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Diverse Pathways for Power Sector Decarbonization in Texas Yield Health Cobenefits but Fail to Alleviate Air Pollution Exposure Inequities

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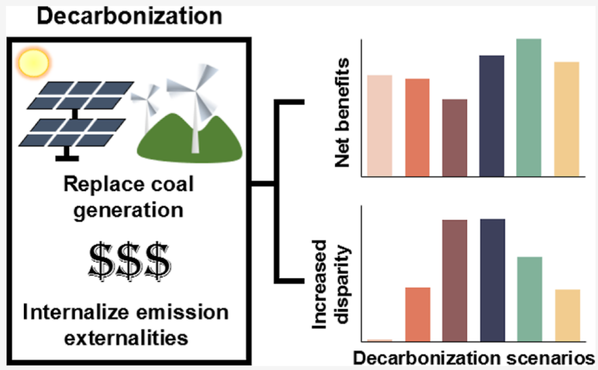

ABSTRACT: Decarbonizing power systems is a critical component of climate change mitigation, which can have public health cobenefits by reducing air pollution. Many studies have examined strategies to decarbonize power grids and quantified their health cobenefits. However, few of them focus on near-term cobenefits at community levels, while comparing various decarbonization pathways. Here, we use a coupled power system and air quality modeling framework to quantify the costs and benefits of decarbonizing the Texas power grid through a carbon tax; replacing coal with natural gas, solar, or wind; and internalizing human health impacts into operations. Our results show that all decarbonization pathways can result in major reductions in CO_2 emissions and public health impacts from power sector emissions, leading to large net benefits when considering the costs to implement these strategies. Operational changes with existing infrastructure can serve as a transitional strategy during the process of replacing coal with renewable energy, which offers the largest benefits. However, we also find that Black and lower-income populations receive disproportionately higher air pollution damages and that none of the examined decarbonization strategies mitigate this disparity. These findings suggest that additional interventions are necessary to mitigate environmental inequity while decarbonizing power grids.

KEYWORDS: *power system decarbonization, $PM_{2.5}$ exposure, public health, cost-effectiveness, environmental justice*

■ INTRODUCTION

Global climate change has profound impacts on ecosystems, human health, and the economy.[1−5] To reduce these negative impacts, nearly 200 countries adopted the Paris Agreement to reduce global greenhouse gas (GHG) emissions in an effort to limit the global temperature rise to 2 °C above preindustrial levels. Many low- or zero-emission pathways have been proposed to achieve this goal.[6,7]

The power sector is one of the largest sources of GHG emissions. In the United States, electricity production contributes approximately 25% of national GHG emissions.[8] Strategies and technologies to reduce carbon emissions from power generation have been extensively explored, and the challenges associated with decarbonizing this sector have been identified in prior studies.[9−13] Many federal, state, and local policies have been implemented to increase renewable energy, reducing CO_2 emissions from power plants.[14,15] As carbon capture and storage (CCS) technology has yet to be deployed at a significant scale, reducing power sector emissions is predominantly achieved by shifting coal to natural gas or displacing either fossil fuel with renewable energy. These climate change mitigation strategies also have cobenefits to air quality from decommissioning or reducing the operations of coal power plants, which in turn reduces local and regional air pollutant emissions.

There is high interest in quantifying the air quality cobenefits of climate change mitigation strategies to inform policy-making.[16−18] However, individuals may benefit to varying degrees from these strategies, resulting in an inequitable energy transition.[19] Air pollution associated with the consumption of goods and services in the U.S. is largely attributable to the non-Hispanic white majority, but racial and ethnic minorities experience higher pollution levels.[20] Although pollutant concentrations in the U.S. have decreased over the past three decades, these exposure disparities persist.[21,22] Nearly all emission sectors contribute to the $PM_{2.5}$ exposure disparity affecting racial minorities.[23] Exposure to $PM_{2.5}$ specifically caused by electricity generation is highest among Black

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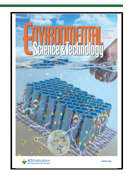

Americans, even when controlling income differences.[24] Prior studies also show that the health benefits of emissions mitigation strategies adopted by the power sector have strong spatial heterogeneity.[25,26] Without specific interventions to ensure an equitable energy transition, air quality impacts may be concentrated in certain areas,[27] which may lead to greater inequalities in air pollution exposure.

In this study, we quantify the human health cobenefits that can be achieved in the near term under several power system decarbonization approaches for the Texas power system. The Texas power grid is significant for several reasons. Texas has the second-largest population and the highest population growth among U.S. states. Texas's population has a high degree of racial and ethnic diversity, with people of color accounting for the vast majority of the state's population growth during the past decade.[28] Additionally, ERCOT is a large and predominantly isolated power grid, enabling us to build a power system model that is both highly detailed and computationally tractable [as in analyses by Arbabzadeh et al. (2019), de Sisternes et al. (2016), and Craig et al. (2018)[11,29,30]]. This allows us to study health benefits distribution at the census-tract level and among different population groups, considering race and ethnicity, income, and age. To do this, we combine a state-of-the-science air quality model and a unit commitment and economic dispatch model and consider decarbonization approaches ranging from immediate operational changes to new infrastructure possible within 10 years.

We calculate and compare the reductions in human health impacts associated with the following power sector CO_2 emission reduction approaches: carbon-pricing at (1) $40 and (2) $80 per ton of CO_2 using existing power infrastructure; (3) redispatching existing power plants after internalizing health damages associated with SO_2 and NO_x emissions. In addition to these operational strategies, we also consider replacing coal generators with (4) natural gas plants, (5) solar power, and (6) wind power. Each scenario is designed to maintain comparable power system functionality, which requires using energy storage for the wind and solar energy pathways. Across all scenarios, we estimate the cobenefits of near-term decarbonization and assess public health impacts across demographic groups. We compare commonly used decarbonization strategies by jointly considering their relative climate benefits, health cobenefits, and additional costs. We also show the persistence of disparity in air pollution exposure after decarbonizing the power grid in Texas, highlighting the need for additional policies specifically designed to ensure a just energy transition.

■ METHODS

Power System Description. The analysis is conducted for the power system served by the independent system operator in Texas—the Electric Reliability Council of Texas (ERCOT)—which has a mix of coal, natural gas, and nuclear power plants, as well as high penetration of wind power. A detailed description of the power system model used in the project is included in the Supporting Information. Due to its reliance on fossil fuels, Texas has the highest power sector emissions of SO_2 and NO_x across all states.[31] Additionally, it has limited transmission interconnection to other regions, offering an isolated system for analysis. To represent the intrastate transmission system, we use a zonal power system configuration consistent with the National Renewable Energy Laboratory's (NREL) Regional Energy Deployment System (ReEDS).[32] In ERCOT, the majority of fossil fuel-fired power plants are located in eastern Texas, close to population centers, while most wind generation is located in the west. Transmission of renewable energy in the state from west to east is limited by the capacity of transmission lines connecting the two regions.[33] Nameplate capacity of coal-fired power plants in Texas started to drop in 2016.[34] To study the potential health impacts before recent decarbonization efforts in ERCOT, we use data in 2015 to build proposed scenarios, which are introduced in detail in the following section.

