Inequality in energy transitions: Subnational air pollution disparities resulting from national decarbonization strategies

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Abstract

Energy transitions and decarbonization require rapid changes to a nation's generation mix. There are a host of possible decarbonization pathways, yet there is vast uncertainty about how different decarbonization 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 lead to air pollution inequality across different vulnerabilities (e.g., low-income, energy poverty). If an equitable energy transition is the goal (i.e., one that reaches total equality), using least cost optimization capacity expansion models without strict renewable energy technology mandates will not accomplish this. Thus, it is imperative that decisions regarding national decarbonization pathways have strict mandates for equality outcomes or be driven by an equality focused paradigm.

Introduction

As countries push for electricity system decarbonization, there is the possibility that these infrastructure investments can simultaneously combat climate change while also driving economic recovery. However, 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^{1,2}. 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 (NO_x, SO₂, PM emissions) of the electricity sector. Currently, most national electricity planning models investigate how the nation can decarbonize the electricity sector using least cost optimization³, without considering how different decarbonization strategies will impact distributional equality of greenhouse gas and co-pollutant emissions across a nation⁴⁻⁶. This paper adds to the literature by evaluating the environmental sustainability (i.e., national air pollution emissions) and equality (i.e., distribution of air pollution) of eight national decarbonization strategies. Our equality analysis is focused on the distribution of air pollution emissions, with total equality being defined as each region having equal levels of air pollution emissions from the electricity sector. A key contribution of our work is highlighting how a myopic, single-objective view of energy transition decision making impacts distribution of air pollution across the US, and how the benefits of decarbonization (i.e., reduced emissions) are spread across different demographics (i.e., income groups, types of poverty experienced).

National and regional sustainability are often measured through four different dimensions: economic, environment, social, and technical⁷⁻⁹. Some studies look at different aspects of sustainability in the electricity sector to compare renewable and non-renewable options through multi-criteria decision analysis (MCDA)^{7,8,10,11}, while others use life-cycle assessments (LCA) to measure the sustainability of implementing renewable energy into the electricity sector^{12,13}. To evaluate the sustainability of electricity, system transitions a host of models have been proposed³, with the most prevalent being least cost optimization models. Often in these models environmental sustainability metrics are calculated after the optimization has solved, or integrated as one of the constraints^{14,15}, when in reality environmental and

social objectives lend themselves more to a multiple objective optimization problem. Thus, economic optimization drives the model decision making while environmental factors are considered as a constraint or post analysis, potentially missing how myopic decision-making impacts national co-pollutant emissions, and vulnerable groups.

While much of the literature addresses environmental sustainability, there is a need for a deeper understanding regarding how different decarbonization pathways will affect pollution distribution across vulnerable groups¹⁵. Often social dimensions (i.e. equality, equity, and justice) are nonexistent, considered as retroactive analyses, or analyzed separately from capacity expansion models^{15,16}. Based on the review of energy transition literature, Kohler et al. (2019)¹⁶ illuminates the need for exploration in how energy transitions may place undue burden on regions with high poverty rates or low-income populations. Turkson et. al (2020)¹⁵ indicates that there is a gap in the holistic understanding of energy systems and transitions on the four dimensions of sustainability. Our analysis addresses these limitations by quantifying how national energy transition policies, designed using a least cost paradigm, impact regional equality.

In previous electricity equality studies, one paper investigated the social and environmental implications of expanding power systems in developing countries with little to no existing infrastructure¹¹ at a subnational level. In Nock et al. the primary goal was to investigate how different stakeholder preferences towards equality (i.e., distribution of electricity access) impacted power grid construction¹¹. The authors did not investigate how the distribution of air population emissions would change under different electrification strategies, nor did they determine the implications of using least-cost paradigms for vulnerable communities. Another researched the sustainability and equity impacts of reaching electricity sector targets across European countries¹³. While this paper looks at four different optimization objective scenarios (base case, cost, equality, and renewable generation), their focus is on intercountry equality considerations. We build on this work by investigating how least cost optimization (dominant decision paradigm) impacts regional equality objectives across eight unique decarbonization scenarios, some of which include 100% renewable penetration requirements. Another key contribution of our work is creating a framework for investigating and quantifying the social and environmental impact of energy transitions across different vulnerability indicators.

