Inequality in energy transitions: Air pollution disparities amidst national decarbonization strategies

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Abstract

Energy transitions and decarbonization require rapid changes to a nation's electricity generation mix. There are many feasible decarbonization pathways for the electricity sector, yet there is vast uncertainty about how these pathways will advance or derail the nation's energy equality goals. We present a framework for investigating how decarbonization pathways, driven by a least-cost paradigm, will impact air pollution inequality across different vulnerability groups in the US (e.g., low-income, high poverty or minority communities). We find that using least-cost optimization capacity expansion models without strict carbon or renewable energy technology mandates will fall short of achieving national energy equality. We find that Black or poor communities have higher co-pollutant concentrations during the energy transition, until a national mandate requires full deployment of renewable or low-carbon technologies. Thus, decisions regarding national decarbonization pathways must have strict mandates for equality outcomes or be driven by an equality-focused paradigm throughout the energy transition.

Introduction

As countries push for electricity system decarbonization, there is a risk that electricity transition investment can lead to outcomes that worsen social inequalities if marginalized groups are excluded from the benefits due to explicit exclusion or implicit human biases[1–3]. Thus, there is large uncertainty regarding the degree to which decarbonization policies will exacerbate or alleviate social inequalities and how they will impact co-pollutants [nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter (PM) emissions] of the electricity sector. Currently, most national electricity planning models investigate how the nation can decarbonize the electricity sector using least-cost optimization[4], without considering how different decarbonization strategies impact the distribution of air pollution emissions across a nation[5–7]. Achieving distributional energy justice requires that there is an equitable distribution of a society's technological and environmental risks, harms, and benefits[8]. In our paper, the harms and risks stem from air pollution exposure, and the benefits relate to the reduction of aur pollution exposure following power plant retirements. Incorporating key principles from distributional energy justice begin to address the gap in electricity planning models by identifying how the benefits and harms of future energy transitions will be shared across a nation[8,9]. We add to the literature by evaluating the environmental sustainability (i.e., national air pollution emissions) and equality (i.e., distribution of air pollution) across eight national decarbonization strategies focusing specifically on the electricity sector. Our equality analysis focuses on the distribution of air pollution emissions, with total equality defined as each community having equal air pollution emissions from the electricity sector. A key contribution of our work is highlighting how the benefits of decarbonization (i.e., reduced emissions) impact different demographic groups.

Four sustainability dimensions (economic, environmental, social, and technical) often are used to measure national and regional sustainability[10–12]. While much of the literature addresses environmental sustainability from a national perspective (i.e., total emissions across a country), there is a need for a deeper understanding of how different decarbonization pathways will affect pollution distribution across vulnerable groups (distributional equality)[13]. Based on the review of energy transition literature, Kohler et al. (2019) illuminates the need for exploration in how energy transitions may place an undue burden on regions with high poverty rates or low-income populations[14]. Likewise, in a review of energy justice literature, Carley et al. (2020) indicates that it is known that energy transitions may exacerbate inequalities[1]. However, these two reviews indicate that there is a gap in understanding the magnitude and geographic distribution of energy inequalities and how energy systems transitions will impact the four dimensions of sustainability[1,14].

At a national level, air pollution is responsible for 100,000 to 200,000 excess deaths every year in the US and severe health effects, like lung heart, and brain diseases[15–17] yet these effects are often greatest felt in minority communities[18–21]. As the nation decarbonizes, the electricity sector, air pollution across US is likely to improve, but the distribution of air pollution may not be equal throughout the energy transition (e.g., some regions may be left with higher concentrations of pollution, and more negative health impacts). Some studies have investigated the air quality co-benefits of decarbonization policies (i.e., additional reductions in other emissions like $PM_{2.5}$). In general, mitigating greenhouse gas emissions results in positive co-benefits in $PM_{2.5}$ emissions[22–24] at the system level, but there is still uncertainty regarding the spatial distribution of these emission reduction benefits. Some papers have investigated the air pollution exposure disparities across different racial and income groups using a retroactive analysis, finding that low-income, Black, Asian, and Hispanic or Latinx communities were exposed to higher levels of $PM_{2.5}$ in the US in 2000, 2014, and 2016[25,26]. While it is valuable to understand the level of historical injustices, countries also need a framework to that evaluates future disparities in air pollution distributions across the nation under different decarbonization plans, in order to mitigate and reduce future inequalities. Here we create a forward-looking analysis framework for assessing how decarbonization benefits will shared across different demographic groups by tying a capacity expansion model with a local equality analysis.

A host of proposed models can evaluate the sustainability of electricity system transitions[4], with the most prevalent being least-cost optimization models. In these models, system level environmental sustainability metrics are calculated after the optimization has been solved or integrated as one of the constraints[13,27]. Social dimensions (i.e., equality, equity, and justice) are often nonexistent, used as assumptions in models, or analyzed separately from capacity expansion models[13,14,28]. Thus, economic optimization drives the model decision-making, while environmental and social factors are considered a constraint or post-analysis at the system or sometimes country level[29], in which low spatial resolutions may miss specific impacts on people or communities. Our analysis addresses these limitations by quantifying how national energy transition policies impact sub-national equality at a high spatial resolution, designed using a least-cost paradigm for power plant investment decisions.

While least-cost optimization models often exclude equality considerations, some papers have integrated equality into the electricity system decision making paradigm. One paper investigated the social and environmental implications of expanding power systems in developing countries with little to no existing infrastructure[30] at a subnational level. In Nock et al. (2021), the primary goal was to investigate how different stakeholder preferences towards equality (i.e., distribution of electricity access) impacted power grid construction[30]. However, the authors did not investigate how the distribution of air population emissions would change under different decarbonization strategies or the distributional impacts a high resolution. Sasse & Trutnevyte (2020) investigated researched the sustainability and equity impacts of reaching electricity sector targets across European countries[29]. While this paper looks at four different optimization objective scenarios (base case, cost, equality, and renewable generation), their focus is on intercountry equality considerations[29], which miss local level equality impacts. Sergi et al. (2020) does a forward-looking analysis to investigate the impact of including co-benefits of decarbonization by including damages from air pollution in the objective function, but they do not explore distributional energy justice or equality of air pollution across different decarbonization scenarios[31]. We build on this work by investigating how least-cost optimization (dominant decision paradigm) impacts local equality objectives across eight unique decarbonization scenarios, some of which include 80–100% renewable penetration, national carbon caps, or 100% low carbon technology requirements.

This paper investigates and quantifies the distributional equality air pollution impacts at a local scale by tying a capacity expansion model with a sustainability and equality analysis. The capacity expansion model optimizes the US electricity sector from 2010 to 2050 on a least cost paradigm[5]. The capacity and electricity generation from the capacity expansion model are fed into the environmental sustainability model, which calculates air pollution emissions at the regional and national level. We investigate local air pollution concentrations and associated disparities using a reduced complexity air pollution model, which ties source emissions to its transport and deposition. Using this model, we build a high-resolution analysis to quantify air pollution concentrations across different demographic groups at the census tract level. Specifically, our equality analysis examines the way different national decarbonization policies will impact the distribution of air pollution emissions across different demographic groups (e.g., median income, poverty, and race or ethnicity). Our air pollution analysis focuses on the generation co-pollutants (NO_x, SO_2, and $PM_{2.5}$). CO_2eq. emissions will not have local air pollution effects, but rather impact global greenhouse gas emissions. CO_2eq. emissions and system level co-pollutant emissions are the focus of our national analysis, while co-pollutant emissions and their local effects are the focus of our equality analysis.

