California Hydrogen Business Council

Hydrogen Air Quality Impact Assessment for South Coast Air Basin

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Project Report Prepared for the California Hydrogen Business Council

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Executive Summary

California is pursuing ambitious climate goals, targeting an 85% reduction in total greenhouse gas emissions from 1990 levels by 2045. Green hydrogen is a key component of this strategy, offering a promising pathway to decarbonize challenging sectors such as on-road heavy-duty vehicles. The California Air Resources Board's (CARB) Scoping Plan presents a comprehensive scenario for statewide hydrogen deployment, projecting a 1,700-fold increase in renewable hydrogen production by 2045, with 87% allocated to the transportation sector. Although the air quality and health co-benefits of clean energy transitions are widely acknowledged, the specific benefits attributable to hydrogen have not been well quantified. Such quantification is essential for accurately assessing the full value of hydrogen, clarifying the contributions of individual sectors, and determining how benefits are distributed across diverse communities.

To address this gap, this study uses an integrated modeling approach—incorporating scenario definition, vehicular emission modeling, air quality modeling, and public health assessment—to evaluate the spatial distribution of air quality and health benefits associated with hydrogen fuel cell electric vehicle (FCEV) adoption in California's on-road sectors, with a focus on the South Coast Air Basin (SoCAB) under CARB's Scoping Plan for 2045.

Key Findings:

Baseline Impacts: Without Scoping Plan measures, on-road sector emissions are estimated to result in a population-weighted average $PM_{2.5}$ concentration of 1.2 μg/m³, leading to 1,631 $PM_{2.5}$-attributable deaths annually across the SoCAB in 2045.

Emission Reductions: Adoption of FCEVs in the on-road sectors leads to a 43% reduction in NO_x emissions and a 12–18% reduction in other $PM_{2.5}$ precursor pollutants compared to the business-as-usual baseline in 2045.

Air Quality and Health Benefits: These emission reductions yield a population-weighted average decrease in $PM_{2.5}$ exposure of 0.21 μg/m³ (an 18% reduction from baseline), resulting in an estimated 296 avoided deaths annually (with a range of 132 to 300 reflecting uncertainty). The corresponding health savings are valued at $3 billion/year (ranging from $1.3 to $3.1 billion/year).

Distribution Among Communities: The benefits are not distributed evenly. Communities with higher historical pollution burdens (as indicated by higher CalEnviroScreen percentiles) receive greater air quality and health benefits from hydrogen adoption. The most disadvantaged communities (CES percentiles > 75th) receive $1.3 billion/year, accounting for 44% of the total benefits.

Sector Contributions: The heavy-duty vehicle (HDV) sector is the largest contributor, responsible for approximately 70% ($2.1 billion/year) of the total economic value of hydrogen-related benefits. Medium-duty vehicles (MDVs) contribute 15.5%, drayage trucks 8.5%, and hydrogen adoption in on-road vehicles outside the SoCAB provides 5% of the total local benefits, reflecting the regional impact of statewide actions.

Glossary

BAU	Business as usual
Caltrans	California Department of Transportation
CalVAD	California Vehicle Activity Database
CARB	California Air Resources Board
CES	CalEnviroScreen
CNG	Compress Natural Gas
DAC	Disadvantaged communities
EIC	Emission Inventory Code
EMFAC	EMission FACtors model
ESTA	Emissions Spatial and Temporal Allocator
GHG	Greenhouse Gas
HDV	Heavy duty vehicle
FCEV	Hydrogen Fuel Cell Electric Vehicle
InMap	Intervention Model for Air Pollution
ISRM	InMap Source Receptor Matrix
LADWP	Los Angeles Department of Water and Power
LDV	Light Duty Vehicle
MDA8	Maximum Daily 8-hour Average
MDV	Medium duty vehicle
NG	Natural Gas
NH_3	Ammonia
NO_x	Nitrogen Oxides
O_3	Ozone
OEHHA	Office of Environmental Health Hazard Assessment
$PM_{2.5}$	Particulate matter with a diameter of 2.5 micrometers or smaller
PHEV	Plugin Hybrid Electric Vehicle
RH2	Renewable Hydrogen
SB	Senate Bill
SLTRP	Strategic Long-Term Resource Plan
SoCAB	South California Air Basin
SO_x	Sulfur Oxides
SP	Scoping Plan
TDM	Travel Demand Model
VOC	Volatile Organic Compound
ZEV	Zero Emission Vehicle

1. Introduction

California has established itself as a global leader in the transition toward a low-carbon energy future in the coming decades. With some of the most ambitious decarbonization goals in the United States—including a statewide target[1] of carbon neutrality by 2045—the state is rapidly transforming its energy and transportation sectors to reduce greenhouse gas (GHG) emissions. Within this context, green hydrogen (hydrogen produced from renewable energy sources) has emerged as a promising solution for meeting California's climate goals, particularly for decarbonizing hard-to-abate end use sectors such as the on-road heavy duty diesel vehicles.

Several prominent energy transition plans have proposed to scale up hydrogen use in California. California Air Resources Board (CARB) released its Scoping Plan in 2022 for achieving the 2045 carbon neutrality goal, including a 1,700-fold increase in renewable hydrogen production by 2045, 87% of which is allocated to the transportation sectors (CARB 2022). A large focus of California and federal hydrogen funding programs is on projects using hydrogen fuel cell technology in medium- and heavy-duty transportation and ports. The Los Angeles Department of Water and Power's (LADWP) Strategic Long-Term Resource Plan (SLTRP) aims to use hydrogen to power all of its electricity generating units to meet regular power demand by 2035.

While the primary motivation for adopting hydrogen and other clean energy technologies is to mitigate climate change by reducing GHG emissions, these actions also deliver substantial air quality co-benefits (Wang et al. 2020; Huang et al. 2025). Fossil fuel combustion is a major source not only of carbon dioxide but also of criteria air pollutants (such as nitrogen oxides and particulate matter) and toxic air contaminants that contribute to poor air quality and adverse public health outcomes, especially in communities already burdened by air pollution (Tessum et al. 2021). In California, transportation sectors account for about 40% of GHG emissions and about 80% of nitrogen oxides (NO_x) emissions (California Air Resources Board 2021). Policies targeting GHG reductions in the transportation sectors, therefore, have the potential to simultaneously reduce emissions of these harmful co-pollutants, leading to cleaner air and improved health for Californians.

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[1] As directed in Assembly Bill 1279, the California Climate Crisis Act. (2022)

This is particularly relevant in the South Coast Air Basin (SoCAB) (***Figure 1a***), which encompasses Los Angeles, Orange, Riverside, and San Bernardino counties. The region is home to over 17 million people with a regional GDP (gross domestic product) surpassing $1.2 trillion[2]. However, it has also been recognized as one of the most polluted air basins in the United States with a long history of nonattainment for federal and state air quality standards, especially for ozone and fine particulate matter ($PM_{2.5}$). More than 35% of the SoCAB population live in communities disproportionately burdened by multiple sources of pollution as indicated by score above the 75th percentile under the CalEnvironScreen 4.0 method established under SB 535 (***Figure 1b***). The combination of high population density, heavy on-road vehicle traffic, industrial activities, and meteorological conditions conducive to pollutant formation has resulted in persistent air quality challenges and significant health impacts for local communities.

While the potential co-benefits of clean energy transitions are widely recognized, there remains a critical need to explicitly quantify both the magnitude and spatial distribution of air quality and health benefits associated with hydrogen technology adoption—especially in regions like the South Coast Air Basin, where the stakes for public health and environmental justice are especially high. Such quantification is essential for accurately assessing the full value of hydrogen, clarifying the contributions of individual sectors, and determining how benefits are distributed across diverse communities. This information is crucial for guiding policy decisions and ensuring that the transition to a hydrogen-powered transportation system maximizes benefits for both climate and public health.

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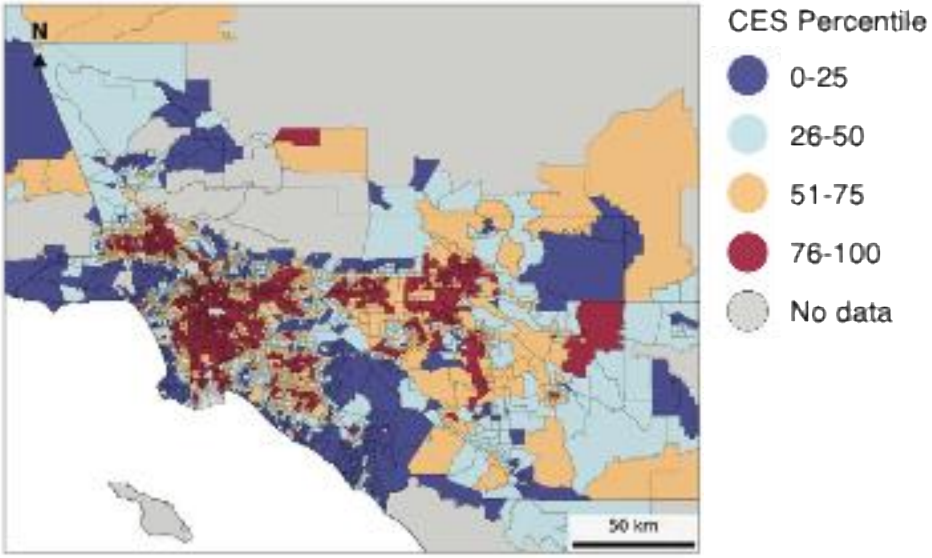
[2] Bureau of Economic Analysis, GDP by County, Metro, and Other Areas. (2023)

Figure 1: Study domain and population distribution.

(a) SoCAB Boundary

(b) CalEnvironScreen score percentile distribution



This report aims to address this need by evaluating and quantifying the air quality and health co-benefits in SoCAB associated with hydrogen fuel cell (HFC) electric vehicle adoption in California’s on-road end use scenarios defined by CARB’s Scoping Plan. In ***Section 2*** we summarize the existing literature on hydrogen air quality co-benefit studies and identifies the research gaps to be addressed by this project. In ***Section 3***, we describe the project’s data inputs and integrated modeling approach. ***Section 4*** reports the results and ***Section 5*** concludes.

2. A Brief Survey of Hydrogen Air Quality Co-Benefit Literature

California has set ambitious goals to achieve an 85% reduction of total GHG emissions from 1990 levels by 2045 and offset the rest through carbon removal strategies to achieve statewide carbon neutrality. Mitigation measures to reduce GHG emissions can synergistically reduce the co-emitted pollutants that would have been produced through the fossil fuel combustion processes, and thus lead to improved air quality and health co-benefits. The air quality and health co-benefits are important dimensions to consider when evaluating the impact of the clean energy transition because poor air quality is responsible for over eight million premature deaths per year and is now the second leading risk factor for mortality worldwide (Health Effects Institute 2024).