Equitable energy transitions and energy justice have social, technical, and economic aspects^{1, 17–21}. Stemming from this intersection, the energy sector experiences injustices at three scales: micro, meso, and macro²². Micro scale injustices relate to local impacts on the environment and community health. Meso scale injustices are more focused on national-scale issues such as unequal access to renewable technologies. Lastly, macro scale injustices include global issues such as waste disposal²². Multiple studies have reviewed current energy justice research^{19,20}, while others have provided frameworks for evaluating social sustainability^{23–25}. One key study highlights that energy transitions and policies must focus on equity and centering communities who are disproportionately affected by air pollution in the current energy system to correct historical injustices²⁶.

In this paper, we investigate and quantify the distributional equity impacts at the meso scale (i.e. national) and incorporate equality metrics into our analysis. Specifically, our social sustainability analysis is focused on investigating the way different national decarbonization policies will impact the distribution of air pollution emissions across vulnerable groups. Vulnerable groups included in our analysis are as follows: low income, those in a region with high poverty rates, those with a high percent of income spent on energy bills, and those residing in a high cost of living area. We accomplish this by tying an electricity optimization model with an equality and sustainability analysis (see Methods). Here the electricity planning model is the Regional Energy Deployment System (ReEDS) model which determines the mix of power plants, and their operation based on a least cost framework. This model disaggregates national energy planning into 134 regions across the contiguous United States, allowing for a sub national analysis. One limitation is the spatial granularity of national electricity planning models, where sometimes the smallest region resolution is at the state level. While we use the smallest subnational disaggregation in our analysis, we acknowledge that the intraregional differences in air pollution may vary across different demographic groups, based on where power plants are located, and wind flow patterns in that part of the country^{27–29} (see Methods for more limitations).

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 a 40-year time-period (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 (see Methods Table 1 for scenario descriptions).

The annual generation by technology for the decarbonization scenarios is shown in Figure 1. For Scenario A (the Base Case), that implements no additional carbon constraints or policies, generation in 2010 has the majority of the generation is supplied by coal, and natural gas and nuclear, but by 2050 we see coal generation decrease to 7.5% (0.41 PWh), natural gas generation slightly increase to 20.0% (1.08 PWh), onshore wind increase to 33.8% (1.83 PWh), and solar PV generation increase to 20.9% (1.14 PWh) of total generation. The carbon cap scenarios (B and C), which place a strict limit on CO₂ emissions from the electricity sector, achieve their carbon caps primarily through deploying solar PV and onshore wind. In both scenarios, wind and solar represent less than 3% of the generation in 2010, but by 2050 we see solar PV [B: 20.3% (1.11 PWh), C: 27.8% (1.55 PWh)] and onshore wind generation [B: 37.0% (2.0 PWh), C: 50.0% (2.78 PWh)] supplying a large share of total generation in 2050. Scenario C specifically sees 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 CO₂eq. emissions, which are allotted to an increase in coal generation 2040 to 2050 (1.67% of generation in 2040 to 4.67% of generation in 2050).

Onshore wind generation increases the most in technology specific scenarios with an implemented renewable portfolio standard (RPS) (D, E, and F): Scenario D averages a 25.8% annual increase, Scenario F averages a 27.3% annual increase, and Scenario E averages a 28.7% annual increase. These annual increases lead to onshore wind representing approximately 50% of generation by 2050 in all three scenarios. Scenarios D, E, and F also see large solar deployment, again due to the implemented RPS. The highest generation of solar PV, CSP, biopower, and battery storage are deployed to meet the 100% renewable requirement by 2035 in Scenario E, with solar PV technology representing 35.0% of total generation by 2040. In the other seven scenarios, solar PV is still a large contributor to generation, with solar PV supplying 15-20% of total generation in 2040.

Scenarios that require low carbon technology [renewable sources, nuclear, or natural gas carbon capture and storage (CCS)] by 2035 (Scenario G) and 2050 (Scenario H) strategies primarily rely on natural gas generation until their low carbon requirement year when it is completely retired. Upon reaching the technology mandate natural gas is primarily replaced with natural gas CCS. Thus, without a mandate this technology would most likely continue to provide 10-20% of the total generation needs. See Table S-4 in Supplemental Information (SI) for summary of generation profiles by decade for each scenario.