Results

National energy transitions under decarbonization goals. We investigate the environmental impacts (i.e., total air pollution emissions) and equality (i.e., regional distribution of emissions) of different electricity generation investment strategies under eight decarbonization strategies over 40 years (see Table 1 in Methods). Our decarbonization scenarios include the base case with no additional carbon constraints (Scenario A), two carbon cap scenarios which meet either the US nationally determined contributions (NDC) from the Paris Agreement or a pathway to stay under 1.5°C warming (Scenarios B and C respectively), and five technology specific portfolios which deploy either renewable energy (Scenarios D – F) or low carbon (Scenarios G and H) generation.

Figure 1 shows the annual generation by technology for the decarbonization scenarios. For Scenario A (the Base Case), which implements no additional carbon constraints or policies, coal, natural gas and nuclear mainly supply generation. By 2050 we see coal generation decrease to 7.5% of total generation (0.41 PWh), natural gas generation slightly increases to 20.0% (1.08 PWh), onshore wind generation increases to 33.8% (1.83 PWh), and solar PV generation increases to 20.9% (1.14 PWh) of total generation. The carbon cap scenarios (B and C), which place a strict limit on CO_2eq. emissions from the electricity sector, achieve their carbon caps primarily through deploying solar PV and onshore wind. In both scenarios, wind and solar represented less than 3% of the generation in 2010. Still, by 2050 we see solar PV and onshore wind generation supplying 20–30% or 37–50% of total generation in 2050 respectively. Scenario C specifically sees the complete retirement of coal by 2035 and almost complete retirement of natural gas by 2050 (0.2% of generation). However, contrasting to Scenario C, the carbon cap defined in Scenario B allows an increase of CO_2eq. emissions, resulting in an increase in coal generation from 2040 to 2050 (1.67% of generation in 2040 to 4.67% of generation in 2050).

Scenarios with an implemented renewable portfolio standard (RPS) (D, E, and F) invest in onshore wind generation to meet their renewable energy mandates. By 2050, onshore wind represents approximately 50% of generation in all three scenarios. Scenarios D, E, and F also see large solar deployment due to the implemented RPS. Scenario E deploys the highest generation of solar PV, CSP, biopower, and battery storage to meet the 100% renewable requirement by 2035, with solar PV technology representing 35.0% of total generation by 2040. Solar PV is still a significant contributor to generation in the other seven scenarios, with solar PV supplying 15–20% of US generation in 2040.

Natural gas in the low carbon scenarios (G and H) is relied on until their low carbon requirement year, when natural gas is retired due to the mandate. Upon reaching the technology mandate, natural gas CCS replaces natural gas. Thus, this technology would most likely continue to provide 10–20% of the total generation needs without a mandate. See Table S-4 in SI for a summary of generation by technology and scenario.

National environmental sustainability. Figure 2 shows the emissions impacts of the changing power plant profiles, which depicts the national operating emissions over the model timeline 2010–2050. Operating emissions are emissions produced directly from the power plant creating electricity. These results discuss the national operating emissions trends from CO_2eq., NO_x, SO_2, and $PM_{2.5}$. From Fig. 2, we see all pollutants have similar trends, with emissions decreasing through 2050 but at varying magnitudes across scenarios. Scenario A (base case) is an upper bound for national emissions across all pollutants in our analysis, indicating that implementing carbon or technology mandate policies will decrease emissions compared to no policies.

By 2035, operating emissions from Scenarios C, E, and G are under 100 Mt CO_2eq. emissions. Coal has entirely retired by 2035 in these scenarios, so it does not contribute to emissions, and natural gas or natural gas CCS contributes under 10% of generation. By phasing out coal and natural gas plants, emissions from co-pollutants like NO_x, SO_2, and $PM_{2.5}$ also fall significantly, with NO_x levels at or below 0.02 Mt, SO_2 levels below 0.003 Mt, and PM levels below 0.002 Mt. $PM_{2.5}$ emissions (d) in Scenario E rise from 2035 to 2050 due to investments in biopower to maintain the 100% renewable energy mandate. Because of this, Scenarios C and F have lower levels of $PM_{2.5}$ emissions in 2050.

Figure 2: *National operating emissions across scenarios 2010–2050 (megatonnes, Mt). The emissions shown here are*: a) *CO_2eq. operating emissions*, b) *NO_x operating emissions*, c) *SO_2 operating emissions, and* d) *$PM_{2.5}$ operating emissions. Note that the y-axes are not consistent. We see the base case (black line) as an upper bound on all emissions types, and Scenarios C (solid yellow line) and E (dotted blue line) as a lower bound across all emissions types. Scenario E emissions reach close to zero by 2035, its mandate year, and remains close to zero 2035 to 2050 for CO_2eq., NO_x, and SO_2 emissions. However, $PM_{2.5}$ emissions in Scenario E rise because of investments in biopower, which help maintain the 100% renewable grid but still have co-pollutants that will be emitted.*

Air pollution distribution. While national-level emissions analyses are important for measuring progress across the energy system as a whole, regional inequalities resulting from energy transitions can manifest in the unequal distribution of air pollution emissions. The operational co-pollutants will broadly impact people's health within the region, so operating emissions reductions of these pollutants will result in regional health benefits[32–35]. Therefore, we present an analysis of operating co-pollutant emissions (NO_x, SO_2, $PM_{2.5}$) to illuminate how different decarbonization scenarios could impact emissions globally and regionally.

Once emitted from the power plant, air pollution travels through the air before depositing into communities and causing health impacts[36]. We use a reduced complexity model, InMAP, to model air pollution travel and understand where emissions are landing after being emitted from power plants for different decarbonization scenarios. Figure 3 displays the annual average total $PM_{2.5}$ emissions across census tracts for 2020, 2035, and 2050. The NO_x and SO_2 emissions distribution reported similar trends to $PM_{2.5}$ (see SI Figures S-7 and S-8). $PM_{2.5}$ emissions in 2020 across scenarios have exposures over 1.0 $\mu g/m^3$ in the Midwest and Eastern US. In 2035, Scenarios A, D, and H have concentrations over 1.0 $\mu g/m^3$ located in the Eastern US and from Ohio to Iowa. Meanwhile, $PM_{2.5}$ concentrations in Scenarios C, E, and G are under 0.25 $\mu g/m^3$ across all regions by 2035 because of an aggressive carbon cap (C) or clean technology mandates (E and G). Similarly, when Scenarios F and H reach their 2050 mandate year, $PM_{2.5}$ exposure is under 0.25 $\mu g/m^3$ across all regions, indicating that total equality of emissions is achieved when the technology mandate year is met (2035 or 2050).

