

# Climate, air quality, and equity benefits from hydrogen substitution for fossil fuels used in process heat

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Fossil fuel combustion for process heat in heavy industry accounts for ~15% of all United States CO<sub>2</sub> emissions and emits PM<sub>2.5</sub> and its precursors, emissions that have a disproportionate impact on minority populations. Decarbonizing process heat in the U.S. via hydrogen substitution presents an opportunity to reduce emissions of CO<sub>2</sub> and PM<sub>2.5</sub> and mitigate resulting exposure disparity. Here, we show that hydrogen substitution in steelmaking provides a large reduction in CO<sub>2</sub> emissions and air quality-related premature mortality, while hydrogen substitution in petroleum refining substantially benefits disadvantaged communities. When reductions in CO<sub>2</sub> emissions and premature mortality are monetized using standard regulatory values, we find that the sum of air pollution and climate benefits outweighs the difference in private cost associated with hydrogen substitution in steelmaking, regardless of the method of hydrogen production. The approach developed here can support evaluations of equity-focused decarbonization strategies in other industries and for specific sites.

Fossil fuel combustion for process heat in heavy industry accounted for ~15% of all United States (U.S.) CO<sub>2</sub> emissions in 2019<sup>1</sup>. Concomitantly, fossil fuel combustion in industry also emits substantial amounts of particulate matter of aerodynamic diameter less than 2.5 micrometers (PM<sub>2.5</sub>) and precursor air pollutants that lead to the formation of PM<sub>2.5</sub> in the atmosphere. Chronic exposure to elevated concentrations of PM<sub>2.5</sub> increases the risk of premature mortality<sup>2,3</sup>, such that industrial emissions of PM<sub>2.5</sub> and its precursors are estimated to cause upwards of 16,000 deaths annually in the U.S.<sup>4</sup> This mortality burden is disproportionately experienced by historically marginalized populations, particularly people of color<sup>4–6</sup>. Average PM<sub>2.5</sub> concentrations experienced by people of color caused by industrial emissions are 20% higher than the national average, a result associated with redlining<sup>7</sup> and preferential siting of polluting industries near minority communities<sup>8</sup>. These racial and ethnic disparities in PM<sub>2.5</sub> exposure have been a major focus of federal policy; a standing executive order

from the Clinton administration mandates that federal agencies include an assessment of environmental justice in their major decisions<sup>9</sup>, and the Biden administration's Justice40 initiative aimed to provide 40% of the benefits of climate policy to historically disadvantaged communities (DACs)<sup>10–13</sup>. Beyond climate benefits, decarbonizing industrial heat thus has both substantial public health and equity co-benefits in the form of reduced premature mortality in these DACs.

Hydrogen is a technologically feasible fossil fuel alternative in three CO<sub>2</sub>-intensive industries: petroleum refining, steelmaking, and cement manufacturing<sup>14–16</sup>. In petroleum refining and cement manufacturing, the most common fossil fuels are natural gas and coal, respectively; hydrogen can directly replace fossil fuel combustion to meet process heat requirements. In steelmaking, coke is substituted with hydrogen to provide both process heat and a reducing agent for iron ore, producing direct reduced iron that is then fed into an electric

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arc furnace. While most hydrogen today is produced via steam methane reforming (SMR), essentially a fossil energy carrier from natural gas, with a CO<sub>2</sub>-equivalent (CO<sub>2</sub>e) intensity of 9 kg per megajoule (MJ), hydrogen is potentially a low- or zero-carbon fuel if produced via steam methane reforming with carbon capture and sequestration (SMR-CCS, which we assume has a CO<sub>2</sub>e intensity of 0.9 kg per MJ) or electrolysis with zero-carbon energy sources (ZCE, which has a CO<sub>2</sub>e intensity of 0), respectively<sup>17</sup>. Transitioning from fossil fuels to hydrogen combustion also reduces emissions of PM<sub>2.5</sub> and most of its precursors, except nitrogen oxides (NO<sub>x</sub>) whose emissions on a per-energy basis may remain constant or increase<sup>18</sup> (see Supplementary Note 1 for further discussion).

Past studies have examined intersections between decarbonization policy, air quality, and environmental justice, though relatively few have focused on industrial decarbonization. In the power sectors, many studies have assessed the disparate air quality impact of power generation on socially vulnerable communities (i.e., poor, racial/ethnic minority, or rural communities), finding that existing fossil generation technologies have a disproportionate impact on rural, poor, and Black populations<sup>19–26</sup>, such that decarbonizing electricity generation may result in environmental justice benefits. This unequal impact across subpopulations has been incorporated into decision-making regarding coal power plant retirement<sup>27</sup>. However, some studies have noted that without explicit consideration of environmental justice in decarbonization strategies, socially vulnerable communities may be left behind. In the transportation sector, a variety of studies have found that vehicle electrification may reduce PM<sub>2.5</sub> exposure disparity by up to 10% for some race/ethnic minorities<sup>28–32</sup>, but that vehicle electrification under an existing power grid shifts the burden of traffic-related air pollution from urban centers to rural areas where power generation is typically located<sup>23,33–37</sup>. While some studies have examined the impact of industrial decarbonization policies on domestic air quality and environmental justice<sup>38,39</sup>, these studies considered broad decarbonization portfolios instead of specific technologies, presenting an opportunity to evaluate how specific technologies, such as hydrogen substitution in heavy industry, impact both air quality and environmental justice. Our analysis aims to provide improvements to in-depth analyses of individual decarbonization approaches by evaluating the trade-offs between climate, air quality, and equity across a variety of technology scenarios.