National environmental sustainability. The environmental impacts of the changing power plant profile can be seen in Figure 2, which depicts the national life cycle and operating emissions over the model timeline 2010 – 2050. Operating emissions are classified as emissions produced directly from the power plant creating electricity, while life cycle emissions stem from the production, generation, and retirement of power plants (emissions over their entire lifetime). We estimate life cycle and operational emissions using power plant emissions factors from literature estimates (see Methods). In these results, we discuss life cycle and operating emissions from CO₂eq., NO_x, SO₂, and PM. PM emissions accounted for in life cycle analysis are total PM emissions, whereas PM emissions accounted for in operating emissions analysis is PM_{2.5}. From Figure 2, we find CO₂eq. and NO_x have similar trends, with emissions decreasing through 2050, but at varying magnitudes across scenarios. SO₂ and PM life cycle emissions also see similar trends to each other with emissions rising from 2010 to 2022 due to increased investments in natural gas, but then we see a turning point for SO₂ and PM, with emissions decreasing through 2050. Scenario A (base case) is an upper bound for national emissions across all pollutants in our analysis.

In the carbon cap scenario where emissions are limited to hold the climate at or below 1.5°C (Scenario C), and the technology specific scenarios with the 2035 deadline (Scenarios E and G) life cycle greenhouse gas emissions fall below 500 megatonnes (Mt) of CO₂eq. by 2035 and plateau. For operating emissions, these scenarios fall close to zero emissions by 2035.

The lower bound for the emissions is Scenario E (100% renewable by 2035). Life cycle emissions for SO₂ reach 1 Mt and PM reach 0.30 Mt emissions by 2035; these emissions then subsequently plateau. Life

cycle CO₂eq. and NO_x emissions in Scenario E in 2050 are at levels 76-93% below their 2010 levels. In SO₂ and PM emissions, we see life cycle emissions across all scenarios rise 2010 to 2022 in the interim, driven primarily by increases in natural gas generation.

In the Scenarios A and B, the life cycle PM emissions in 2050 are 9-13% below their 2010 levels, while SO₂ emissions in Scenario A and B are just 1-4% lower in 2050 than their 2010 levels. Since scenarios A and B do not require retirements of fossil fuels completely, the PM and SO₂ emissions are not mitigated, and instances of associated health implications, like lung and heart disease, will continue if emissions increase or stay the same.

Operating emissions across all pollutants are decreasing over the modeling time horizon, resulting from high deployment of renewable and low carbon technologies. Scenario A again has the highest operating emissions (all pollutants) 2010 – 2050 because it does not have any carbon reduction requirements. The high operating emissions in Scenario A are driven by coal power plants (see SI Figures S-7 – S-10).

By 2035, operating emissions from Scenarios C, E, and G are under 100 Mt CO₂eq. emissions. Coal has completely retired by 2035 in these scenarios, so it is not contributing to emissions, and natural gas or natural gas CCS contribute under 10% of generation. By phasing out coal and natural gas plants, emissions from co-pollutants like NO_x, SO₂, and PM also fall significantly, with NO_x levels at or below 0.02 Mt, SO₂ levels below 0.003 Mt, and PM levels below 0.002 Mt.

Air pollution distributional regional equality. While national level emissions analyses are important for measuring progress across the energy system as a whole, there are multiple entities that make decisions in the electricity sector (e.g., utilities, states). Regional inequalities resulting from energy transitions can manifest themselves in the unequal distribution of air pollution emissions across regions. There will be differences between who is responsible for emissions (life cycle emissions), and which populations bear the brunt of those emissions due to where they live (operational emissions). Life cycle emissions are important for global CO₂eq. emissions, due to greenhouse gases impacting people regardless of where emissions are generated³⁰. However, the operational co-pollutants will largely impact the health of people within the region, so operating emissions reductions of these pollutants will result in regional health benefits^{31–34}. We present an analysis of both life cycle and operating greenhouse gas emissions (CO₂eq.) and operating co-pollutant emissions (NO_x, SO₂, PM_{2.5}) to illuminate how different decarbonization scenarios could impact emissions globally and regionally.

Figure 3 presents subnational (134 regions) regional life cycle emissions (in tonnes/capita) in 2035 and 2050 across all scenarios for CO₂eq emissions. These maps indicate how much greenhouse gas emissions each region is responsible for from their power plants. With only 45% of regions beneath the 2.5 metric tons (t) CO₂eq. per capita threshold in 2050, Scenario A (no policy implementation) has the largest distribution of emissions across regions. In 2035, we find that Scenarios C, E, and G have 80-90% of regions below 2.5 tonnes CO₂eq./capita and does not see much change over the next 15 years where

2050 has the same 80-90% of regions below that threshold. Therefore, once technology or carbon mandates are met in 2035, life cycle CO₂eq. emissions in regions do not change. The regions that have more CO₂eq. emissions in these scenarios (part of Montana, Arizona, Kansas are a few) will therefore be more responsible for global CO₂eq. emissions than other regions.