Emissions across vulnerable groups. Beyond regional analyses that measure the magnitude of air pollution, it is useful to understand the distribution of operating emissions across different demographic and socioeconomic indicators (race, ethnicity, income, poverty, urban or rural, etc.) across regions. This investigation shows the impact of different energy transitions on vulnerable regions. We focus on operating NO_x, SO_2, and $PM_{2.5}$ emissions, due to the local health impacts of these co-pollutants.

Figure 4 compares the average concentration of $PM_{2.5}$ to the percentage of a given race or ethnicity in a census tract. Census tracts were grouped by percentages of a race or ethnicity (< 10%, 10–20%, 20–30%, 30–50%, 50–70%, and > 70%. See SI Table S-3 for groups and sample sizes). Figure 5 shows five scenarios since Scenarios C, E, and G and Scenarios F and H have almost identical trends (see SI Figure S-9 for all scenarios). When census tracts have over a 30% Black population, the average $PM_{2.5}$ concentrations are higher than those under 30% Black population. This trend continues in 2035 and 2050 for decarbonization scenarios that do not have technology mandates or a carbon cap that cause emissions to become minimal. Based on these results, Black populations are at risk for higher $PM_{2.5}$ concentrations and its associated health impacts in energy transitions until renewable or low carbon mandates reach 100% renewable or low carbon technologies. The group with the second highest $PM_{2.5}$ concentrations are non-Latinx white populations. NO_x and SO_2 concentrations showed almost identical trends and can be seen in SI Figures S-10 and S-11.

The distribution of operating emissions across different median incomes (Fig. 5) illustrates the disparities between high- and low-income regions (see SI for group definitions and the aggregation of median income census tracts to the ReEDS regions). SO_2 and $PM_{2.5}$ emissions have higher exposures in low-income communities over time, so these regions will continue to bear the brunt of emissions (and associated health impacts)[26] unless a technology mandate or carbon cap requires fossil fuels to be retired (as seen in Scenarios C and F). NO_x emissions are higher in higher-income areas in 2020 and plateaus over time to very little difference in concentration across income groups. However, higher-income people have more access to the health care facilities and insurance, so low-income groups with the same concentrations may be left worse off since they cannot access healthcare for health impacts from air pollution as easily[37]. SI Figures S-13 and S-14 show the results for high poverty populations and rural populations respectively. We see regions with high poverty have higher concentrations of all co-pollutants and rural populations have higher concentrations of $PM_{2.5}$ until technology mandates are met in 2035 or 2050.

Discussion & Conclusions

We investigated how national level decarbonization policies translate to national emissions and the distribution of emissions at the local level. Our analysis finds that no decarbonization scenario reaches operating emission distributional equality until they meet their mandate year of 2035 or 2050 (Scenarios C, E, F, G, and H). However, there are clear trade-offs between national emissions reductions and distribution of emissions across regions: to maintain a 100% renewable requirement after 2035, biomass power plants are deployed, which emit SO_2 and PM. While biomass can be considered a carbon neutral source of energy, a policy question would be investigating the differences in where the emissions are emitted and absorbed. The emissions directly from biomass plants will negatively affect surrounding communities and cause greater inequality across distributional air pollution. We find that the carbon cap scenario, which aims to keep warming under 1.5°C, has less national reduction in emissions compared to 2035 technology mandates results in an equal distribution of air pollution (0 emissions) by 2050 for CO_2eq. and co-pollutants. The 100% renewables by 2050 (Scenario F) and low carbon technology mandates (Scenario G and H) also see this trend. This further highlights the multiple objectives, and often conflicting nature, of energy transition planning.

When addressing the multi-faceted lens of decarbonization, it is important to weigh both the aggregate national emissions reductions and the distribution of those emission reductions. For example, reaching 100% renewable energy by 2050 will help the US decarbonize its electricity sector entirely. However, before the mandate is reached in 2050, there are air pollution inequalities as the nation decarbonizes, with poor, or Black communities seeing the highest emissions. This result may be a byproduct of the least cost paradigm being the primary objective guiding technology deployment. In this analysis we created a framework for social impact assessments to identify who may be burdened with higher levels of air pollution in national decarbonization transitions. This could help advise decision makers on who loses in energy transitions and help build policy to compensate them. The continued air pollution inequality from historical trends will exacerbate health impacts among the most vulnerable communities. Four scenarios reach zero (or close to zero) operating emissions by their mandate in either 2035 (E and G) or 2050 (F and H), but not beforehand. This result indicates that achieving 100% renewable energy or low carbon by a given year may ensure an equal future beyond those years, but beforehand, poor and Black communities are burdened with the highest emissions.

All scenarios with carbon policies implemented see improvements from Scenario A, which implements no additional carbon policies after 2020. There is at least a 20% reduction in co-pollutant emissions in the lowest income group in 2050 in the other scenarios compared to Scenario A. However, a gap persists between the best off and worse off regions across all demographic variables and time periods we consider. If an equitable energy transition is the goal (i.e., one that reaches total equality), decarbonization policies in the absence of strict technology mandates and those guided by least-cost optimization capacity expansion models may fall short of environmental justice and equality goals. Thus, decisions regarding national decarbonization pathways must have strict mandates for equality outcomes or be driven by an equality-focused paradigm. Two opportunities for future analysis present themselves. The first is to investigate how changing the decision-making paradigm (i.e., changing the optimization objective function) influences the equality outcomes between regions. The second is to investigate the trade-offs of air pollution distribution with other equality (e.g., distribution of costs and electricity bill increases), equity (e.g., health impacts), environmental (e.g., water consumption and land-use), and cost objectives. A deeper analysis of health impacts from energy transitions could also necessitate greater quantification of the monetary damages or deaths from air pollution[38–41].

Equitable energy transitions exist at the intersection of technical, economic, and social justice objectives[1,8,42–45]. Achieving the goal of an equitable energy transition requires a multi-disciplinary lens to understand who wins and loses in energy transitions. Our work begins to do this by using a least-cost optimization model coupled with a sustainability and equality analysis that measures air pollution across regions and demographic groups. This research is a first step in investigating an equitable energy transition by analyzing how national policies translate to subnational equality. We have shown that a single objective of minimizing cost leaves vulnerable groups at risk of existing in regions with higher air pollution concentrations throughout the transition. When crafting public policy for energy transitions, decision-makers can use this work as a source for indicating the need for holistic multiple objective approaches to energy system planning if we are going to ensure an equitable and sustainable future.

Methods

Here we discuss the electricity system modeling, decarbonization scenarios, and the sustainability and equality analyses. We conclude this section by discussing the limitations of our analysis. Our work investigates the air pollution equality of decarbonization scenarios at the national and sub-national level across 134 regions in the US. We do this by tying a national capacity expansion model with an air pollution assessment and distributional equality analysis.

Electric power system model. Our electricity system analysis uses the Regional Energy Deployment System (ReEDS) from the National Renewable Energy Lab (NREL) to define the resulting electricity generation profiles under different decarbonization scenarios, such as a carbon cap or national renewable portfolio standard to reach different energy transition goals. The model outputs generator capacity, generator generation, system cost, generator retirements, and transmission data for regions in the US defined by ReEDS for each model year. We use these data to analyze the impact of different decarbonization scenarios and, ultimately, the overall cost, sustainability, and equality trade-offs. ReEDS is a least-cost, linear program that minimizes the cost of the future electricity system subject to load, operating, and transmission constraints. ReEDS runs sequentially, meaning that each model year is solved individually before continuing to the next model year.