A large body of literature has explored the air quality and health co-benefits associated with energy system decarbonization via adoption of clean technologies (Thompson et al. 2014; Dimanchev et al. 2019; Peng et al. 2025; Huang et al. 2025; Zhao et al. 2019; Wang et al. 2020; Picciano et al. 2023). These studies estimated that in the United States, climate and clean energy policies that reduce future ambient fine particulate matter concentrations could prevent as many as 20,000 premature deaths in 2030.

Hydrogen has frequently been identified as a key component in these decarbonization pathways, particularly in hard-to-electrify sectors. However, studies that specifically isolate and quantify the co-benefits attributable to hydrogen are limited. Most scenario analyses either do not specify the share of hydrogen or its end-use applications in detail, or aggregate hydrogen with other clean technologies such as battery electrification when reporting the emission and pollution reductions. For example, in cases where hydrogen is explicitly included in the scenarios, the resulting air quality and health co-benefits are typically reported for the combined effects of both battery electric and hydrogen fuel cell technologies, making it difficult to disentangle the unique contributions of hydrogen. As a result, there remains a gap in the literature regarding the hydrogen-specific air quality and health co-benefits within broader decarbonization efforts.

Table 1 provides a summary view for a list of twelve recent (year 2016 and after) studies from peer reviewed journal articles and government reports that explicitly included hydrogen in their decarbonization scenario design. These representative studies are identified from a literature search and screening process that meet the following criteria:

- Explicit hydrogen context: the studies should explicitly identify hydrogen as a key component in their scenario design.
- Hydrogen adoption sectors/scenarios: the studies must detail specific sectors or scenarios where hydrogen is adopted.
- Co-benefits: the studies should include co-benefit evaluation in air quality and/or public health.
- Quantitative evidence: the studies should provide quantitative data to support their findings.
- California focused grey literature: grey literature, such as government reports, will be included if the geographic focus is on California, reporting results on the South Coast Air Basin.

The twelve studies can be further divided into two categories (as color coded in ***Table 1***):

- Hydrogen specific co-benefits: seven studies directly reported hydrogen specific co-benefit, or their scenario design enabled a meta-analysis to isolate the co-benefit contribution from hydrogen.
- Combined co-benefits: five studies explicitly included hydrogen in their energy scenario analyses but only reported the overall co-benefits from combined clean energy technology adoptions (such as battery electric vehicles).

We collect information on co-benefits with respect to the study regions, the types of hydrogen technologies assessed, the sectors considered, and the hydrogen life-cycle stages included. Detailed description of findings from individual studies are provided in ***Appendix A***, with key takeaways summarized below.

2.1 Overall Takeaways

Hydrogen specific co-benefits (the seven studies in purple in ***Table 1***) were evaluated for a diverse range of hydrogen technologies evaluated in various end-use sectors. Hydrogen fuel cell technology was most commonly examined technology adopted by the transportation sectors (on-road and ports) (Zhu et al. 2022; Kinnon et al. 2016; Brighty et al. 2025; Peng et al. 2021). Other technologies included pipeline blending of renewable hydrogen for combustion in natural gas end-use sectors (e.g., Kinnon et al. 2025), direct combustion of hydrogen in power plants (e.g., Heath et al. 2021), and the use of ammonia as a hydrogen carrier for energy applications (e.g., Lu et al. 2017).

Most of these studies consistently found that adoption of hydrogen technologies led to significant air quality improvements, with the most pronounced benefits observed in the transportation sectors—including both on-road vehicles and port operations—where ambient $PM_{2.5}$ concentrations were reduced by up to 2.85 $\mu g/m^3$. Notable air quality gains were also reported in natural gas end-use sectors, such as industry and buildings for heat and power, with reductions in ambient $PM_{2.5}$ up to 1.8 $\mu g/m^3$. In contrast, the use of renewable hydrogen for electricity generation in the power sector resulted in smaller decreases in $PM_{2.5}$ concentrations, typically less than 0.5 $\mu g/m^3$. This comparatively modest impact in the power sector reflects California's current dependence on natural gas, which produces lower emissions than coal and thus offers limited additional air quality benefits when replaced by hydrogen.

Conversely, the use of ammonia as a hydrogen carrier was found to have mixed impacts on air quality according to a study conducted in Japan (Lu et al. 2017). While use of ammonia hydrogen reduced summer $PM_{2.5}$ concentrations by 3.5%, it increased wintertime $PM_{2.5}$ by 11.7%. Additional ammonia was emitted due to its incomplete decomposition to hydrogen, which led to secondary $PM_{2.5}$ formation in the atmosphere. These air quality impacts should also be evaluated in additional regions and for other ammonia-based hydrogen technologies, such as direct combustion, to fully understand their effects.

2.2 SoCAB Specific Findings

The South Coast Air Basin has long faced persistent air quality challenges and associated health burdens (OEHHA 2021). These issues are driven by significant emission sources and by geographic and meteorological conditions that trap pollutants, exposing the region's dense urban populations to elevated air pollution levels. As a result, SoCAB is poised to benefit substantially from large-scale deployment of clean technologies. Notably, the California Air Resources Board's (CARB) Scoping Plan (CARB 2022) estimated that SoCAB could realize the greatest air quality improvements from statewide decarbonization efforts, with approximately $140 billion/year in avoided health costs—accounting for the largest share of the projected $200 billion/year in statewide benefits in 2045.

In CARB's Scoping Plan, hydrogen plays a significant role in the transportation sectors, accounting for 87% of the total renewable hydrogen allocated. However, the co-benefits are reported for the combined effects of decarbonization (such as adoption of battery electric and hydrogen fuel cell technologies) across all sectors (CARB 2022). The aggregated approach makes it difficult to disentangle the unique contributions of hydrogen from individual sub-sectors. Only two studies (Zhu et al. 2022; Heath et al. 2021) have specifically quantified the air quality benefits in the SoCAB region attributable to hydrogen adoption, focusing on the port and power end-use sectors; findings for other sectors remain largely unavailable. While hydrogen adoption in power and port sectors shows promise for air quality improvement, there is a clear need for further research to quantify hydrogen-specific benefits across additional sectors within the region.

Towards filling the research gaps identified above, this project determines the distributed air quality and public health benefits in SoCAB that are associated with hydrogen fuel cell adoption in California's on-road end use sectors defined by CARB's Scoping Plan. More specifically, we will quantify the spatially resolved changes in the ambient $PM_{2.5}$ concentrations associated with individual on-road sectors; monetize the health benefits of avoided mortality; and determine the benefit distributions among communities. The findings from this project are essential for accurately assessing the full value proposition of hydrogen, delineating the role of individual sectors, determining geographic distributions of benefits across the diverse communities in California's mostly populated air basin.

Table 1. Selected hydrogen air quality co-benefit studies

					Co-benefits			
Citation	**Study Region**	**Sectors Assessed**	**Lifecycle Stage of Hydrogen**	**Hydrogen Technology**	**CAP Emissions (NO_x)**	**Air Quality ($PM_{2.5}$)**	**Mortality**	**Health Benefit Valuation**
Zhu et al. (2022a)	South Coast Air Basin	Port	End use	HFC	-25 tons/day	up to -2.57 µg/m^3		$3-7M/day
Heath et al. (2021)	South Coast Air Basin	Power	End use	Combustion	-0.13 tons/day	< -0.05 µg/m^3	-1/yr	$6-9M/yr
Kinnon et al. (2025)	California	Natural gas end use sectors	End use	RH2 blend; Combustion	-50 tons/day (-6%)	-1.8 µg/m^3 (winter)	-2.44/winter	~$32M in a summer month, and ~$35M in a winter month
Kinnon et al. (2016)	California	Transportation, power; refinery	Production and end use	HFC	-52% to -100%	up to -2.85 µg/m^3		
Brighty et al. (2025)	UK	All	Production and end use	Combustion; HFC	-55.4%	-20%		
Lu et al. (2018)	Kanto, Japan	Power	End use	Ammonia Hydrogen		winter: +11.7%; summer: -3.5%	351/yr	
Peng et al. (2021)	China	Transportation and Power	Production and end use	HFC	-41%	-7.5 µg/m^3 (winter)		$2.6M/yr
Forrest et al. (2023)	South Coast Air Basin	Transportation	End use	HFC	-1,300 tons/yr			
Zhu et al. (2022b)	California	Transportation and Building	End use	HFC		-0.59 µg/m^3	-5,300/yr	$51B/yr
CARB (2022)	California	All	End use	Combustion; HFC	-598 tons/day	-3.1 µg/m^3	-20,181/yr	CA total $200B/yr SoCAB $140B/yr
Fu et al. (2024)	China	Transportation and Power	Production/ Transport/ End use	HFC	-44.7%	-2.1 µg/m^3 (-7.9%)	-4 million	
Lott et al. (2017)	UK	Energy Sectors	Production and end use	HFC; Combustion	-25%	-45%		