The distribution of operating emissions for NO_x, SO₂, and PM is seen in Figure 4 (a, b, c) respectively. Once the technology mandate is met in 2035 (Scenarios E and G) or 2050 (Scenarios F and H), the operating co-pollutant emissions reach their lowest values. However, in Scenario E, PM operating emissions are worse in some regions in 2050 than they were in 2035. The large PM emission increases results from biopower being deployed in the Eastern US to meet the 100% renewable technology requirement. We also find that the low carbon mandate scenarios (G and H) have greater operating NO_x and PM emissions in the Eastern US due to emissions from biopower and natural gas CCS investments. Thus, this highlights the need to consider co-pollutants in energy transitions due to local health effects (e.g., asthma) that results from increases in these emissions^{35,36}

Emissions distribution 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 (median income, poverty rate, cost of living, energy burden) across regions. This investigation shows the impact of different energy transitions on vulnerable regions. See Methods for data information about the demographic groups, and methods for the analysis. Here, we focus on operating NO_x, SO₂, and PM emissions, due to the local health impacts of these co-pollutants. Here we define inequality between regions as the difference in emissions per capita between the worst off (e.g., median income <\$50k) and best off (e.g., median income >\$70k) demographic groups. While there are multiple avenues for measuring vulnerability, we focus on two measures. The first is an absolute measure, while the second is a relative measure. Absolute measures indicate vulnerability based on a threshold (poverty level or median income), while relative measures indicate vulnerability based on income spent on a given expense (i.e., energy, transportation, rent).

Absolute vulnerability indicators. Our absolute vulnerability analysis focuses on median income and poverty rate across regions. The distribution of life cycle and operating emissions across different median income (Figure 5) illustrates the disparities between high- and low-income regions (see Methods for group definitions and the aggregation of median income census tracts to the ReEDS regions). Operating emissions across median income groups will impact health of vulnerable groups within regions, since pollutants like NO_x, SO₂, and PM have more local health affects^{1,37,38}. In 2010, regions with the lowest median income see the highest incidence of emissions, and our findings suggest that these regions will continue to bear the largest burden of emissions from these pollutants (and associated health impacts)³⁵. For scenarios that have large penetrations of renewable and low carbon technologies, the distribution of operating NO_x and SO₂ emissions across median income groups become equal (0 kg/capita) the year the carbon or technology requirement is mandated (2035 or 2050), but PM emissions remain greater in low-income regions even past the mandate year of 2035 because of biopower and

natural gas CCS investments. Furthermore, 5 years before the scenario's mandate, PM operating emissions in these technology mandate scenarios (E, F, G, and H) are 59-71% higher in the lowest income group than the highest income group, so reaching the mandate does help reach equality in NO_x and SO₂ emissions, but before those are met, the worse-off groups are still the most impacted. However, PM emissions past the mandate year (2035) in Scenarios E and G are still the highest in the lowest income group, indicating that a single-objective approach could leave vulnerable groups worse off even as we reach a low-carbon or 100% renewable energy system. Similar trends are seen across NO_x and SO₂ emissions in these scenarios five years prior to their mandates: NO_x emissions in the lowest income group are 50-74% higher than the highest income group, and SO₂ emissions are 18-74%. Low-income communities have been disproportionately affected by NO_x emissions³⁹, and our analysis shows that across different decarbonization scenarios, the lowest income regions continue to have the highest NO_x operating emissions, unless a national mandate requires complete retirement of fossil fuels (as seen in Scenarios E and F).

In addition to median income, percent of poverty within a region can identify regional vulnerability as another absolute measurement. Poverty groups were identified by the percent of the population in a region that is experiencing poverty, which the US Office of Management and Budget classifies as a family who is under a certain threshold given their family makeup⁴⁰. The group of regions with the highest percentage of residents in poverty (>15%) consistently had the highest life cycle and operating emissions per capita across 2010 – 2050 for all co-pollutants (SI Figure S-16).