Scenario Design. We simulate power generation, emissions, and health impacts in ERCOT under seven scenarios. The business-as-usual (BAU) scenario reflects operations in ERCOT in 2015 without additional CO_2 mitigation measures. Here, unit commitment and economic dispatch of electricity generation are determined by the physical constraints and the operational costs of electricity generating units (EGUs), including fuel, operation and maintenance (O&M), and start-up costs.

To decarbonize the grid, we first consider operational changes that can be implemented using existing infrastructure. The carbon-pricing (CP) scenarios examine the operational response to carbon taxes of $40/ton and $80/ton of CO_2 (CP40 and CP80) applied to combustion emissions. Unit commitment and economic dispatch of generation are reoptimized including this carbon emission cost associated with coal and gas combustion. Existing facilities in the current power system are retained to estimate the immediate benefits of operational changes that could be achieved through a price placed on carbon emissions. In a separate scenario, health damage internalization (HDI), we explicitly consider the monetized costs of air-pollution-related human health damages associated with power plant emissions in the optimization. Specifically, we consider the impacts of fine particulate matter ($PM_{2.5}$) on premature mortality, which accounts for the vast majority of the public health costs of air pollution.[35−37] Temporally and spatially varying health damage costs at the unit level are quantified by a dispersion model with simplified chemistry and then integrated into unit commitment and economic dispatch decisions. Similar to CP40 and CP80, no new infrastructure is added. Due to the higher health impacts associated with generation from coal-fired EGUs, this scenario tends to reduce carbon emissions by reducing electricity generated by coal combustion. Additional details of this approach are included in the Supporting Information and were discussed by Luo et al.[38]

In a different set of scenarios, we consider the implications of near-term decarbonization requiring new capital investment. Namely, we model the retirement and replacement of ERCOT's coal power fleet. Under the coal replaced by gas (CRG) scenario, coal is replaced with natural gas, which has a lower CO_2 emissions intensity. Some decarbonization pathways consider natural gas as a transitional fuel towards a net zero-emission future, decreasing carbon emissions while providing the system flexibility needed with high penetration of renewable energy.[39−41] Under this scenario, all coal-fired EGUs are replaced by natural gas combined-cycle (Gas-CC) EGUs with the same capacity at the same location to avoid additional transmission infrastructure. The average heat rate and carbon intensity of existing Gas-CC units built after 2010 in ERCOT are used for the newly added Gas-CC EGUs. We also consider replacing coal with renewable energy. Coal replaced by solar (CRS) retires all coal and adds solar power at the same location. The nameplate capacity of new solar power is selected to provide the same energy (MWh) as the replaced coal generation. To maintain a resource adequacy level comparable to the BAU case, the

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equivalent firm capacity of the solar power is calculated, and additional energy storage is incorporated such that the solar power and storage provide the same firm capacity as the replaced coal power. Under the coal replaced by wind (CRW) scenario, coal is substituted by wind power. Similar to CRS, annual wind generation in this scenario matches the displaced coal generation, with new energy storage added to maintain equivalent levels of firm capacity. A key difference between the CRS and CRW scenarios is that new wind generation is located in western Texas due to the high-quality resource availability. The capacity of transmission lines connecting eastern and western Texas is increased to maintain a transmission limit proportional to the BAU case.

Unit Commitment and Economic Dispatch. Electricity generation is determined by the unit commitment and economic dispatch model under all scenarios. However, different scenarios include different terms in their objective functions (Table 1),

Table 1. Objective Functions under Different Scenarios

scenario(s)	objective function
BAU, CRG, CRS, CRW	$\min \sum_{h=1}^{H} \sum_{j=1}^{J} [(F_j + R_j)z_{j,h} + T_j v_{j,h}]$ (1)
CP40, CP80	$\min \sum_{h=1}^{H} \sum_{j=1}^{J} [(F_j + R_j + \mathrm{CP}_j)z_{j,h} + T_j v_{j,h}]$ (2)
HDI	$\min \sum_{h=1}^{H} \sum_{j=1}^{J} [(F_j + R_j + H_{j,h})z_{j,h} + T_j v_{j,h}]$ (3)

including fuel cost (F_j, \$/MWh), variable O&M cost (R_j, \$/MWh), carbon emission costs (CP_j, \$/MWh), start-up costs (T_j, \$/start), marginal health damage costs ($H_{j,h}$, \$/MWh), electricity generation ($z_{j,h}$, MWh), and a binary startup variable ($v_{j,h}$, 0 or 1) for each EGU j at hour h, across all EGUs (J) and hours (H) considered.

For the BAU, CRG, CRS, and CRW scenarios, the model minimizes the system's operational costs, including fuel, variable O&M, and start-up costs. We assume that renewable energy has no variable operational costs. Under the CP scenarios, we add carbon emission costs to the objective function, calculated from the carbon tax applied, EGU efficiency, and fuel carbon intensity. In the HDI scenario, health damage costs of SO_2 and NO_x emissions are included in the objective function. Unlike the carbon pricing scenarios, health damage costs vary by time and location. To capture seasonal variability, electricity dispatch under the BAU, CP, CRG, CRS, and CRW scenarios is simulated for four months in 2015—January, April, August, and October. Due to the high computational costs of simulating spatially and temporally varying marginal health damage costs, the analysis of the HDI scenario is limited to January and August.

The model, while simplified compared with those used in real power markets, captures the most important constraints in electricity generation, including constraints on unit commitment, the balance between load and generation, generator up-/downtime, operational range, ramping, and transmission capacity. These constraints are further detailed in the Supporting Information.

Determination of Solar, Wind, and Energy Storage Capacity. The System Advisor Model (SAM)[43] developed by the National Renewable Energy Laboratory is used to calculate the nameplate capacity of renewable energy needed to generate the same energy produced by coal-fired EGUs, as

$$\text{renewable nameplate capacity (MW)} = \frac{\text{annual generation by coal (MWh)}}{\text{annual energy yield of renewable resource (MWh/MW)}} \quad (4)$$

SAM uses typical meteorological year data from the National Solar Radiation Database (NSRDB) and the Wind Integration National Dataset (WIND) Toolkit for solar and wind resources, providing location-specific values of energy yield reflective of local meteorological conditions. Wind farms or photovoltaic (PV) panels have different energy yields, with SAM providing values based on the location and corresponding meteorological conditions. Energy storage capacity under different scenarios is determined by the nameplate capacity of replaced coal, the nameplate capacity of renewable energy, and the capacity value (CV) of renewable energy added to the grid, as

$$\text{storage capacity (MW)} = \text{coal nameplate capacity (MW)} - \text{renewable nameplate capacity (MW)} \times \text{renewable CV (\%)} \quad (5)$$

The duration of energy storage under all scenarios is 4 h. The CV of solar and wind energy in Texas is calculated by applying the net load curve approximation approach used in ReEDS.[42]

Air Pollution from Electricity Generation. Under each scenario, electricity generated from each EGU is determined by the power system model with corresponding constraints and objective functions. Hourly SO_2 and NO_x emissions from each fossil fuel-fired generator are calculated from annual average emission rates and hourly electricity generation at the unit level.[44] These hourly emissions are combined with those from other sectors, such as transportation and agriculture, by the Sparse Matrix Operator Kernel Emissions (SMOKE) system to prepare emission inputs for air quality modeling.[45] The Community Multi-scale Air Quality Modeling system (CMAQ version 5.3) is used to simulate ambient $PM_{2.5}$ concentration. Additional details about the CMAQ configuration used are provided in the Supporting Information. When compared with concentrations recorded by the Air Quality System (AQS) network,[46] the ability of the model to reproduce observed 24 h average $PM_{2.5}$ concentrations meets recommended statistics and benchmarks for photochemical model performance (Table S1).