In this study, we developed a methodology and present results for optimally using hydrogen as a substitute for process heat in petroleum refining, steelmaking, and cement manufacturing industries in the contiguous U.S. with respect to four metrics: hydrogen demand for process heat, CO<sub>2</sub> offset potential, reduction in premature mortality associated with PM<sub>2.5</sub>, and the percentage of air quality benefits occurring in DACs that could form one part of a more comprehensive analysis of conformance with the Biden Administration's Justice40 initiative. In aggregate, we considered the construction of a hypothetical SMR, SMR-CCS, or ZCE hydrogen production plant collocated with all current industrial sites in the lower 48 states for the three industries we analyzed (see Supplementary Note 2 for further discussion of this assumption), estimating the change in CO<sub>2</sub>, PM<sub>2.5</sub>, and PM<sub>2.5</sub>-precursor emissions associated with each industry-hydrogen production method pair ("scenario") at an industry level. We predicted health impacts using the InMAP source-receptor matrix (ISRM)<sup>40</sup> (a derivative of the reduced-complexity air quality model InMAP) and combined the predicted PM<sub>2.5</sub> concentration fields with population data to estimate total and demographically disparate air quality and health impacts. InMAP predicts changes in PM<sub>2.5</sub> concentrations from perturbations in emission inventories, which are then used to predict changes in health effects (i.e., premature mortality) based on the proximity of population to the largest changes in PM<sub>2.5</sub> concentration; for more details on the model, see<sup>40</sup>. In a world of limited resources and the need to sequence capital deployment, the results from our

study can inform sectoral decisions about where hydrogen substitution can provide the greatest decarbonization and air quality benefits and demonstrate methods that could be applied at a site level.

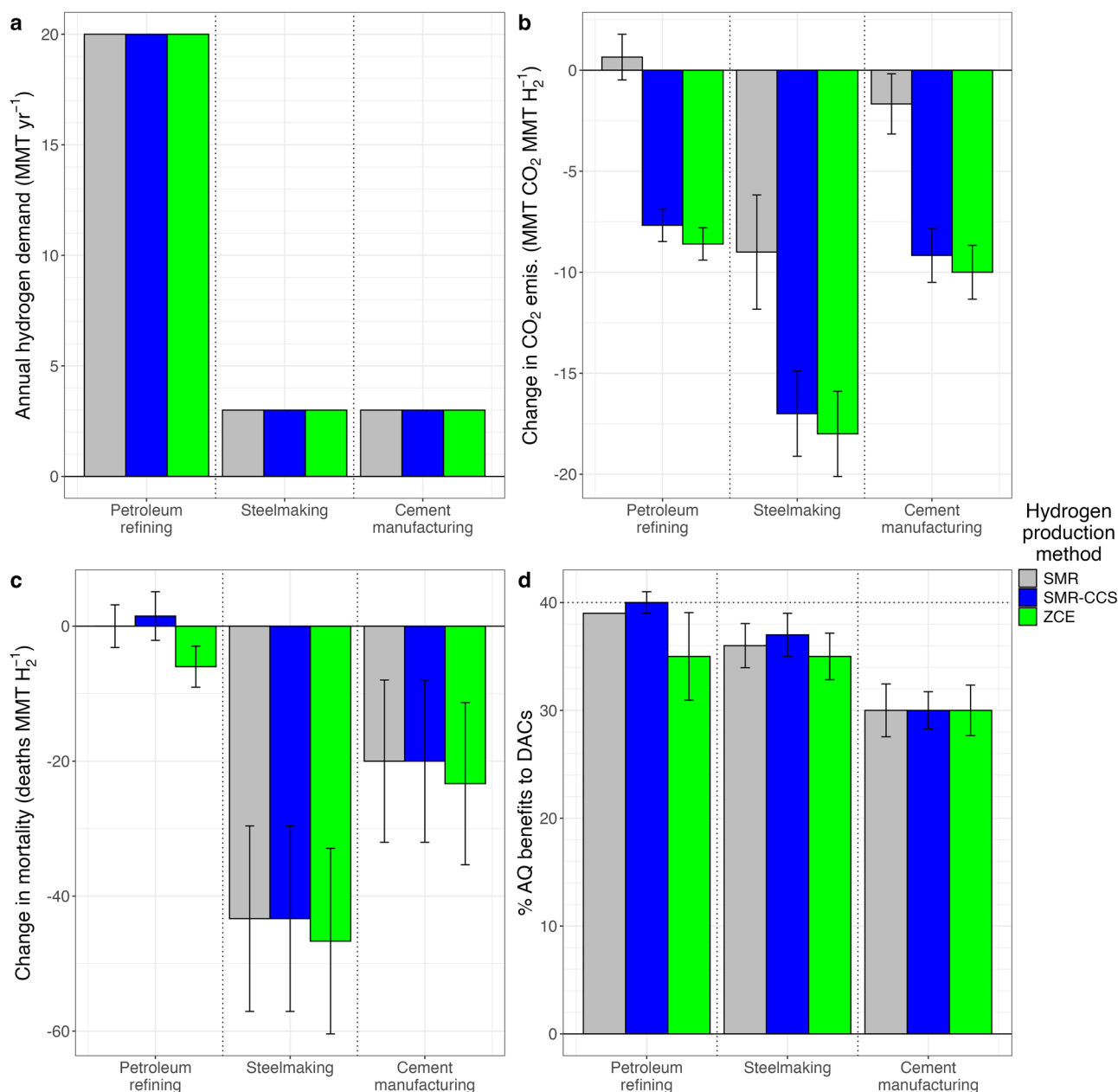
## Results

### Changes in CO<sub>2</sub> emissions, premature mortality, and equity

We evaluated nine total technology scenarios representing pairs of industry and hydrogen production methods. We considered three industries: petroleum refining, steelmaking, and cement manufacturing; and three hydrogen production methods: SMR, SMR-CCS, and ZCE hydrogen. For each technology scenario, we assessed four metrics for industry-wide hydrogen substitution using a functional unit of million metric tons (MMT) of hydrogen substituted in the industry: annual hydrogen demand to fully replace fossil fuel combustion for process heat at 2018 industry levels in the lower 48 states (MMT per year); change in annual CO<sub>2</sub> emissions normalized by hydrogen usage (MMT CO<sub>2</sub> per MMT H<sub>2</sub>); change in annual all-population PM<sub>2.5</sub>-related premature mortality normalized by hydrogen usage (deaths per MMT H<sub>2</sub>); and percentage of annual PM<sub>2.5</sub>-related mortality changes occurring in Census tracts previously designated by the Department of Energy (DOE) as DACs (%), a part of a more comprehensive analysis determining compliance with Justice40. Our goal is to provide a systematic framework for evaluating decarbonization scenarios and selecting optimal scenarios based on multi-criteria decision-making of important metrics (1: production feasibility to meet demand, 2: decarbonization potential, 3: mortality co-benefits, and 4: equitable distribution of co-benefits).