Relative vulnerability indicators. Or relative vulnerability analysis focuses on energy burden or cost-of-living. Energy burden is defined as the percent of household income spent on satisfying energy needs. As nations deploy more technologies, there is a chance that grid costs, and subsequently energy bills, could rise⁴¹, which would affect the people who currently have trouble paying for their energy bills. Thus, we highlight how emissions will change across groups that will likely experience difficulty paying for electricity should costs rise. For the aggregation of energy burden and cost-of-living metrics to the ReEDS regions, see Methods. Operating emissions (Figure 6) across different energy burden groups show the highest energy burden group having the highest emissions per capita either across the entire timeline (Scenarios A, B, D) or until the year the carbon cap or technology mandate requirement is 100% low carbon or renewable energy (Scenarios C, E, F, G, H). Before reaching these years (2035 or 2050) the highest energy burden group is worse off. In 2030 in Scenario E, NO_x, SO₂, and PM operating emissions are 42%, 18%, and 38% lower respectively in the lowest energy burden (energy burden <2.75%) group than in the highest (energy burden >3.75%) before falling to a 0% difference in 2035. Likewise in 2045 in Scenario F, NO_x and PM operating emissions are 28% and 40% respectively lower in the lowest energy burden group compared to the highest. Once 2050 is reached, these emissions fall to 0 kg/capita and a 0% difference between the groups. Therefore, without strict fossil fuel retirement mandates tied to decarbonization strategies the most vulnerable regions will continue to experience the highest emission burden.

Cost-of-living is another relative measurement used to understand disparities of air pollution distribution, which is classified as the percent of income spent on housing and transportation. We recognize that absolute income does not capture the relative cost of achieving a certain standard of living in different parts of the country. When accounting for different costs-of-living across regions we find similar results: where the operating emissions are greater in the highest cost of living group (greater than 66% of income to housing and transportation needs) until the year of the technology mandate. The highest and lowest cost-of-living groups have decreasing inequality across all pollutants in all scenarios, meaning the emissions between the highest cost-of-living group is approaching the emissions in the lowest cost-of-living group. (NO_x: difference of 18.3 kg/capita in 2010 to an average difference across scenarios of 2.6 kg/capita, SO₂: difference of 55.6 kg/capita in 2010 to an average difference of 7.1 kg/capita, PM: difference of 1.8 kg/capita in 2010 to an average difference of 0.32 kg/capita) (SI Figure S-15).

Discussion

Here we investigated how national level decarbonization policies translate to national emissions and the distribution of emissions at subnational regions. In our analysis, we find 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 meet a 100% renewable requirement by 2035, there is a larger deployment of biomass power plants, which emit SO₂ and PM. These emissions from biomass plants will therefore cause surrounding communities to be negatively affected by these emissions and 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 but results in a more equal distribution of air pollution (0 emissions) by 2050 for CO₂eq. and co-pollutants like NO_x, SO₂, and PM. 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 objective, and often conflicting nature, of energy transition planning.

When addressing the multi-faceted lens of decarbonization, it is important to weigh both the national emissions and the distribution of those emissions. For example, reaching 100% renewable energy by 2050 will help the US decarbonize its electricity sector completely by then, but there are air pollution inequities as the nation decarbonizes, with the low-income regions seeing the highest emissions until the goal is met in 2050. This may be a byproduct of the least cost paradigm being the primary objective guiding technology deployment and makes the case for more multi-objective modelling efforts. Without a multi-objective view to energy planning, vulnerable groups could be burdened with greater amounts of emissions while the US decarbonizes. The continued inequality of air pollution distribution 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, low-income and poor regions 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, it is imperative that decisions regarding national decarbonization pathways 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. 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. Deeper analysis of health impacts from energy transitions could also necessitate greater quantification of the monetary damages of air pollution^{27,42-44}.

Equitable energy transitions exist at the intersection of technical, economic, and social justice objectives^{1,17-21}. Working to achieve this goal of an equitable energy transition requires a multi-disciplinary lens to understand who wins and losses 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 is a first step in investigating the progress of achieving an equitable energy transition, by performing an analysis of how national policies translate to subnational equality. We have shown that a single objective of minimizing cost does not result in an equitable transition and vulnerable groups are at risk of existing in regions with higher emissions. When crafting public policy for energy transitions, decision makers can use this work as a source for indicating the need for a holistic multiple objective approach to energy system planning if we are going to ensure an equitable and sustainable future.

Methods

Here we present the methods of our work. We start by discussing how the electricity system and decarbonization scenarios are modeled, followed by the sustainability and equality analysis. We conclude this section by discussing the limitations of our analysis. Our work investigates the equality of decarbonization scenarios at the national and subnational level across 134 regions in the US. We do this by tying a national capacity expansion model with an air pollution assessment and distributional equity analysis.

A. Electric power system model

In our electricity system analysis, we use the Regional Energy Deployment System (ReEDS) from the National Renewable Energy Lab (NREL) to define the resulting electricity generation profiles under different decarbonization scenarios, like a carbon cap or national renewable portfolio standard to reach different energy transition goals. The model outputs capacity, generation, emission, cost, retirements, and transmission data for regions in the US defined by ReEDS for the model years. This data was used to analyze the impact of different decarbonization scenarios and ultimately the overall cost, sustainability, and equality trade-offs.