🟪 **Hydrogen Focused Co-benefit**

Hydrogen specific co-benefit can be quantified through study design

🟦 **Combined Co-benefit**

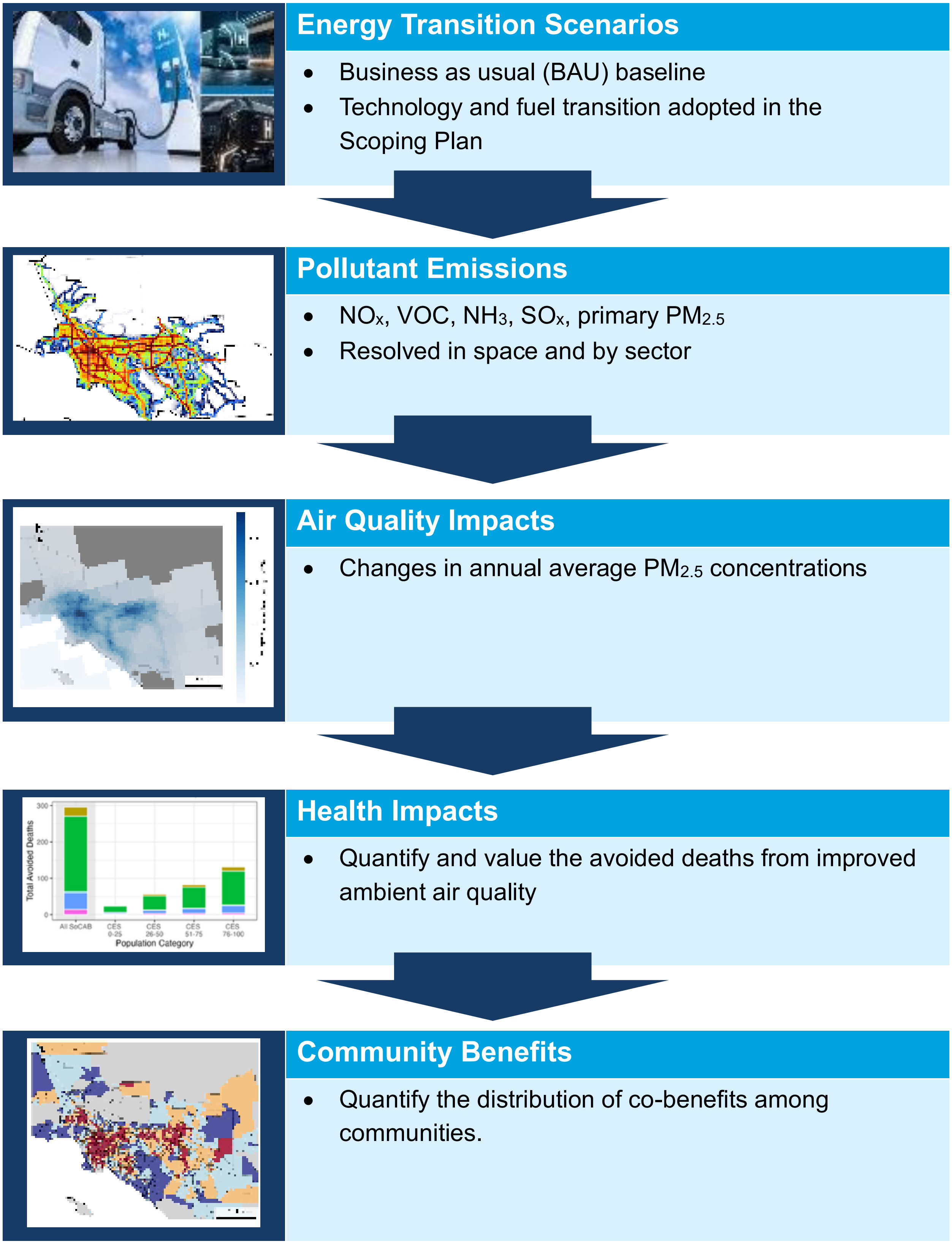
Hydrogen explicitly included in scenarios but hydrogen specific co-benefits are not isolated (co-benefits shown here are for the overall scenario)

3. Project Approach

This section provides an overview of the integrated modeling approach to support evaluation of air quality and health co-benefits in SoCAB that are associated with hydrogen fuel cell adoption in California's on-road end use sectors in CARB's Scoping Plan scenario relative to the business-as-usual baseline scenario.

Figure 2 presents the step-by-step process used for the co-benefit assessment, which integrates scenario definition, vehicular emission modeling, air quality modeling, and public health assessment. Specifically, based on the energy transition scenarios, we first perform detailed emission modeling for individual on-road sectors to estimate the spatial and temporal changes in emissions resulting from the adoption of hydrogen fuel cell technologies. Next, we use InMap (**In**tervention **M**odel for **A**ir **P**ollution), a reduced-order regional chemical transport model (Tessum et al. 2017b), to simulate the spatial differences in annual average $PM_{2.5}$ concentrations between the Scoping Plan scenario and the Baseline scenario. These spatially resolved concentration changes are then combined with population data using a concentration-response function to estimate the health outcomes associated with changes in annual $PM_{2.5}$ exposure. Finally, the geographical distribution of health impacts is quantified across communities, taking into account their historical pollution burdens as identified by CalEnviroScreen 4.0 (OEHHA 2021). Detailed descriptions of data and methods are provided in the subsections below.

Figure 2: The integrated co-benefit assessment approach.



Energy Transition Scenarios

- Business as usual (BAU) baseline
- Technology and fuel transition adopted in the Scoping Plan

Pollutant Emissions

- NO_x, VOC, NH_3, SO_x, primary $PM_{2.5}$
- Resolved in space and by sector

Air Quality Impacts

- Changes in annual average $PM_{2.5}$ concentrations

Health Impacts

- Quantify and value the avoided deaths from improved ambient air quality

Community Benefits

- Quantify the distribution of co-benefits among communities.

3.1 Scoping Plan Scenario for On-road Sectors

California Air Resources Board (CARB) released its Scoping Plan in 2022 for achieving the 2045 carbon neutrality goal, providing the most comprehensive scenario for hydrogen deployment economy-wide over the coming decades. The Scoping plan including a 1,700-fold increase in renewable hydrogen production by 2045, 87% of which is allocated to the transportation sectors (CARB 2022). The on-road sectors include light-duty vehicles (LDV), medium-duty vehicles (MDV), heavy-duty vehicles (HDV), and buses that operates throughout the road networks; and drayage trucks that typically operated between ports and warehouses and distribution centers.

For the on-road sectors, the Scoping Plan outlines a roadmap that requires 100% of new light-duty vehicle sales to be zero-emission vehicles (ZEVs)—primarily battery electric—by 2035, with vehicle miles traveled 30% below the 2019 level by 2045. It also mandates that 100% of new medium-duty and heavy-duty vehicle sales, including hydrogen fuel cell vehicles, and all drayage trucks be zero-emission by 2040. Accounting for vehicle turnover rates, these policies are projected to result in 45% of heavy-duty trucks, 20% of buses, and 15% of medium-duty vehicles operating on hydrogen fuel cell technology by 2045 according to the PATHWAYS model outputs. A business-as-usual (BAU) projection of vehicle stock and fuel consumption is also provided in the PATHWAYS model, which will serve as a baseline.

3.2 Emission Modeling

3.2.1 Projection of total emissions to 2045

The county level total emissions from the on-road sectors were previously projected to 2045 based on the vehicle stock and fuel consumption outputs determined by California PATHWAYS model (CARB 2022)[3]. Both the BAU Baseline and Scoping Plan scenarios are projected from CARB's 2020 base year emission inventory at the EIC (**E**mission **I**nventory **C**ode) level. The EICs are defined in CARB's EMFAC2014 (**EM**ission **FAC**tors model) representing specific combinations of vehicle class, fuel type, activity sector, and control technology (e.g., light-duty gasoline passenger vehicle running exhaust with catalyst, heavy-duty diesel truck brake wear). Additionally, the projection factors differ by pollutant species, including nitrogen oxides (NO_x), primary $PM_{2.5}$, volatile organic compounds (VOCs), sulfur oxides (SO_x), and ammonia (NH_3), that lead to $PM_{2.5}$ air pollution. The projection factors therefore reflect assumptions of anticipated changes in vehicle fleet composition, activity levels, fuel usage, and the implementation of statewide air quality and climate policies through 2045. The factors were then applied to the 2020 inventory, disaggregated by EIC and species, to estimate on-road emissions in 2045.

3.2.2 Isolating Hydrogen Contribution

Under the Scoping Plan scenario, mitigation strategies include the adoption of both battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs). To isolate the hydrogen specific contribution to emission reductions in 2045, we calculate the proportion of FCEVs among zero-emission vehicles (ZEVs) based on the difference in vehicle stock between the Scoping Plan and Baseline scenarios (***Figure 3***). The total vehicle stock is the same in both the Business-As-Usual (BAU) and Scoping Plan (SP) scenarios from the PATHWAYS outputs; the difference lies in the composition of the fleet. By comparing the two scenarios, we can determine the net number of FCEVs and BEVs replacing fossil fuel-powered vehicles. For example, in the heavy-duty vehicle (HDV) sector, 0.4 million diesel trucks are removed from the BAU scenario, with 62.6% replaced by FCEVs and the remainder by BEVs. Therefore, we attribute 62.6% of the emission reductions in the heavy-duty sector to hydrogen. Using the method, we determine hydrogen accounts for 62.6%, 0.1%, and 20.2% of the emission reductions in the HDV, LDV, and MDV sectors, respectively.

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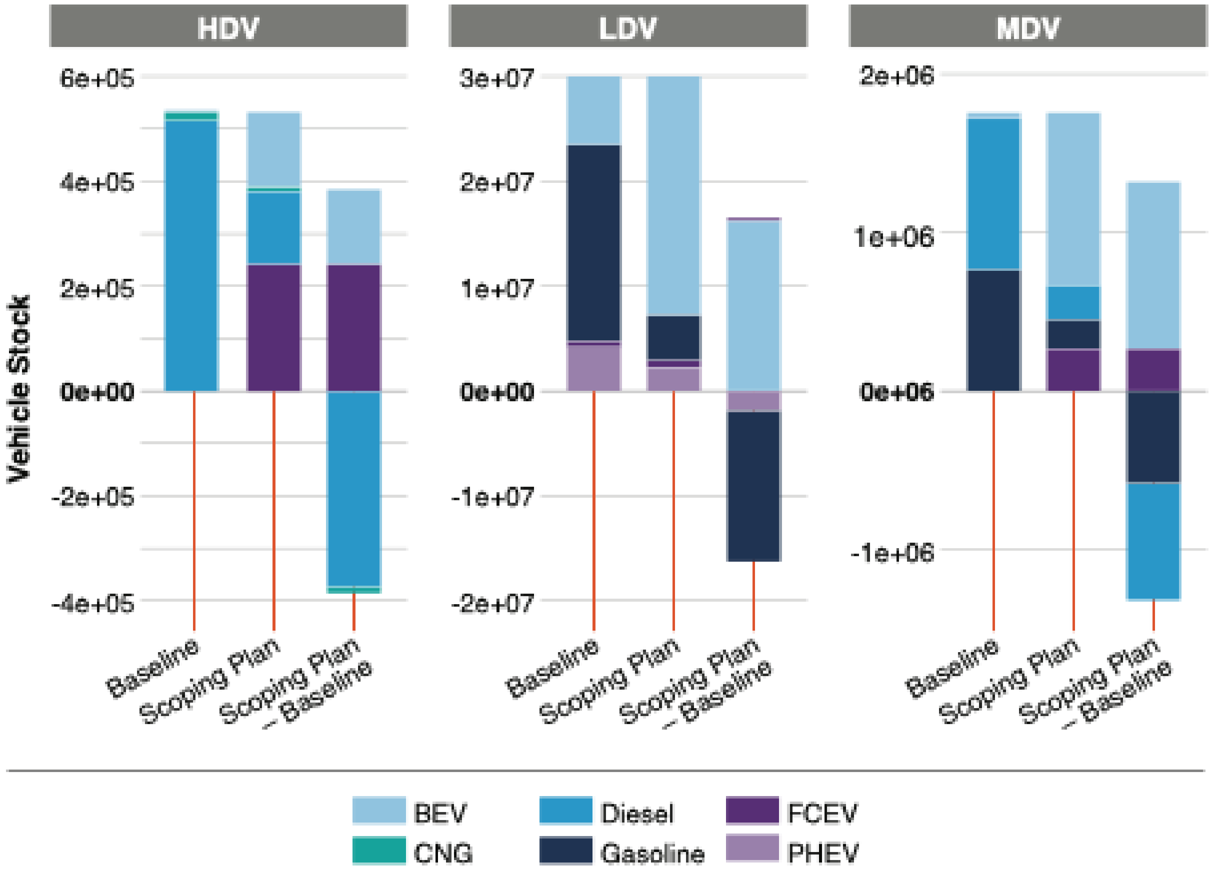
[3] See Appendix H (AB 32 GHG Inventory Sector Modeling) in the Scoping Plan documents.