We calculated industry-wide hydrogen demand in petroleum refining and cement manufacturing by dividing total heat requirements in each industry<sup>41,42</sup> by the lower heating value (LHV) of hydrogen, and in steelmaking by using reference values for hydrogen required to produce one metric tonne of steel<sup>43</sup>. This analysis considers hydrogen production only to provide heat (and, in the case of steelmaking, a reducing agent for iron oxide); most hydrogen today is used as a chemical feedstock in petroleum refining and ammonia production, a use of hydrogen we did not consider in this analysis. For our analysis, we used data from 2018<sup>44</sup> to avoid temporary fluctuations in energy demand due to the coronavirus pandemic; our core results would not change with updated data because there has not been a large enough shift in production to substantially change conclusions. We found that hydrogen demand in each industry for complete fossil fuel replacement is relatively large compared to existing hydrogen production capacity, which was approximately 10 MMT per year in 2022<sup>45</sup>. Of the three industries considered in this analysis, petroleum refining has the largest heat demand and thus the largest potential hydrogen demand, at approximately 20 MMT per year, while steelmaking and cement manufacturing each require approximately 3 MMT per year, as shown in Fig. 1a. Hydrogen demand does not vary by hydrogen production method, since method of production does not influence per-mass energy content. The DOE's National Clean Hydrogen Strategy<sup>46</sup> suggests hydrogen production capacity will reach 40–50 MMT per year by 2050, with just 5 MMT per year for all heat demands, an insufficient supply to meet the demands of all three industries analyzed here. However, DOE's H2@Scale project<sup>45</sup> suggests that with aggressive research and development, more than 100 MMT per year could be produced, potentially meeting this demand.

We calculated changes in industry-wide CO<sub>2</sub> emissions by comparing business-as-usual CO<sub>2</sub> emissions to potential CO<sub>2</sub> emissions under hydrogen substitution for each method of hydrogen production. For petroleum refining and cement manufacturing, this is the difference between CO<sub>2</sub> emissions from fossil fuel combustion and the hydrogen production emissions of CO<sub>2</sub> to meet energy requirements. For steelmaking, this is the difference between the combined coking and steel production emissions of CO<sub>2</sub> and the combined hydrogen production and electric arc furnace emissions of CO<sub>2</sub>. See methods for



**Fig. 1 | Summary of normalized metrics for each industry/hydrogen production scenario (hydrogen production methods are steam methane reforming [SMR], steam methane reforming with carbon capture and sequestration [SMR-CCS], and zero-carbon electrolysis [ZCE]).** Panel (a) annual hydrogen demand in each industry, which does not vary by hydrogen production method. Panel (b) million metric tons (MMT) of CO<sub>2</sub> offset per MMT of hydrogen used. Panel (c) change in

premature mortality in deaths averted per MMT of hydrogen used. Panel (d) the percentage of air quality benefits (reduced mortality) occurring in Department of Energy-designated disadvantaged communities (DACs). The error bars represent the 95% confidence interval of the reported metric, based on the uncertainty in emissions factors.

more details. A summary of current fuel mixes and CO<sub>2</sub> emission factors for each industry is produced in Supplementary Table 5, Supplementary Figs. 3, 5, and 7, respectively.

Across the technology scenarios we considered, hydrogen substitution in these three industries generally reduced CO<sub>2</sub> emissions (Fig. 1b). For all considered industries, substitution with ZCE hydrogen provided the largest CO<sub>2</sub> emission reduction, followed by substitution with SMR-CCS hydrogen. As expected, SMR hydrogen performed the poorest on this metric, even increasing emissions in petroleum refining. CO<sub>2</sub> emission reductions were largest in steelmaking, with 18, 17, and 9 MMT CO<sub>2</sub> offset per MMT of hydrogen under ZCE, SMR-CCS, and SMR steelmaking, respectively. CO<sub>2</sub> reductions in petroleum refining and cement manufacturing ranged from 5–7 MMT offset per

MMT of hydrogen under SMR-CCS and ZCE petroleum refining and SMR-CCS and ZCE cement manufacturing. For one scenario, SMR petroleum refining, hydrogen substitution increased CO<sub>2</sub> emissions due to a larger assumed CO<sub>2</sub> emissions factor of SMR hydrogen production than through combustion of the fossil fuel alternative itself; SMR hydrogen production emits approximately 80 g CO<sub>2</sub> per MJ<sup>47</sup>, while natural gas combustion emits approximately 50 g CO<sub>2</sub> per MJ<sup>48</sup>. This causes SMR hydrogen production to be unviable as a decarbonization strategy for this industry's process heat CO<sub>2</sub> emissions.

Across the technology scenarios considered, annual premature mortality due to long-term PM<sub>2.5</sub> exposure generally decreased (Fig. 1c). For the three industries, substitution with ZCE hydrogen reduced premature mortality the most because it produces the lowest

air pollutant emissions of the hydrogen production methods, followed by SMR-CCS and then SMR hydrogen. Hydrogen substitution in steelmaking had the highest air quality-related mortality benefits, with roughly 45 U.S. deaths averted per MMT for any of the hydrogen production methods, a consequence of offsetting the emissions of both coking and steel production, which combined have higher emission factors of local air pollutants on a per-energy basis than cement manufacturing and petroleum refining (Supplementary Figs. 4, 6, and Supplementary Fig. 8). Hydrogen substitution in U.S. cement manufacturing had the second-highest air quality-related mortality benefits, with approximately 22 deaths averted per MMT for all three hydrogen production methods. Hydrogen substitution in U.S. petroleum refining increased premature mortality under the SMR and SMR-CCS petroleum refining scenarios by 0–3 deaths per MMT of hydrogen used, and reduced premature mortality under ZCE petroleum refining by 5 deaths per MMT of hydrogen. Mortality reduction is largely undifferentiated by hydrogen production method because air pollutant emissions from hydrogen production are relatively small. However, premature mortality remains constant or increases under SMR and SMR-CCS hydrogen production in petroleum refining because the reduction in non-NO<sub>x</sub> PM<sub>2.5</sub> precursor emissions associated with hydrogen combustion is not enough to offset the increased mortality due to hydrogen production, a result of higher usage of natural gas as a fuel in petroleum refining compared to predominantly coal-based fuels in steelmaking and cement manufacturing (Supplementary Table 5).