To perform decarbonization scenarios, a carbon cap was implemented as an exogenous input to the model. The carbon cap specifies the number of allowed emissions in the national electric sector for each year of the model run (2010 to 2050). As the ReEDS model solves each year, the operating emissions generated from the system cannot surpass the specified carbon cap. The model will not continue to the next solve year until it can find a solution that meets the carbon cap emissions.

B. Decarbonization scenarios

Eight decarbonization scenarios were created for this analysis and are summarized in Table 1. Each decarbonization scenario was then run in ReEDS to forecast the US electricity system 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 description of inputs).

Scenario	Scenario description	Scenario approach	Source
A	Base	All current policies and standards are included (state RPS, tax credits, etc.), but no new policies implemented.	4
B	US NDC	United States Nationally Determined Contributions via the 2015 Paris Agreement. Carbon cap implemented in ReEDS to follow emissions allotted.	45
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.	45
D	80% RE 2050	National RPS implemented beginning in 2020 at 20% and increasing linearly to 80% renewable energy in 2050.	4
E	100% RE 2035	National RPS implemented beginning in 2020 at 20% national RE generation and increasing linearly to 100% RE generation in 2035.	46
F	100% RE 2050	National RPS implemented beginning in 2020 at 20% national RE generation and increasing linearly to 100% RE generation in 2050	4
G	Low Carbon 2035	National technology mandate implemented beginning in 2020 at 20% and increasing linearly to 100% renewable energy, natural gas CCS, or nuclear in 2035.	47
H	Low Carbon 2050	National technology mandate implemented beginning in 2020 at 20% and increasing linearly to 100% renewable energy, natural gas CCS, or nuclear in 2050.	47

C. Environmental sustainability assessments

In this analysis, life cycle and operating emissions represent environmental sustainability. Life cycle emissions are assumed to be the emissions created in the production, operation, and end-of-life of each technology type. Operating emissions are the emissions created while the power plant is generating electricity. Since life cycle emissions measure the emissions that each region is responsible for, but not necessarily emitted in the region, we are not considering the transport of emissions across regions.

Life cycle and operating emissions were calculated for each region by taking the sum of the generation (g_n) in MWh of each technology (n) multiplied by its emissions rate ($e_{r,n}$) in g/kWh for each model year (Equation 1). The operating emissions is 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) (Equation

2). The total life cycle or operating emissions are the sum of emissions from each technology (n). See Table S-3 for heat rates for each power plant.

$$E_L = \sum_{i=1}^n g_n e_{r,n} \quad (1)$$

$$E_O = \sum_{i=1}^n g_n e_{f,n} H_n \alpha \quad (2)$$

Life cycle and operating emission rates for powerplants were obtained from literature. We assumed that operating emissions from renewable and nuclear sources were zero. Note that the life cycle emissions rates obtained from literature are in g/kWh of electricity generated, whereas the operating emissions rates are in pounds/MMBtu because they are fuel emission rates (see Eq. 2).

Table 2

Life cycle and operating emission rates used in environmental sustainability analysis. See Table S-2 in SI for sources, and Figure S-6 for life cycle emissions sensitivity analysis. *

	Life Cycle Emission Rates				Operating Fuel Emissions Rates			
	[g/kWh]				[pounds/MMBtu]			
	CO ₂ eq.	NO _x	SO ₂	PM	CO ₂ eq.	NO _x	SO ₂	PM _{2.5} **
Biopower	39	0.51	0.09	0.095	0	0	0.08	0.1013
Solar photovoltaic	57	0.2	0.422	0.121	0	0	0	-
Concentrated solar power (CSP)	22.7	0.2 ¹	0.0996	0.036	0	0	0	-
Onshore wind	8.37	0.031	0.0359	0.0269	0	0	0	-
Offshore wind	11.4	0.022	0.0723	0.0396	0	0	0	-
Nuclear	7.3	0.027	0.0255	0.0062	0	0	0	-
Natural gas combustion turbine (CT)	830	2.7	0.0925	0.757 ²	117	0.15	0.0152	0.0065
Natural gas combined cycle (CC)	527	0.38	3.78	0.757	117	0.02	0.0051	0.0065
Natural gas CCS	247	0.38 ³	4.68	0.916	11.7	0.02	0.0051	0.0065
Hydropower	4.9	0.0345	0.007	0.0155	0	0	0	0
Geothermal	37.8	0.23	0.032	0.018	0	0	0	0
Oil-Gas-Steam	779	0.99	2.9	0.245	137	0.1723	0.299	0.1159
Coal	933	1	1.1	0.335	211	0.1533	0.470	0.0157 ⁵
IGCC	791	1 ⁴	1.1	0.183	211	0.085	0.056	0.0157 ⁵

¹Assumed to be the same as solar PV.