Figure 3: Vehicle stock composition in 2045.



The Scoping Plan requires that all drayage trucks be zero-emission vehicles but does not specify how these should be divided between battery electric vehicles and hydrogen fuel cell vehicles. We assume 43.1% of the emission reductions is due to hydrogen according to (Forrest et al. 2023). This study determined the shares of BEVs and FCEVs among zero-emission vehicles according to the practicality of installing electric charging and hydrogen refueling stations in the area.

The absolute number and fuel composition of buses are identical between the Baseline and Scoping Plan scenarios according to PATHWAYS model outputs[4]. In each scenario, hydrogen fuel cell buses make up 20% of the bus fleet. This indicates that the Scoping Plan does not assume any additional hydrogen use beyond what is projected under the business-as-usual conditions. As a result, in this study, the bus sector does not contribute to hydrogen related emission changes in the Scoping Plan scenario relative to the BAU scenario. However, such assumption may change in current industry trends.

The above sector specific contributions of hydrogen fuel cell vehicles are incorporated into the projected changes in emissions. This approach ensures that the projected benefits of hydrogen adoption are accurately reflected in the Scoping Plan mitigation estimates.

3.2.3 Spatial Allocation

County-level on-road emissions are then spatially resolved at 1 km^2 resolution, using CARB's Emissions Spatial and Temporal Allocator (ESTA), which distributes emissions to the modeling grid based on vehicle activity and land-use data. For most vehicle types, California Vehicle Activity Database (CalVAD) was used to develop VMT-based (i.e., Vehicle Miles Traveled) spatial surrogates. For linehaul trucks, surrogates were derived from California Department of Transportation (CalTrans) Travel Demand Model (TDM), which provide more complete coverage of long-haul freight movement. Non-moving emissions, such as vehicle starts and resting losses, were allocated using city-level household data to better capture residential patterns. Idling emissions were assigned using blended surrogates, with EMFAC2014 split assumptions.

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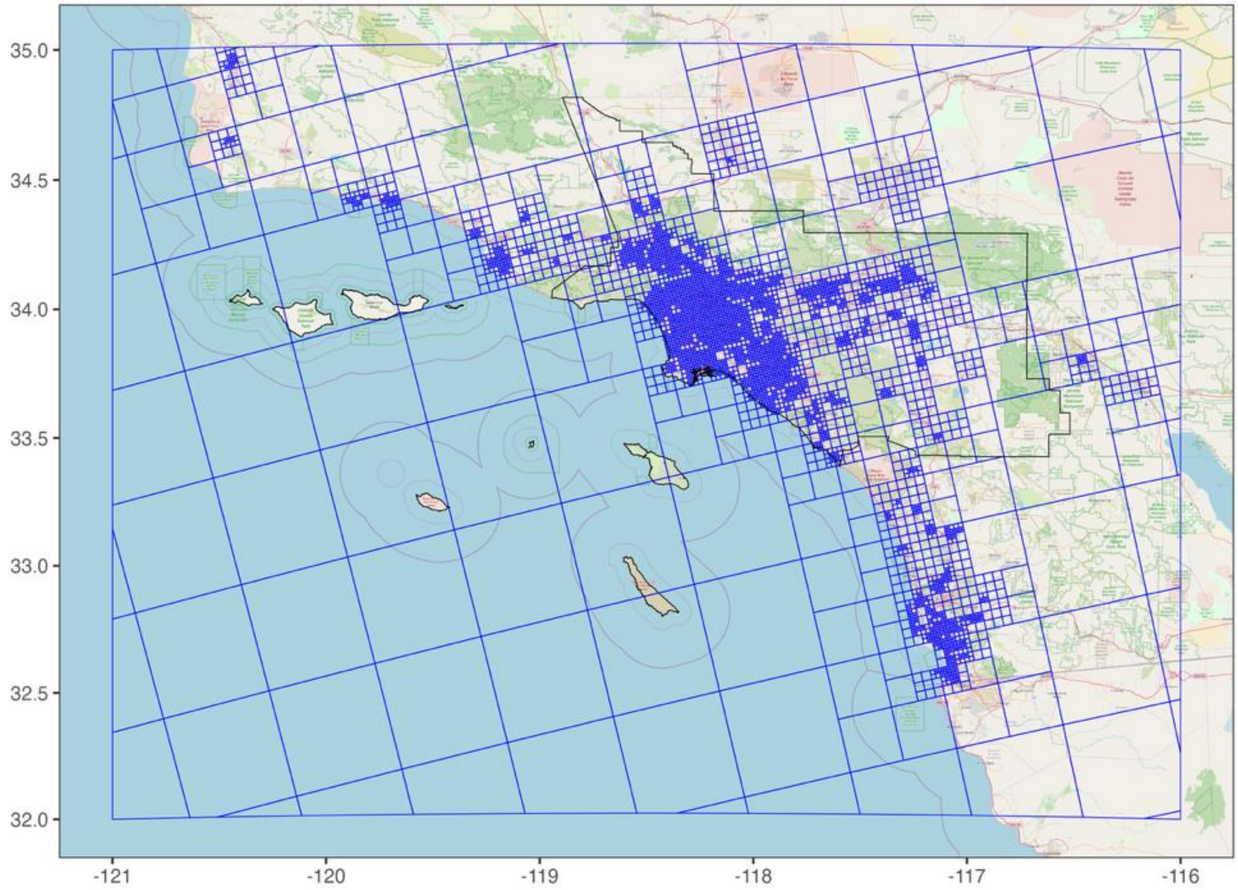
[4] Table 2-1 in Scoping Plan Report and E3's Scoping Plan PATHWAYS Model Outputs

3.3 Air Quality and Health Co-benefit Assessment

3.3.1 Air Quality Modeling

The Intervention Model for Air Pollution (InMAP) derived Source Receptor Matrix (ISRM) (Goodkind et al. 2019; Tessum et al. 2017a) was used to map the annual changes in emissions from individual on-road sectors to spatially resolved impact on $PM_{2.5}$ air pollution. InMAP (Tessum et al. 2017a) uses a simplified representation of physical and chemical processes and transformations to map changes in pollutant emissions at any given source location to the change in annual average $PM_{2.5}$ concentration, including both dispersed primary $PM_{2.5}$ and chemically formed $PM_{2.5}$ from precursors species (NH_3, NO_x, SO_2, and VOC) in a grid location. InMAP uses a variable grid, from 1 km × 1 km in densely populated areas to 48 km × 48 km in rural areas (***Figure 4***). The higher resolution InMAP/ISRM uses in more populated areas allows for reasonably accurate measures of exposure.

Figure 4: InMAP/ISRM variable grids for air quality modeling.



3.3.2 Health Outcome Analysis

InMap/ISRM further estimates the mortality resulting from the changes in $PM_{2.5}$ concentrations assuming home-based population exposures. We choose to evaluate morality as the health endpoint, because the majority (~90%) of the monetized benefits of air pollution regulations arise from reductions in premature mortality associated with exposure to fine particulate matter ($PM_{2.5}$) (NASEM 2017; CARB 2022).

In this study, the changes in mortality are determined assuming a 14% increase in mortality for every 10 $\mu g/m^3$ increase in annual average exposure to $PM_{2.5}$, as reported by Lepeule et al (Lepeule et al. 2012). We further assume that both the baseline mortality rate and population remain constant at their 2019 levels, obtained from American Community Survey[5] and the National Vital Statistics collected by Center for Disease Control and Prevention[6]. This assumption allows the health outcomes evaluated to be consistent with the CalEnviroScreen 4.0 population data used to define disadvantaged communities (OEHHA 2021).

It is important to note that the estimated health outcomes depend on (1) the choice of concentration-response relationship and (2) the population characteristics used in the analysis such as the size and age composition of the population. The main results reported in this study for the mortality outcome are based on the concentration-response function from Lepeule et al. (2012), which assumes a relatively high sensitivity of health outcomes to changes in $PM_{2.5}$ exposure. A sensitivity analysis result using the exposure-response relationship from Krewski et al. (Krewski 2009) will also be reported, which lowers the estimated number of avoided deaths by about 56%. Additionally, the main results are based on the 2019 SoCAB population to be consistent with the CalEnviroScreen 4.0 population. If population growth projections from the California Department of Finance[7] are incorporated, the estimated number of avoided deaths will increase slightly by 1.5%.

The health cost savings from avoided deaths are determined using a value of statistical life (VSL) of $10.2 million (in 2019 U.S. dollars) as recommended by U.S. EPA (EPA 2020).

Finally, the estimated health savings are quantified for census tracts grouped by their CalEnviroScreen 4.0 (CES 4.0) score percentiles to understand the geographic

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[5] The American Community Survey (ACS) is the premier source of detailed information about the nation's people and housing.

[6] Accessed at http://wonder.cdc.gov/ucd-icd10.html on Sep 30, 2024

[7] California Department of Finance. Demographic Research Unit. Report P-2A: Total Population Projections, California Counties, 2020-2070 (Baseline 2023 Population Projections; Vintage 2025 Release). Sacramento: California. Assessed April 2025.

distribution of the air quality and health impacts and benefits among heterogenous communities in SoCAB. CES 4.0 assigns each census tract a composite score based on pollution burden and population characteristics and rank order the score into percentiles, with higher percentiles indicating greater cumulative environmental and social burdens.

3.3.3 Scenario Evaluation and Sectoral Disaggregation

We use the modeling approach described above to evaluate both the baseline air quality and health impacts resulting from the 2045 business-as-usual (BAU) on-road emissions, as well as the improvements associated with hydrogen adoption in the on-road sector under the Scoping Plan for the year 2045. Baseline air pollution levels and health impacts, in the absence of Scoping Plan measures, are simulated using InMap/ISRM with on-road emissions from the BAU scenario as input. Air quality and health improvements are then estimated based on the emission reductions attributable to the adoption of hydrogen fuel cell vehicles. By quantifying both the baseline impacts and the projected improvements, we can interpret the benefits of the Scoping Plan within the context of existing conditions.