In this analysis, the BAU scenario serves as the base case; concentration differences between BAU and other scenarios are considered to be the air quality benefits of the different decarbonization strategies. To quantify the health impacts of electricity generation, we use the Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE version 1.5.0.4) to estimate air pollution-related mortality.[47] We use the log-linear concentration-response function developed by Krewski et al. (2009) to estimate premature deaths for different age, racial, and income-level groups.[48] This function, representing national estimates of the risk of death from ambient $PM_{2.5}$ pollution, has been widely used in studies quantifying health impacts caused by power plant emissions.[49,50] BenMAP estimates age- and county-specific mortality data in 2015 based on 2012−2014 data from the Centers for Disease Control's (CDC) WONDER database (http://wonder.cdc.gov). Additionally, BenMAP uses race-, ethnicity-, and age-stratified incidence rates from the WONDER database. In our results, we compare census-tract-level mortality differences across race and ethnicity, age, and income level,

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relying on demographic data from the Integrated Public Use Microdata Series (IPUMS), CDC, and BenMAP.[51−53]

RESULTS

Renewable and Energy Storage Capacity. The average annual yield of wind power, calculated from 2015 wind capacity and wind generation in ERCOT, is 2,770 GWh/GW, representing a 32% capacity factor. Due to limited solar generation in ERCOT, the average annual yield of solar power is calculated using Typical Meteorological Year data at the location of coal-fired power plants and estimated at 2100 GWh/GW, corresponding to a 24% capacity factor (AC power). Total generation from the coal-fired power plants in 2015 was 97,655 GWh. To replace the electricity produced by coal-fired EGUs, 35.8 GW of wind or 47.2 GW of solar (AC nameplate capacity) is needed (Table S2). Solar power has a higher CV than wind power because solar energy is available during peak demand hours (3−7 pm) and less solar generation exists in the current power system (Table S2). The capacity of energy storage added to meet the peak power demand under the CRW and CRS scenarios is 19.5 and 15.1 GW, respectively, with a 4 h duration. We assume that the energy storage is sited in the balancing zones where renewable energy exists.

To maintain a transmission limit similar to that of the BAU scenario, the capacity of transmission lines connecting eastern and western Texas is increased proportionally based on the nameplate capacity of current and added wind energy under the CRW scenario. The new transmission capacity is 3.2 times as large as the capacity in 2015 (Table S3).

Reductions in Emissions and $PM_{2.5}$ Concentrations. Table 2 shows monthly average emissions from ERCOT under the BAU and decarbonization scenarios. Emissions in January and August are generally higher than those in April and October due to greater electricity demand. The CRS and CRW scenarios result in the greatest reductions in carbon emissions, as all coal-fired power plants are replaced with zero-emission renewable energy. The HDI scenario has the smallest reduction in carbon emissions because the target of this strategy is to minimize health impacts using existing facilities without an explicit goal to reduce carbon emissions. The CP40 scenario yields a lower carbon emission reduction than others, especially during summer when electricity demand is high and some high-emission EGUs are needed to meet these peak demand periods (Table S7). Increasing the price of carbon to $80/ton (CP80) decreases carbon emissions but still has higher average CO_2 emissions than most other scenarios. However, emission reductions under the CP scenarios are limited to operational changes and do not reflect infrastructure investments that may follow.

Table 2. Monthly Average Emissions from ERCOT under All Scenarios[a]

scenarios	CO_2 emissions 1000 tons	SO_2 emissions tons	NO_x emissions tons
BAU	15,380	10,291	4554
CP40	12,206 (20.6%)	871 (91.5%)	2618 (42.5%)
CP80	12,087 (21.4%)	384 (96.3%)	2714 (40.4%)
HDI[b]	16,376 (12.9%)	3,150 (80.4%)	4375 (30.2%)
CRG	11,781 (23.4%)	42 (99.6%)	1592 (65.0%)
CRS	8229 (46.5%)	29 (99.7%)	1331 (70.8%)
CRW	7930 (48.4%)	28 (99.7%)	921 (79.8%)

[a]Emission reductions under decarbonization scenarios relative to BAU are shown in parenthesis. [b]The value for the HDI scenario is a two-month average (January and August), while that for other scenarios is a four-month average (January, April, August, and October).

Compared with the decrease of CO_2, emissions of SO_2 and NO_x are reduced to a greater extent by the decarbonization strategies, as coal-fired generators are responsible for the vast majority of air pollutant emissions from the power sector, especially those of SO_2. The magnitude and distribution of SO_2 and NO_x emissions vary by decarbonization scenarios, leading to differences in the $PM_{2.5}$ concentration reductions attained under each scenario. Figure 1 shows the distribution of monthly average $PM_{2.5}$ concentration decreases under the CP40, HDI, and CRS scenarios during the winter and summer months (additional scenarios are included in Supporting Information). Most emission reductions occur in eastern Texas where most coal-fired power plants are located. We also observe that in August, the reduction in $PM_{2.5}$ concentrations is significantly higher and covers a larger area than in January, a consequence of differences in electricity demand and meteorology across months. The distribution of $PM_{2.5}$ concentration decreases is very similar under the CRG, CRS, and CRW scenarios for all months considered.

Health Benefits. Across the six decarbonization scenarios, the emissions reductions from electricity generation in ERCOT range from 80 to 99% for SO_2 and 30 to 83% for NO_x. This results in marked decreases in $PM_{2.5}$ concentrations in Texas and associated negative health impacts. All demographic groups (race, ethnicity, and income) benefit significantly under those decarbonization scenarios. Mortality related to power plant emissions in the demographic groups considered is reduced by at least 79% under the carbon pricing scenarios, 78% under the health damage internalization scenario, and 93% under the coal replacement scenarios. Table 3 shows monthly avoided premature deaths under each scenario. All decarbonization strategies yield significant benefits to human health, reducing mortality caused by power plant SO_2 and NO_x emissions by 69−98%. The mitigation is achieved by reductions in SO_2 and NO_x emissions, either through direct coal power replacement (CRG, CRS, and CRW) or decreased generation from coal-fired plants.