ReEDS implements a carbon cap or technology mandate as an exogenous input to the model. The carbon cap specifies allowed emissions in the US electric sector for each model year (2010 to 2050). The operating emissions generated from the system cannot surpass the specified yearly carbon cap in the model. The model will not continue to the next solve year until it can find a solution that meets the carbon emissions cap. The technology mandate specifies a percentage of chosen technologies (i.e., solar and wind) that are required generate a certain percentage of electricity each year. As with the carbon cap, the model must satisfy the share of generation from the specified technologies before continuing to the following year.

Decarbonization scenarios. We ran eight decarbonization scenarios for this analysis, summarized in Table 1. Each decarbonization scenario was then run in ReEDS to simulate the US electricity system from 2010 to 2050. See SI Table S-1 for details by year of carbon caps (Scenarios B and C) and national technology mandates (Scenarios D – H).

Table 1
Description of decarbonization scenarios and their implemented policies in ReEDS (See SI Table S-1 for a description of ReEDS carbon policy inputs for each scenario).

Scenario	Scenario description	Scenario approach	Source
A	Base	Includes all current policies and standards (state RPS, tax credits, etc.) but implements no new carbon policies.	5
B	US NDC	United States Nationally Determined Contributions via the 2015 Paris Agreement. Carbon cap implemented in ReEDS to follow emissions allotted.	46
C	1.5°C Pathway	Based on policy required to maintain global warming under 1.5°C. Carbon cap implemented in ReEDS to follow emissions allotted.	46
D	80% RE 2050	National RPS implemented beginning in 2020 at 20% and increased linearly to 80% renewable energy in 2050.	5
E	100% RE 2035	National RPS implemented beginning in 2020 at 20% national RE generation and increasing linearly to 100% RE generation in 2035.	47
F	100% RE 2050	National RPS implemented beginning in 2020 at 20% national RE generation and increasing linearly to 100% RE generation in 2050	5
G	Low Carbon 2035	National technology mandate implemented beginning in 2020 at 20% and increased linearly to 100% renewable energy, natural gas CCS, or nuclear in 2035.	48
H	Low Carbon 2050	National technology mandate implemented beginning in 2020 at 20% and increased linearly to 100% renewable energy, natural gas CCS, or nuclear in 2050.	48

Environmental sustainability (emissions) assessments. This analysis uses operating emissions to represent environmental sustainability. Operating emissions are classified by the emissions produced while the power plant is generating electricity.

The operating emissions are a function of the fuel emissions rate (e_f) in pounds/MMBtu, heat rate (H) in MMBtu/MWh, generation (g_n) in MWh, and pounds to grams conversion (α) (Eq. 1). The total operating emissions are the sum of emissions from each technology (n). See Table S-3 for heat rates for each power plant. The emissions used in this analysis are carbon dioxide equivalent (CO_2eq.), nitrous oxides (NO_x), sulfur dioxide (SO_2), particulate matter with diameter less than 2.5 microns ($PM_{2.5}$).

$$E_O = \sum_{i=1}^{n} g_n e_{f,n} H_n \alpha \qquad (1)$$

We obtained operating emission rates for powerplants from the literature (See SI Table S-2 for sources). We assumed that operating emissions from renewable and nuclear sources were zero.

Table 2
Operating emission rates used in environmental sustainability analysis. See Table S-2 in SI for sources.*

	Operating Fuel Emissions Rates [pounds/MMBtu]			
	CO_2eq.	NO_x	SO_2	$PM_{2.5}$**
Biopower	0	0	0.08	0.101
Solar photovoltaic (PV)	0	0	0	-
Concentrated solar power (CSP)	0	0	0	-
Onshore wind	0	0	0	-
Offshore wind	0	0	0	-
Nuclear	0	0	0	-
Natural gas combustion turbine (CT)	117	0.15	0.015	0.007
Natural gas combined cycle (CC)	117	0.02	0.005	0.007
Natural gas CCS	11.7	0.02	0.005	0.007
Hydropower	0	0	0	0
Geothermal	0	0	0	0
Oil-Gas-Steam	137	0.172	0.299	0.116
Coal	211	0.153	0.470	0.016[1]
IGCC	211	0.085	0.056	0.016[1]
Coal CCS	21.1	0.085	0.056	0.016[1]
Cofire	179	0.130	0.411	0.029
Battery storage	0	0	0	0
Pumped hydropower	0	0	0	0

[1]Assumed Bituminous coal.

* Dashed line indicates no reported value.

** For renewable energy and nuclear technologies, we assumed PM operating emissions were negligible.

Air pollution equality assessments. The equality metrics we use in this analysis are median income, percent of the population in poverty, and race or ethnicity. We obtained these datasets from the American

Community Survey (ACS) from the US Census Bureau [49] (median income, percent population in poverty, race or ethnicity) at the census tract level. We split regions into groups based on each metric better to understand the distribution of emissions across these equality metrics. For example, we grouped median income across census tracts intervals of $25,000 (see Table S-5 in SI for group intervals and their respective sample sizes). We compare these equality metrics to air pollution concentrations to investigate the inequalities across regions for each decarbonization scenario. These estimations are from 2018, so they may not accurately represent what median income, percent in poverty, or demographics may look like in future time periods. Thus, one limitation is the lack of projection regarding human migration patterns at the subnational level, which may be impacted by rising temperatures and changing weather patterns.

Air pollution across vulnerable groups. Within the US electricity sector, Black and non-Latinx white communities have the most deaths per 100,000 people from $PM_{2.5}$ from electric generating units[26]. To understand how energy transitions may exacerbate or reduce local air pollution disparities, we use a reduced complexity model, the Intervention Model for Air Pollution (InMAP), to quantify where co-pollutants (NO_x, SO_2, and $PM_{2.5}$) settle after being emitted from power plants. Reduced complexity models are commonly used to evaluate the impact of air pollution disparities across race, ethnicity, and income groups[26,50] as well as the health impacts, estimated deaths, and monetary damages from air pollution in the US[16,38]. Figure 6 summarizes how the analysis estimates air pollution from the ReEDS region level to the census tract level. InMAP uses the quantities of power plant emissions (in kg) as shapefile inputs and uses area-weighting to allocate emissions from our electricity capacity expansion model (ReEDS) regions to the more spatially granular grid. Area-weighting means the model equally distributes emissions from the ReEDS regions to the InMAP grid based on the size of the InMAP region (see SI for area-weighting equation). Then, InMAP calculates annual average emissions for NO_x, SO_2, and $PM_{2.5}$ using a reaction-advection-diffusion Eq. 5[1]. From InMAP, we obtain the annual average air pollution estimates from InMAP, which we then distribute to census tracts and calculate the air pollution exposure across different groups by census tract.