²Assumed natural gas CT to have the same PM life cycle emissions rate as natural gas CC.

³Assumed NO_x life cycle emissions rate for natural gas CCS is the same as natural gas CC.

⁴Assumed NO_x life cycle emissions rate for IGCC is the same as coal.

⁵Assumed Bituminous coal and PM 2.5.

	Life Cycle Emission Rates [g/kWh]				Operating Fuel Emissions Rates [pounds/MMBtu]			
Coal CCS	263	0.42	1.23	0.381	21.1	0.085	0.056	0.0157 ⁵
Cofire					179	0.130	0.411	0.0285
Battery storage	32.6	-	-	-	0	0	0	0
Pumped hydropower	256.63	-	-	-	0	0	0	0
¹ Assumed to be the same as solar PV.								
² Assumed natural gas CT to have the same PM life cycle emissions rate as natural gas CC.								
³ Assumed NOx life cycle emissions rate for natural gas CCS is the same as natural gas CC.								
⁴ Assumed NOx life cycle emissions rate for IGCC is the same as coal.								
⁵ Assumed Bituminous coal and PM 2.5.								

* Dashed line indicates no reported value.

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

D. Equality assessments

Median income, percent of population in poverty, energy burden, and cost of living are equality metrics used in this analysis. These datasets were obtained from the American Community Survey (ACS) from the US Census Bureau ⁴⁸ (median income, percent population in poverty), US Department of Energy ⁴⁹ (energy burden), and US Department of Housing and Urban Development ⁵⁰ (cost of living) at the census tract level. To find these metrics for each region, census tract level data was aggregated up to the region level by taking the mean of each equality metric across census tracts within each region. To better understand the distribution of emissions across these equality metrics, regions were split into groups based on each metric (e.g. median income <\$50k, \$50k-\$60k, \$60k-\$70k, >\$70k), and the mean of emissions per capita was taken. Using these groups, the emissions per capita values were averaged across them to get the mean emissions per capita (see Equation 3). The average emissions per capita for the defined vulnerable group (ϵ) is calculated from the sum of total emissions in the regions (E_r) and the sum of the population in the regions (P_r). The groups were created to have about an equal number of regions in them (See SI Figures S-12 to S-15 for group assignments for regions).

$$\varepsilon = \frac{\sum E_r}{\sum P_r} \quad (3)$$

These equality metrics can be compared to air pollution to investigate the inequalities across regions for each decarbonization scenario. Data for median income and percent poverty were obtained from US Census Bureau, cost of living from ACS, and energy burden from US Department of Energy. A limitation of these equality metrics is that they are estimations from 2018, so they may not accurately represent what median income, percent in poverty, or energy burden may look like in future time periods. Thus, one limitation is lack of projection regarding human migration patterns at the subnational level, which may be impacted by rising temperatures, and changing weather patterns.

E. Limitations & caveats

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

Equality at the subnational level will depend on location of power plants and the demographics of the population living in the region. Our subnational analysis for the US investigated disparities across 134 regions, with some of these regions being as large as a state. Some limitations stemming from the subnational resolution is that 1) there can be disparities within our regions, 2) aggregating the poverty metrics to the regional level can mute intrastate disparities, and 3) power plant operational emissions make impact communities outside of the region they are situated in²⁷. The goal of our work was to highlight potential inequalities under different decarbonization strategies. Before this work is implemented in a region, we recommend a detailed subnational analysis involving potential power plant locations, and detailed demographic information to future highlight intraregional risk.

For the life cycle emissions, we should note that the places responsible for the emissions can differ from the place the emissions are generated once the power plant is built. This would have the biggest impact on wind and solar since the majority of emissions stem from refining the materials used to build the generators⁵¹. On the other hand fossil fuel power plants see the largest emissions from the operation of the power plants⁵². Thus, we believe the operational emissions highlight the greatest potential disparity at the subnational level. We leave the global air pollution disparities caused by life cycle emissions for future work. We show the life cycle emissions by technology in in SI Figure S-2 - S-5.