The health benefits of carbon pricing depend on the magnitude of the carbon tax selected. When the lower cost of carbon emissions ($40 per ton) is used, average health cobenefits are lowest among all decarbonization scenarios and up to 20% less than those achieved under other scenarios in August. However, a high carbon price ($80 per ton) still leads to lower health cobenefits in August when electricity demand is high, indicating limited potential for carbon pricing to decrease power sector emissions solely through operational changes. The HDI scenario leads to the lowest health benefits in January but higher benefits in August due to varying health damage costs. The CRW and CRS scenarios result in the lowest SO_2 and NO_x emissions and most avoided deaths in all months considered, with similar results achieved through solar or wind generation. Due to seasonal variability in electricity loads and meteorology, premature deaths vary significantly across the months examined. High electricity demand and meteorology favoring $PM_{2.5}$ formation lead to more deaths avoided by decarbonization in August. Additionally, the limited availability of renewable energy in October results in relatively lower mortality reduction rates for the CRW and CRS scenarios during the month.

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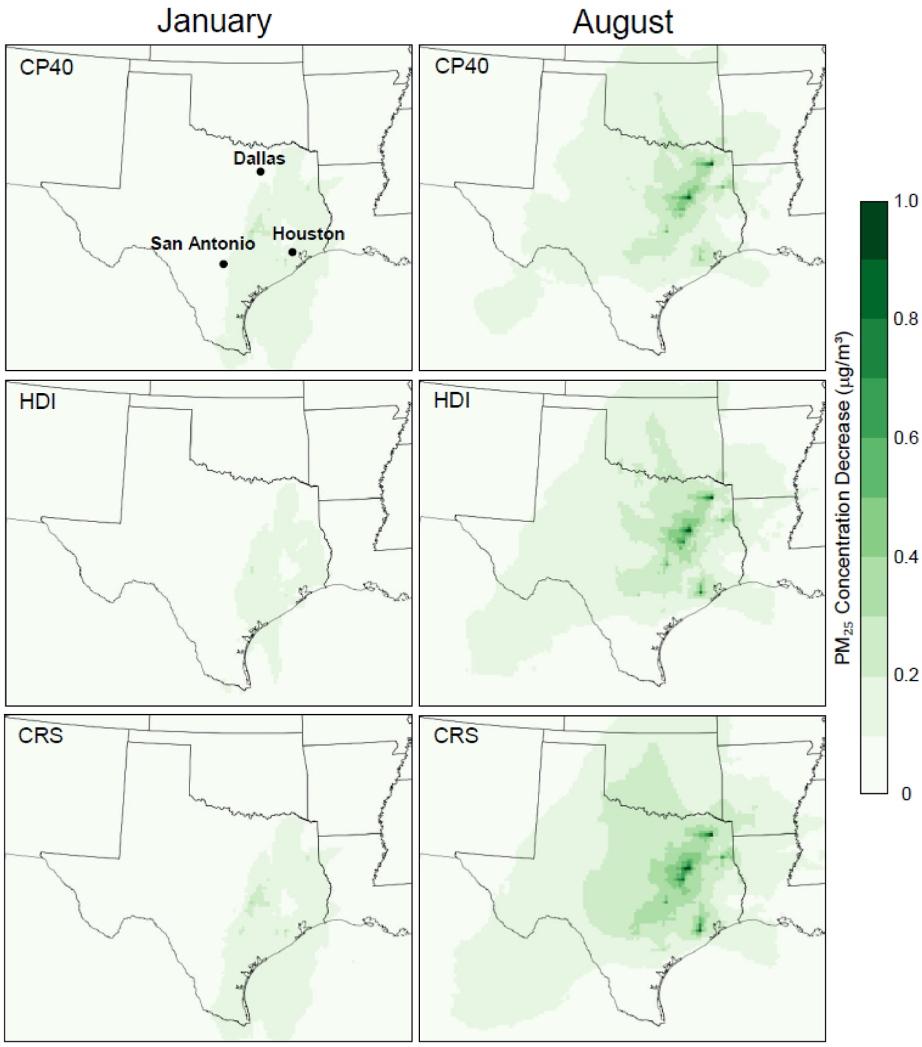

Figure 1. January and August average $PM_{2.5}$ concentration reductions under the CP40, HDI, and CRS decarbonization scenarios relative to the BAU scenario. BAU: business as usual; CP40: carbon price at \$40/ton of CO_2; HDI: health damage costs internalization; and CRS: coal-fired generators replaced by solar power.

Table 3. Monthly Premature Deaths in the U.S. Avoided by Decarbonizing ERCOT[a]

	Jan	Apr	Aug	Oct	4-month average	2-month average[b]
CP40	16.0 (11.0, 21.5)	20.5 (9.7, 27.2)	40.6 (27.4, 53.7)	5.0 (3.3, 6.6)	20.5	28.3
	92.8%	96.5%	75.0%	70.6%	82.4%	79.3%
CP80	16.4 (11.1, 21.8)	20.8 (14.0, 27.4)	44.7 (30.2, 59.1)	5.0 (3.3, 6.6)	21.7	30.5
	95.2%	97.6%	82.6%	70.6%	87.1%	85.6%
HDI	12.0 (8.1, 15.8)		44.7 (30.2, 59.1)			28.3
	69.6%		82.6%			79.4%
CRG	15.6 (10.6, 20.7)	20.4 (13.8, 27.0)	51.1 (34.5, 67.6)	4.9 (3.3, 6.5)	23.0	33.3
	90.3%	96.1%	94.5%	69.4%	92.3%	93.5%
CRS	16.8 (11.3, 22.2)	20.9 (14.1, 27.7)	50.8 (34.3, 67.3)	5.9 (4.0, 7.8)	23.6	33.8
	97.1%	98.4%	95.7%	82.4%	95.6%	96.0%
CRW	16.8 (11.4, 22.3)	20.9 (14.1, 27.7)	50.8 (34.3, 67.3)	5.9 (4.8, 9.3)	24.9	35.7
	97.6%	98.4%	94.0%	83.5%	94.8%	94.9%

[a]95% confidence intervals are shown in parenthesis. Percentages are the reduction rates relative to the BAU scenario. [b]2-month average of January and August values.

To assess the cost-effectiveness of each decarbonization strategy, we estimate their net benefits, considering operational costs, new facility costs (for the CRG, CRS, and CRW scenarios),[54] social cost of carbon (at \$55 per ton CO_2, 2022 USD),[55] and health damage costs from $PM_{2.5}$ formed from power plant emissions. Figure 2 shows a breakdown of the monthly average costs and benefits of each scenario relative to the BAU scenario. All strategies lead to major positive net benefits, mainly driven by climate benefits from avoided CO_2 emissions and health cobenefits from SO_2 and NO_x emission

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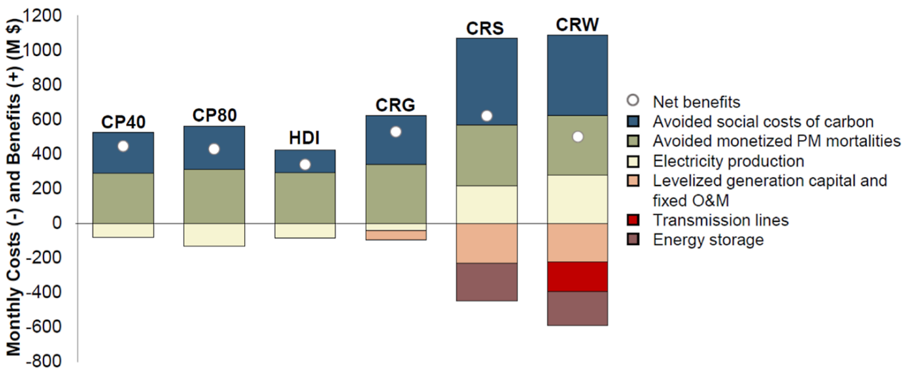

Figure 2. Two-month (January and August) average net benefits of each decarbonization scenario. BAU: business as usual; CP40: carbon price at $40/ton of CO_2; HDI: health damage costs internalization; and CRS: coal-fired generators replaced by solar power. Costs and benefits are relative to the BAU scenario and include electricity production costs, air pollution health impacts, carbon emissions, and costs of new generation facilities and transmission lines. All costs and benefits are calculated in 2022 USD.