InMAP calculates the annual average concentration of pollutants by using equations that account for the travel and deposition of air pollution (advection, mixing, chemical reactions and deposition equations) across a variable spatial grid. Advection is the transport of air pollution from the wind. Mixing equations account for the transport of air pollution from turbulent mixing (not wind). Chemical reactions account for secondary $PM_{2.5}$ that NO_x or SO_2 can form. Deposition equation estimates where and how much air pollution is deposited in the region. InMAP uses a variable grid with square grids ranging from 1 to 48 km as its spatial resolution. The InMAP documentation provides more detail on the model formulation[51].

Limitations & caveats. Our work presents a subnational analysis of national decarbonization strategies' environmental sustainability and equality impacts. Here we present some limitations and caveats for the work presented here.

The population and equality metrics data collected were in 2010 (population) and 2018 (equality metrics). Our equality and per capita calculations will likely change if we use a model to simulate population migration patterns across our modeling time horizon (2010–2059). However, there is evidence that low-income groups have fewer resources and thus are less likely to move over time[52], so our current metrics will likely have little change over time and are valid estimations and assumptions.

The ReEDS model operates over a 40-year time horizon, so there is inherent uncertainty in its outputs (i.e., location of power plants, generation of those power plants in each model year). See SI Section A for model assumptions made in this analysis. The ReEDS documentation by NREL documents all assumptions in model inputs and solve[5]. Due to a least-cost paradigm directing the model, its final outputs may vary as costs of technology fall, demand changes, or implementation of different policies. These cost decreases will vary by location, workforce, labor costs, and scarcity or abundance of input materials over time. The goal of our analysis was not to perfectly simulate which technologies would be used in future generation mixes but to highlight how different decarbonization pathways might impact vulnerable groups. See SI for model specifications used in this analysis.

Reduced complexity models, like InMAP, were created to offer an extensive air pollution model that does not require the expertise or computing power that chemical transport models need[41]. In a comparative analysis between InMAP and a chemical transport model, InMAP reported $R^2 = 0.90$ and a mean fractional bias of -17%[41], indicating InMAP results are within the bounds for its air quality results to be valid. However, there is also uncertainty in using a reduced complexity model. One point of uncertainty is the area-weighting of the emissions from the ReEDS region level to the InMAP grid level (see SI Eq. S-1 for area-weighting calculation). Emissions are distributed across the region and not at the power plant level because ReEDS does not identify power plant locations in its simulating. Future work could estimate ReEDS level emissions to the power plant level by allocating ReEDS level emissions to fossil fuel power plants.

Declarations

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Author Contributions

Teagan Goforth designed and performed the analysis, wrote and edited the paper. Dr. Destenie Nock formed the research idea, outlined the analysis steps, oversaw the research process, and edited and reviewed the paper.

Competing Interest

The authors have no competing interests.

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Figures

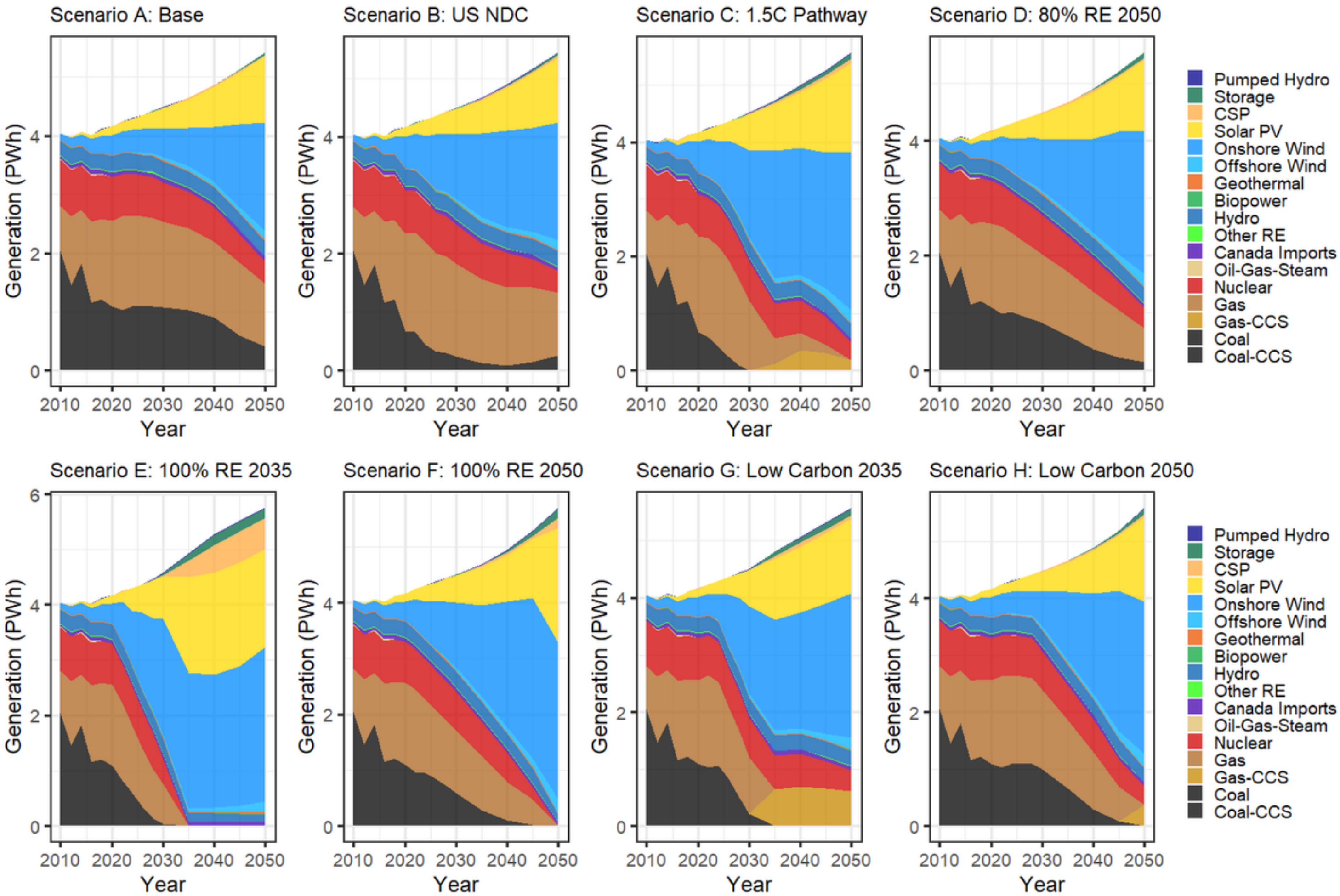

Figure 1

Annual generation mix (PWh) 2010 – 2050 by technology for each decarbonization scenario resulting from the ReEDS model. We highlight that the renewable and low carbon technology mandates accommodate additional energy needs primarily through expanded wind and solar generation investments. We see that the base case, US NDC, and 80% renewable energy decarbonization pathways retain coal generation through 2050.