Population and equality metrics data are collected in the years 2010 (population) and 2018 (equality metrics). These indicators are bound to change over our model timeline of 2010 – 2050. Our equality and per capita calculations are likely to change if we used a model to forecast population migration patterns due to the changing climate. However, there is evidence that low-income groups have less resources, and

thus are less likely to move over time⁵³, so our current metrics may have little change and are valid estimations and assumptions.

In this analysis, we chose to look at emissions per capita across regions and equality metric groups. This approach may cause emissions to be weighted greater in rural areas, due to smaller populations. However, our initial analysis of total emissions across regions and equality groups showed the most populous regions with the highest emissions, as is expected, and with the spatial granularity of the regions to be sometimes even at the state level, we felt the emissions across regions would be best compared through emissions per capita. Emissions per capita represents the burden of emissions on each person in the region.

The ReEDS model operates over a 40-year time horizon, so there is an inherent uncertainty in its outputs (i.e., location of power plants, generations of those power plants in a given time period). See SI Section A for model assumptions made in this analysis. The ReEDS documentation by NREL documents all assumptions in model inputs and solve⁴. Due to this model being directed by a cost paradigm, its final outputs may vary as costs of technology fall, demand changes, or different policies are implemented. These cost decreases will vary by location, workforce, and labor costs, as well as scarcity or abundance of input materials overtime. Future demand will vary based on level of electrification of transportation sector, industrial sector, and buildings. Steinberg et al. (2017) projects that under high electrification scenarios, demand will double, with the transportation sector accounting for 50% of incremental load. The goal of our analysis was not to perfectly forecast 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.

Declarations

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Author Contributions

Teagan Goforth designed and performed the analysis, wrote and edited the paper. Dr. Destenie Nock formulated the intimal 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 mandate scenarios accommodate additional energy needs primarily through expanded investments in wind and solar generation. Here we see that the base case, US NDC, and 80% renewable energy decarbonization pathways retain coal generation through 2050.

Figure 2

National life cycle (emissions from production, operation and retirement) and operating emissions (emissions from generating electricity) across scenarios 2010 – 2050 (megatonnes, Mt). Note that the y-axes are not consistent.

2035

2050

Figure 3

Regional per capita (t/capita) life cycle emissions for CO₂eq. in 2035 and 2050 for all decarbonization scenarios. Regional emission inequalities are a by-product of different technology investments across the nation. Lifecycle emissions capture the total emissions created over the lifetime of the power plant, resulting from electricity demand in different parts of the country. CO₂eq. life cycle emissions identify which regions' electricity systems are contributing to greater amounts of greenhouse gas emissions, regardless of where the emissions are emitted.

(a) NO_x

(b) SO₂

(c) PM

Figure 4

Regional operating emissions per capita (kg/capita) in 2035 and 2050 for (a) NO_x, (b) SO₂, and (c) PM. Regional emission inequalities are a by-product of different technology investments across the nation. The operating emissions indicate who bears the burden of the emissions once the power plant is operating (operational emissions). In 2035 we find Scenarios F and H (RE and low carbon 2050 targets), we see high levels of operating co-pollutant emissions, indicating that rapid renewable and clean

technology deployment will be required to drastically reduce regional emissions within a 15-year time period. In contrast, in 2050 Scenario E (RE 2035 target) we see SO₂ and PM emissions increase from 2035 to 2050. This highlight two key risks of strict mandates: waiting until the deadline to rapidly deploy or increasing emissions levels once the target have been achieved.

Figure 5

Distribution of NO_x (left column), SO₂ (middle column), and PM (right column) operating emissions per capita across median income groups 2010 – 2050. Median income is an absolute vulnerability metric. We highlight operating emissions because the annual operating emissions will have a myriad of effects on different communities. We highlight co-pollutant emissions due to the health risks resulting from living near a high emitter of people within the region. Here we see that under all decarbonization scenarios the lowest median income groups see the highest CO₂eq. and PM emissions under all scenarios. The policies with the great reduction are the strict technology mandates (Scenarios E, F, G, and H), where the income groups reach close to equality by the mandate year. However, if a strict mandate is not followed then the carbon cap scenario (Scenario C) is the next best option due to carbon cap requirements of under 850 Mt operating CO₂eq. emissions in 2030 – and trending downwards.

Figure 6

Distribution of NO_x (left column), SO₂ (middle column), and PM (right column) operating emissions per capita across energy burden groups 2010 – 2050. Energy burden is defined as the percent of income spent on energy. This measure of vulnerability highlights regions who may have higher electricity costs and therefore a larger burden on low to median income households. Here we see the regions in the highest energy burden group have the greatest NO_x, SO₂, and PM emissions.

Supplementary Files

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