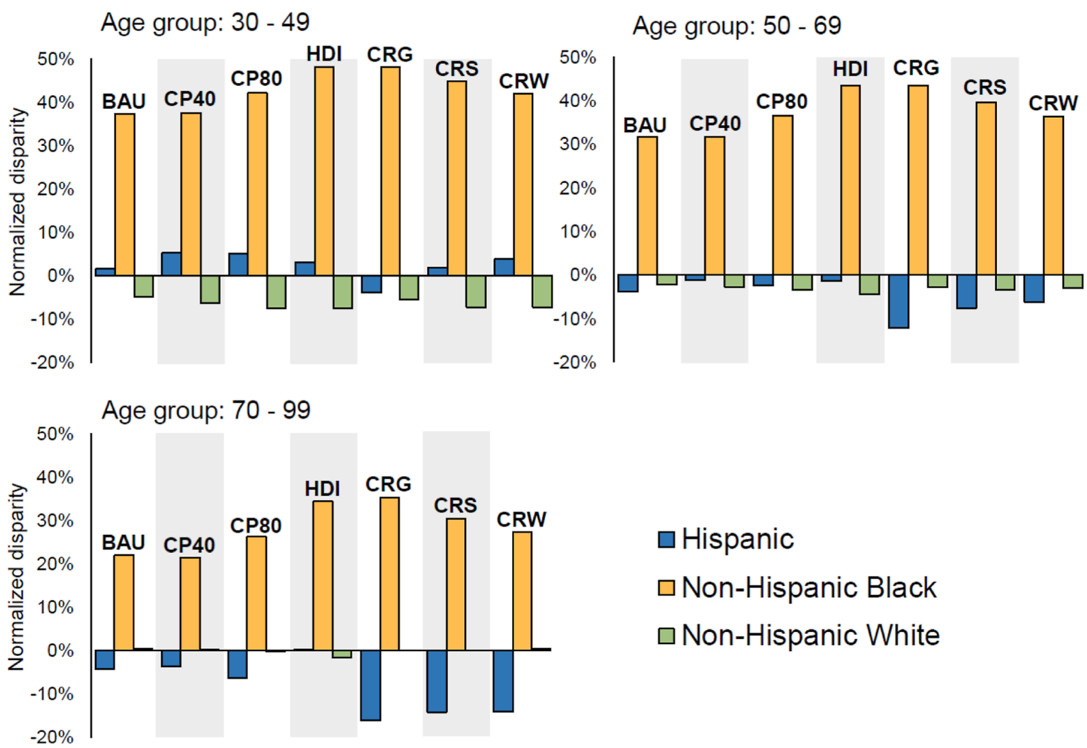

Figure 3. Disparity in mortality impacts of power sector SO_2 and NO_x emissions normalized by population among racial and age groups across decarbonization scenarios.

reductions. Another significant benefit of the CRS and CRW scenarios is fuel cost savings. Net benefits in January and August are higher than those in April and October, mainly due to greater health cobenefits (Figure S3).

Compared with others, the CRS and CRW scenarios have additional costs from the energy storage required to maintain reliable grid operations. However, such costs are dropping rapidly, potentially leading to greater net benefits in the future.[56] The net economic benefits of adding natural gas power are similar to those of adding renewable energy, but result in approximately half the CO_2 reductions achieved under the CRS and CRW scenarios. Although currently it is less costly to build new natural gas power plants than wind farms or utility-scale PV panels, renewables yield greater cost reductions from electricity generation, carbon emissions, and health impacts. Given the decreasing costs of renewable energy and energy storage, the benefits of adding renewable power can be expected to grow and exceed those of adding natural gas generation. In this study, we do not consider the possibility of converting natural gas to renewable energy or implementing CCS. It is notable that monetized health cobenefits exceed the avoided social costs of carbon emissions in all decarbonization scenarios, especially during August when the electricity demand is high. This emphasizes the importance of considering health cobenefits when conducting cost-benefit analysis for decarbonization policies.

When normalized by CO_2 emission reduction, average net benefits across scenarios vary from $40 to $135 per ton of CO_2 emission reduced (Table S9). This value under the CP40, CP80, and HDI scenarios, greater than the social cost of carbon when priced at $55 per ton, indicates high potential benefits of decarbonizing the power grid with operational changes using

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existing facilities. Due to new facility costs and more CO_2 emission reductions, the CRS and CRW scenarios have lower normalized net benefits. The variability in normalized net benefits highlights the importance of considering the benefits of decarbonization strategies from multiple aspects, beyond solely focusing on CO_2 emission reductions.

Exposure Inequity. To investigate inequity in exposure to air pollution caused by power plant emissions and the potential of decarbonization strategies to mitigate it, we compare premature deaths associated with power sector emissions in ERCOT among selected racial and ethnic groups, age groups, and income levels with those of the total population. For each population group, we define disparity in air pollution impacts as the difference between the fraction of mortalities incurred by the group and the fraction of the total population it includes, normalized by the fraction of the total population

$$\text{normalized group disparity} = \frac{\text{fraction of mortalities} - \text{fraction of population}}{\text{fraction of population}} \quad (6)$$

A positive disparity value indicates that a population group receives disproportionately higher air pollution damages from the power sector.

Figure 3 shows disparities in deaths attributable to ERCOT power plant emissions distributed by racial, ethnic, and age groups. Across all age groups and scenarios, non-Hispanic Black residents consistently receive a higher fraction (20−50%) of the damages relative to their share of the population. This inequity is larger among younger age groups. Furthermore, all decarbonization strategies except for the CP40 scenario increase disparity among the non-Hispanic Black population by 5−10%. After decarbonization, especially under the HDI and CRG scenarios, most significant $PM_{2.5}$ reductions occur near Texas metropolitan areas (Dallas, Houston, and Austin) and do not extend to areas with large fractions of non-Hispanic Black residents in eastern Texas, exacerbating the disparity. Among younger age groups, Hispanic residents generally receive disproportionately high damages from power sector emissions (a positive normalized disparity in the 30−49 age group in Figure 3). However, older Hispanic residents receive disproportionately lower damages (a negative normalized disparity in the 70−99 age group in Figure 3), as much of this population is located in western and southern Texas where $PM_{2.5}$ levels are comparatively low. Under the CRG, CRS, and CRW scenarios, power sector-related $PM_{2.5}$ pollution nearly ceases in regions where many older Hispanic residents live, allowing this group to benefit from disproportionately fewer damages. Non-Hispanic white residents under 70 receive fewer damages relative to their population across all scenarios, with this disparity growing slightly after decarbonization.