Additionally, we simulate changes in ambient $PM_{2.5}$ concentrations, population exposure, and mortality using spatially resolved on-road emissions from all subsectors as well as from individual subsectors—LDVs, MDVs, HDVs, buses, and drayage trucks—which vary in both emission magnitude and geographic distribution. This approach enables us to analyze the contributions of each subsector and identify which ones are the largest contributors to air pollution and associated health impacts.

4. Results

4.1 Emissions

The Scoping Plan scenario results in substantial reductions in pollutant emissions compared to the BAU baseline, due to measures affecting vehicle technologies, fuels, and energy demand in the on-road sectors.

Table 2 summarizes total emissions for both scenarios in 2045, as well as the overall emission reductions and those specifically attributable to hydrogen adoption, for key precursor pollutants contributing to $PM_{2.5}$ air pollution in the South Coast Air Basin. Under the Scoping Plan, total emissions are generally reduced by more than 80% relative to the BAU scenario, reflecting the combined impact of adopting zero-emission vehicles including both battery electric vehicles and hydrogen fuel cell vehicles.

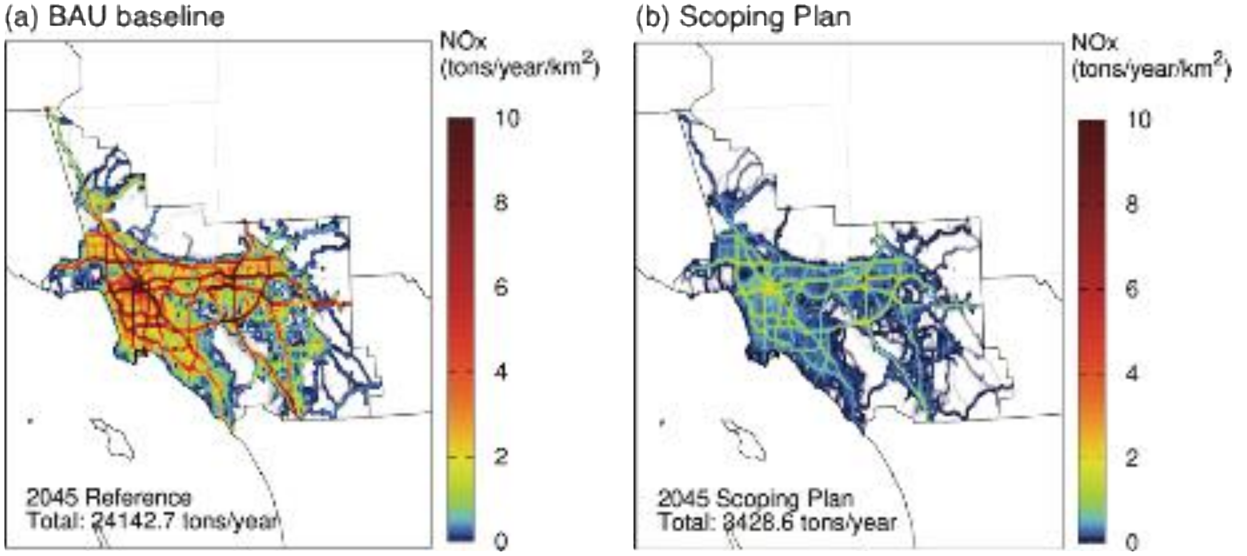
This study specifically evaluates the air quality benefits of hydrogen by isolating the emission reductions resulting from the adoption of hydrogen fuel cell electric vehicles (FCEVs), as shown in the last column of ***Table 2***. FCEVs are responsible for a 43% reduction in NO_x emissions compared to the BAU baseline, and a 12–18% reduction in other pollutants. The substantial reduction in NO_x is largely due to the heavy-duty vehicle sector, which is a major source of NO_x emissions and is projected to have the highest adoption rate of FCEVs (about 63% of the total ZEVs adopted in this sector, see ***Section 3.2.2***).

Table 2. Total On-road Pollutant Emissions and Reductions in 2045 for the SoCAB region (tons/year)

Pollutant	BAU Baseline	Scoping Plan	Total Emission Change from BAU	Hydrogen Related Change from BAU
NH_3	5,781	912	-4,869	-1,034
SO_x	319	50	-269	-54
NO_x	24,143	3,429	-20,714	-10,432
VOC	17,353	2,779	-14,574	-2,527
Primary $PM_{2.5}$	2,038	671	-1,367	-262

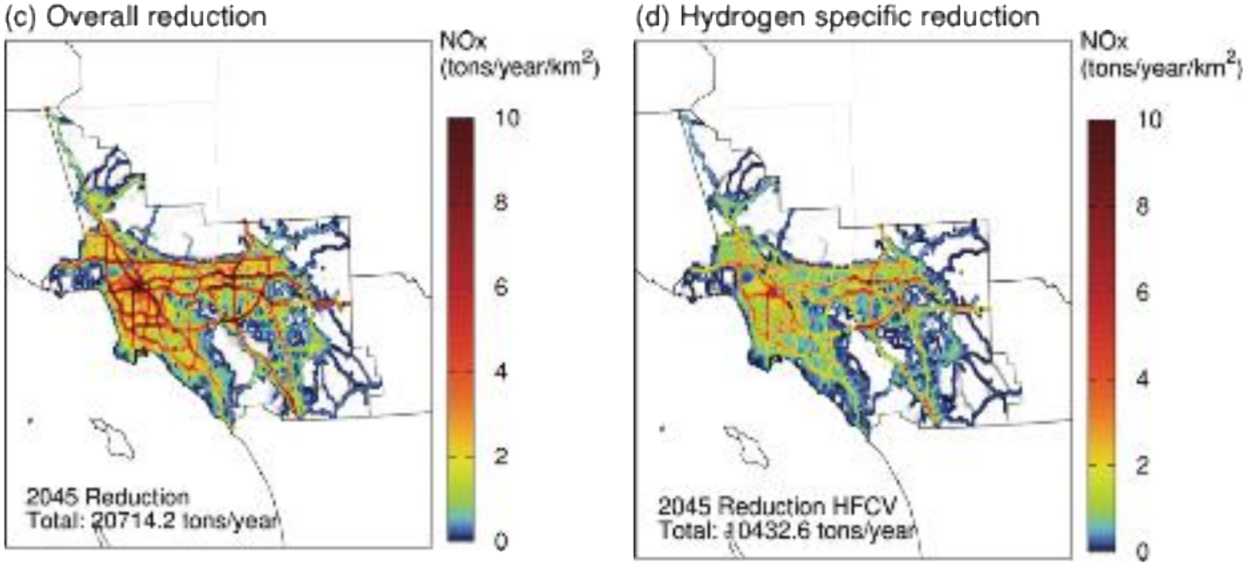
Figure 5 displays the spatial distribution of NO_x emissions from the two scenarios (***Figure 5ab***) as well as the overall and hydrogen specific emission reductions (***Figure 5cd***) in the Scoping Plan Scenario relative to the BAU baseline in 2045. As expected, both on-road emissions and emission reductions are most pronounced along major road networks and in urban areas of the SoCAB, reflecting the high concentration of vehicle activities in these regions.

Figure 5: On-road NO_x Emissions Resolved at 1 km^2 resolution in SoCAB in 2045.



(a) BAU baseline

(b) Scoping Plan



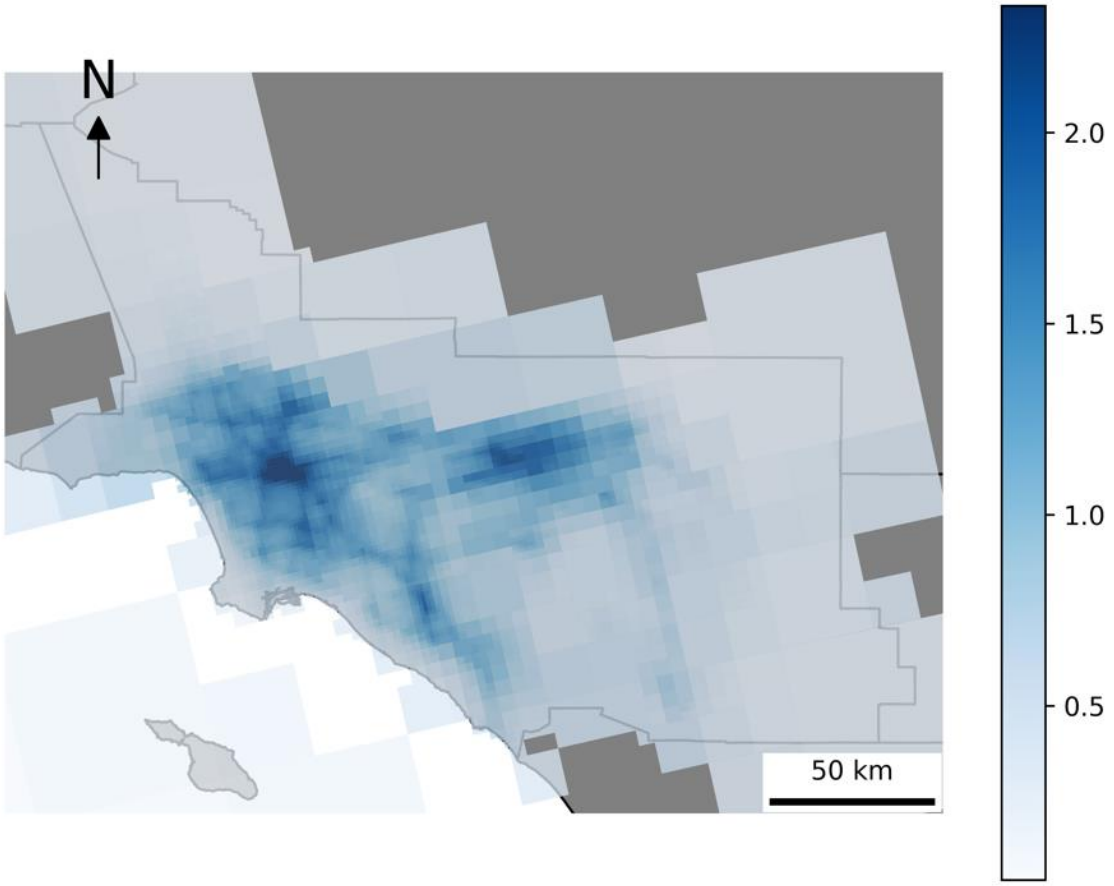
(c) Overall reduction

(d) Hydrogen specific reduction

4.2 Baseline Air Pollution and Health Impacts from On-road Sectors

Baseline air pollution levels and health impacts, in the absence of Scoping Plan measures, provide important context for assessing the relative significance of the benefits from hydrogen adoption. ***Figure 6*** presents the simulated ambient $PM_{2.5}$ concentrations resulting from on-road vehicular emissions under the BAU baseline scenario. The annual average $PM_{2.5}$ levels originated from on-road traffic are generally higher around roadways and urban areas, with peak concentrations reaching 2.7 µg/m^3 in the downtown area. The population weighted average concentration is 1.2 µg/m^3, representing the average exposure to traffic-related $PM_{2.5}$ for residents of the SoCAB. The population-weighted average concentration provides a more accurate estimate of impact of air pollution on the population by considering the spatial distribution of both the pollutant levels and the population.