Changes in PM<sub>2.5</sub> concentrations under these scenarios are mapped in Supplementary Fig. 1. Due to the geographic distribution of the different industries considered, air quality benefits are concentrated in different regions of the U.S. For steelmaking, which is concentrated in the upper Midwest of the U.S., substituting hydrogen provides significant benefits in major population centers like Chicago, Detroit, and Pittsburgh. Petroleum refining is particularly concentrated along the Gulf Coast in Texas and Louisiana, and as a result, these regions see the largest reduction in PM<sub>2.5</sub> concentrations. Cement manufacturing is relatively distributed across the U.S., and so there is no one region that particularly benefits from hydrogen substitution in cement manufacturing.

The results presented so far have been normalized by the amount of hydrogen required for each industry. We report absolute results in Supplementary Fig. 9. Absolute changes in CO<sub>2</sub> emissions under each technology scenario are shown in Supplementary Fig. 9a. Due to the amount of hydrogen required to meet heat demand in petroleum refining, both SMR-CCS and ZCE hydrogen substitution in petroleum refining offset the most CO<sub>2</sub>, at approximately 150 MMT per year. Absolute changes in premature mortality are reported in Supplementary Fig. 9b. Although petroleum refining requires a larger amount of hydrogen to meet heat demand, hydrogen substitution in steelmaking still reduces premature mortality the most, with approximately 140 premature deaths averted per year.

We also estimated the percentage of the air quality-related mortality benefits that occurred in tracts previously designated by the DOE as a DAC<sup>11</sup> and compared this fraction to the Biden Administration's Justice40 initiative goal that 40% of all benefits associated with climate policy accrue to DACs. For this analysis, we only considered the air quality-related mortality benefits accruing in each community because damages from air pollution carry large external costs, and the location of these damages can be determined via air quality modeling. A more complete evaluation of all potential benefits (e.g., labor impacts) would be necessary to judge conformance with the Justice40 goal, which could be addressed in future work.

Assuming new hydrogen-fueled industrial plants are located at the existing plant locations, hydrogen substitution in petroleum refining provided the largest percentage of air quality-related mortality benefits to DACs at approximately 40%, followed by steelmaking at

35% and cement manufacturing at 30%. Only hydrogen substitution in petroleum refining met the 40% threshold based on air quality-related mortality benefits alone, while hydrogen substitution in steelmaking and cement manufacturing did not, a function of the distribution of these industries across the U.S. and their proximity to DACs. For this analysis, we assessed industry-wide hydrogen substitution; individual hydrogen substitution projects at specific industrial sites may provide more than 40% of air quality-related mortality benefits to DACs.

Considering the four metrics calculated here, we identified the co-optimal industry-hydrogen production method combination by determining the rank ordering of the scenarios for each metric and implementing a multi-criteria decision-making procedure<sup>49</sup> to identify the Pareto optimal scenarios; results of this analysis are produced in Supplementary Table 6. ZCE hydrogen technology scenarios performed equal to or better than all SMR-CCS and SMR hydrogen scenarios on each metric across industries, making ZCE hydrogen substitution the co-optimal technology based on the four metrics calculated here. ZCE hydrogen in steelmaking and petroleum refining each maximize at least one of the four metrics: steelmaking has the lowest hydrogen demand, the largest decarbonization potential per metric tonne of hydrogen used, and the largest offset of premature mortality per metric tonne of hydrogen used, while petroleum refining has the highest percentage of benefits accruing to DACs. These two scenarios are potentially co-optimal applications of hydrogen in heavy industry based on the metrics considered here.

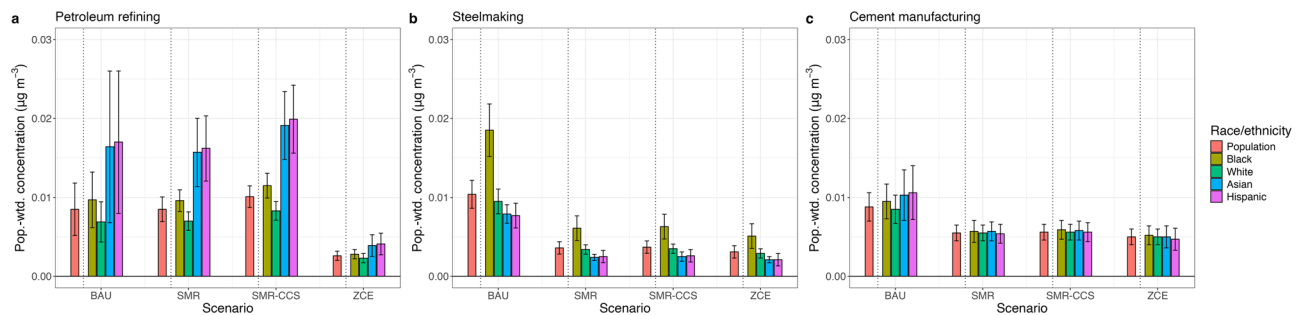
### Racial and ethnic exposure disparities

We have evaluated the percentage of air quality-related mortality benefits accruing to U.S. DACs. In this section, we evaluate the annual-average, population-weighted PM<sub>2.5</sub> concentration by race and ethnicity for each technology scenario. Racial and ethnic minorities experience higher PM<sub>2.5</sub> concentrations nationally, exacerbating existing health disparities<sup>4,5</sup>. Reduction in racial and ethnic exposure disparity is thus posited as a goal for equity-focused technology scenarios. We adopt a national, systemic view of environmental justice, considering how hydrogen substitution in these industries influences national exposure disparities of PM<sub>2.5</sub>.