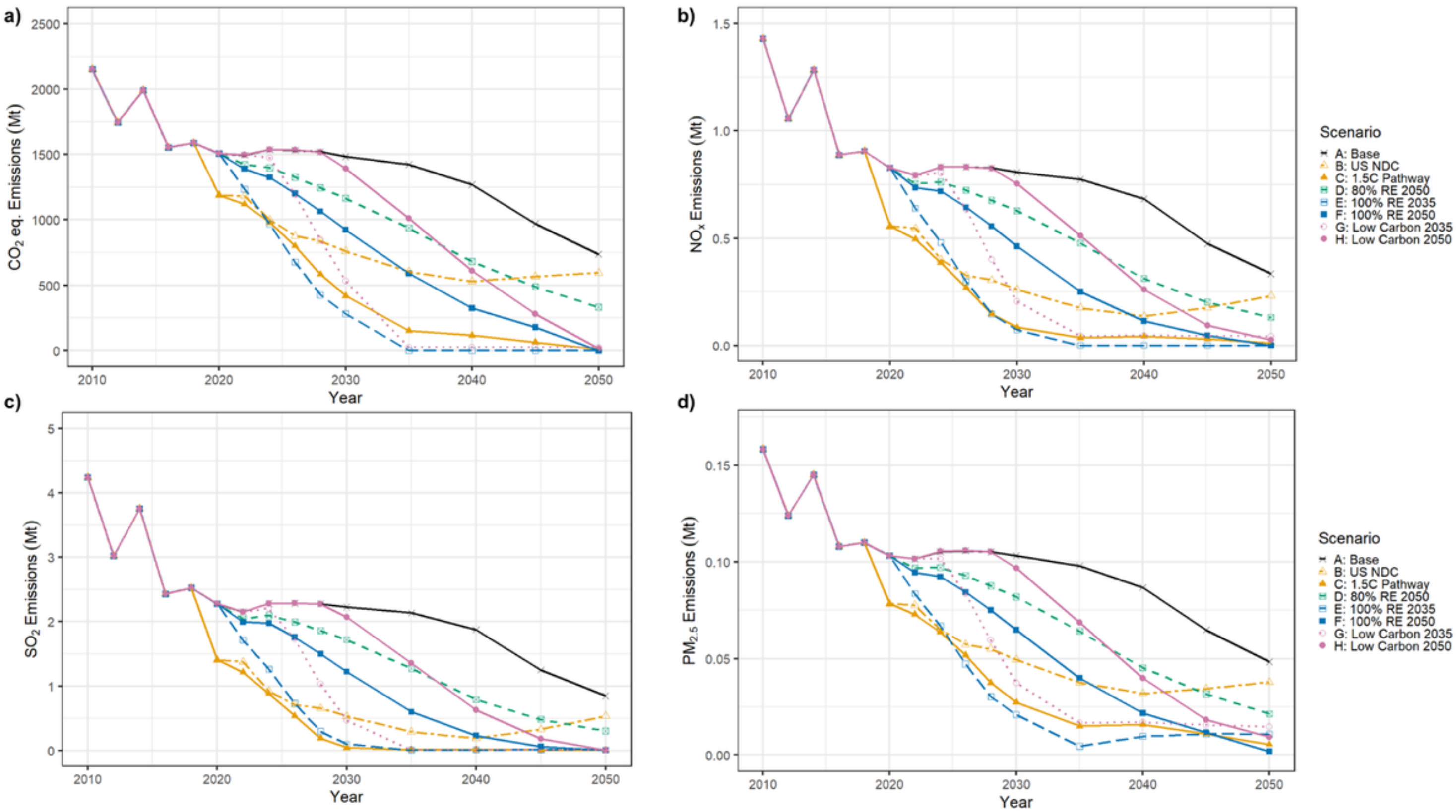

Figure 2

National operating emissions across scenarios 2010 – 2050 (megatonnes, Mt). The emissions shown here are: ***a)*** *CO_2eq. operating emissions,* ***b)*** *NO_x operating emissions,* ***c)*** *SO_2 operating emissions, and* ***d)*** *$PM_{2.5}$ operating emissions. Note that the y-axes are not consistent. We see the base case (black line) as an upper bound on all emissions types, and Scenarios C (solid yellow line) and E (dotted blue line) as a lower bound across all emissions types. Scenario E emissions reach close to zero by 2035, its mandate year, and remains close to zero 2035 to 2050 for CO_2eq., NO_x, and SO_2 emissions. However, $PM_{2.5}$ emissions in Scenario E rise because of investments in biopower, which help maintain the 100% renewable grid but still have co-pollutants that will be emitted.*