Figure 6: Baseline Annual $PM_{2.5}$ Concentrations Attributed to Emissions from On-road Sectors in 2045

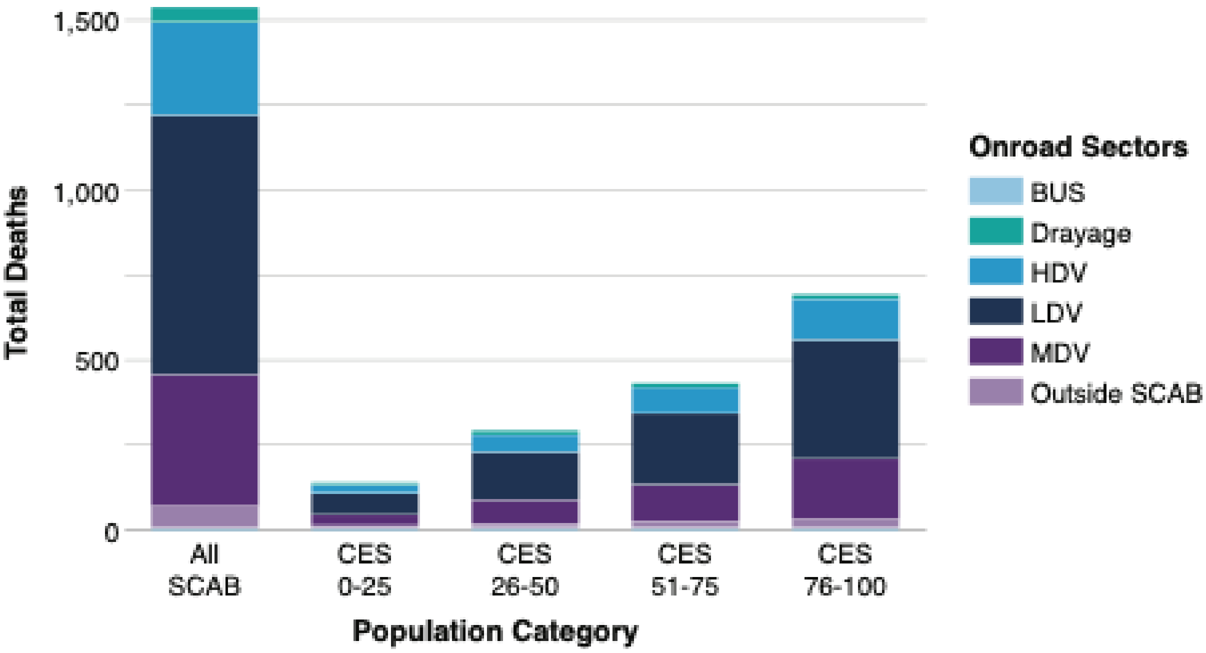


From the spatial variation in exposure to the traffic related $PM_{2.5}$, we estimate a total of 1,631 annual $PM_{2.5}$-attributable deaths across the SoCAB. When accounting for uncertainties in the number of avoided deaths (see ***Section 3.3.2***), the estimated number range from 725 to 1,655 per year.

LDVs are the largest contributing subsector, accounting for 50% of these deaths, followed by HDVs at 26% and MDVs at 18% (see the first bar in ***Figure 7***). Additionally, on-road sources originated outside of the SoCAB can be transported in the atmosphere to the region, contributing to 3% of the total deaths from traffic-related air pollution within the SoCAB.

Figure 7 further breaks down the total number of deaths by community groups, categorized according to the CalEnvironScreen (CES) percentiles. CES 4.0 assigns each census tract a composite score based on pollution burden and population characteristics and ranks them into percentiles, where higher percentiles indicate greater cumulative environmental and social burdens. Communities in higher CES percentiles generally experience a greater number of incidences of deaths. Notably, 45% of all $PM_{2.5}$-attributable deaths occur in communities ranked above the 75th percentile, highlighting a disproportionate health burden from traffic-related air pollution in these communities. Note that occupational health burdens of truck or bus drivers can also be important but yet to be quantified.

Figure 7: 2045 Baseline $PM_{2.5}$ Attributable Deaths Caused by On-road Sectors by Population Groups in the BAU Scenario.



4.3 Air Quality Improvements from On-road Hydrogen End Uses

Emission reductions through the hydrogen fuel cell vehicle adoption in the on-road sectors lead to widespread of air quality improvements, with the most pronounced decrease in annual average $PM_{2.5}$ levels (up to 0.51 μg/m^3) occurring near major highway corridors (***Figure 8***). This pattern aligns with the areas of the highest emission reductions shown in ***Figure 5d***. These reductions correspond to a population-weighted average decrease of 0.21 μg/m^3, representing an 18% reduction from the baseline level reported in ***Section 4.2***.

Figure 8: Hydrogen-related Changes in Annual $PM_{2.5}$ Concentrations by On-road Sectors.

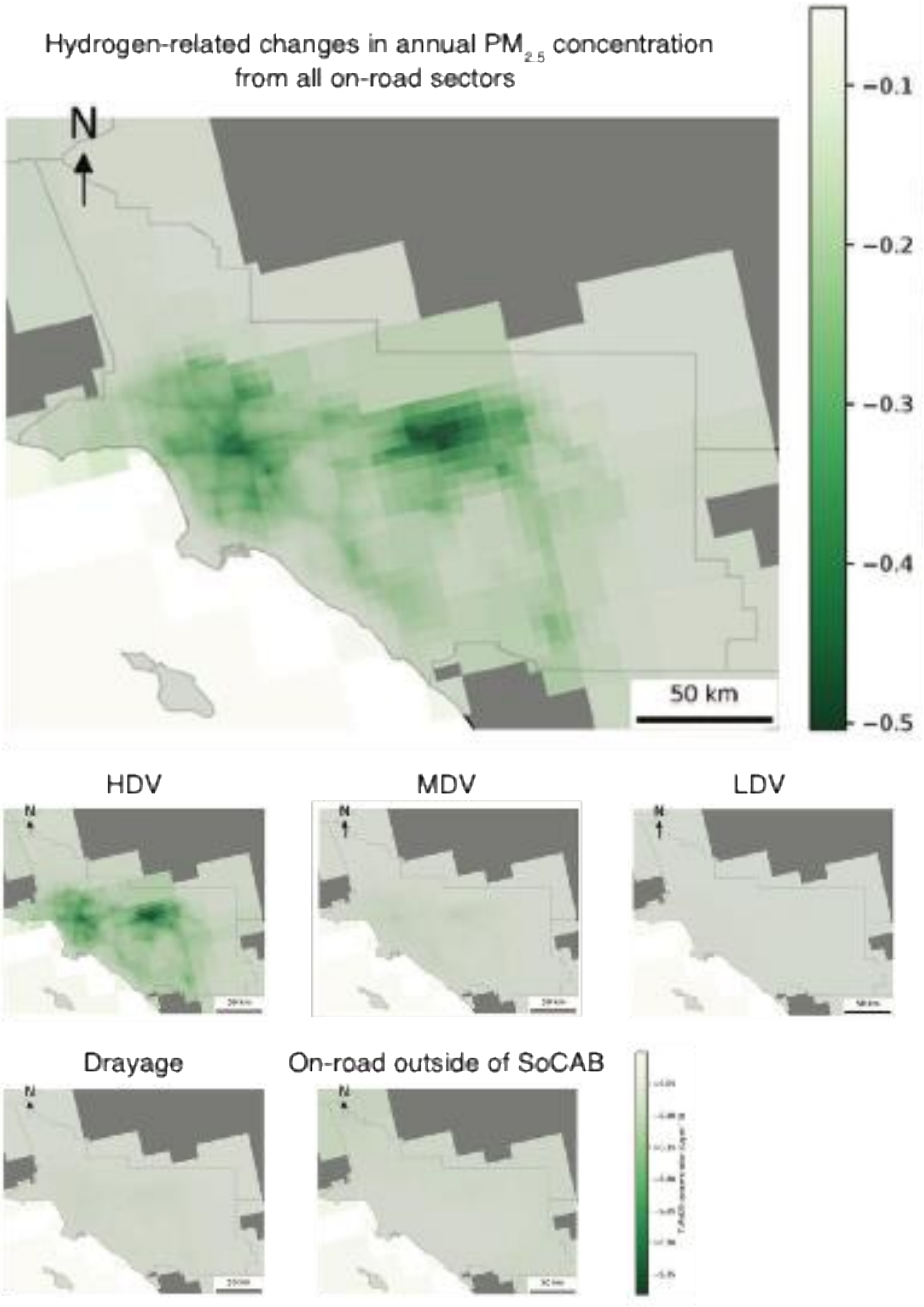
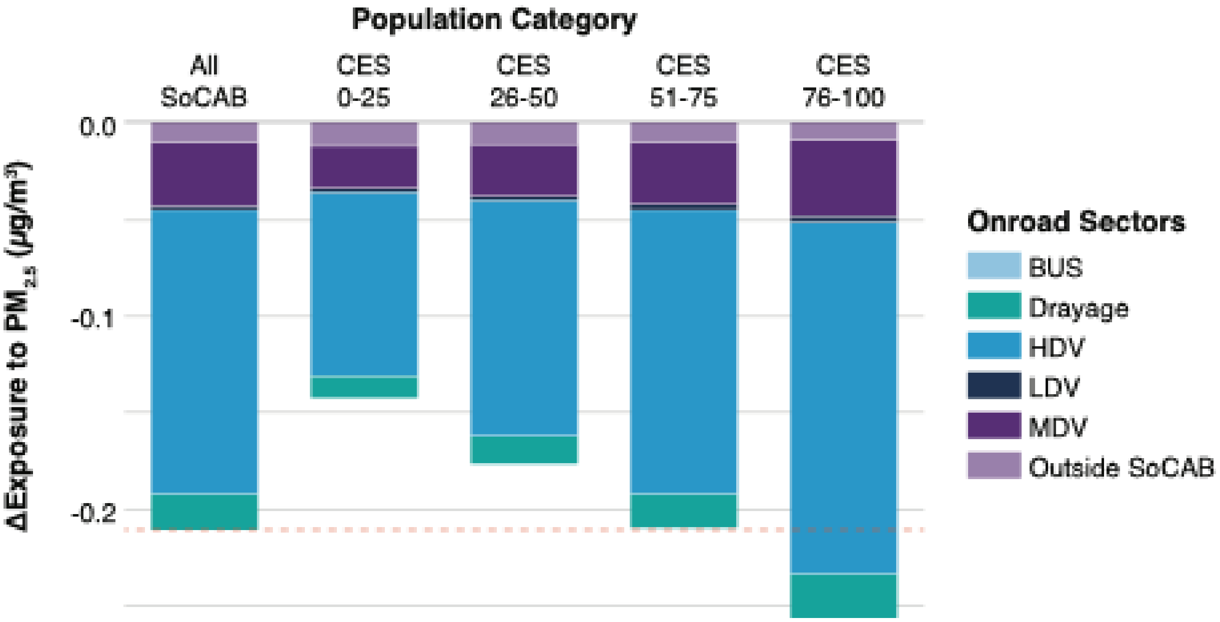


Figure 8 further breaks down the air quality improvements by on-road subsector, highlighting the dominant role of the HDV sector. As shown in ***Figure 9***, the HDV sector accounts for approximately 70% of the total reduction in $PM_{2.5}$ exposure across the SoCAB from the FCEV adoption under the Scoping Plan scenario relative to the BAU baseline. Furthermore, communities with higher historical pollution burdens (as indicated by higher CES percentiles) experience higher reduction in traffic-related $PM_{2.5}$ exposure. This result highlights the role of FCEV adoption in the on-road sectors contributing to narrowing the disparity of exposure to traffic related air pollution across communities.