We additionally divide all census tracts into higher- and lower-income tracts based on median household income[51] and find that residents living in the 50% of census tracts with higher income are subjected to lower rates of health damages from power sector emissions (Figure 4). Similar to the mortality impacts among racial and ethnic groups, decarbonization scenarios can worsen this inequity. Although all proposed decarbonization strategies achieve a significant decrease in the mortality burden of power sector emissions, none of them effectively mitigate existing disparities in air pollution exposure across racial, ethnic, or income-level groups.

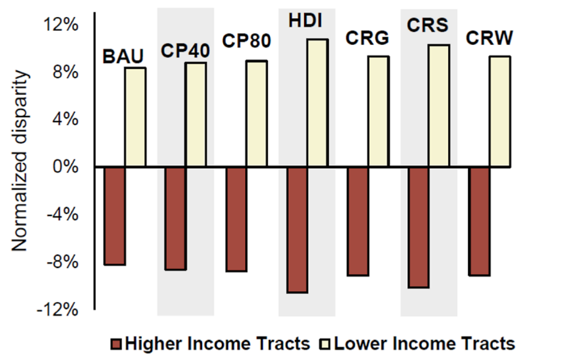

Figure 4. Disparity in mortality impacts of power sector SO_2 and NO_x emissions normalized by population among income groups across decarbonization scenarios.

IMPLICATIONS FOR DECARBONIZATION POLICY AND PLANNING

We compare the emission reduction, health impacts, and exposure inequity across six decarbonization scenarios that could be implemented in the near term for Texas. Emission reductions vary from 13 to 48% for CO_2, 80 to 99% for SO_2, and 30 to 80% for NO_x. All strategies mitigate more than 80% of the mortality associated with power plant SO_2 and NO_x emissions. Coal-fired generation, responsible for most of the adverse health impacts, is eliminated or greatly reduced under all scenarios. Scenarios replacing coal generation with solar power yield the greatest reductions in carbon emissions and negative health impacts—a drop of nearly 50% in emitted CO_2 and 95% in premature deaths, compared with BAU operations. From 2015 to 2021, renewable penetration in ERCOT increased from 2% to over 10%. Although more than 20% of the installed coal capacity (4 GW) was retired, ERCOT has also added 4 GW of new natural gas power.[57,58] As a result, 13.6 GW of coal and 56.9 GW of natural gas capacity remain in the power system, demonstrating continued decarbonization potential.

The decarbonization scenarios considered include strategies that rely on existing electricity generation facilities and can be implemented through operational changes (CP40, CP80, and HDI) and strategies that rely on new investments in generation, achievable within a decade (CRG, CRS, and CRW). Replacing coal-fired generation with renewable energy yields major benefits to climate change mitigation, air quality, and electricity production costs, but requires new construction, a challenge that is particularly significant when major transmission investments are needed. In contrast, the CP and HDI approaches require no capital investment and could be implemented quickly. It is important to note that our results for the CP and HDI scenarios show the immediate benefits of an operational change (i.e., adding a price to emissions) using existing infrastructure. A price on emissions sustained across multiple years may also result in retirements of high-emitting units and additional investments in renewable energy. While future capacity expansion is beyond the scope of this study, our results for the CRW and CRS scenarios offer insights into such impacts. CP and HDI can serve as transitional strategies during the process of coal-fired power plant retirement and renewable energy addition. The CRG scenario reflects the current trend among utilities that are retiring coal but adding natural gas in their operations to maintain resource adequacy. Adding natural gas generators may yield near-term GHG reductions and public health benefits, but lead to carbon lock-in given their multidecadal lifetime, making

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it harder to achieve deep levels of decarbonization. As the net benefits of the CRG scenario are not significantly higher than those of the CRS and CRW scenarios, retiring coal with natural gas generation is unlikely to be an optimal long-term approach.

Under the BAU scenario, we find the projected mortality associated with power sector SO_2 and NO_x emissions is disproportionately higher among the non-Hispanic Black population and lower-income residents, indicating the existence of significant disparities in exposure to air pollution from the current power system. All decarbonization scenarios show that these disparities persist across racial, ethnic, age, and income-level groups after decarbonization. Rather than mitigating the inequity, in most cases, the decarbonization strategies considered can exacerbate it, especially for non-Hispanic Black residents. Although this study focuses on the Texas power system, it demonstrates an important example of the persistence of disproportionate negative impacts on certain populations when disaggregated impacts of decarbonization are not explicitly considered. Many global regions are beginning to decarbonize their power grids. Early identification of potential environmental justice issues is essential to achieve equitable decarbonization outcomes. The results of this study call for greater consideration of the environmental justice implications of decarbonizing power systems. Most existing power system models optimize based on the costs. Here, we monetize negative impacts on climate and public health so that power system operations take these externalities into account. However, integrating environmental justice dimensions into power systems modeling remains a challenge. New tools and frameworks able to internalize demographic inequities in power system operations are needed to ensure just energy transition.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c00881.

> Air quality model settings and performance evaluation; additional information on the power system model and decarbonization scenarios; and additional results of reductions in emissions, $PM_{2.5}$ concentrations, and health impacts achieved by the decarbonization scenarios considered (PDF)

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Notes

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■ REFERENCES

(1) Pörtner, H.-O.; Roberts, D.; Poloczanska, E.; Mintenbeck, K.; Tignor, M.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; Okem, A. *Climate Change 2022 Impacts, Adaptation and Vulnerability Summary for Policymakers*, 2021. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf (accessed 20 April 2022).

(2) Garcia-Menendez, F.; Saari, R. K.; Monier, E.; Selin, N. E. U. S. Air Quality and Health Benefits from Avoided Climate Change under Greenhouse Gas Mitigation. *Environ. Sci. Technol.* **2015**, *49*, 7580−7588.

(3) Wuebbles, D. J.; Fahey, D. W.; Hibbard, K. A. *Climate Science Special Report: Fourth National Climate Assessment (NCA4)*, 2017; Vol. *1*.

(4) Cronin, J.; Anandarajah, G.; Dessens, O. Climate change impacts on the energy system: a review of trends and gaps. *Clim. Change* **2018**, *151*, 79−93.

(5) Shukla, P.; Skea, J.; Calvo Buendia, E.; Masson-Delmotte, V.; Pörtner, H.; Roberts, D.; Zhai, P.; Slade, R.; Connors, S.; Van Diemen, S.; Ferrat, M. *IPCC, 2019: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Intergovernmental Panel on Climate Change (IPCC), 2019. https://www.ipcc.ch/srccl/ (accessed January 25, 2022).

(6) Rogelj, J.; Hare, W.; Lowe, J.; van Vuuren, D. P.; Riahi, K.; Matthews, B.; Hanaoka, T.; Jiang, K.; Meinshausen, M. Emission pathways consistent with a 2 °C global temperature limit. *Nat. Clim. Change* **2011**, *1*, 413−418.

(7) Rogelj, J.; Schaeffer, M.; Meinshausen, M.; Knutti, R.; Alcamo, J.; Riahi, K.; Hare, W. Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.* **2015**, *10*, 105007.