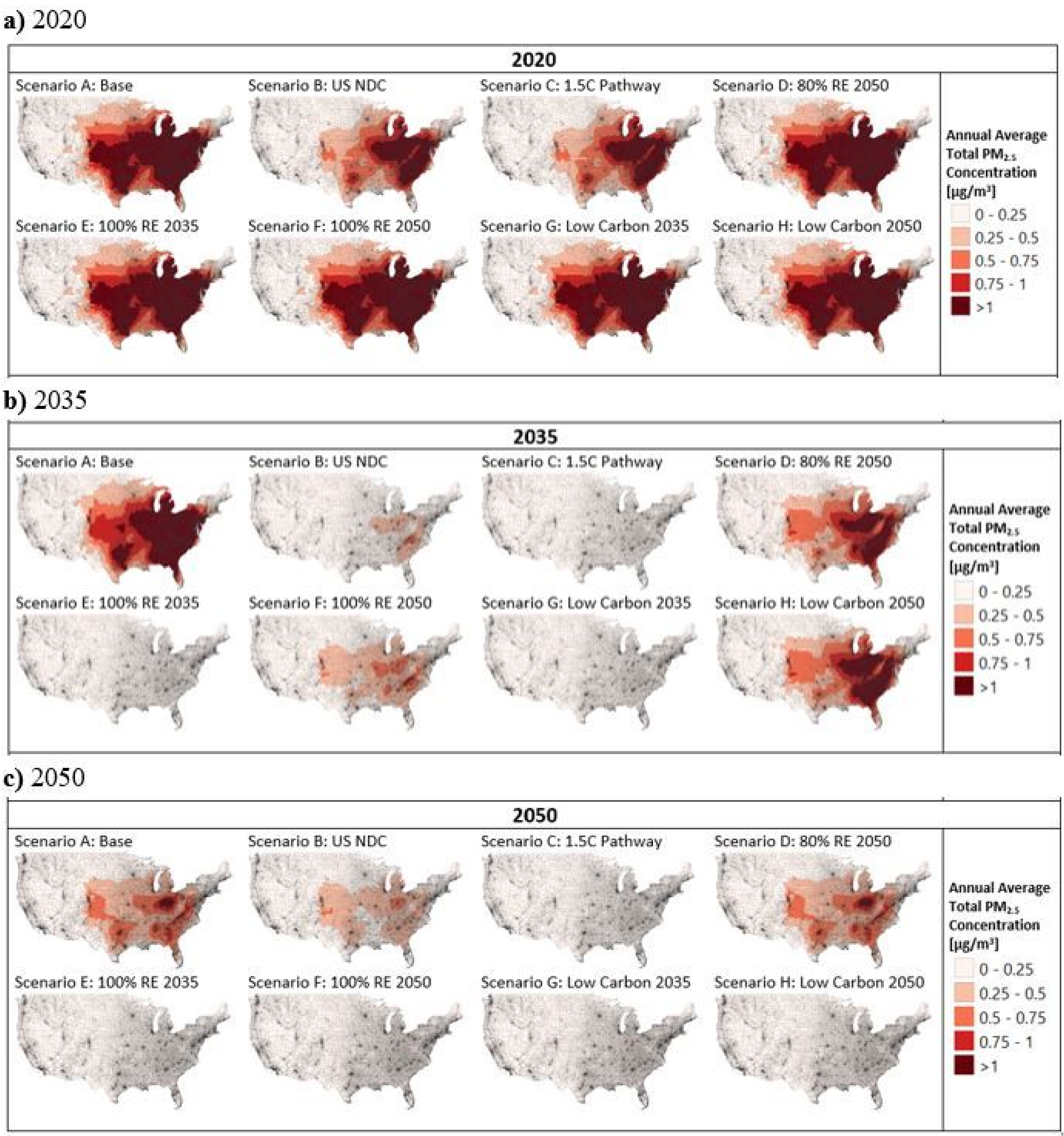

Figure 3

*$PM_{2.5}$ from power plants across scenarios **a)** 2020, **b)** 2035, and **c)** 2050. By 2035, Scenarios C, E, and G, which have either an aggressive carbon cap (C) or a technology mandate with a 2035 goal of 100% low carbon or renewable technologies, have 100% of regions below the threshold of 0.25 μg/m^3.*

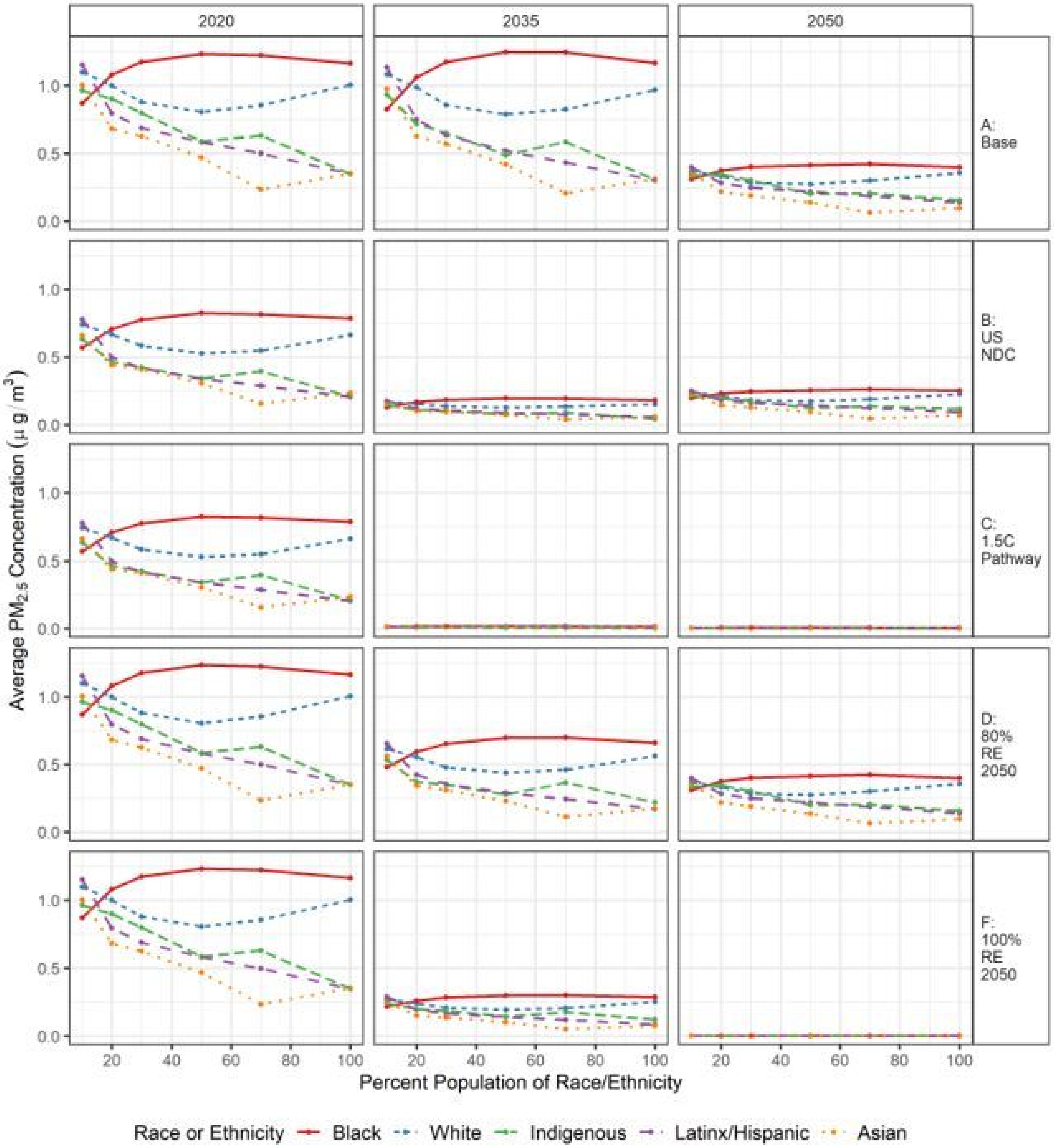

Figure 4

Average $PM_{2.5}$ concentration ($\mu g/m^3$) based on the percentage of the population of a specified race or ethnicity within census tracts across years 2020, 2035, and 2050 for each scenario. Over time, $PM_{2.5}$ concentration is decreasing across all racial or ethnic groups. Still, census tracts with over 20% Black populations maintain higher $PM_{2.5}$ concentrations compared to census tracts with higher percentages of other race or ethnic groups until a scenario reaches 100% renewable or low carbon technology (as seen in Scenarios C and F – where concentrations across all groups are 0 $\mu g/m^3$). Only five scenarios are *included here because Scenario E and G have almost identical trends to Scenario C, and Scenario H has almost identical trends to Scenario F.*