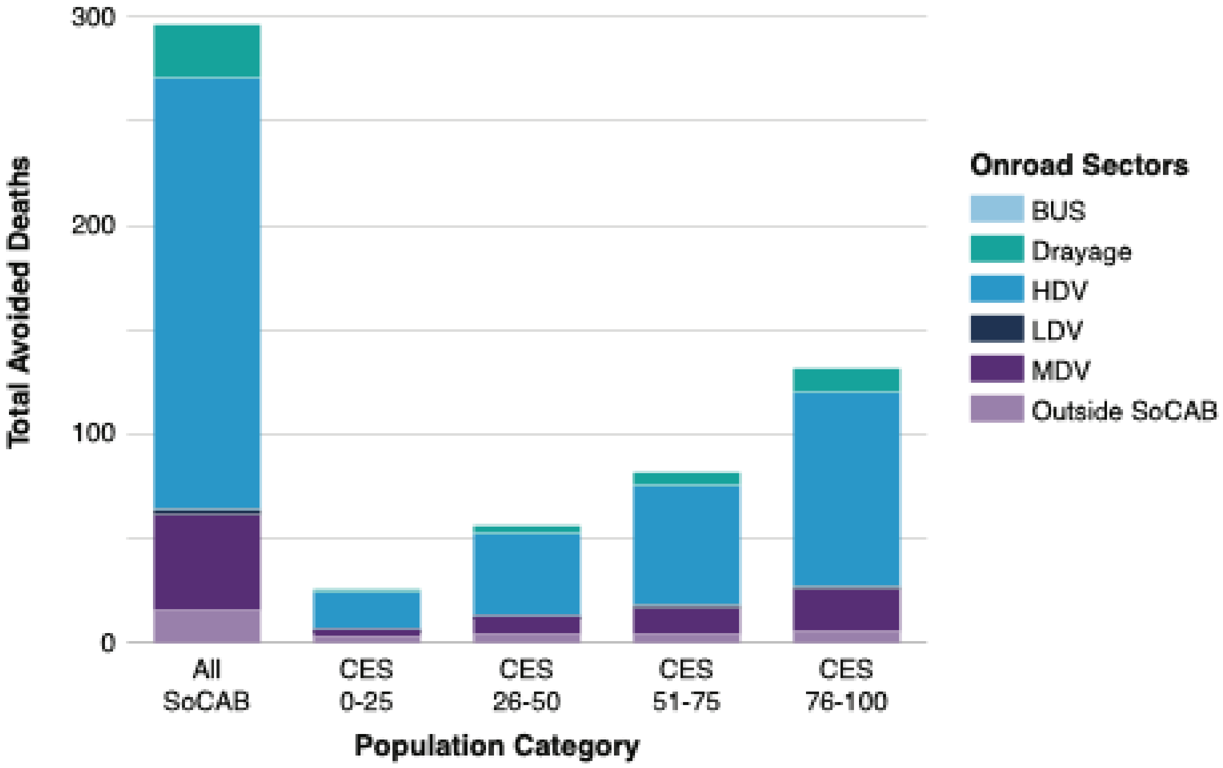
Figure 9: Change of Exposure to $PM_{2.5}$ from Hydrogen Use in the On-road Sectors under Scoping Plan relative to the BAU in 2045.



4.4 Health Benefits and Valuation

The reductions in the annual $PM_{2.5}$ exposure from FCEV adoption in the on-road sectors under the Scoping Plan are estimated to avoid a total of 296 incidence of all-cause mortality across the SoCAB (see the first bar in **Figure 10**) in 2045. When accounting for uncertainties in the number of avoided deaths (see **Section 3.3.2**), the estimated number range from 132 to 300. This represents approximately 18% of the baseline mortality attributable to the on-road sectors emissions in the BAU scenario. A greater number of avoided deaths occur in communities with higher historical burdens as indicated by higher CES percentiles (***Figure 10***).

Figure 10: Avoided Deaths from Hydrogen Use in the On-road Sectors under Scoping Plan in 2045



Notable health benefits, reflected in the economic value of the avoided deaths, are associated with FCEV adoption in the on-road sector. In total, the benefits amount to $3.0 billion/year the SoCAB in 2045. When accounting for uncertainties in the number of avoided deaths, the estimated benefits range from $1.3 billion/year to $3.1 billion/year.

As shown in ***Figure 11***, the majority of these benefits are concentrated in more disadvantaged communities indicated by higher CES percentiles. The most disadvantaged communities (CES percentiles > 75th) receive $1.3 billion benefits, accounting for the largest share (44%) of the total benefits.

Figure 11: Economic Value of Hydrogen Related Health Benefits Received by the Community per year

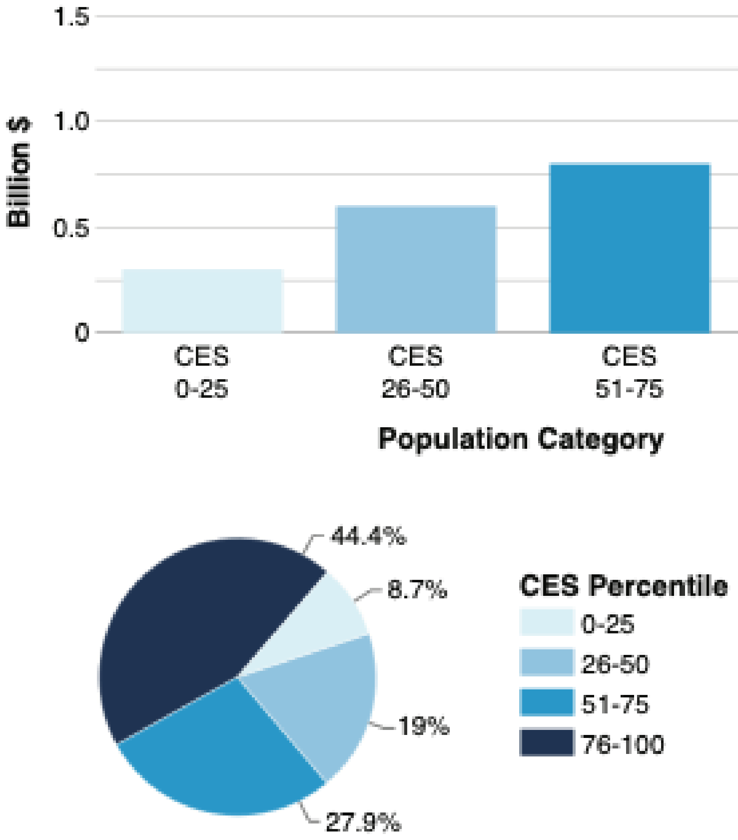
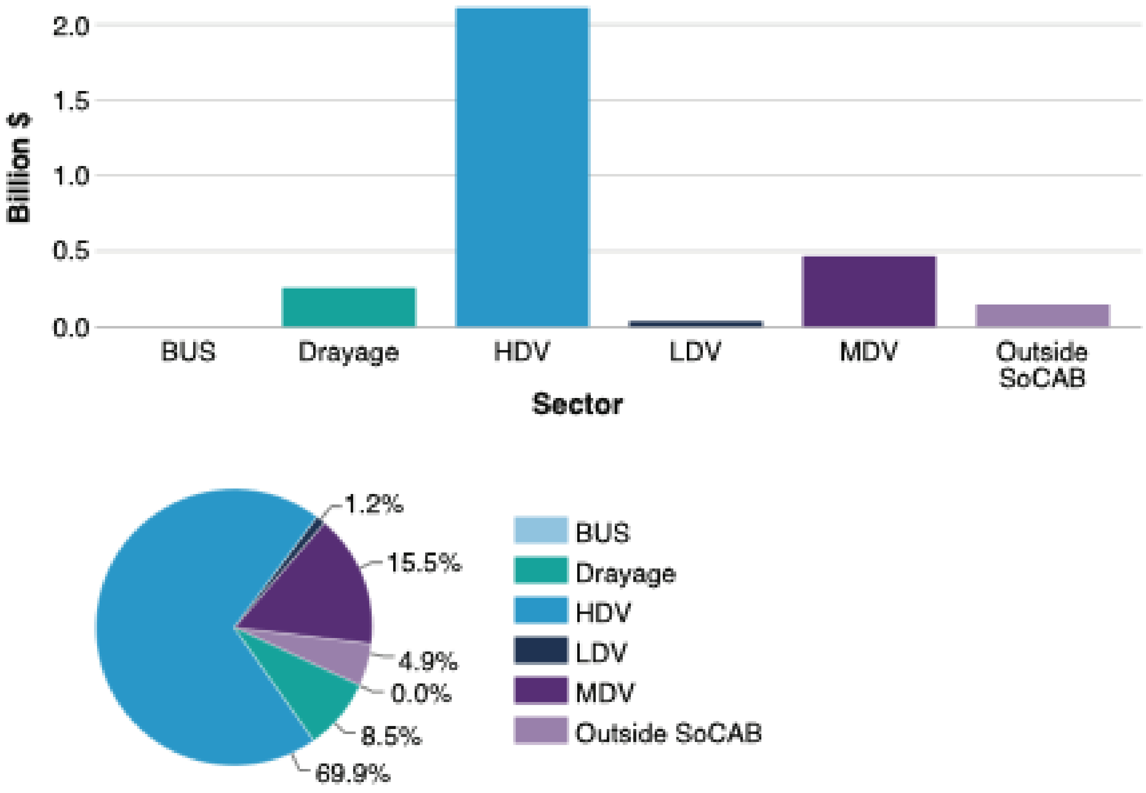


Figure 12 presents the sectoral contributions to the health benefits. Consistent with earlier findings on exposure reduction, the HDV sector is the largest contributor to hydrogen related health benefits, accounting for approximately 70% ($2.1 billion/year) of the total economic value. Other sectors also contribute to the total benefits in the SoCAB, with the MDV sector contributing 15.5% and drayage trucks contributing 8.5%. In contrast, hydrogen use in light-duty vehicles and buses make minor contributions under the Scoping Plan scenario. Additionally, hydrogen adoption in on-road vehicles outside the SoCAB provides 5% of the total benefits within the air basin, as cleaner air is transported into the region. This highlights the regional impact of statewide actions.

