ (Kerr et al. 2021).

While we do not quantify the impact of HAPs, previous research has considered the equity implications of industrial facility locations (Faber and Krieg 2002, Mohai et al. 2009a) and the exposure burden from industrial HAP emissions by racial/ethnic groups (James et al. 2012). For example, Mohai et al. (2009a) found that Black people are statistically more likely to live within 1 mile of an industrial facility compared to White people. Along the Mississippi River in Louisiana, researchers have found 16% higher cancer risk in black-dominant census tracts compared to white-dominate census tracts from HAPs (James et al. 2012). A more recent study evaluated both satellite-derived PM$_{2.5}$ concentrations and EPA estimates of respiratory and immunological hazards and found that all three disproportionately burden census tracts with larger Black populations (Terrell and James 2022).

4. Conclusion

These results highlight the importance of accounting for regional, sectoral, and racial differences in air quality co-benefits from energy systems changes in the U.S. The approach of evaluating policy endpoints with a linear air quality model allows for results to be scaled for analysis of incremental energy system change.

We find distributive EJ impacts of air pollution co-benefits from decarbonizing large-scale sectors in the U.S. All decarbonization scenarios are found to yield positive air quality and health benefits for all people in all counties of the U.S. A decarbonized electricity sector would produce the largest average reduction in ambient PM$_{2.5}$, 0.21 $\mu$g m$^{-3}$, compared with a 0.19 $\mu$g m$^{-3}$ reduction associated with carbon-free industrial activity, and a 0.08 $\mu$g m$^{-3}$ reduction associated with carbon-free LDV transportation. However, a decarbonized industrial sector would create larger health benefits, valued at $90.5$ billion per
year nationally, compared with $66.1 billion per year from the decarbonized electricity scenario and $43.3 billion per year from the decarbonized transportation scenario.

Spatial patterns in emission sources interact with spatial patterns in population to create differentiated benefits by U.S. region and racial group. Concentrations of PM$_{2.5}$ in five of the ten U.S. EPA regions benefits most from decarbonized industry, whereas PM$_{2.5}$ in four of the ten regions benefits most from carbon-free electricity, and only EPA Region 9 (including the areas of California, Nevada, and Arizona in the contiguous U.S.) would experience the most reduction in PM$_{2.5}$ from carbon-free LDVs. Urban versus rural counties also differ in their response to decarbonization scenario, with urban counties benefitting more from non-emitting LDV transportation.

Decarbonization strategies also vary in terms of the racial/ethnic groups most benefitting from each scenario, due to regional and urban/rural patterns in emission sources and population demographics. Black populations are the only group to experience relative exposure reduction benefits compared to the total population in every scenario. Industrial decarbonization yields the greatest RRB for Black communities (23%), which is even larger for rural Black populations (73%). The largest relative reduction in PM$_{2.5}$ exposure was found for Asian populations in the carbon-free LDV transportation scenario (43%). Only carbon-free electricity yields disproportionate benefits for White populations, whereas carbon-free industry and carbon-free LDV scenarios yield disproportionate benefits for Asian and Hispanic populations, as well as communities of color as a group.

Our policy relevant research evaluates three decarbonization scenarios, quantifying the upper bounds of the air quality and EJ impacts from those sectors. While we compare our results with previous nationwide EJ air quality research, the novel analyses in this paper disaggregates the regional differences in emissions, air quality improvement, and equity impacts. We calculate RRB by urban and rural counties, investigate the disparity between total pollution decreases and relative reduction benefit for communities of color by EPA regions, and determine which decarbonization scenarios advance the goals of the Justice40 Initiative.

The COBRA Screening Tool was developed by the U.S. EPA explicitly to support state and local decision-makers, and is computationally inexpensive and easy-to-use that is appropriate for EJ air quality policy questions. We hope the combination of this user-friendly RFM combined with our newly developed metrics of EJ analysis (RRB) can be applied to other EJ questions around climate co-benefits and air pollution.

Important questions beyond the scope of this study relate to air pollution variability, sub-county impacts, and pollutants other than PM$_{2.5}$, as COBRA is limited to annual, county-scale, PM$_{2.5}$ simulations. Past EJ air pollution studies typically use Census tract or block data (Ash and Fetter 2004, Bell and Ebisu 2012, Tessum et al. 2021) since larger spatial units can obscure heterogeneity. Any decarbonization transition will be gradual, and analysis of the temporal deployment could support the prioritization of high impact initiatives.

Climate change presents compounding inequities. The most vulnerable populations contribute fewer emissions yet face the worst climate impacts both internationally (i.e. developed compared to developing countries; (Füssel 2010) and within the U.S. (Gamble et al. 2016). Almost half of U.S. households that are energy insecure, meaning financially burdened to pay their energy bill, are Black (Drehobl and Ross 2016). Communities of color also have less access to reliable transportation systems, including both public transit and personal vehicles (Fleming 2018). Higher average temperatures from climate change will increase energy bills, compound vulnerability to climate impacts, and exacerbate poor air quality (Abel et al. 2018). The intersection of energy, climate, and air quality disparities highlights the need for analysis of climate policies and impacts on equity.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iD

Ciaran L Gallagher  https://orcid.org/0000-0002-6460-1206

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