Figure 2 displays the national, population-weighted, annual-average PM<sub>2.5</sub> concentrations for the total population and by race and ethnicity for each technology scenario. Our results indicate that business-as-usual (BAU) and scenario emissions from the U.S. petroleum refining and steelmaking industries have a disproportionate impact on race/ethnic minorities, but that reductions in emissions reduce absolute disparities. Under BAU operations, petroleum refining causes national, population-weighted PM<sub>2.5</sub> concentrations in Asian and Hispanic/Latino populations approximately two times higher than in the total population; similarly, BAU steelmaking operations cause population-weighted PM<sub>2.5</sub> concentrations in Black populations approximately 80% higher than in the total population. While there is some variation in national, population-weighted PM<sub>2.5</sub> concentrations from cement manufacturing by race/ethnicity, this variation is significantly smaller than for petroleum refining and steelmaking, indicating a more equal impact across race/ethnicity. Hydrogen scenarios that reduce national PM<sub>2.5</sub> exposure (all but SMR and SMR-CCS hydrogen in petroleum refining) tend to reduce PM<sub>2.5</sub> exposure disparity as well; while some disparity persists in ZCE hydrogen scenarios for all three industries, the absolute magnitude of disparity shrinks by 70–85%.

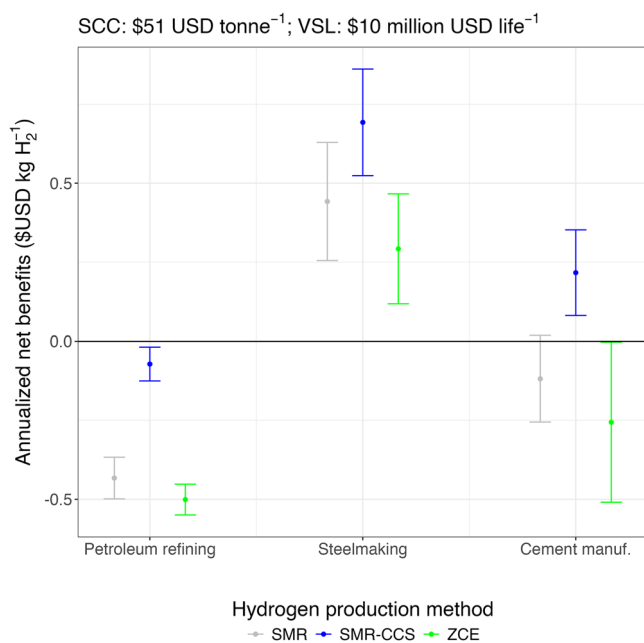
### Private and social costs

Recent U.S. legislative activity, particularly the Inflation Reduction Act (IRA), has created subsidies for clean hydrogen production, the largest of which is the 45V Hydrogen Production Tax Credit<sup>50</sup> (see Supplementary Note 3 for a discussion of other applicable U.S. tax credits). This tax credit may prompt U.S. industries to adopt clean hydrogen



**Fig. 2 | Annual average PM<sub>2.5</sub> population-weighted concentrations for the total population (Population, orange bar) and for four race/ethnicities (Black, white non-Hispanic, Asian, Hispanic/Latino) under each hydrogen production scenario (business-as-usual operations [BAU] and hydrogen production methods are steam methane reforming [SMR], steam methane reforming with carbon capture and sequestration [SMR-CCS], and zero-carbon electrolysis [ZCE]) for a petroleum refining, b steelmaking, and c cement manufacturing. Asian and**

Hispanic/Latino populations experience especially high PM<sub>2.5</sub> concentrations from emissions from petroleum refining, while Black populations experience higher PM<sub>2.5</sub> concentrations from steelmaking. ZCE hydrogen scenarios tend to “even out” annual average concentrations for race/ethnic minorities. The error bars represent the 95% confidence interval on population-weighted concentration, based on uncertainty in emissions factors.



**Fig. 3 | Summary of benefit-cost analysis. Annualized net benefits are defined as the difference between monetized air quality and climate benefits and the net private cost.** Positive values indicate net societal benefits, while negative values indicate net societal costs. Benefits are monetized using the social cost of carbon (SCC) and value of statistical life (VSL). The error bars represent the 95% confidence interval on annualized net benefits, based on uncertainties in emissions factors. Hydrogen production methods are steam methane reforming [SMR], steam methane reforming with carbon capture and sequestration [SMR-CCS], and zero-carbon electrolysis [ZCE]. All values are reported in 2022 \$USD.

technologies if the subsidy exceeds their net private cost (the difference between the cost of BAU operations and operations with hydrogen).

We estimated net private cost in each industry, normalized by the amount of hydrogen required to fully decarbonize each industry, based on 2020 prices of hydrogen production projected in the year 2020<sup>50</sup>. We then compared the net private cost to total social benefits (i.e., the sum of monetized benefits of averted CO<sub>2</sub> emissions and air quality-related premature mortality) generated by these technology scenarios. Finally, we compared the net private cost to amortized subsidies that may be provided by the 45V tax credit for each hydrogen production method (currently US\$3 per kg for our assumed CO<sub>2</sub>

intensity of ZCE hydrogen, US\$1 per kg for our assumed CO<sub>2</sub> intensity of SMR-CCS hydrogen, and US\$0 per kg for SMR hydrogen), discounting future payments to year 2022 with a discount rate of 7% over a time horizon of 10 years, to determine if existing subsidies provided by 45V are large enough to encourage hydrogen substitution in heavy industry.

Social benefits (assuming central estimates of SCC and VSL) provided by hydrogen substitution exceed the net private cost in four technology scenarios (all steelmaking scenarios and SMR-CCS hydrogen substitution in cement manufacturing) (Fig. 3). However, sensitivity analysis (Supplementary Fig. 2) reveals that the SCC and VSL value significantly influences the magnitude of social benefits. If CO<sub>2</sub> emissions are valued at US\$5 per tonne, then only two scenarios, SMR and SMR-CCS hydrogen substitution in steelmaking, are potentially socially beneficial as a result of the large air quality benefits. Conversely, if the SCC increases to US\$185 per tonne per recently scholarly work<sup>51</sup>, then all scenarios, including all SMR hydrogen scenarios apart from SMR hydrogen substitution in petroleum refining, are cost-beneficial. Similarly, if the VSL is low enough, ZCE hydrogen substitution in steelmaking is no longer cost-beneficial due to the high net private cost outweighing the mortality benefits.