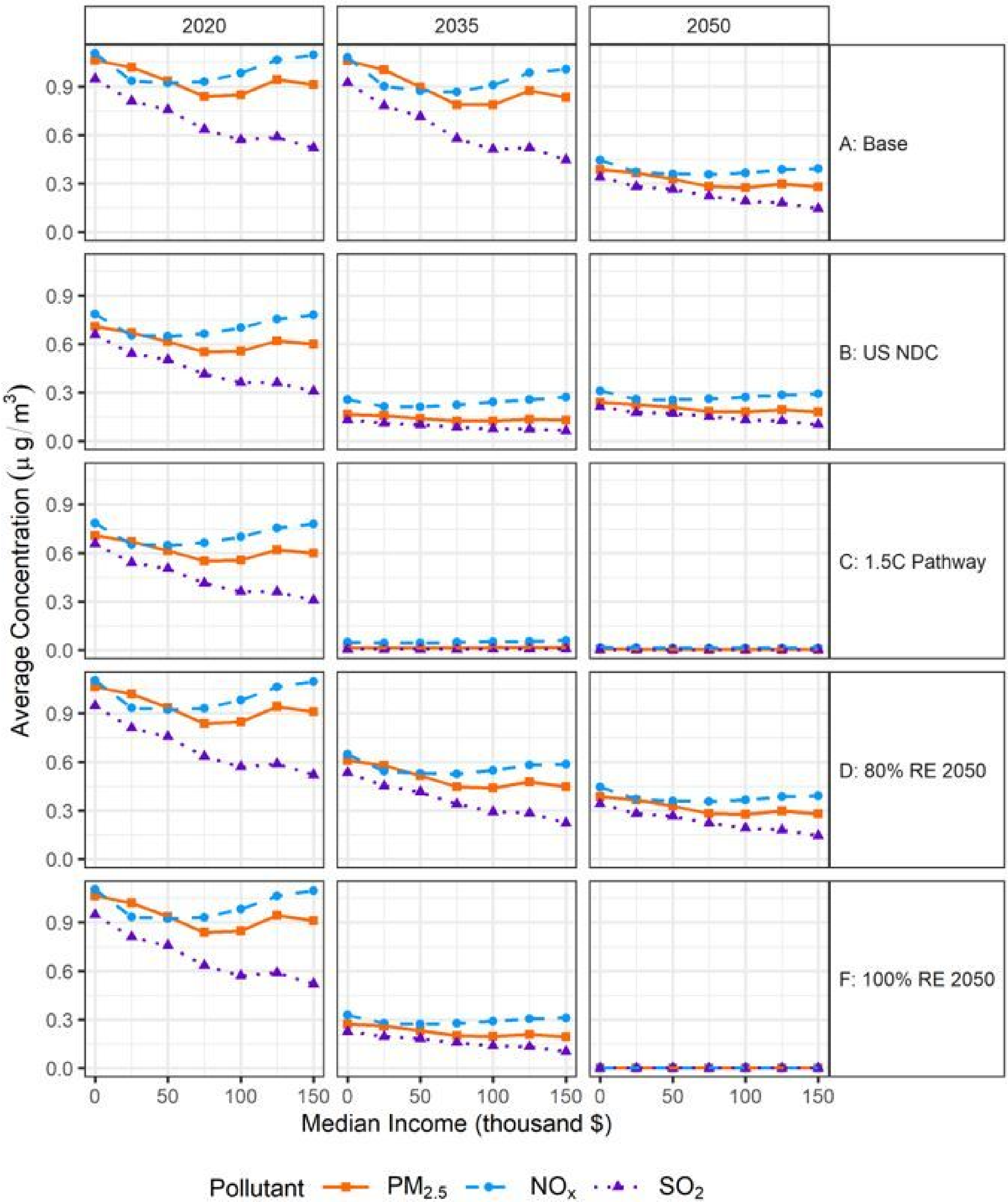

Figure 5

Average $PM_{2.5}$ concentration ($\mu g/m^3$) across different median income groups (<$25k, $25-$50k, $50-$75k, $75-$100k, $100-$125k, $125-$150k, >$150k). The points on the plot represent the minimum *median income in each group (e.g., the point at $0k represents the <$25k income group). Census tracts with income <$25k have higher levels of $PM_{2.5}$, NO_x, and SO_2 in their communities until clean energy mandates in 2035 or 2050 are reached (and emissions are 0 across all groups). NO_x emissions are also higher in higher-income areas. Only five scenarios are included here because Scenario E and G have almost identical trends to Scenario C, and Scenario H has almost identical trends to Scenario F.*

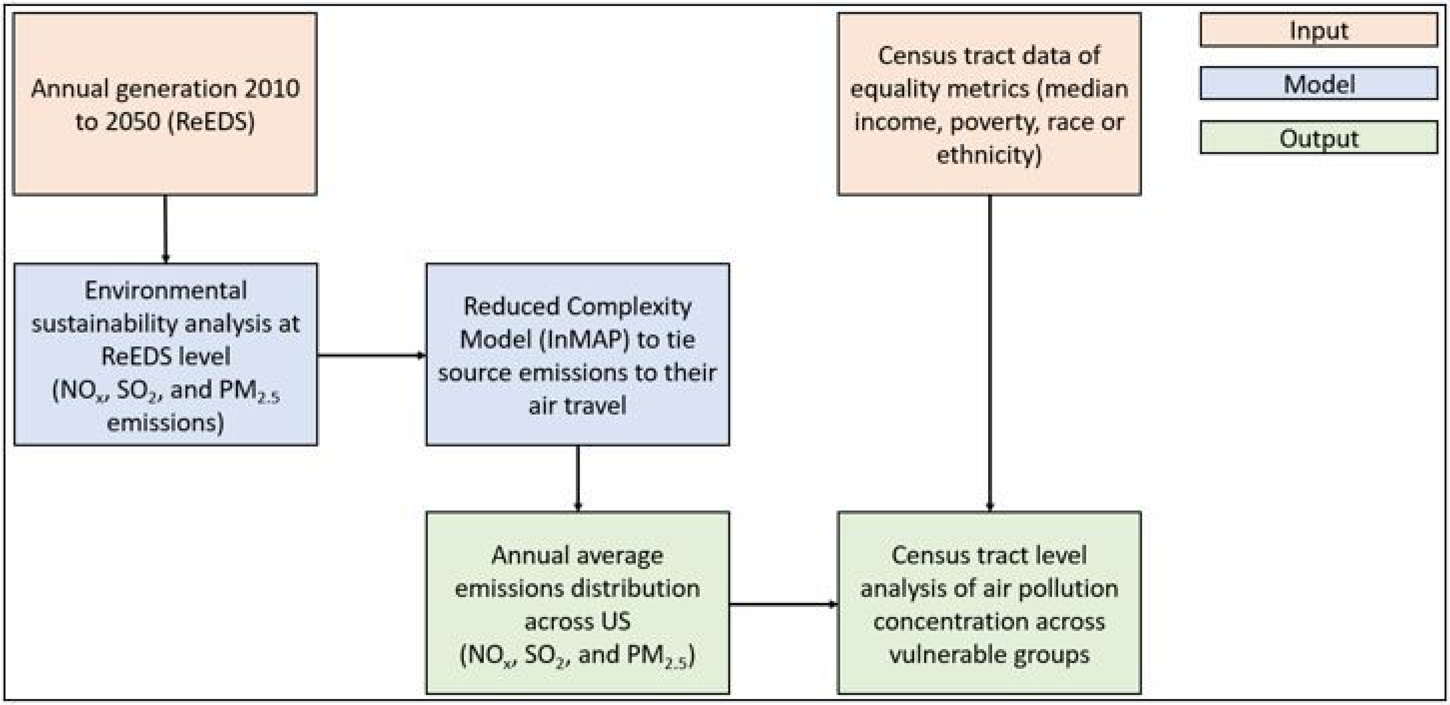

Figure 6

Equality analysis methods using a capacity expansion model (ReEDS) and a reduced complexity air pollution transport model (InMAP) to investigate where emissions are settling after being emitted from power plants.

Supplementary Files

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