Figure 12: Sectoral Contributions to the Economic Value of Hydrogen Related Health Benefits



5. Conclusions

This study employs an integrated modeling approach—combining scenario definition, vehicular emission modeling, air quality modeling, and public health assessment—to evaluate the spatially distributed air quality and health benefits associated with hydrogen fuel cell technology adoption in California's on-road sectors, as outlined in CARB's Scoping Plan for 2045.

In the absence of Scoping Plan measures, baseline air quality impacts from the on-road sectors in 2045 are estimated to result in a population-weighted average $PM_{2.5}$ concentration of 1.2 μg/m³, leading to a total of 1,631 $PM_{2.5}$-attributable deaths annually (ranging from 725 to 1655 when considering uncertainties) across the South Coast Air Basin.

Adopting hydrogen fuel cell vehicles in the on-road sectors leads to a substantial 43% reduction in NO_x emissions compared to the business-as-usual baseline, and a 12–18% reduction in other precursor pollutants that contribute to $PM_{2.5}$ air pollution. These emission reductions translate to widespread improvements in air quality, with a population-weighted average decrease in $PM_{2.5}$ exposure of 0.21 μg/m³—an 18% reduction from baseline levels. As a result, an estimated 296 deaths (ranging from 132 to 300 when considering uncertainties) are avoided annually across the South Coast Air Basin in 2045, corresponding to health savings of $3.0 billion/year (ranging from $1.3 to $3.1 billion/year).

Communities with higher historical pollution burdens (as indicated by higher percentiles of CalEnvironScreen score) receive greater hydrogen related air quality and health benefits. In particular, the most disadvantaged communities (CES percentiles > 75th) benefit the most, receiving $1.3 billion/year benefits, accounting for the largest share (44%) of the total benefits.

The heavy-duty vehicle sector is the primary contributor to the hydrogen related co-benefits under the Scoping Plan, accounting for approximately 70% ($2.1 billion/year) of the total economic value. Other sectors also contribute to the total benefits in the SoCAB, with the MDV sector contributing 15.5% and drayage trucks contributing 8.5%. Additionally, hydrogen adoption in on-road vehicles outside the SoCAB provides 5% of the total benefits within the air basin, reflecting the regional impact of statewide actions.

The findings on sectoral contributions underscore the important role of hydrogen fuel cell technologies in replacing diesel trucks as projected by the Scoping Plan. Heavy-duty diesel trucks are typically challenging to electrify with battery electric powertrain due to issues such as limited range, long refueling times, and the need for higher payload capacity. By addressing these barriers, hydrogen fuel cell vehicles offer a practical solution for decarbonizing the heavy-duty sector and delivering substantial health and economic benefits.

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Appendix A:

Literature Summary

This appendix section provides detailed description of findings from individual studies in the selected literature listed in ***Table 1***.

Seven studies directly reported hydrogen specific co-benefit, or their scenario design enabled a meta-analysis to isolate the co-benefit contribution from hydrogen.

Zhu et al. (Zhu et al. 2022) focused on port operation; evaluated hydrogen deployment in the transportation sector of the South Coast Air Basin, with 75% fuel cell electric trucks (FCET) and 79% heavy-duty fuel cell trucks (HDFCT). At full end-use implementation, the study estimated reductions of 35 tons/day in NO_x and 65 tons/day in PM emissions. These changes led to significant air quality improvements, including a 5.1 ppb peak reduction in 8hr O_3 and 2.57 μg/m^3 peak reduction in daily $PM_{2.5}$ concentrations. Moreover, the improvements in ozone and $PM_{2.5}$ attain benefits to public health ranging from $3,209,700 to $7,108,100 per day for short-term exposure, which is a conservative estimate.

In the LA100 study, Heath et al. (Heath et al. 2021) quantified the air quality and health effects due to air pollutant emissions reductions from changes in the power sector, changes in electrification of end-use sources, and from combined changes in power sector and end-use electrification in 2045. Only the power sector explicitly considered contribution from hydrogen, assuming LADWP-owned power plants to burn 100% hydrogen by 2045 to the extent they are utilized. We derived the hydrogen specific contribution from their scenario design for the power sector, with estimated reduction of 0.13 tons/day NO_x, and 0.03 tons/day $PM_{2.5}$ emissions, and reduction of exposure less than 0.05 μg/m^3 for $PM_{2.5}$ and 0.05 ppb for O_3, leading to avoided deaths about 1 person per year and health savings of 6-9 million dollars.

Kinnon et al. (Kinnon et al. 2025) evaluated the integration of 20% renewable hydrogen (RH_2) in California's power sector by 2035. The end-use hydrogen deployment led to a 4.0 ppb reduction in summer ozone concentrations and a 1.8 μg/m^3 decrease in winter $PM_{2.5}$ levels in the managed case. These air quality improvements were associated with 1.37 and 2.44 fewer premature deaths due to lower ozone and $PM_{2.5}$ exposure, respectively.

Kinnon et al. (Kinnon et al. 2016) examined the effects of fully replacing heavy-duty vehicles with hydrogen-fueled alternatives in California. Considering both production and end-use stages, the study found emissions from power sectors were reduced by up to 75%, light-duty and heavy-duty vehicle were reduced by up to 100%, and petroleum fuel infrastructure by up to 52%. These emission reductions were associated with notable air quality improvement, including 4.23 ppb peak reduction in 8-hr O_3 and 0.62 $\mu g/m^3$ peak reduction in daily $PM_{2.5}$ concentrations (based on the 100% hydrogen in HDV scenario).

Brighty et al. (Brighty et al. 2025) projected a 55.4% reduction in NO_x emissions in UK energy and end use sectors under a full hydrogen evolution scenario, which led to 60% and 20% reduction in NO_x and $PM_{2.5}$ exposure concentration, respectively.

Lu et al. (Lu et al. 2017) analyzed hydrogen use in the power sector in Kanto, Japan, assuming 20% of electricity consumption sourced from hydrogen. While hydrogen deployment led to a slight summer reduction in $PM_{2.5}$ concentrations (-3.5%), it increased wintertime $PM_{2.5}$ by 11.7%, resulted in estimated 351 additional premature deaths. This study attributed the $PM_{2.5}$ increase to additional NH_3 emissions from incomplete decomposition of NH_3 to hydrogen used for combustion, highlighted potential unintended consequences of hydrogen use without emission control.

Peng et al. (Peng et al. 2021) assessed a scenario in China combining max adoption of alternative energy vehicles (50-100%) with 85% renewable energy for hydrogen production. Focusing on the production and end-use stage, the study reported 41% reduction in NO_x and 15% reduction in $PM_{2.5}$ emissions. These improvements translated into decreases of 4.9 ppb in summer MDA8 O_3 and 7.5 $\mu g/m^3$ in winter $PM_{2.5}$ population-weighted concentrations, which yields estimated health benefits valued at \$2,500/day for O_3 and \$4,600/day for $PM_{2.5}$.

Five studies explicitly included hydrogen in their energy scenarios analyses but only reported the overall co-benefits from combined clean energy technology adoptions (such as battery electric vehicles).

Forrest et al. (Forrest et al. 2023) analyzed partial hydrogen adoption across three classes of medium- and heavy-duty vehicles in South Coast Air Basin: drayage, long-haul, and transit. With hydrogen penetration levels of 40%, 45-50%, and 12%, respectively, the study estimated notable NO_x reduction: 1,200 tons for drayage, 4,000 tons for long-haul, and 115 tons for transit; and $PM_{2.5}$ reduction: 15 tons for drayage, 1 ton for transit, and no changes in long-haul vehicles.

Zhu et al. (Zhu et al. 2022) estimated that statewide, total avoided deaths were ~6,100 under the building electrification scenario and ~5,300 under the truck electrification scenario. Focusing on disadvantaged communities, which include most of the value of statistical life (VSL) and many areas of SoCAB, the building electrification scenario would avoid ~1,800 deaths in comparison to ~1,500 avoided by the truck electrification scenario, or 28.9% and 29.3% of statewide totals in each case, respectively. Statewide, applying the VSL of $9.70 million per life, the economic value of deaths avoided in the building electrification and truck electrification scenarios in 2050 were estimated to be $59 billion and $51 billion, respectively.

CARB's Scoping Plan (CARB 2022) estimated emission reductions of NO_x by 598 tons/day, $PM_{2.5}$ by 94.8 tons/day; VOCs by 267 tons/day. The state level reduction in criteria air pollutant emissions leads to significant improvement in air quality, reducing annual exposure to $PM_{2.5}$ by 3.1 $\mu g/m^3$ and O_3 by 2.7 ppb, and avoiding 20181 deaths. The Scoping Plan found that (1) significant health benefits in $200 billion/year health cost saved, with the greatest benefits anticipated in the SoCAB region (~$140 billion/year), and (2) disadvantaged communities realize roughly 36% of health benefits in 2035 and in 2045 in terms of costs avoided.

Fu et al. (Fu et al. 2024) evaluated a scenario in China with 21% hydrogen and 79% electric and alternative energy vehicles, considering emissions across the production and end-use stages. The study found substantial emission reductions, with NO_x and $PM_{2.5}$ decreasing by 44.7% and 20.9%, respectively. These changes led to population-weighted average O_3 reduced by 0.57 ppb and $PM_{2.5}$ reduced by 2.1 $\mu g/m^3$, preventing estimated 0.197 million and 4.22 million premature deaths related to O_3 and $PM_{2.5}$ exposure, respectively.

Lott et al. (Lott et al. 2017) projected that decarbonization of the UK energy sector from 2010 to 2050 could lead to a 45% reduction in $PM_{2.5}$ concentrations. The differences in NO_x emission levels in 2050 across scenarios were also notable, with an additional 25% (125 kt) and 18% (84 kt) reduction in emissions in the low GHG scenario compared to the base and reference cases.