Figure 4 shows that amortized 45V subsidies do not equal net private costs. In all cases, the net private cost is greater than the amortized 45V subsidy, and thus the industries considered here would not be incentivized to substitute current process heat for hydrogen based on private economic benefits alone. Table 1 reports what subsidy level is required under each technology scenario to equal net private costs (i.e., the breakeven point). We find that even under breakeven subsidy levels, net social benefit exists, suggesting that subsidies targeted at specific end-uses of hydrogen in steelmaking and cement manufacturing could be increased while still providing social benefit. A more comprehensive analysis for site-specific hydrogen substitution projects that may qualify for other financial incentives could be conducted in future work.

## Discussion

Through our analysis of various hydrogen technology scenarios, we identified two Pareto-optimal applications of hydrogen in heavy industry: ZCE hydrogen substitution in petroleum refining to replace fossil fuel combustion for process heat, and ZCE hydrogen substitution in steelmaking to supplant conventional coke-based iron reduction and process heat. These two Pareto-optimal scenarios maximize a set of objectives combining decarbonization potential, air quality-related mortality benefits, and the more equitable distribution of those mortality benefits. ZCE hydrogen provides by far the greatest benefits

of the hydrogen production methods considered here. In addition, based on assumptions made herein and current regulatory benefit values, we found that hydrogen substitution in steelmaking is cost-beneficial from a societal perspective, regardless of the production method of hydrogen. Hydrogen substitution in petroleum refining currently has too high a cost barrier and too low social benefits to provide net societal benefits, but under sensitivity (Supplementary Fig. 2 with a higher social cost of carbon), net societal benefits emerge. Additionally, while current hydrogen production is insufficient to meet demand in each of these industries, a clearer and more widespread understanding of the combined decarbonization, mortality and equity benefits of hydrogen substitution may induce more production. Further discussion of our sensitivity analysis and other considerations is provided in Supplementary Note 4.

While our work is focused on the U.S., these same technology scenarios would also have decarbonization and air quality benefits in a global context, albeit different because of differences in locations, population, industry fuel sources, etc. Much larger absolute benefits could be achieved if hydrogen substitution occurs in primary steel-making industries globally; in the U.S., only 30% of steel is produced via primary production methods, while 70% of global production of steel is primary<sup>43</sup>. However, assessing the equitable distribution of air quality benefits would require its own dedicated analysis in other national contexts. Our partial assessment of compliance with Justice40 is a policy specific to the U.S., and similar definitions of DACs would

need to be developed in any country in which this analysis is performed. Doing this same analysis at the state level is also possible, as many states have their own definitions of DACs, including Texas, Indiana, and North Carolina. Finally, the subsidies we considered for hydrogen production are specific to the U.S., and different economic analysis would need to be conducted in different countries, for example, using subsidies provided by the European Commission for clean hydrogen projects<sup>52</sup>.

Our work defined a set of hydrogen technology scenarios to reduce CO<sub>2</sub> emissions from carbon-intensive processes across a variety of industries. Future work could expand to address other industrial processes that remain large emitters of CO<sub>2</sub> or to consider alternative technology options not included here, such as point-source carbon capture and sequestration. Our modeling framework is generalizable, and offers a consistent methodology with which to evaluate climate policies with regards to air quality co-benefits and equity.

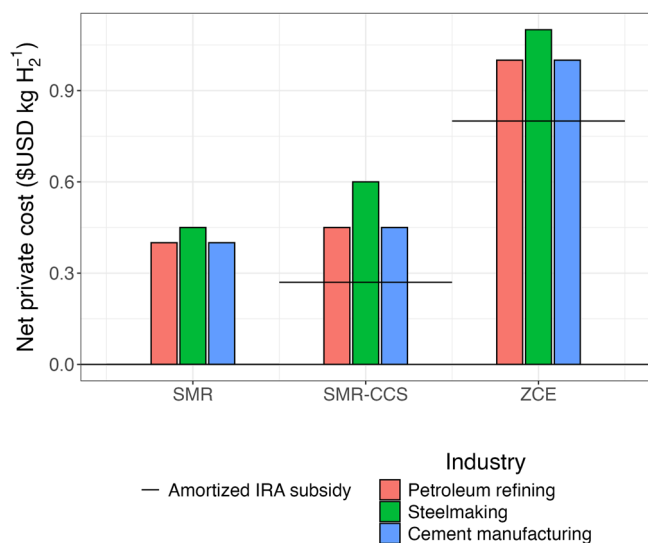
## Methods

### Technological requirements of fuel switching and system boundaries of analysis

The purpose of this section is to explicitly define the system boundaries of our analysis, which is motivated by the technological requirements of fuel switching in each industry.

In petroleum refining and cement manufacturing, relatively few changes to technology are required to facilitate a switch to hydrogen. In petroleum refineries, process heaters combust fossil fuels to directly heat process fluid, which is transported to provide heat elsewhere. Hydrogen is also used in petroleum refining as a chemical feedstock, a usage of hydrogen we did not consider here. Additionally, we did not consider the potential flaring of waste gas in petroleum refining that is currently used as a source of heat in petroleum refining, instead assuming this waste gas is freely disposed; this assumption merits future consideration in other work. Hydrogen combusts similarly to natural gas, just with a lower energy density on a volume basis and a higher flame temperature. This could necessitate new combustors for hydrogen-based operation<sup>53</sup>, but we assume that hydrogen is a drop-in substitute for natural gas, neglecting this potential capital cost. Similarly, in cement kilns, fossil fuels are combusted to directly heat the raw materials used in cement production, so few changes are required for cement kilns<sup>54</sup>. Additionally, since we assume that hydrogen production occurs on-site with existing industrial locations, costs associated with transporting hydrogen from where it is generated to where it is used are not considered.