(8) U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990−2019*, 2021. EPA430-R-21-005. https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf (accessed January 25, 2022).

(9) Breyer, C.; Bogdanov, D.; Aghahosseini, A.; Gulagi, A.; Child, M.; Oyewo, A. S.; Farfan, J.; Sadovskaia, K.; Vainikka, P. Solar photovoltaics demand for the global energy transition in the power sector. *Prog. Photovoltaics Res. Appl.* **2018**, *26*, 505−523.

(10) Davis, S. J.; Lewis, N. S.; Shaner, M.; Aggarwal, S.; Arent, D.; Azevedo, I. L.; Benson, S. M.; Bradley, T.; Brouwer, J.; Chiang, Y.-M.; Clack, C. T. M.; Cohen, A.; Doig, S.; Edmonds, J.; Fennell, P.; Field, C. B.; Hannegan, B.; Hodge, B.-M.; Hoffert, M. I.; Ingersoll, E.; Jaramillo, P.; Lackner, K. S.; Mach, K. J.; Mastrandrea, M.; Ogden, J.; Peterson, P. F.; Sanchez, D. L.; Sperling, D.; Stagner, J.; Trancik, J. E.; Yang, C.-J.; Caldeira, K. Net-zero emissions energy systems. *Science* **2018**, *360*, No. eaas9793.

(11) Arbabzadeh, M.; Sioshansi, R.; Johnson, J. X.; Keoleian, G. A. The role of energy storage in deep decarbonization of electricity production. *Nat. Commun.* **2019**, *10*, 3413.

(12) Kaufman, N.; Barron, A. R.; Krawczyk, W.; Marsters, P.; McJeon, H. A near-term to net zero alternative to the social cost of carbon for setting carbon prices. *Nat. Clim. Change* **2020**, *10*, 1010−1014.

(13) Papadis, E.; Tsatsaronis, G. Challenges in the decarbonization of the energy sector. *Energy* **2020**, *205*, 118025.

(14) National Conference of State Legilatures. *Energy State Bill Tracking Database*. https://www.ncsl.org/research/energy/energy-legislation-tracking-database.aspx (accessed May 20, 2021).
(15) Center for Climate and Energy Solutions. *Market-Based State Policy*. https://www.c2es.org/content/market-based-state-policy (accessed May 20, 2021).
(16) Saari, R. K.; Selin, N. E.; Rausch, S.; Thompson, T. M. A self-consistent method to assess air quality co-benefits from U.S. climate policies. *J. Air Waste Manage. Assoc.* **2015**, *65*, 74−89.
(17) Rao, S.; Klimont, Z.; Leitao, J.; Riahi, K.; van Dingenen, R.; Reis, L. A.; Calvin, K.; Dentener, F.; Drouet, L.; Fujimori, S.; Harmsen, M.; Luderer, G.; Heyes, C.; Strefler, J.; Tavoni, M.; van Vuuren, D. P. A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environ. Res. Lett.* **2016**, *11*, 124013.
(18) Li, M.; Zhang, D.; Li, C.-T.; Mulvaney, K. M.; Selin, N. E.; Karplus, V. J. Air quality co-benefits of carbon pricing in China. *Nat. Clim. Change* **2018**, *8*, 398−403.
(19) Carley, S.; Konisky, D. M. The justice and equity implications of the clean energy transition. *Nat. Energy* **2020**, *5*, 569−577.
(20) Tessum, C. W.; Apte, J. S.; Goodkind, A. L.; Muller, N. Z.; Mullins, K. A.; Paolella, D. A.; Polasky, S.; Springer, N. P.; Thakrar, S. K.; Marshall, J. D.; Hill, J. D. Inequity in consumption of goods and services adds to racial−ethnic disparities in air pollution exposure. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116*, 6001−6006.
(21) Colmer, J.; Hardman, I.; Shimshack, J.; Voorheis, J. Disparities in PM2. 5 air pollution in the United States. *Science* **2020**, *369*, 575−578.
(22) Jbaily, A.; Zhou, X.; Liu, J.; Lee, T.-H.; Kamareddine, L.; Verguet, S.; Dominici, F. Air pollution exposure disparities across US population and income groups. *Nature* **2022**, *601*, 228−233.
(23) Tessum, C. W.; Paolella, D. A.; Chambliss, S. E.; Apte, J. S.; Hill, J. D.; Marshall, J. D. PM2. 5 polluters disproportionately and systemically affect people of color in the United States. *Sci. Adv.* **2021**, *7*, No. eabf4491.
(24) Thind, M. P.; Tessum, C. W.; Azevedo, I. L.; Marshall, J. D. Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environ. Sci. Technol.* **2019**, *53*, 14010−14019.
(25) Sergi, B. J.; Adams, P. J.; Muller, N. Z.; Robinson, A. L.; Davis, S. J.; Marshall, J. D.; Azevedo, I. L. Optimizing emissions reductions from the US power sector for climate and health benefits. *Environ. Sci. Technol.* **2020**, *54*, 7513−7523.
(26) Larson, E.; Greig, C.; Jenkins, J.; Mayfield, E.; Pascale, A.; Zhang, C.; Drossman, J.; Williams, R.; Pacala, S.; Socolow, R.; Baik, E.; Birdsey, R.; Duke, R.; Jones, R.; Haley, B.; Leslie, E.; Paustian, K.; Swan, A. *NET-ZERO AMERICA: Potential Pathways, Infrastructure, and Impacts*, 2021. https://netzeroamerica.princeton.edu/ (accessed April 20, 2022).
(27) Sasse, J.-P.; Trutnevyte, E. Regional impacts of electricity system transition in Central Europe until 2035. *Nat. Commun.* **2020**, *11*, 4972.
(28) U.S. Census Bureau. *2020 Census Data*, 2020. https://www.census.gov/programs-surveys/decennial-census/about/rdo/summary-files.html#P1 (accessed April 22, 2022).
(29) de Sisternes, F. J.; Jenkins, J. D.; Botterud, A. The value of energy storage in decarbonizing the electricity sector. *Appl. Energy* **2016**, *175*, 368−379.
(30) Craig, M. T.; Jaramillo, P.; Hodge, B.-M. Carbon dioxide emissions effects of grid-scale electricity storage in a decarbonizing power system. *Environ. Res. Lett.* **2018**, *13*, 014004.
(31) U.S. Environmental Protection Agency. *Air Pollutant Emissions Trends Data: State Average Annual Emissions Trend*. https://www.epa.gov/sites/production/files/2018-07/state_tier1_caps.xlsx/ (accessed May 26, 2020).
(32) Cohen, S. M.; Becker, J.; Bielen, D. A.; Brown, M.; Cole, W. J.; Eurek, K. P.; Frazier, A.; Frew, B. A.; Gagnon, P. J.; Ho, J. L. *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2018*; National Renewable Energy Laboratory: Golden, CO, 2019. (NREL). NREL/TP-6A20- 72023. https://www.nrel.gov/docs/fy19osti/72023.pdf (accessed April 20, 2022).
(33) Electric Reliability Council of Texas. *Analysis of Transmission Alternatives for Competitive Renewable Energy Zones in Texas*, 2006. https://www.ercot.com/files/docs/2006/12/01/attch_a_crez_analysis_report.pdf (accessed May 20, 2021).
(34) U.S. Energy Information Administration. *Existing Nameplate and Net Summer Capacity by Energy Source, Producer Type and State (EIA-860)*, 2021. https://www.eia.gov/electricity/data/state/ (accessed April 20, 2022).
(35) National Research Council and others. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*; National Academies Press, 2010..
(36) U.S. Environmental Protection Agency. *The Benefits and Costs of the Clean Air Act from 1990 to 2020 Summary Report*, 2011. https://www.epa.gov/sites/production/files/2015-07/documents/summaryreport.pdf (accessed December 12, 2021).
(37) Ou, Y.; Shi, W.; Smith, S. J.; Ledna, C. M.; West, J. J.; Nolte, C. G.; Loughlin, D. H. Estimating environmental co-benefits of US low-carbon pathways using an integrated assessment model with state-level resolution. *Appl. Energy* **2018**, *216*, 482−493.
(38) Luo, Q.; Johnson, J. X.; Garcia-Menendez, F. Reducing human health impacts from power sector emissions with redispatch and energy storage. *Environmental Research: Infrastructure and Sustainability* **2021**, *1* (2), 025009.
(39) Luderer, G.; Pehl, M.; Arvesen, A.; Gibon, T.; Bodirsky, B. L.; de Boer, HS; Hejazi, O.; Humpenöder, M.; Iyer, F.; Mima, G.; Mouratiadou, S.; Pietzcker, I.; Popp, R.; van den Berg, A.; van Vuuren, M.; Hertwich, D.; Hertwich, E. G. Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nat. Commun.* **2019**, *10*, 5229.
(40) Zhao, B.; Wang, T.; Jiang, Z.; Gu, Y.; Liou, K.-N.; Kalandiyur, N.; Gao, Y.; Zhu, Y. Air quality and health cobenefits of different deep decarbonization pathways in California. *Environ. Sci. Technol.* **2019**, *53*, 7163−7171.
(41) Zhou, W.; McCollum, D. L.; Fricko, O.; Fujimori, S.; Gidden, M.; Guo, F.; Hasegawa, T.; Huang, H.; Huppmann, D.; Krey, V.; Liu, C.; Parkinson, S.; Riahi, K.; Rafaj, P.; Schoepp, W.; Yang, F.; Zhou, Y. Decarbonization pathways and energy investment needs for developing Asia in line with 'well below'2 C. *Clim. Pol.* **2020**, *20*, 234−245.
(42) Frew, B. A.; Cole, W. J.; Sun, Y.; Mai, T. T.; Richards, J. *8760-based Method for Representing Variable Generation Capacity Value in Capacity Expansion Models*; National Renewable Energy Laboratory (NREL): Golden, CO, 2017. NREL/CP-6A20-68869. https://www.nrel.gov/docs/fy17osti/68869.pdf (accessed April 20, 2022).
(43) Freeman, J. M.; DiOrio, N. A.; Blair, N. J.; Neises, T. W.; Wagner, M. J.; Gilman, P.; Janzou, S. *System advisor model (SAM) general description (version 2017.9. 5)*; National Renewable Energy Laboratory (NREL): Golden, CO, 2018. NREL/TP-6A20-70414. https://www.nrel.gov/docs/fy18osti/70414.pdf (accessed April 20, 2022).
(44) U.S. Environmental Protection Agency. *Air Markets Program Data (AMPD)*. https://ampd.epa.gov/ampd/ (accessed May 12, 2020).
(45) Baek, B.; Seppanen, C. *Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System*. 2018. https://doi.org/10.5281/zenodo.1421403 (accessed April 20, 2022).
(46) U.S. Environmental Protection Agency. *Air Quality System (AQS)*. https://www.epa.gov/aqs (accessed December 12, 2021).
(47) Sacks, J. D.; Lloyd, J. M.; Zhu, Y.; Anderton, J.; Jang, C. J.; Hubbell, B.; Fann, N. The Environmental Benefits Mapping and Analysis Program−Community Edition (BenMAP−CE): A tool to estimate the health and economic benefits of reducing air pollution. *Environ. Model. Software* **2018**, *104*, 118−129.
(48) Krewski, D.; Jerrett, M.; Burnett, R. T.; Ma, R.; Hughes, E.; Shi, Y.; Turner, M. C.; Pope, C. A., III; Thurston, G.; Calle, E. E. *Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality*; Health Effects Institute: Boston, MA, 2009.
(49) Heo, J.; Adams, P. J.; Gao, H. O. Public health costs of primary PM2. 5 and inorganic PM2. 5 precursor emissions in the United States. *Environ. Sci. Technol.* **2016**, *50*, 6061−6070.