While secondary steelmaking via an electric arc furnace (EAF) pathway can largely be decarbonized by using renewable energy to power the EAF, standard primary steelmaking is more difficult to decarbonize. Primary steelmaking is performed using the blast furnace/basic oxygen furnace (BF/BOF) technology, where iron in the form of iron oxide is heated in the presence of coke to reduce the iron oxide to pig iron within the BF and the pig iron is exposed to oxygen in the BOF to remove impurities such as sulfur and produce steel. Hydrogen-based steelmaking, typically direct reduction of iron with hydrogen (H<sub>2</sub>-DRI), functions by heating iron ore in the presence of hydrogen, which also reduces the iron oxide to produce direct



**Fig. 4 | Comparison of net private cost to amortized subsidies provided by the 45V tax credit under the Inflation Reduction Act (IRA).** In all cases, the subsidy provided by the 45V tax credit is not large enough to cover the net private cost, suggesting it is insufficient to prompt industrial decarbonization. Hydrogen production methods are steam methane reforming [SMR], steam methane reforming with carbon capture and sequestration [SMR-CCS], and zero-carbon electrolysis [ZCE]. All values are reported in 2022 \$USD.

**Table 1 | Summary of existing and predicted breakeven subsidies under four technology scenarios that provide net social benefits (see Fig. 3)**

Scenario	SMR H <sub>2</sub> in steelmaking	SMR-CCS H <sub>2</sub> in steelmaking	SMR-CCS H <sub>2</sub> in cement manufacturing	ZCE H <sub>2</sub> in steelmaking
Existing 45V subsidy (\$USD per kg)	0	1	1	3
Predicted breakeven subsidy (\$USD per kg)	1.50	2.10	1.60	4.10

Hydrogen production methods are steam methane reforming [SMR], steam methane reforming with carbon capture and sequestration [SMR-CCS], and zero-carbon electrolysis [ZCE].

reduced iron. This DRI is then fed into an electric arc furnace to produce steel. When considering a fuel switch to hydrogen within steelmaking, we assumed that existing primary steelmaking facilities would be replaced on-site by a hydrogen production plant, an H<sub>2</sub>-DRI plant, and an electric arc furnace. We do not consider decarbonization of secondary steelmaking. Additionally, we neglected emissions associated with power generation to power the electric arc furnaces, assuming this electricity is generated from a carbon-free source.

As a result of this difference in technology between industries, our analysis had different system boundaries for each industry. For petroleum refining and cement manufacturing, we only considered the net effect of the reduction in emissions associated with combustion of fossil fuels and the increased emissions from producing hydrogen, while for steelmaking, we considered the reduction in emissions associated with both production and combustion of coke as well as the increased emissions from producing hydrogen. Similarly, we only considered the fuel costs associated with hydrogen substitution in petroleum refining and cement manufacturing, assuming the capital costs of combustor upgrades would be negligible compared to fuel costs, while for substitution in steelmaking, we leveraged capital cost data from recent studies to estimate the total cost of building entirely new facilities replacing existing ones.

### Generating emissions inventories and uncertainty analysis

Emissions inventories are datasets describing where, when, and how much of a number of pollutants are emitted. For this analysis, we looked at process heat emissions from three industries (petroleum refining, primary steelmaking, and cement manufacturing) continuously emitting over the course of one year for four PM<sub>2.5</sub> precursors (primary PM<sub>2.5</sub>, NO<sub>x</sub>, SO<sub>2</sub>, and NH<sub>3</sub>). We cataloged the locations and production capacities (activity data) for each industry. For petroleum refining, we used data from the Energy Information Administration<sup>44</sup> to estimate the barrels of crude oil produced by each plant, in millions of barrels per year. For steelmaking, we used data from the American Metal Market<sup>55</sup> to estimate the amount of steel produced by each primary steelmaking facility in the U.S. For cement manufacturing, we gathered data from three tiers of sources, using the best data available. Some cement manufacturers publicly post their plant-level capacity data; these data were used when available. If these data were not available, we used reported production capacity in local newspapers. When such data were also unavailable, we used outdated Environmental Protection Agency (EPA) production capacity data<sup>56</sup>. A full list of each cement plant in the U.S., its production capacity, and the source of data is provided in the SI (Supplementary Table 4).

We estimate facility-level emissions by multiplying activity data by emissions factors. To estimate emissions factors under business-as-usual operations, we divided emissions in the EPA's National Emissions Inventory (NEI, Supplementary Tables 1 through 3)<sup>57</sup> by production capacity for each individual facility. For PM<sub>2.5</sub> and precursor emissions in each industry, we identified processes in the NEI associated with fossil fuel combustion for process heat and aggregated unit-level emissions to estimate plant-level emissions of primary PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>x</sub> associated with process heat. We then divided these plant-level emissions by plant-level production capacity to get a range of emissions factors, one associated with each plant. These generated distributions of emissions factors for each pollutant and industry pair are produced in the SI (Supplementary Fig. 3 through 8).

To account for uncertainty in emissions factors in both the business-as-usual and technology emissions inventories, we generated  $N=1000$  emissions inventories for each scenario and processed each through the InMAP source-receptor matrix to get a range of possible social costs. In the business-as-usual scenarios, we sampled from our distributions of emissions factors described in the previous paragraph for each individual industrial site, essentially “scrambling” the emissions factors across all industrial sites. For our hydrogen scenarios, we

sampled hydrogen production emissions factors from Sun et al.<sup>47</sup> using the distributions defined in that paper. We assumed that combustion of hydrogen has no associated emissions of PM<sub>2.5</sub>, SO<sub>2</sub>, or NH<sub>3</sub>, but that NO<sub>x</sub> emissions would remain at the same level as they are with fossil fuel combustion (see Supplementary Note 1 for further discussion), such that operations with hydrogen produce the same amount of NO<sub>x</sub> as business-as-usual operations. We used the InMAP source-receptor matrix (ISRM) to compute the marginal change in PM<sub>2.5</sub> concentration across the U.S. due to the marginal change in emissions in our inventories.

Additionally, we performed the same analysis described above for CO<sub>2</sub> instead of PM<sub>2.5</sub> precursors. This produces a range of emissions factors for CO<sub>2</sub> under each scenario. For steelmaking, we used facility-level CO<sub>2</sub> emissions as a surrogate for CO<sub>2</sub> emissions due to process heat. Other processes may contribute additional CO<sub>2</sub> emissions, but the bulk of the CO<sub>2</sub> emissions comes directly from fossil fuel combustion. For cement manufacturing, we also used facility-level CO<sub>2</sub> emissions due to process heat, but scaled these down to 40% of their original value to account for the fact that approximately 60% of CO<sub>2</sub> emissions from cement manufacturing come from the reduction of limestone to lime. For petroleum refining, we approximated the CO<sub>2</sub> emissions factor using emissions and energy data from the DOE<sup>32</sup>. To account for uncertainty in emissions factors in both the business-as-usual and technology emissions inventories, we generated  $N=1000$  CO<sub>2</sub> emissions estimates for each scenario.

### Impact assessment

We assessed the air quality and decarbonization benefits using standard approaches in the literature. For air quality benefits, we used the InMAP source-receptor matrix (ISRM) to estimate the change in PM<sub>2.5</sub> concentrations at the Census tract level, then combined those changes in concentrations with tract-level population data and county-level baseline all-cause mortality data to estimate the change in premature mortality at the tract level using a standard Cox hazards model with a median risk ratio of 1.078<sup>2,3,40</sup>. For decarbonization benefits, we simply summed the total change in CO<sub>2</sub> emissions for a given scenario.

We used two approaches to assess the distribution of air quality-related mortality benefits for environmental justice analysis. First, per the federal Justice40 initiative, we estimated the total air quality-related mortality benefits that accrued to Census tracts classified by the federal government as disadvantaged communities. We summed the change in premature mortality in Census tracts designed as DACs and divided by the total change in premature mortality to obtain a percentage of benefits accruing to DACs.

In the early stages of the Justice40 initiative, federal agencies are each defining their own classification of Census tracts based on metrics appropriate to the specific agency. For our main analysis, we used the DOE's definition of DACs<sup>11</sup>, which classifies a tract as a DAC or not based on aggregate performance in 36 different metrics relating to demographics, air and water pollution, and dependence on fossil fuels. For our sensitivity analysis, we redid this analysis using the Department of Transportation's (DOT) definition of DACs<sup>13</sup>. We also generated our own classification of DACs based solely on PM<sub>2.5</sub> exposure, classifying a tract as DAC if it is in the top 20% of EPA's PM<sub>2.5</sub> EJ index<sup>58</sup>.

Separately from our Justice40 analysis, we estimated the population-weighted PM<sub>2.5</sub> concentrations for the overall population and four major race/ethnic groups in the U.S. (white non-Hispanic, Black, Asian, and Hispanic/Latino) under each technology scenario, allowing us to assess how PM<sub>2.5</sub> exposure changes under technology scenarios for race/ethnic minorities. These results are presented in the SI.

### Cost-benefit analysis

We performed an analysis of the private costs associated with fuel substitution under each technology scenario as a component of our cost-benefit analysis. For our baseline scenario, we used projected natural gas prices on a per-unit-energy basis as a proxy for fuel costs in

petroleum refining and cement manufacturing, and current per-unit-steel costs for steelmaking, to assess the total private cost to industries over the next decade. For our technology scenarios, we used the amortized cost of hydrogen production by production method (SMR, SMR-CCS, and ZCE) from H2@Scale<sup>45</sup> to assess both capital and fuel costs of hydrogen production over the next decade, and obtained capital cost estimates of new steelmaking facilities from Bhaskar et al.<sup>43</sup> to assess fuel substitution in steelmaking. H2@Scale assumes a hydrogen plant lifetime of 20 years. We assumed that hydrogen can be directly substituted into burners in cement manufacturing and petroleum refining, meaning there are no capital costs associated with changing the burners in these two industries; this may underestimate the total capital costs, a point for future work. We defined the net private cost as the difference between business-as-usual operating expenses and operating expenses with hydrogen, assuming hydrogen is produced on-site. For all baseline and technology scenarios, we used a 7% discount rate to discount future costs over a time horizon of 10 years, discounting according to equation (1), where  $C_i$  represents a cost occurring in year  $i$  and  $r$  is the discount rate of 0.07. We used a 10-year time horizon due to limitations with projecting air quality impacts far in the future and a static 7% discount rate per guidance from the Office of Management and Budget.

$$NPV = \sum_{i=0}^9 \frac{C_i}{(1+r)^i} \quad (1)$$

One purpose of this paper is to quantify the external social costs associated with greenhouse gas and local air pollutant emissions in each of these industries under hydrogen technology scenarios. Our emissions inventories under policy scenarios contain both the change in emissions of CO<sub>2</sub> as well as the change in premature mortality associated with shifts in local air pollutant emissions. We assessed the social costs of these changes using a US\$51 per tonne social cost of carbon and a US\$10 million value of statistical life for premature mortality associated with air pollution. For sensitivity scenarios, we considered an increase in the SCC to US\$185 per tonne<sup>47</sup>, according to recent academic literature and policy movement, as well as a decrease in SCC to US\$5 per tonne as a lower bound. We also considered two other values for VSL, US\$1 million and US\$5 million.

## Data availability

Locations of industrial sites for each industry, along with emission factors for each industry, are available at <https://doi.org/10.6084/m9.figshare.26824078>. Source data are provided with this paper.

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## Author contributions

G.A.H., V.R., A.L.R., and P.J.A. designed the study. B.M.G. conducted the analysis. B.M.G., G.A.H., V.R., A.L.R., and P.J.A. interpreted the results of the analysis. G.A.H. and V.R. supervised the research. B.M.G. wrote the first draft of the manuscript. B.M.G., G.A.H., V.R., A.L.R., and P.J.A. contributed to revising the final draft of the manuscript.

## Competing interests

The authors declare no competing interests.

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