https://doi.org/10.1021/acs.est.2c00881
Environ. Sci. Technol. 2022, 56, 13274−13283

(50) Strasert, B.; Teh, S. C.; Cohan, D. S. Air quality and health benefits from potential coal power plant closures in Texas. *J. Air Waste Manage. Assoc.* **2019**, *69*, 333−350.
(51) Manson, S.; Schroeder, J.; Riper, D. V.; Kugler, T.; Ruggles, S. *IPUMS National Historical Geographic Information System*, Version 16.0 [dataset]. 2021. http://doi.org/10.18128/D050.V16.0 (accessed May 26, 2021).
(52) Centers for Disease Control and Prevention. *CDC Wide-ranging ONline Data for Epidemiologic Research (CDC WONDER)*. https://wonder.cdc.gov/ (accessed May 12, 2021).
(53) U.S. Environmental Protection Agency. *U.S. EPA. Environmental Benefits Mapping and Analysis Program: Community Edition (BenMAP-CE) User Manual and Appendices*, Version 1.4.8), 2018. https://www.epa.gov/benmap/benmap-ce-manual-and-appendices (accessed May 26, 2021).
(54) U.S. Energy Information Administration. *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021*, 2021. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf (accessed May 26, 2021).
(55) Interagency Working Group and others. *Technical support document: social cost of carbon, methane, and nitrous oxide interim estimates under executive order 13990*, 2021. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf (accessed April 20, 2022).
(56) Cole, W.; Frazier, A. W.; Augustine, C. *Cost Projections for Utility-Scale Battery Storage: 2021 Update*; National Renewable Energy Laboratory (NREL): Golden, CO, 2021. NREL/TP-6A20-79236. https://www.nrel.gov/docs/fy21osti/79236.pdf (accessed April 20, 2022).
(57) Electric Reliability Council of Texas. *Report on the Capacity, Demand and Reserves (CDR) in the ERCOT Region, 2015-2024*, 2014. https://www.ercot.com/files/docs/2015/01/06/capacitydemandandreservereport_may2014.pdf (accessed April 20, 2022).
(58) Electric Reliability Council of Texas. *Report on the Capacity, Demand and Reserves (CDR) in the ERCOT Region, 2022-2031*, 2021. https://www.ercot.com/files/docs/2021/12/29/CapacityDemandandReservesReport_December2021.pdf (accessed April 20, 2022).

https://doi.org/10.1021/acs.est.2c00881
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